



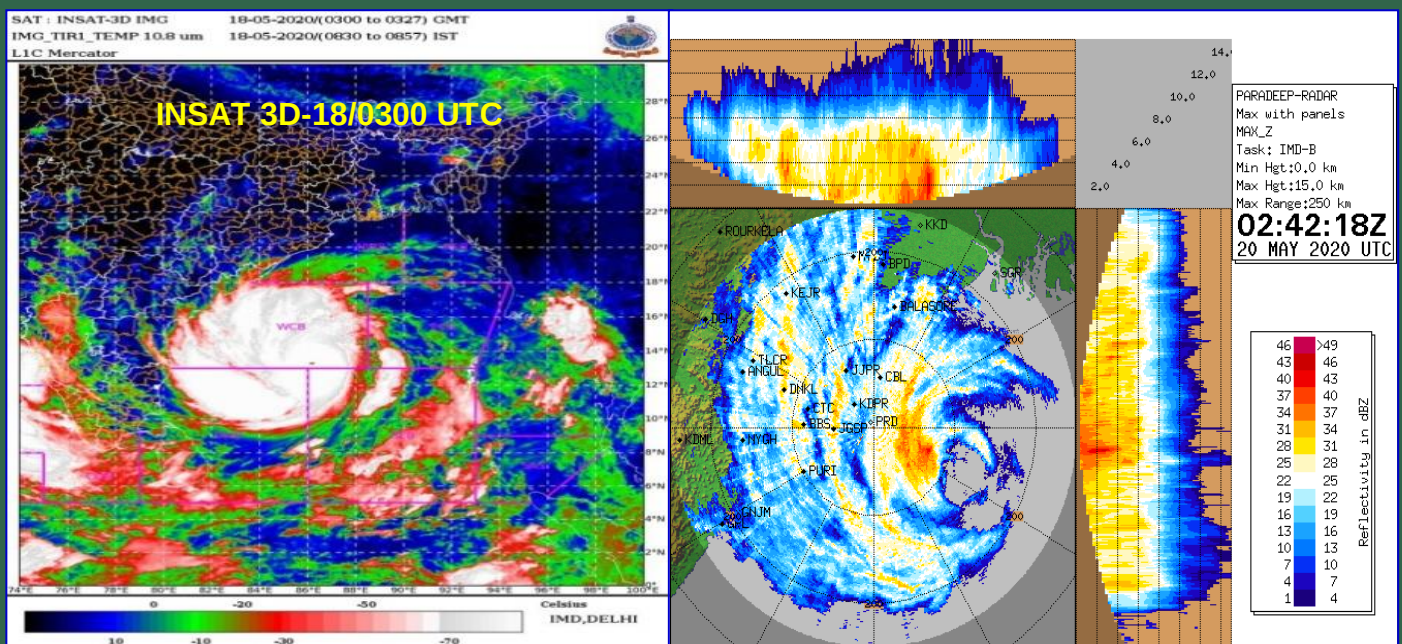
World Meteorological Organisation



Government of India
Ministry of Earth Sciences
India Meteorological Department

No. MOES/IMD/RSMC-Tropical Cyclone Report/01 (2021)/11

REPORT ON CYCLONIC DISTURBANCES OVER NORTH INDIAN OCEAN DURING 2020



SATELLITE AND RADAR IMAGERY OF SUPER CYCLONIC STORM, "AMPHAN"

RSMC-TROPICAL CYCLONES, NEW DELHI

JANUARY, 2021



INDIA METEOROLOGICAL DEPARTMENT



RSMC- TROPICAL CYCLONES, NEW DELHI

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12.	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 2020. 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.

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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, India, Iran, Maldives, Myanmar, Pakistan, Qatar, Sultanate of Oman, Sri Lanka, Thailand, United Arab Emirates, Saudi Arabia 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.
- Organisation of annual training on tropical cyclone monitoring and prediction as well as associated severe weather forecasting and warning services for WMO/ESCAP Panel countries.

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°E and 100°E 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.

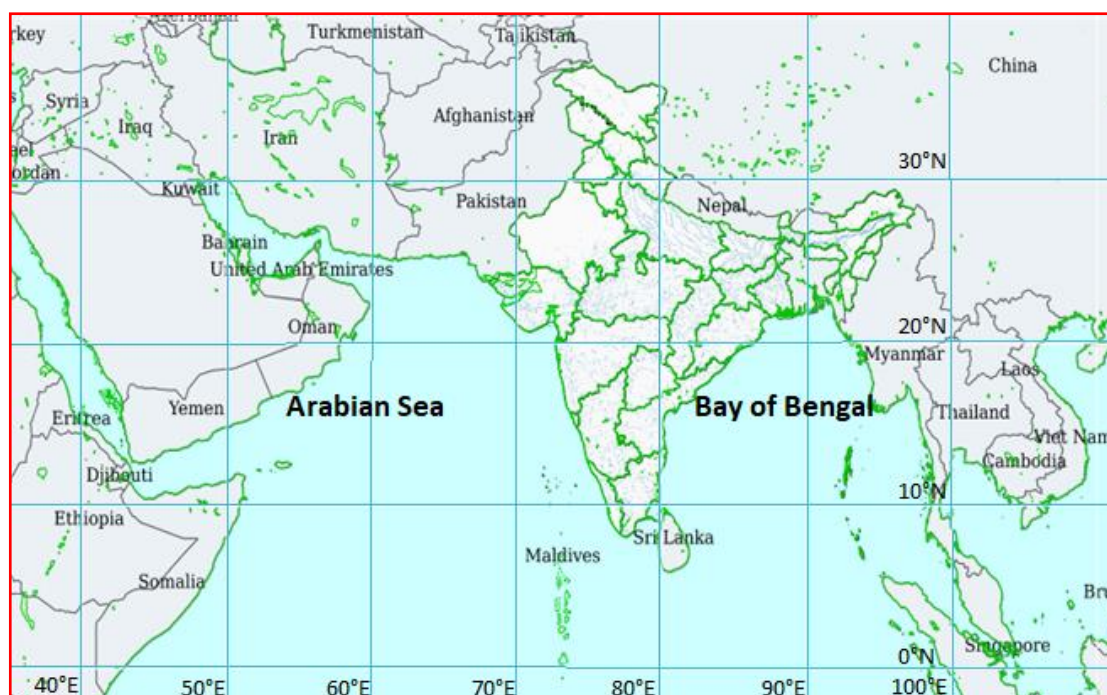


Fig. 1.1 Area of responsibility of RSMC- Tropical Cyclone, New Delhi

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. All the names in the first list effective from September 2004 have been used. The second list in the series was released in April, 2020 with representation from all the 13 WMO member

countries having a total of 169 names. The list started with the name 'NISARGA' which was assigned to the Severe Cyclonic Storm over the Arabian Sea (01st – 04th June 2020). The new list of names is available on RSMC website at <http://www.rsmcnewdelhi.imd.gov.in/images/pdf/cyclone-awareness/tc-names/tc-names.pdf>.

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. 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.

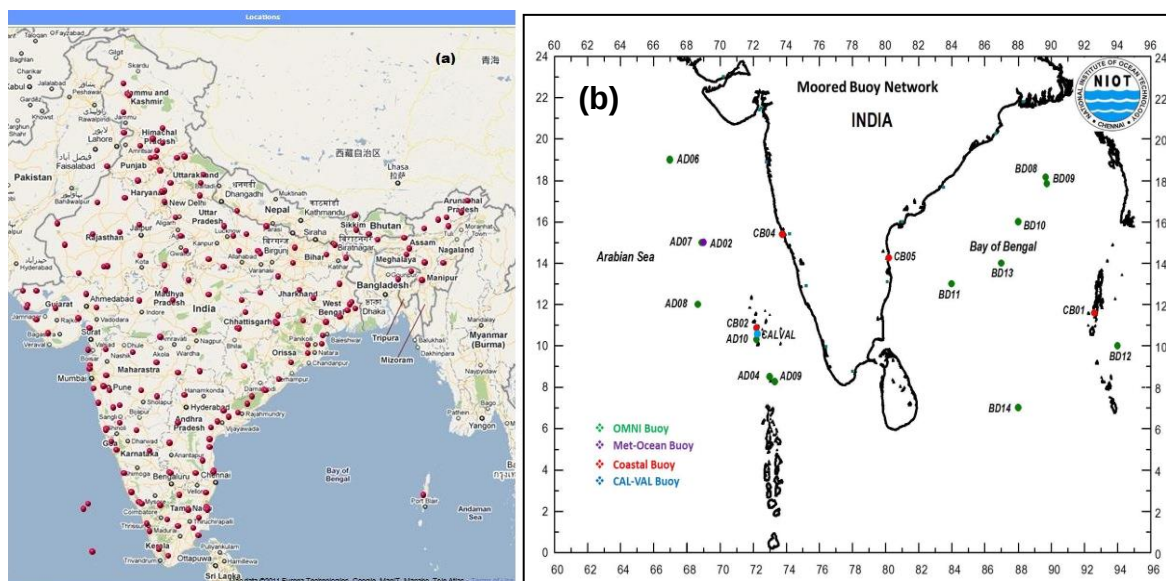


Fig.1.2. (a) The surface Observatory Network of IMD (b) Buoy network of NIOT

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. 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.

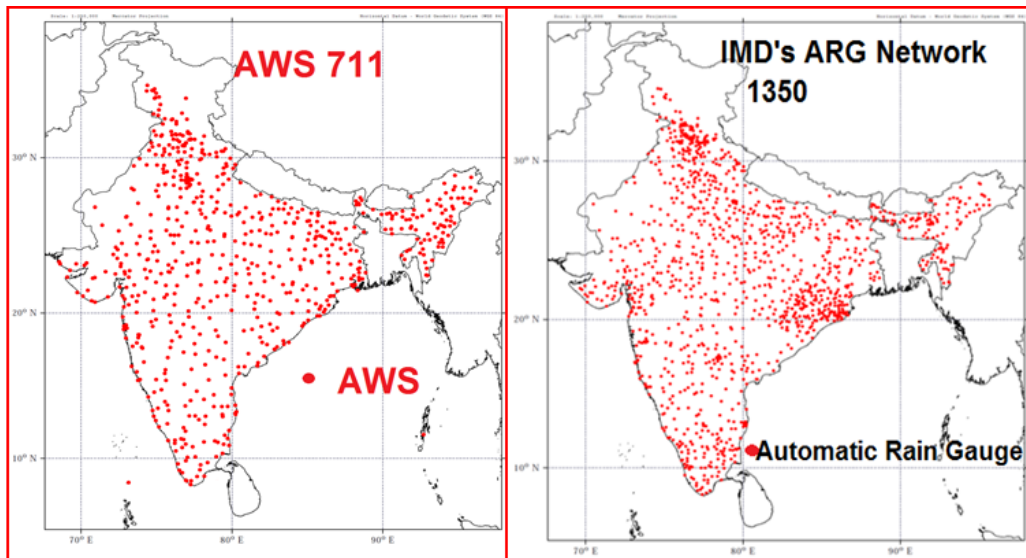


Fig. 1.3 (a) Network of 711 AWS and (b) 1350 ARGs.

1.3.2 Upper Air Observatories

There are at present 62 Pilot Balloon Observatories, 56 Radiosonde/ Radio wind observatories. All the 56 stations are latest of the art- GPS based observatories. Out of 56, 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

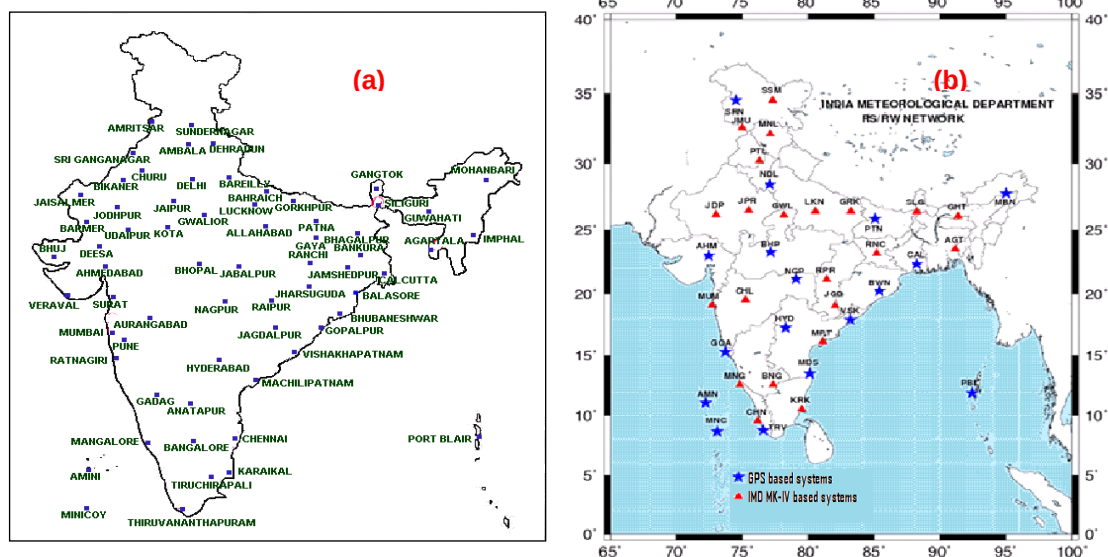


Fig.1.4 (a) Network of Pilot Balloon Observatories (PBO) and (b) Network of Radiosonde/ Radio wind observatories

To monitor the daily ascent status and the stock of various consumables, an 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.

1.3.3 Radars

1.3.3.1 Current status

Weather radar network of India is managed by IMD, and consists of twenty eight Doppler weather radars (DWRs) presently spreading across the country. It includes twenty one S-band, two C-band Polarimetric DWRs and one in X-band DWR. Two indigenously manufactured S-band polarimetric DWRs have been installed at Kochi and Gopalpur. IMD also utilizes the DWR installed by ISRO at Thiruvananthapuram, Sohra (erstwhile Cherrapunji) and SHAR (Sriharikota High Altitude Range).

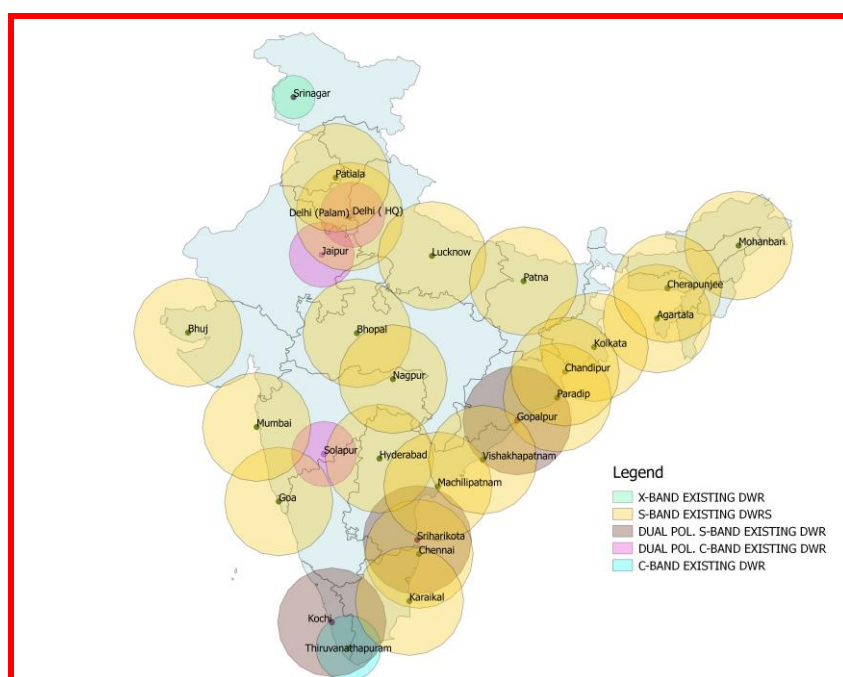


Fig. 1.5 Network of Radar

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

Radars of IMD are being used for detection of rainfall, hail storm, thunder storms and for 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, direction of movement, structure and intensity. The existing DWRs have also been networked to provide near real time data to super computers for ingesting into numerical weather prediction (NWP) models for short range forecasting. Composite images are also 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. Radar data products are also provided to various users through the web portals of the Department. Open source GIS platforms are used to display the radar data on the web pages. Upper Air Instrument (UAI) division of IMD has now combined radar data with lightning data and satellite imagery for a unified display on the website using GIS platform. This now provides accurate positional information of the location of the storm cells.

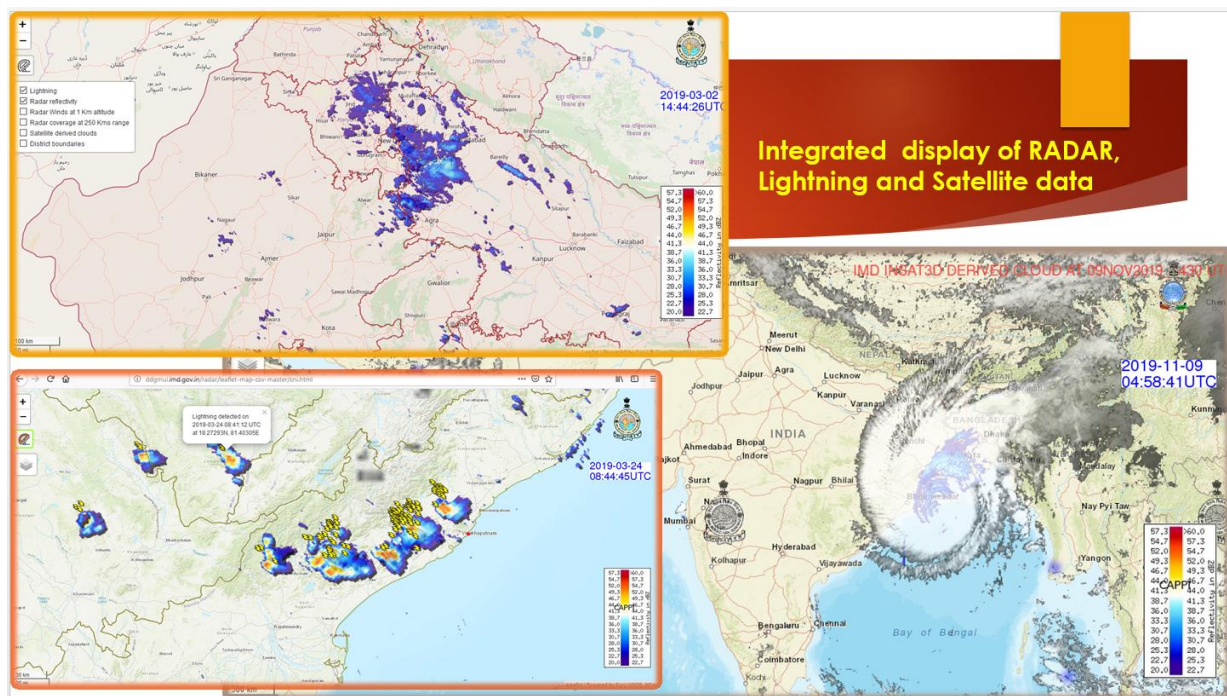


Fig. 1.6: Integrated display using RADAR, Lightning and Satellite data

Location specific information of lightning is also being generated in the radar data center and is available in the web page. A unique audio alert system announces the location and number of lightning occurrences district wise which alerts the forecaster and other end users to severe weather events.

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 & Uttarakhand, 11 C-band radars in the plains of the country and 8 X-band radars in the northeastern states. The network of proposed radars is presented in **Fig. 1.7**.

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.

Indian land region and every one and half hour hourly data of Indian Ocean region is obtained for generating multi-level imageries and vertical profiles of humidity and temperature. Multi Mission Meteorological Data Receiving and Processing System (MMDRPS) is being used on an operational basis to receive and process meteorological data from INSAT-3D and INSAT3-DR satellites on round the clock basis in Satellite Meteorological Division. Cloud Imagery and derived products data are disseminated to forecasting offices of the IMD as well as to the other users in India and foreign countries through dedicated web pages and online analysis and visualization tool (RAPID). All the received and processed data from the satellite are archived on a dedicated storage of MMRDPS.

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

- Enhanced grey scale imagery of cyclone.
- Enhanced coloured imagery of cyclone.
- Outgoing Long wave Radiation (OLR) at pixel resolution
- The following Quantitative Precipitation Estimation (QPE)
 - ❖ GPI three hourly accumulated at 1x1 degree resolution,
 - ❖ Hydro estimator (HE) at pixel level
 - ❖ INSAT-Multi spectral Rainfall (IMR) at 0.1x0.1-degree resolution
 - ❖ Improved IMR at pixel level.
- Sea Surface Temperature (SST) at pixel resolution
- Upper Tropospheric Humidity (UTH) at pixel resolution
- Cloud Motion Vector (CMV)
- Water Vapour derived Wind (WVW)
- Vis/MIR wind
- Wind derived products such as: Lower level Vorticity, Upper level Divergence, Lower level convergence, Vertical wind shear & Wind shear tendency
- Temperature, Humidity profile
- Value added parameters from sounder products
 - Geo-potential Height
 - Layer Precipitable Water
 - Total Precipitable Water
 - Lifted Index
 - Dry Microburst Index
 - Maximum Vertical Theta-E Differential
 - Wind Index
 - Ozone

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 along with 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. Spectral Band images and product images are archived online for last 6 months. These are available to all users through ftp.

INSAT-3DR Imager payload is used to conduct rapid scans during active cyclones following a standard operating procedure. Each Rapid scan covers up 3 degree in N-S direction (6 Blocks/240 scan lines) in 4.5 minutes. Rapid scan data are being used to track these cyclones in real time basis. The processed data is being disseminated on a dedicated webpage (http://satellite.imd.gov.in/rapid/rapid_scan.htm)

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 by Indian Institute of Tropical Meteorology and 157 by Indian Air Force). The area of lightning during preceding 10 min., 20 min. and 30 min. are superimposed with satellite and radar imageries. It helps 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.1.8.

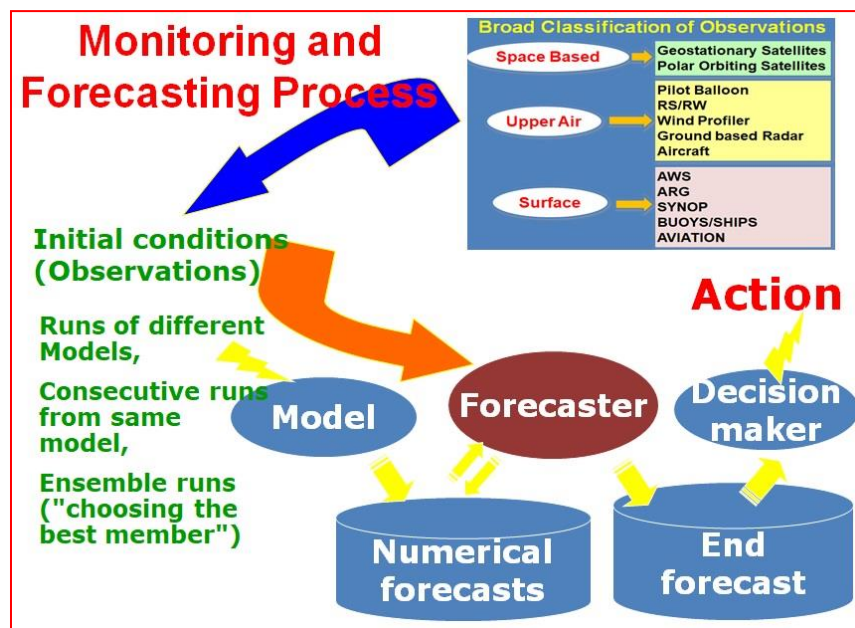


Fig.1.8. Strategy adopted for cyclone analysis and forecasting

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 Centres through internet.

Cloud imageries from Geostationary Meteorological Satellites 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 scatterometry 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 WVV 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 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 2020

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 four times in a day (00, 06, 12 and 18 UTC). 00 & 12 UTC runs are available for next 10 days forecast period. 06 & 18 UTC runs are available for 3 days forecast period. 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. 23°S to 46°N long 40°E to 120°E 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 $80^{\circ}\times 80^{\circ}$, $24^{\circ}\times 24^{\circ}$ and $7^{\circ}\times 7^{\circ}$ 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 are being provided since FANI cyclone over Bay of Bengal.

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 increase from 0% to 100% when

the total number of indices satisfied increases from zero to eight. The forecasts are made available in real time since 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) in 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. GEFS model is run twice a day based on 00 & 12 UTC initial conditions.

1.5.6. Models run at NCMRWF

The NCUM-G (Rajagopal et al., 2012; George et al., 2016) uses a seamless modeling approach. It has a horizontal grid resolution of ~12 km and 70 vertical levels (reaching 80 km height), is being used for the 240 hrs numerical weather forecast since 2018 (Kumar et al., 2018). These model and assimilation systems have been updated periodically to adapt to various scientific and technical developments. Advanced ENDGame dynamical core is used in the model, which provides improved accuracy of the solution of primitive model equations and reduced damping. ENDGame also increases variability in the tropics, which leads to an improved representation of TCs and other tropical phenomena (Walters et al., 2017). An advanced data assimilation method Hybrid 4D-Var is used for the

creation of NCUM global atmospheric analysis. Ensemble Transform Kalman Filter (ETKF) based on the NCUM ensemble prediction system (NEPS) provides flow-dependent background errors to this Hybrid 4D-Var system. Utmost importance has been given to the assimilation of Indian satellite observations in this data assimilation system. INSAT-3D Atmospheric Motion Vector (AMV), MeghaTropiques (MT)-SAPHIR radiance, Scatsat Ocean Surface Winds are being assimilated in the operational NCUM global data assimilation system, in addition to other global observations. A list of observations assimilated in the latest NCUM global data assimilation system is given in Table-2. Salient Features of NCUM Assimilation–Forecast System is shown in Table-3

NCUM global data assimilation system produces analyses at 00, 06, 12, and 18 UTC. In each 6 hourly data assimilation cycle, the available observations distributed over the 6 hour assimilation window (center of the analysis cycle ± 3 hr) are combined with the model background to produce the NCUM-G analysis. Table 1 summarizes the model configurations operational at NCMRWF. Details on the model parameterizations schemes, data assimilation, etc., can be found in Kumar et al. (2018).

NCUM-R has a horizontal grid resolution of ~ 4 km and 80 vertical levels, with the model top at 38.5 km and 14 model levels below 1 km. The model has a time step of 1 minute. The model domain covers India and the adjacent oceanic regions and is operationally producing 72hrs forecasts. In this convection-permitting model configuration, sub-grid scale deep convection is not parameterized. The prognostic cloud fraction and prognostic condensate (PC2) scheme used in this model is based on Wilson (2008 a & b). The sub-grid turbulence scheme used is a blended scheme (Boutle et al., 2014), which dynamically combines the one-dimensional (1D) boundary-layer scheme of Lock et al. (2000) with a 3D Smagorinsky scheme using a mixing factor of 0.5. The model employs NASA Shuttle Radar Topographic Mission (SRTM) 90 m digital elevation map orography.

NCUM-R uses the high resolution analysis prepared by the 4D-Var data assimilation (DA) system. In addition to most of the observations used in the NCUM global data assimilation system (even though data thinning strategies are different), Indian Doppler Weather Radar observations of radial wind are also used in the regional DA system with a time window of ± 3 hours. The vortex initialization scheme is also employed in the NCUM-R. The model domain covers the South Asian region, covering BOB and part of the Arabian Sea (6°S - 41°N and 62° - 106°E). The details of NCUM-R model configuration can be found in Dutta et al. 2019, Jayakumar et al. 2019 and Bush et al. 2020.

NCMRWF Ensemble Prediction System (NEPS-G) 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 operational NCMRWF Ensemble Prediction System (NEPS) has 22 ensemble members. The horizontal resolution of NEPS is ~ 12 km. The NCUM model analysis is used as the initial condition for the control model forecast. The perturbations are generated by Ensemble Transform Kalman Filter (ETKF) method which is added to the global deterministic analysis to create 22 perturbed initial conditions. These are used for generating ensemble member forecasts. One control and 11 perturbed ensemble members run from initial condition of 00UTC of current day and 11 more perturbed members run from 12 UTC of previous day to give 23 members (11 + 11 + 1 control) ensemble

forecasts up to 10 days lead time. More details about NEPS-G are available in Mamgain et al. (2018). The new 12-km NEPS-G is the highest resolution for Ensemble forecasting.

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> and is also transmitted by email to WMO, WMO/ESCAP panel member countries and various scientists and researchers in the country.

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.mausam.imd.gov.in,

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.mausam.imd.gov.in**, **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 and coastal inundation model. Recently INCOIS Hyderabad has developed an ADvanced CIRCulation (ADCIRC) Storm Surge and Coastal Inundation model which is running experimentally since 2013. It is 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 providers 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 tropical cyclones/ depressions, 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 for the entire 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 $\geq$ 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, change in intensity, 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. The text and graphical bulletins are also uploaded on www.rsmcnewdelhi.imd.gov.in

1.6.7 Tropical cyclone warning bulletin at national level

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, twitter and whatsapp. An interactive map on observed and forecast track and intensity of cyclonic disturbances in a web-GIS platform has been introduced in 2020 (www.rsmcnewdelhi.imd.gov.in).

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. IMD introduced COU forecast upto a lead period of 72 hours in 2009 from Cyclone "WARD". The lead period was further extended to 120 hours in 2013 from Cyclone "VIYARU". COU values were revised in 2014 from cyclone "Hudhud" based on the errors during 2009-13. From cyclone FANI, 2019, the COU values have been revised based on the errors during 2014-18. The standard errors (nm) as radius of the circle around the forecast position (lat/long) so as to construct the cone of uncertainty in the track forecast for 00, +06, +12, +18, +24, +36, +48, +60, +72, +84, +96, +108 and +120 hrs lead period have been fixed as 10, 20, 30, 40, 45, 55, 70, 85, 95, 115, 130, 145 and 160 nm since April, 2019. Typical observed and forecast track alongwith cone of uncertainty demonstrating accuracy in track forecast during Super Cyclonic Storm Amphan is presented in Fig. 1.9 (a). This product is uploaded on various websites of IMD viz. www.rsmcnewdelhi.imd.gov.in and www.mausam.imd.gov.in in .png format and appended with the national and tropical cyclone advisory bulletins. Since, severe cyclonic storm "Nisarga" in June, 2020, this product was also made available on GIS based interactive platform at www.rsmcnewdelhi.imd.gov.in

1.6.9 Wind forecast for different quadrants

The forecast of the radius of maximum sustained wind in four quadrants of a cyclone valid upto 72 hrs commenced with effect from the cyclone, GIRI during October 2010. It was extended to 120 hrs forecast since 2013. 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.1.9 (b). This quadrant wind forecast is issued as a bulletin from the deep depression stage onwards to various users through a global telecommunication system. This product is uploaded on various websites of IMD viz. www.rsmcnewdelhi.imd.gov.in and www.mausam.imd.gov.in in .png format and appended with the national and tropical cyclone advisory bulletins. Since, severe cyclonic storm “Nisarga” in June, 2020, this product was also made available on GIS based platform at www.rsmcnewdelhi.imd.gov.in. It is also uploaded on RSMC, New Delhi website in textual form.

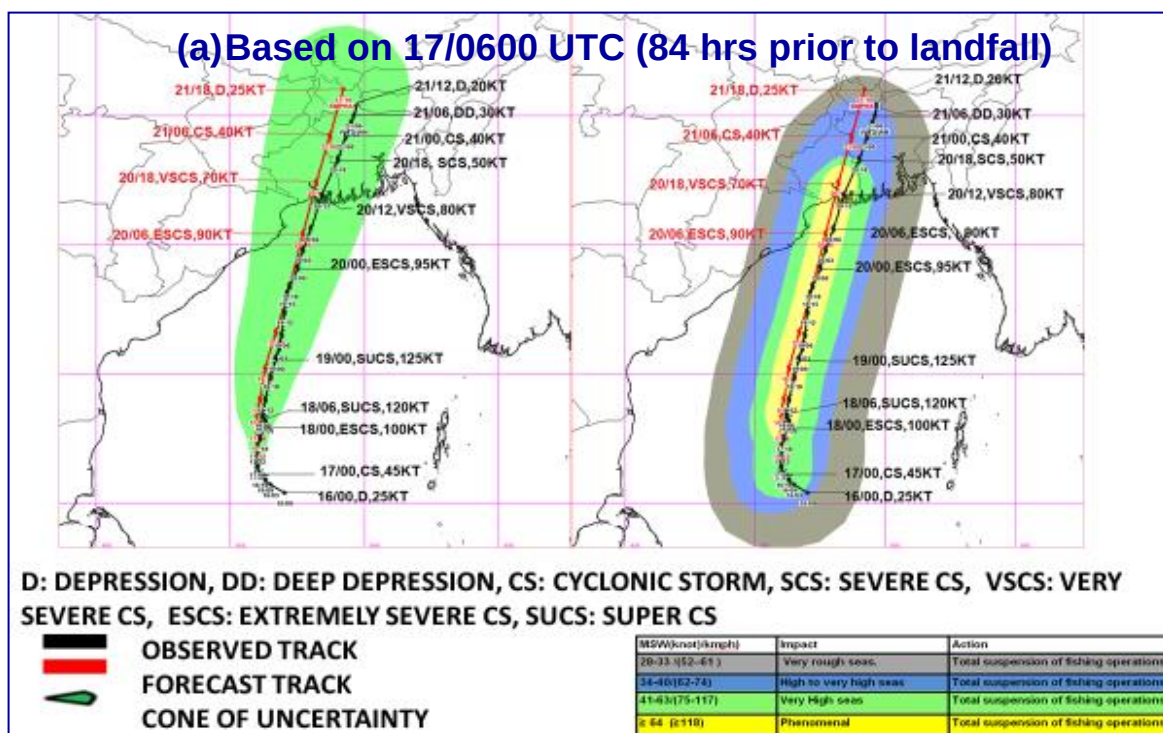


Fig.1.9: Typical example of observed and forecast track along with cone of uncertainty and wind distribution around the centre during super cyclonic storm Amphan demonstrating accuracy in track, landfall point and intensity

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 bulletin 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. New IMD website dedicated to general public (<https://mausam.imd.gov.in>) was launched by Hon'ble Minister of Earth Sciences, Dr Harsh Vardhan on 27th July, 2019. Cyclone related bulletins are uploaded on this site also since July, 2019. 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 NAVIC 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.

Since 2019, IMD is also notifying cyclone warnings on mobile Apps (Umang and Meghdoot) and through IMD' another mobile app, Mausam since 2020. IMD has also started the dissemination of weather information through common alert protocol. The URL of RSS feed is <https://cap-sources.s3.amazonaws.com/in-imd-en/rss.xml>. During Super Cyclone

Amphan, 2020, cyclone warnings were transmitted through CAP also. IMD also sends the warning through WMO's Global Multihazard Alert System (GMAS) for international use.

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 2020, the FDP campaign commenced on 12th October and was extended upto 15th December 2020. Like previous years (2008-2019), several national institutions participated for joint observational, communicational & NWP activities during 2020. There was an improved observational campaign with the observation from Buoys, Scatterometer based satellite and microwave imageries products. 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. During the period intense observation period was declared for a total of 16 days for various coastal states of India along the east & west coasts, Oman, Yemen and Somalia in association with depressions/deep depression over Bay of Bengal, tropical cyclones Nivar & Burevi over Bay of Bengal and Gati over the Arabian Sea. All the bulletins issued during the period have been archived and are available on the RSMC, New Delhi website. The detailed report on implementation of FDP-2020 is also available in RSMC, New Delhi website.

CHAPTER-II

2.1. CYCLONIC ACTIVITIES OVER NORTH INDIAN OCEAN DURING 2020

There were 9 cyclonic disturbances (CDs) i.e. depressions and cyclones over the north Indian Ocean (NIO) & adjoining land regions during 2020 against the long period average (LPA) of 12 disturbances per year based on data of 1961-2019. Out of 9 CDs, 5 intensified into tropical cyclones against the normal frequency of 4.5 cyclones per year over north Indian Ocean (NIO) based on LPA. It included including 1 cyclonic storm (CS), 1 severe cyclonic storm (VSCS), 2 very Severe Cyclonic Storm and 1 Super Cyclone.

Table 2.1 Brief statistics of Ccyclonic disturbances over NIO and adjoining land areas during 2020:

1.	Super Cyclonic Storm (SuCS) AMPHAN over Southeast Bay of Bengal during 16-21 May
2.	Depression over the south coastal Oman and adjoining Yemen during 29 May-01 June
3.	Severe Cyclonic Storm NISARGA over eastcentral and adjoining southeast Arabian Sea during 01-04 June
4.	Deep Depression over the Bay of Bengal during 11-14 October
5.	Depression over Arabian Sea during 17-19 October
6.	Depression (D) over the Bay of Bengal during 22-24 October
7.	Very Severe Cyclonic Storm GATI over Arabian Sea during 21-24 November
8.	Very Severe Cyclonic Storm Nivar over Bay of Bengal during 22-26 November
9.	Cyclonic Storm Burevi over Bay of Bengal during 30 Nov-05 December

The salient features of the cyclonic activity over the NIO are mentioned below:

Arabian Sea witnessed above normal activity during 2020 with the formation of 4 CDs including 2 cyclones (Nisarga & Gati) against the normal of 1.7 CDs and 1 cyclone per year. The activity over the BoB was subdued this year with the formation of only 3 cyclones during 2020 against the normal of 4 per year. However, the frequency of severe category of cyclones was normal over BoB with the formation of 2 severe category storms (Amphan & Nivar) against the normal of 2 per year. Considering seasonal distribution, while one cyclone (super cyclonic storm Amphan) and another (severe cyclonic storm Nisarga) formed during pre-monsoon and monsoon season respectively, three cyclones (very severe cyclonic storm, Gati and Nivar and cyclonic storm Burevi) formed during post-monsoon season. No CDs formed over BoB during monsoon season.

All the cyclones during 2020 exhibited unique characteristics w.r.t track, intensity and landfall. SuCS Amphan in May, 2020 was the first super cyclone over BoB after the Odisha super cyclone of 1999. Nisarga in June, 2020 was the first severe cyclonic storm (SCS) which crossed Maharashtra coast as a severe category storm after the SCS that crossed Maharashtra coast on 24th May, 1961. It was also the 4th cyclone crossing Maharashtra coast during the period 1961-2020. GATI in November, 2020 was the first very severe cyclonic storm crossing Somalia coast during satellite era. Gati was the 5th cyclone crossing Somalia coast after a cyclonic

storm in November, 1994, Murjan in 2012, Sagar in 2018 and Pawan in 2019. Nivar was the first cyclonic storm over BoB during post monsoon season. It caused intense rainfall over activity over north Tamil Nadu & Puducherry, Rayalaseema and south coastal Andhra Pradesh during 24th-26th November. Two very severe cyclonic storms, viz., Nivar over BoB and Gati over AS occurred simultaneously during 21st-26th November. Such simultaneous occurrence was last observed in 2019 during 5th-7th November with ESCS Maha over AS and Bulbul over BoB. Burevi was the 14th cyclone that crossed Sri Lanka coast during the period 1891-2019. A system analogous to that of CS 'BUREVI' occurred during 15-17 January 1906 which crossed the east coast of Sri Lanka, close to north of Trincomalee, moved across Pamban area and weakened near Ramanathapuram district coast. Burevi had the similar track & intensity characteristic as the cyclonic storm in January, 1906. Burevi also exhibited strange behaviour w.r.t. movement. It remained practically stationary for nearly 36 hours over the Pamban area and became less marked over the same area. Last such stationary characteristic was observed during 1999 Super Cyclone over Odisha which remained stationary for 33 hours.

All the five cyclones over the NIO during 2020 were **landfalling cyclones**. Amphan crossed West Bengal – Bangladesh coasts as a very severe cyclonic storm on 20th May. Nisarga crossed Maharashtra coast as a severe cyclonic storm on 03rd June. Gati crossed Somalia coast on 22nd November as a very severe cyclonic storm. Nivar crossed Tamil Nadu & Puducherry coasts near Puducherry on 25th November midnight as a very severe cyclonic storm. Burevi crossed Sri Lanka in the midnight of 2nd December and second landfall over Pamban area in the afternoon of 3rd December.

During 2020, two cyclones (Nisarga and Nivar) out of five had a northeastward **recurving track**. While Nisarga recurved northeastward over the Sea before landfall, Nivar recurved northeastward after the landfall over Tamil Nadu coast. All others including Amphan, Gati and Burevi had almost straight track. While Gati had fastest moving track, Burevi had a slow moving track especially over Gulf of Mannar.

Brief description of cyclones during 2020

1. *Super cyclonic storm AMPHAN over the Bengal during 16-21 May*

The Super Cyclonic Storm (SuCS) "AMPHAN" originated from the remnant of a low pressure area which developed over southeast BoB on 13th May morning. It concentrated into a depression (D) over southeast BoB in the early morning of 16th May. It intensified into the cyclonic storm "AMPHAN" over southeast BoB in the evening of 16th. It intensified into a super cyclonic storm (SuCS) around noon (0600 UTC) of 18th. It maintained the intensity of SuCS over westcentral BoB for nearly 24 hours, before weakening into an ESCS over westcentral BoB around noon of 19th May. Thereafter, it weakened slightly and crossed West Bengal – Bangladesh coasts as a VSCS, across Sundarbans, near latitude 21.65°N and longitude 88.3°E during 1530-1730 hrs IST of 20th May, with maximum sustained wind speed of 155 – 165 kmph gusting to 185 kmph. It weakened into a well marked low pressure area over north Bangladesh and neighbourhood around mid night of 21st May.

2. Severe Cyclonic Storm “NISARGA” over the Arabian Sea during 01st-04th June

Severe Cyclonic Storm “NISARGA” developed from a low pressure area which formed over southeast AS in the early morning of 31st May 2020. It concentrated into a depression over eastcentral AS in the early morning of 1st June 2020. It intensified into the cyclonic storm “NISARGA” in the noon of 2nd June. It intensified into a severe cyclonic storm in the early morning of 3rd June 2020. It crossed Maharashtra coast close to south of Alibagh as a severe cyclonic storm during 1230-1430 hrs IST of 03rd June. It weakened into a low pressure area over southeast Uttar Pradesh and adjoining Bihar in the afternoon of 5th June.

3. Very Severe Cyclonic Storm “NIVAR” over the Bay of Bengal during 22nd - 27th November 2020

Very severe cyclonic storm developed from a low pressure area which formed over Equatorial Indian Ocean (EIO) and adjoining central parts of south Bay of Bengal (BoB) on 21st November. It concentrated into a depression over the same region in the early hours of 23rd November. It intensified into the cyclonic storm “NIVAR” in the early morning of 24th over southwest BoB. It intensified into a very severe cyclonic storm in the afternoon of 25th. It crossed Tamil Nadu & Puducherry coasts near Puducherry during midnight of 25th and early hours of 26th as a very severe cyclonic storm. It weakened into a well marked low pressure area over south coastal Andhra Pradesh and adjoining westcentral BoB in the early morning of 27th November.

4. Very Severe Cyclonic Storm “GATI” over the Arabian Sea during 21st – 24th November 2020

Very severe cyclonic storm “GATI” developed from a low pressure area that formed over central parts of south Arabian Sea (AS) in the morning 19th November. It concentrated into a depression over the same region in the midnight of 21st. Moving west-southwestwards, it explosively intensified into the cyclonic storm “GATI” in the morning of 22nd. It explosively intensified into very severe cyclonic storm in the afternoon of 22nd over southwest AS. It reached it's peak intensity of 75 knots in the evening over the southwest AS. It crossed Somalia coast in the night of 22nd as a very severe cyclonic storm. It weakened into a well marked low pressure area in the noon of 24th over Gulf of Aden and adjoining north Somalia.

5. Cyclonic Storm “BUREVI” over the Bay of Bengal during 30th November - 05th December 2020

The cyclonic storm, ‘Burevi’ originated from a low pressure area that developed over South Andaman Sea and adjoining areas on 28th November 2020. It concentrated into a depression in the early morning of 30th November over Southeast Bay of Bengal. It intensified into the cyclonic storm ‘Burevi’ over southwest BoB in the evening of 01st December 2020. It crossed Sri Lanka coast close to north of

Trincomalee during midnight of 2nd December 2020 as a cyclonic storm. Moving across northern parts of Sri Lanka, it emerged into Gulf of Mannar in the morning and lay centred close to Pamban around noon of 03rd December. It crossed Pamban area in the evening of 3rd December. Remaining stationary over Gulf of Mannar close to Ramanathapuram for 36 hours, it gradually weakened into a well marked low pressure area around noon of 05th December. The tracks of these disturbances are shown in Fig. 2.1.

Table 2.2 Some Characteristic features of cyclonic disturbances formed over north Indian Ocean and adjoining region during 2020

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	Super Cyclonic Storm (SuCS) AMPHAN over Southeast Bay of Bengal during 16-21 May	16 th May 2020, 0000 UTC over Southeast Bay of Bengal near (10.4N/87.0E)	Crossed West Bengal – Bangladesh coasts as a very severe cyclonic storm across Sundarbans, near lat.21.65°N/long. 88.3°E during 1000-1200 UTC	920 hPa at 1800 UTC 18 th May 2020 near (14.9N/86.5E)	130 knots at 1800 UTC 18 th May 2020 near (14.9N/86.5 E)	T 6.5
2	Depression over the south coastal Oman and adjoining Yemen during 29 May-01 June	29 th June 2020, 0900 UTC over the south coastal Oman and adjoining Yemen near (17.3N/54.3E)	Weakened into well marked low pressure area over south coastal Oman and adjoining Yemen	1000 hPa at 0900 UTC 29 th June 2020 near (17.3N/54.3E)	25 knots at 0900 UTC 29 th June 2020 near (17.3N/54.3 E)	-

3	Severe Cyclonic Storm NISARGA over eastcentral and adjoining southeast Arabian Sea during 01-04 June	1 st June 2020, 0000 UTC over eastcentral and adjoining southeast Arabian Sea (13.0N/71.4E)	Crossed Maharashtra coast close to south of Alibag near 18.35°N/72.95 °E, as Severe Cyclonic Storm between 0700-0900 UTC of 03 rd June	984 hPa at 0600 UTC 3 rd June 2020 near (18.1N/72.8E)	60 knots at 0600 UTC 3 rd June 2020 near (18.1N/72.8 E)	T 4.0
4	Deep Depression over the Bay of Bengal during 11-14 October	11 th October, 2020, 0000 UTC over Bay of Bengal near (15.3°N/86.5°)	Crossed North Andhra Pradesh coast close to Kakinada (near latitude 17.0°N & longitude 82.4° E)	997 hPa at 0300 UTC 12 th October, 2020 near (15.7N/85.0E)	30 knots at 0300 UTC 12 th October, 2020 near (15.7N/85.0 E)	T2.0
5	Depression over Arabian Sea during 17-19 October	17 th October, 2020, 0300 UTC over Arabian Sea near (17.8°N/69.0°)	Weakened into well marked low pressure area over westcentral Arabian Sea and neighbourhood	1003 hPa at 1200 UTC 17 th October, 2020 near (17.8N/67.5E)	25 knots at 1200 UTC 17 th October, 2020 near (17.8N/67.5 E)	T1.5
6	Depression (D) over the Bay of Bengal during 22-24 October	22 nd October, 2020, 0300 UTC over Bay of Bengal near (18.7°N/87.0°)	Crossed West Bengal & adjoining Bangladesh coasts (near latitude 21.8°N & longitude 88.5° E), between 0600 & 0700 UTC of 23 rd	998 hPa at 0600 UTC 22 nd October, 2020 near (19.0N/87.0E)	25 knots at 0600 UTC 22 nd October, 2020 near (19.0N/87.0 E)	T1.5

			October 2020			
7	Very Severe Cyclonic Storm GATI over Arabian Sea during 21-24 November	21 st November 2020 at 1800 UTC over Arabian Sea near (11.2N/57.4E)	Crossed Somalia Coast near lat 10.450 N and long 51.10 E between 1400 and 1500 UTC of 22nd Nov.	976 hPa at 1200 UTC on 22 nd November 2020 near (10.4N/51.5E)	75 knots at 1200 UTC on 22 nd November 2020 near (10.4N/51.5 E)	T4.5
8	Very Severe Cyclonic Storm Nivar over Bay of Bengal during 22-26 November	22 nd November 2020, 2100 UTC over Bay of Bengal near (8.5N/85.3E)	Crossed Tamilnadu and Puducherry coasts near Puducherry (near Lat 12.10N and Log 79.90 E) during 1800 – 2100 UTC of 25th	982 hPa at 0900 UTC on 25 th November 2020 near (11.2N/81.0E)	65 knots at 0900 UTC on 25 th November 2020 near (11.2N/81.0 E)	T4.0
9	Cyclonic Storm Burevi over Bay of Bengal during 30 Nov-05 December November)	30 th Nov 2020, 0000 UTC over Bay of Bengal near (7.5N/88.0E)	1) Crossed Sri Lanka coast close to north of Trincomalee (near Lat 08.850N and Log 81.00 E) during 1700 – 1800 UTC of 02nd December 2020 2) Crossed Pamban area (near Lat 09.20N and Log 79.350 E)	996 hPa at 0600 UTC 02 nd December 2020 near (8.8N/82.2E)	45 knots at 0600 UTC 02 nd December 2020 near (8.8N/82.2E)	T 3.0

			during 0800 UTC of 03rd December 2020			
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Table 2.3 Statistical data relating to cyclonic disturbances over the north Indian Ocean during 2020

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

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

↔ Peak intensity of the system, LD: Land Depression

B) Life time of cyclonic disturbances during 2020 at different stages of intensity
i. For NIO Region

S.No.	Type	Life Time in (Days)
1	D	13 days 18 hours
2.	DD	05 days 12 hours
3.	CS	05 days 06 hours
4.	SCS	02 days
5.	VSCS	04 days
6.	SuCS	01 day
Total no. of Cyclonic Disturbance days in 2020		31 days 12 hours
Average no. of Cyclonic Disturbance days(1990-2020)		29 days 20 hours

ii. For Bay of Bengal Region

S.No.	Type	Life Time in (Days)
1	D	06 days 21 hours
2.	DD	03 days 06 hours
3.	CS	03 days
4.	SCS	09 hours
5.	VSCS	02 days 15 hours
6.	SuCS	01 day
	Total Life Time in(Days)	17 days 03 hours

iii. For Arabian Sea Region

S.No.	Type	Life Time in (Days)
1	D	06 days 21 hours
2.	DD	02 days 06 hours
3.	CS	02 days 06 hours
4.	SCS	01 day 15 hours
5.	VSCS	01 day 09 hours
6.	SuCS	-
	Total Life Time in(Days)	14 days 09 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	9	6	5	5	4	3	3	1	1	1

D) Basin-wise distribution of cyclonic distribution

Basin	Number of cyclonic disturbances
Bay of Bengal	5
Arabian Sea	4
Land depression	0

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

Year	Basin	D	DD	CS	SCS	VSCS	ESCS	SuCS	Total
1997	BOB	1	4	1	1	1	0	0	8
	ARB	1	0	0	0	0	0	0	1
	Land	0	0	0	0	0	0	0	0
	Total								9
1998	BOB	0	3	0	1	2	0	0	6
	ARB	0	1	1	1	1	0	0	4
	Land	1	0	0	0	0	0	0	1
	Total								11
1999	BOB	2	2	1	0	1	0	1	7
	ARB	0	0	0	0	1	0	0	1

	Land	1	0	0	0	0	0	0	1
	Total								9
2000	BOB	1	1	2	--	2	0	0	6
	ARB	0	0	0	0	0	0	0	0
	Land	1	0	0	0	0	0	0	1
	Total								7
2001	BOB	2	0	1	0	0	0	0	3
	ARB	0	0	2	0	1	0	0	3
	Land	0	0	0	0	0	0	0	0
	Total								6
2002	BOB	1	1	2	1	0	0	0	5
	ARB	0	0	0	0	0	0	0	1
	Land	0	0	0	0	0	0	0	0
	Total								6
2003	BOB	2	2	0	1	1	0	0	6
	ARB	0	0	0	1	0	0	0	1
	Land	0	0	0	0	0	0	0	0
	Total								7
2004	BOB	2	0	0	0	1	0	0	3
	ARB	0	2	0	3	0	0	0	5
	Land	2	0	0	0	0	0	0	2
	Total								10
2005	BOB	2	3	4	0	0	0	0	9
	ARB	2	0	0	0	0	0	0	2
	Land	1	0	0	0	0	0	0	1
	Total								12
2006	BOB	5	2	1	0	1	0	0	9
	ARB	0	1	0	1	0	0	0	2
	Land	1	0	0	0	0	0	0	1
	Total								12
2007	BOB	3	4	1	0	1	0	0	9
	ARB	0	1	1	0	0	0	1	3
	Land	0	0	0	0	0	0	0	0
	Total								12
2008	BOB	1	2	3	0	1	0	0	7
	ARB	1	1	0	0	0	0	0	2
	Land	1	0	0	0	0	0	0	1
	Total								10
2009	BOB	0	2	2	1	0	0	0	5
	ARB	2	0	1	0	0	0	0	3
	Land	0	0	0	0	0	0	0	0
	Total								8
2010	BOB	2	1	0	2	1	0	0	6
	ARB	0	0-	1	0	1	0	0	2
	Land	0	0	0	0	0	0	0	0
	Total								8
2011	BOB	2	2	0	0	1	0	0	5

	ARB	1	2	1		0	0	0	4
	Land	1	0	0	0	0	0	0	1
	Total								10
2012	BOB	0	2	1	0	0	0	0	3
	ARB	0	1	1	0	0	0	0	2
	LAND	0	0	0	0	0	0	0	0
	Total								5
2013	BOB	3	0	1	1	3	0	0	8
	ARB	0	1	0	0	0	0	0	1
	Land	1	0	0	0	0	0	0	1
	Total								10
2014	BOB	2	2	0	0	1	0	0	5
	ARB	0	0	1	0	1	0	0	2
	Land	1	0	0	0	0	0	0	1
	Total								0
2015	BOB	1	1	1	0	0	0	0	3
	ARB		2	1	0	0	2	0	5
	Land	2	2		0	0	0	0	4
	Total								12
2016	BOB	1	2	3	0	1	0	0	7
	ARB	2	0	0	0	0	0	0	2
	Land	1	0	0	0	0	0	0	1
	Total								10
2017	BOB	4	1	1	1	1	0	0	8
	ARB	0	0	0	0	0	0	0	0
	Land	2	0	0	0	0	0	0	2
	Total								10
2018	BOB	3	2	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
2019	BOB	0	1	1	0	1	1	0	4
	ARB	2	1	1	0	2	1	1	8
	Land	0	0	0	0	0	0	0	0
	Total								12
2020	BOB	1	1	1	0	1	0	1	5
	ARB	2	0	0	1	1	0	0	4
	Land	0	0	0	0	0	0	0	0
	Total								9

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

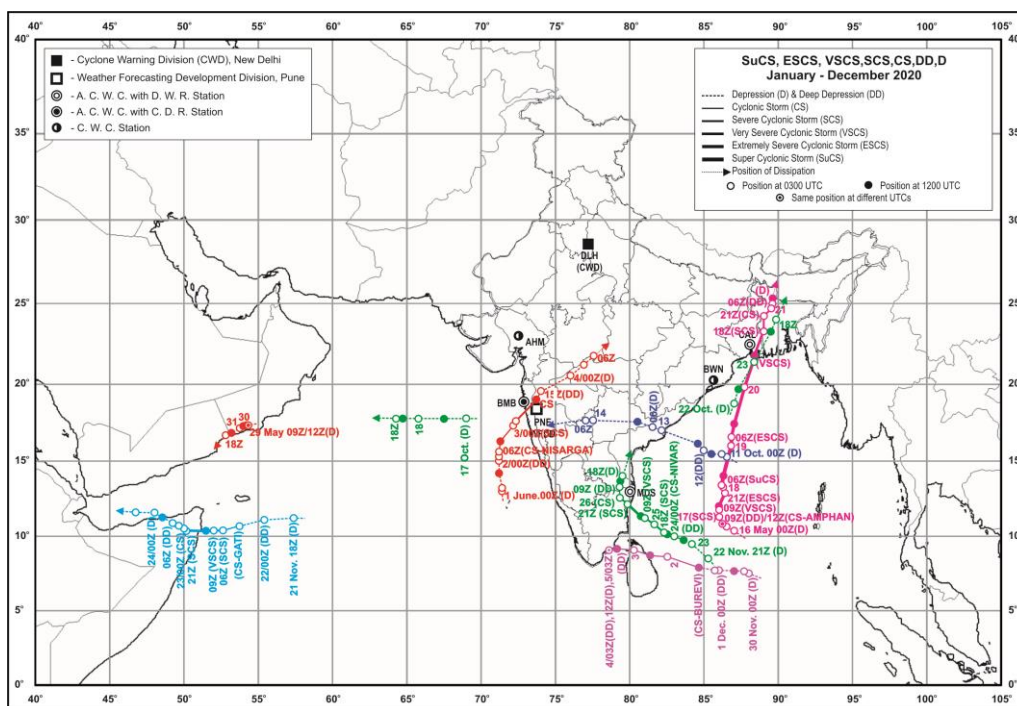


Fig. 2.1.: Tracks of cyclonic disturbances over north Indian Ocean and adjoining land region during 2020

Table 2.5 Average translational speed of Tropical cyclones over the NIO during 2020

TC Name	Basin	Period	Average Translational Speed		
			6 Hr	12 Hr	24 Hr
AMPHAN	BoB	16-21 May	13.8	13.9	13.9
NISARGA	AS	01-04 June	16.6	15.8	15.1
GATI	AS	21-24 November	9.4	9.2	8.9
NIVAR	BoB	22–26 November	22.0	21.7	19.5
BUREVI	BoB	30 Nov-05 Dec	8.9	9.0	9.5

Table 2.6 Energy matrix of Tropical cyclones over the NIO during 2020 (figures given in parentheses represent values from D to D)

TC Name	Velocity Flux (10^2 kt)	Accumulated Cyclone Energy (10^4 kt ²)	Power Dissipation Index (10^6 kt ³)
AMPHAN	16.3(17.0)	15.45(15.62)	16.04(16.08)
NISARGA	2.65(4.70)	1.21(1.74)	0.58(0.72)
NIVAR	5.00(6.60)	2.64(3.08)	1.45(1.58)
GATI	2.35(4.05)	1.43(1.92)	0.9(1.05)
BUREVI	3.25(6.70)	1.33(2.26)	0.55(0.81)
TOTAL	29.55(39.05)	22.06(24.62)	19.52(20.24)

2.2 Super Cyclonic Storm, ‘AMPHAN’ over Southeast Bay of Bengal (16 May – 21 May 2020)

2.2.1 Introduction

- The Super Cyclonic Storm (SuCS) “AMPHAN” originated from the remnant of a Low Pressure Area which occurred in the near Equatorial Easterly wave over south Andaman Sea and adjoining southeast Bay of Bengal (BoB) during 1st – 5th May. Though the Low Pressure Area became less marked on 6th May, its remnant circulation meandered over south Andaman Sea and adjoining southeast BoB during 6th – 12th May. Under its influence, a fresh Low Pressure Area formed over southeast BoB and adjoining south Andaman Sea in the morning (0300 UTC) of 13th May.
- It lay as a well marked low pressure area (WML) over southeast BoB & neighbourhood in the morning (0300 UTC) of 14th May.
- Under favourable environmental conditions, it concentrated into a depression (D) over southeast BoB in the early morning (0000 UTC) of 16th May and further intensified into a deep depression (DD) in the same afternoon (0900 UTC).
- It moved north- northwestwards and intensified into Cyclonic Storm “AMPHAN” (pronounced as UM-PUN) over southeast BoB in the evening (1200 UTC) of 16th May, 2020. Moving nearly northwards, it further intensified into a Severe Cyclonic Storm (SCS) over southeast BoB in the morning (0300 UTC) of 17th May.
- It underwent rapid intensification during subsequent 24 hours and accordingly intensified into a Very Severe Cyclonic Storm (VSCS) by the afternoon (0900 UTC) of 17th, Extremely Severe Cyclonic Storm (ESCS) in the early hours of 18th (2100 UTC of 17th May) and into a Super Cyclonic Storm (SuCS) around noon (0600 UTC) of 18th May, 2020.
- It maintained the intensity of SuCS over westcentral BoB for nearly 24 hours, before weakening into an ESCS over westcentral BoB around noon (0600 UTC) of 19th May.
- Thereafter, it weakened slightly and crossed West Bengal – Bangladesh coasts as a VSCS, across Sundarbans, near latitude 21.65°N and longitude 88.3°E during 1530-1730 hrs IST (1000-1200 UTC) of 20th May, with maximum sustained wind speed of 155 – 165 kmph gusting to 185 kmph. It lay over West Bengal as a VSCS, gradually moving north-northeastwards during late evening to night (1200 – 1500 UTC) of 20th May. It moved very close to Kolkata during this period.
- Moving further north-northeastwards, it weakened into an SCS over Bangladesh & adjoining West Bengal around mid-night (1800 UTC) of 20th May, weakened further into a CS over Bangladesh in the early hours (2100 UTC of 20th) of 21st May, into DD over Bangladesh around noon of 21st May and into a D over north Bangladesh in the evening (1200 UTC) of the same day. It further weakened and lay as a well marked low pressure area over north Bangladesh and neighbourhood around mid-night (1800 UTC) of 21st May.
- The observed track of the system during 16th – 21st May is presented in **Fig. 2.2.1**. Best Track parameters associated with the system are presented in **Table 2.2.1**.

The salient features of the system were as follows:

- i. It was the first SuCS over the BoB, after the Odisha SuCS of 1999.
- ii. Climatologically, during satellite era a total of 7 severe cyclonic storms and above intensity storms developed within the grid $\pm 2.5^\circ$ of the genesis point (10.4°N and 87.0°E). Out of these, 5 crossed Bangladesh coast and 2 crossed north Andhra Pradesh coast (Fig. 2.2.2a). Considering the total number of severe cyclonic storms and above intensity storms crossing West Bengal-Bangladesh coasts in the month of May during satellite era, a total of 2 (1989, 2009) severe cyclonic storms and above intensity storms crossed West Bengal coast and 7 crossed Bangladesh coast (Fig. 2.2.2b).
- iii. It had a clockwise recurving track as it moved initially north-northwestwards till 1200 UTC of 17th and north-northeastwards thereafter. The total track length of the system was 1765 km. It was mainly steered by an anticyclonic circulation in middle & upper tropospheric levels to the northeast of the system centre.
- iv. It underwent intensification during 17th noon (0600 UTC) to 19th May early morning hours (2100 UTC of 18th) over westcentral BoB mainly due to low vertical wind shear (10-15 knots), very warm sea surface temperatures (SSTs – $30\text{--}31^\circ\text{C}$), high tropical cyclone heat potential ($100 - 120 \text{ KJ /cm}^2$) and increased cross equatorial wind surge. During this period, the system experienced an increase in maximum sustained wind speed (MSW) from 50 knots at 0600 UTC of 17th to 130 knots at 2100 UTC of 18th May.
- v. The peak MSW of the cyclone was 240-250 kmph (130 knots) gusting to 275 kmph (145 knots) during 1800 UTC of 18th to 0000 UTC of 19th May over the westcentral BoB. The lowest estimated central pressure was 920 hPa during the same period (Fig.2.2.3a). Thereafter, the system started weakening over westcentral BoB under unfavourable environment (increase in vertical wind shear (20-25 knots)) and low Ocean thermal energy.
- vi. The system crossed West Bengal-Bangladesh coasts as a very severe cyclonic storm across Sundarbans, near lat. 21.65°N /long. 88.30°E during 1000-1200 UTC, with maximum sustained wind speed of 85 knots gusting to 100 knots.
- vii. The system maintained the cyclonic storm intensity for almost 15 hours even after landfall from 1200 UTC of 20th May to 0300 UTC of 21st May.
- viii. The life period (D to D) of the system was 138 hours (5 days & 18 hours) against Long Period Average (LPA) of 134 hours (5 days & 14 hrs) for VSCS/ESCS categories over BoB during pre monsoon season based on the data of 1990-2013.
- ix. It moved with 12 hour average translational speed of 13.9 kmph against LPA (1990-2013) of 14.7 kmph for VSCS category over the north Indian Ocean (Fig.2.2.3b). During initial stages of its development (0000 UTC of 16th to 1200 UTC of 18th May), AMPHAN moved slower than the average. Thereafter the speed increased and reached the maximum (29 kmph at 0600 UTC of 20th May) just prior to landfall.
- x. The Velocity Flux, Accumulated Cyclone Energy (a measure of damage potential) and Power Dissipation Index (a measure of loss) were 16.30×10^2 knots, 15.45×10^4 knots² and 16.04×10^6 knots³ respectively against the LPA during 1990-2013 of 5.28×10^2 knots, 8.6×10^4 knots² and 2.8×10^6 knots³ respectively for tropical cyclones over BoB during pre-monsoon season.

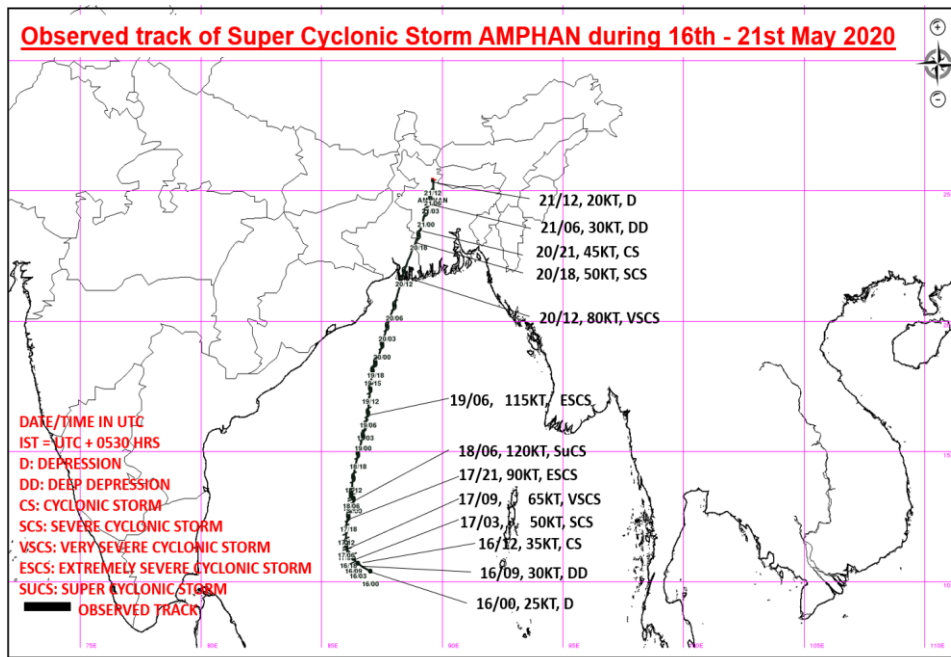


Fig.2.2.1: Observed track of SuCS ‘AMPHAN’ over the southeast Bay of Bengal (16-21 May, 2020)

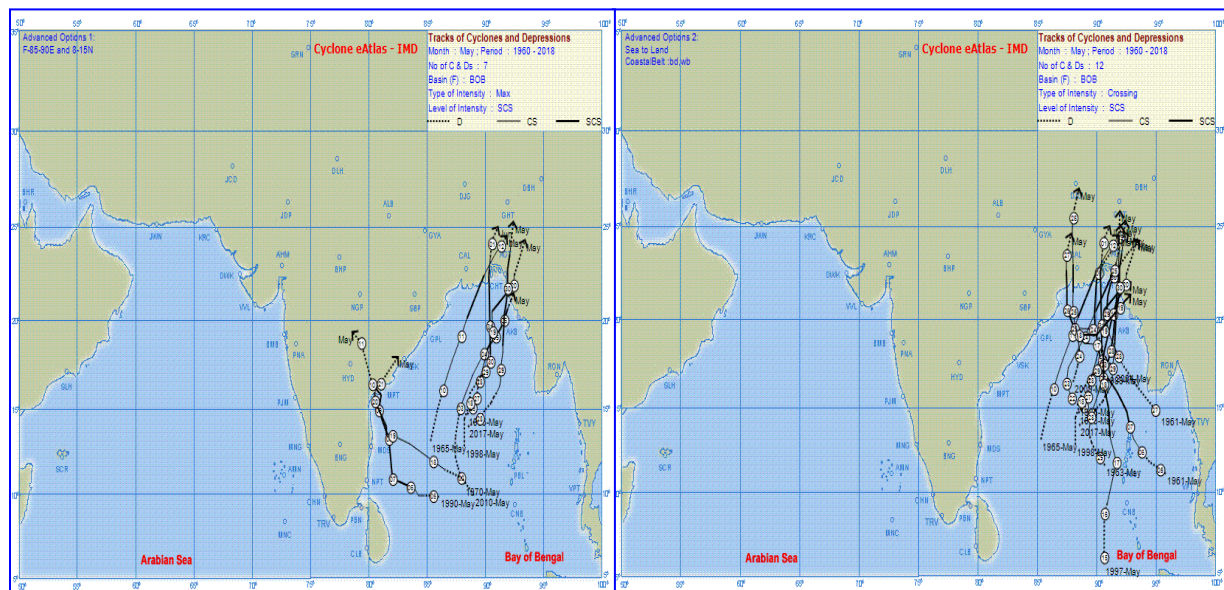


Fig.2.2.2: Tracks of severe cyclonic storms and above intensity storms (a) developing in the grid $\pm 2.5^\circ$ of genesis point and (b) crossing West Bengal-Bangladesh coasts in the month of May during satellite era 1960 onwards

Table 2.2.1: Best track positions and other parameters of the Super Cyclonic Storm, 'AMPHAN' over the Bay of Bengal during 16 May- 21 May, 2020

Date	Time (UTC)	Centre lat. ^o N/ long. ^o E		C.I. NO	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
16/05/2020	0000	10.4	87.0	1.5	1000	25	03	D
	0300	10.7	86.5	1.5	1000	25	03	D
	0600	10.9	86.3	1.5	1000	25	03	D
	0900	10.9	86.3	2.0	998	30	05	DD
	1200	10.9	86.3	2.5	996	35	07	CS
	1500	11.0	86.2	2.5	995	40	08	CS
	1800	11.1	86.1	2.5	995	40	08	CS
	2100	11.3	86.1	3.0	994	45	10	CS
17/05/2020	0000	11.4	86.0	3.0	992	45	10	CS
	0300	11.4	86.0	3.0	990	50	12	SCS
	0600	11.5	86.0	3.5	988	55	15	SCS
	0900	11.7	86.0	4.0	980	65	22	VSCS
	1200	12.0	86.0	4.0	978	70	25	VSCS
	1500	12.8	86.2	4.0	978	70	25	VSCS
	1800	12.5	86.1	4.5	970	80	32	VSCS
	2100	12.9	86.4	5.0	962	90	40	ESCS
18/05/2020	0000	13.2	86.3	5.5	952	100	50	ESCS
	0300	13.3	86.2	6.0	936	115	66	ESCS
	0600	13.4	86.2	6.5	930	120	72	SuCS
	0900	13.7	86.2	6.5	930	120	72	SuCS
	1200	14.0	86.3	6.5	926	125	76	SuCS
	1500	14.5	86.4	6.5	926	125	76	SuCS
	1800	14.9	86.5	6.5	920	130	84	SuCS
	2100	15.2	86.6	6.5	920	130	84	SuCS
19/05/2020	0000	15.6	86.7	6.5	926	125	76	SuCS
	0300	16.0	86.8	6.0	930	120	72	SuCS
	0600	16.5	86.9	6.0	936	115	66	ESCS
	0900	17.0	86.9	6.0	942	110	60	ESCS
	1200	17.4	87.0	5.5	946	105	56	ESCS
	1500	18.1	87.1	5.5	950	100	50	ESCS
	1800	18.4	87.2	5.5	950	100	50	ESCS
	2100	18.7	87.2	5.5	950	100	50	ESCS
20/05/2020	0000	19.1	87.5	5.0	954	95	46	ESCS
	0300	19.8	87.7	5.0	958	90	40	ESCS
	0600	20.6	88.0	5.0	960	90	40	ESCS
	0900	21.4	88.1	5.0	960	90	40	ESCS
	Crossed West Bengal – Bangladesh coasts as a very severe cyclonic							

	storm across Sundarbans, near lat.21.65°N/long. 88.3°E during 1000-1200 UTC, with maximum sustained wind speed of 85 knots gusting to 100 knots.							
	1200	21.9	88.4	-	968	80	32	VSCS
	1500	22.7	88.6	-	978	65	32	VSCS
	1800	23.3	89.0	-	984	50	14	SCS
	2100	24.2	89.0	-	986	45	12	CS
21/05/2020	0000	24.2	89.3	-	988	40	10	CS
	0300	24.7	89.5	-	990	35	08	CS
	0600	25.0	89.6	-	992	30	06	DD
	1200	25.4	89.6	-	995	20	04	D
	1800	Weakened into a well marked low pressure area over north Bangladesh and neighbourhood						

2.2.2 Brief life history

2.2.2.1 Genesis

Under the influence of the remnant cyclonic circulation over south Andaman Sea and adjoining southeast BoB during 6th – 12th May, a fresh Low Pressure Area formed over southeast BoB and adjoining south Andaman Sea in the morning (0300 UTC) of 13th May. At 0000 UTC of 13th May, Madden Julian Oscillation (MJO) index lay in phase 2 with amplitude nearly 1. It was forecast to continue in same phase till 17th May with amplitude remaining more than 1. Thereafter during 18th-21st, it was forecast to move to phase 4 across phase 3 with amplitude remaining less than 1. Thus, MJO was supporting enhancement of convective activity over BOB for next 8 days. SST was 30-31°C over entire BOB and over Andaman Sea. TCHP was more than 100 KJ/cm² over major parts of south & central BOB and eastern parts of Andaman Sea. It was about 60-80 KJ/cm² over remaining parts of Andaman Sea and BOB to the north of 17°N and was decreasing towards extreme north BOB. The lower level positive vorticity was about 20-25 x10⁻⁶sec⁻¹ over some parts of south and eastcentral BOB. Also a small zone of higher positive vorticity (40-50 x10⁻⁶sec⁻¹) lay over southeast BOB with vertical extension upto 500 hPa level and was persisting over the same area during past 24 hours with magnitude remaining the same. The zone of positive lower level convergence zone became more organized and lay over southeast BOB and another over south Andaman Sea (each 10x10⁻⁵sec⁻¹). The zone of positive upper level divergence with same value during the period (10x10⁻⁵sec⁻¹) lay over south Andaman Sea. Vertical wind shear (VWS) was low to moderate (5-20 kts) to the south of 10°N over Andaman Sea and south BOB. It was becoming high to the north of 10°N. The upper tropospheric ridge lay near 9°N over BOB in association with anticyclonic circulation over north Andaman Sea.

At 0300 UTC of 14th May, it lay as a well marked low pressure area (WML) over southeast BOB & neighbourhood. At 0300UTC of 14th, similar MJO and sea conditions prevailed. Strength of higher positive vorticity zone increased during past 24 hours (60-80 x10⁻⁶sec⁻¹) over southeast BOB with vertical extension upto 200 hPa level. The strength of convergence zone over southeast BOB also increased during past 24 hours (15x10⁻⁵sec⁻¹). The upper level divergence increased significantly during the period (15x10⁻⁵sec⁻¹) over southeast BOB. Vertical wind shear (VWS) was moderate (15-20 kts) to the south of 10°N over Andaman Sea and south BOB. It was becoming high to the north of 10°N. The upper tropospheric ridge lay near 10°N over BOB. Total precipitable water imagery at 2241 UTC of 13th May indicated increased cross equatorial flow with significantly high warm moist air incursion into the system.

At 0300 UTC of 15th May, similar sea conditions prevailed. Considering the environmental conditions, the higher positive vorticity zone maintained its strength ($60-80 \times 10^{-6} \text{sec}^{-1}$) over southeast BOB with vertical extension upto 500 hPa level. The convergence zone over southeast BOB was the same during past 24 hours ($15 \times 10^{-5} \text{sec}^{-1}$) and was north-south oriented. Upper level divergence was the same during the period ($40 \times 10^{-5} \text{sec}^{-1}$) over southeast BOB and was north-south oriented. Vertical wind shear (VWS) was moderate (15-20 kts) to the south of 10°N over southwest and adjoining southeast BOB. It was becoming high to the north of 10°N and Andaman Sea. The upper tropospheric ridge lay near 10°N over BOB. The system maintained its intensity of well marked low pressure area.

At 0000 UTC of 16th the system intensified into a depression. Similar sea conditions prevailed. Considering the environmental conditions, the strength of positive vorticity zone increased ($50-100 \times 10^{-6} \text{sec}^{-1}$) over the southeast BOB with vertical extension upto 500 hPa level. The convergence zone over southeast BOB increased during past 24 hours ($30 \times 10^{-5} \text{sec}^{-1}$). Upper level divergence was the same during the period ($40 \times 10^{-5} \text{sec}^{-1}$) over southeast BOB and was north-south oriented. Vertical wind shear (VWS) was moderate (10-15 kts) to the south of 10°N over southwest and adjoining southeast BOB. It was becoming high to the north of 10°N and Andaman Sea. The upper tropospheric ridge lay near 10°N over BOB.

2.2.2.2 Intensification and movement

At 0900 UTC of 16th the system intensified into a deep depression. At that time, the Madden Julian Oscillation (MJO) index lay in phase 2 with amplitude more than 1. It was forecast to continue in same phase till 17th May with amplitude remaining more than 1 and becoming less than 1 thereafter in phase 3. Thus, MJO was supporting enhancement of convective activity over the Bay of Bengal (BOB) for next 5 days. Considering the sea conditions, the sea surface temperature (SST) was $30-31^{\circ}\text{C}$ over entire BOB and over Andaman Sea. The tropical cyclone heat potential was more than 100 KJ/cm^2 over major parts of south & central BOB and eastern parts of Andaman Sea. It was about $60-80 \text{ KJ/cm}^2$ over remaining parts of Andaman Sea and BOB to the north of 17°N and was decreasing towards extreme north BOB. The enhanced positive vorticity zone maintained its strength (more than $150 \times 10^{-6} \text{sec}^{-1}$) around the system centre with vertical extension upto 200 hPa level. The lower level convergence zone over southeast BOB increased and was around $30 \times 10^{-5} \text{sec}^{-1}$ around the system centre. Upper level divergence was the same during the period ($40 \times 10^{-5} \text{sec}^{-1}$) over southeast BOB. Vertical wind shear (VWS) decreased and was low to moderate (15-20 kts) around the system centre. It was high remaining same to the north of 10°N along the expected track. The upper tropospheric ridge lay near 11.5°N over BOB. TPW imagery at 0741 UTC of 16th May indicated warm moist air incursion into the system centre.

At 1200 UTC of 16th, the system further intensified into the cyclonic storm “Amphan”. Similar sea conditions prevailed. The enhanced positive vorticity zone maintained its strength (more than $200 \times 10^{-6} \text{sec}^{-1}$) around the system centre with vertical extension upto 200 hPa level. The lower level convergence zone was around $20 \times 10^{-5} \text{sec}^{-1}$ located over southwest of the system centre. Upper level divergence of $30 \times 10^{-5} \text{sec}^{-1}$ located over southwest of the system centre. Vertical wind shear (VWS) further decreased and was low to moderate (10-15 kts) around the system centre. It was increasing to north of lat. 15°N along the expected track. The upper tropospheric ridge lay

near 12°N over BOB. TPW imagery at 1041 UTC of 16th May indicated warm moist air incursion into the system area.

At 0300 UTC of 17th it intensified into a severe cyclonic storm. Similar sea conditions prevailed. The enhanced positive vorticity zone maintained its strength (more than $200 \times 10^{-6} \text{sec}^{-1}$) around the system centre with vertical extension upto 200 hPa level. The low level convergence zone (around $30 \times 10^{-5} \text{sec}^{-1}$) lay to the southeast of system centre. The upper level divergence was about $60 \times 10^{-5} \text{sec}^{-1}$ around the system centre. Vertical wind shear (VWS) increased and was moderate to high (20-25 kts) around the system centre. It was increasing to north of latitude 15°N along the expected track. The upper tropospheric ridge lay near 13°N over BOB. The system moved nearly northwards along the axis of the ridge and was expected to continue same movement for next 24 hours. Thereafter, the system was likely to move to the north of the ridge axis and recurve north/northeastwards and move faster. Total precipitable water imagery at 0100 UTC of 17th May indicated continued warm moist air incursion into the system area.

At 0900 UTC of 17th, it further intensified into a very severe cyclonic storm. Similar sea conditions prevailed. The enhanced positive vorticity zone maintained its strength (more than $200 \times 10^{-6} \text{sec}^{-1}$) around the system centre with vertical extension upto 200 hPa level. The lower level convergence zone was around $30 \times 10^{-5} \text{sec}^{-1}$ located over southeast of the system centre. The upper level divergence decreased and was about $30 \times 10^{-5} \text{sec}^{-1}$ located around the system centre. Vertical wind shear (VWS) continued to remain moderate to high (20-25 kts) around the system centre. It was increasing to the north of lat. 15°N along the expected track. The upper tropospheric ridge lay near 13°N over BOB. The system moved northwards along the axis of the ridge and was likely to continue the same movement for next 24 hours. Subsequently, the system was expected to move to the north of the ridge axis and would start recurving north/northeastwards and move faster. TPW water imagery of 17th May indicated continued warm moist air incursion into the system centre, mainly in its northwestern sector.

At 2100 UTC of 17th, it further intensified into an extremely severe cyclonic storm. Similar sea conditions prevailed. The positive vorticity increased and was around $(250-300) \times 10^{-6} \text{sec}^{-1}$ around the system centre with vertical extension upto 200 hPa level. The lower level convergence zone was $60-70 \times 10^{-5} \text{sec}^{-1}$ around the system centre. The upper level divergence was about $\times 10^{-5} \text{sec}^{-1}$ to the north of system centre. Vertical wind shear (VWS) was low to moderate (10-15 kts) around the system centre. It was increasing to 20-25 kts to the north between 15-20°N along the expected track. The upper tropospheric ridge lay near 17.0°N over BoB. The system moved near northwards along the periphery of the anticyclone and it was likely to continue in the same direction for some more times. Thereafter, the system was likely to recurve north-northeastwards.

At 0600 UTC of 18th, it further intensified into a super cyclonic storm, MJO index lay in phase 2 with amplitude more than 1 during 18th-20th May. Thus, MJO phase and amplitude were supporting enhancement of convective activity over BoB. SST was 30-31°C over entire BOB. TCHP was more than 100 KJ/cm^2 over major parts of south & central BOB. It was about $60-80 \text{ KJ/cm}^2$ over BOB to the north of 17°N and was decreasing towards extreme north BOB. The positive vorticity was around $(250-300) \times 10^{-6} \text{sec}^{-1}$ around the system centre with vertical extension upto 200 hPa level. The lower

level convergence zone was around $(50-60) \times 10^{-5} \text{sec}^{-1}$ to the southwest of the system centre. The upper level divergence was about $30 \times 10^{-5} \text{sec}^{-1}$ to the west of the system centre. Vertical wind shear (VWS) was low to moderate (10-15 kts) around the system centre. It was increasing to 20-30 kts to the north between $15-20^{\circ}\text{N}$ along the expected track. The upper tropospheric ridge lay near 17.0°N over BOB. The system moved northwards along the periphery of the ridge and it was likely to continue in the same direction for some more time. Thereafter, the system was likely to recurve in the north-northeastward direction. TPW imagery of 18th May indicated continued warm moist air incursion over the system area, mainly in its northwestern sector.

At 0600 UTC of 19th, the system weakened into an extremely severe cyclonic storm. MJO index lay in phase 2 with amplitude more than 1 for next two days. It was forecast to remain in phase 3 with amplitude more than 1 during subsequent three days (20th-22nd). Thus, MJO phase and amplitude were supporting enhancement of convective activity over BoB. SST was $30-31^{\circ}\text{C}$ over entire Bay of Bengal, but system was entering into the area with lower TCHP of $70-90 \text{ KJ/cm}^2$ which was further decreasing towards north BoB along the system track. The positive vorticity was around $(250-300) \times 10^{-6} \text{sec}^{-1}$ around the system centre with vertical extension upto 200 hPa level. The lower level convergence zone was $50 \times 10^{-5} \text{sec}^{-1}$ located around the system centre. The upper level divergence decreased and was about $20 \times 10^{-5} \text{sec}^{-1}$ to northeast of the system centre. Vertical wind shear (VWS) was moderate to high (20-25 kts) around the system centre. It was increasing to 30-40 kts to the north between $15-20^{\circ}\text{N}$ along the expected track. The upper tropospheric ridge lay near 16.0°N over BoB. The system moved north-northeastwards along the periphery of the ridge to its south.

The system crossed the coast during 0900-1200 UTC of 20th. The positive vorticity was around $250-300 \times 10^{-6} \text{sec}^{-1}$ around the system centre with vertical extension upto 200 hPa level. The lower level convergence was $(30-40) \times 10^{-5} \text{sec}^{-1}$ around the system centre. The upper level divergence also reduced to $10 \times 10^{-5} \text{sec}^{-1}$ around the system centre. Vertical wind shear (VWS) was moderate to high (25-30 kts) around the system centre. It was increasing to 30-40 kts to the north of 23°N along the expected track. The upper tropospheric ridge lay near 21.5°N over Bay of Bengal. The system moved north-northeastwards along the periphery of the anticyclone over Myanmar.

At 1800 UTC of 20th, the system further weakened into a severe cyclonic storm. Considering the environmental conditions, the positive vorticity was $250-300 \times 10^{-6} \text{sec}^{-1}$ around the system centre with vertical extension upto 200 hPa level. The lower level convergence was $(30-40) \times 10^{-5} \text{sec}^{-1}$ around the system centre. The upper level divergence reduced to $10 \times 10^{-5} \text{sec}^{-1}$ around the system centre. Vertical wind shear (VWS) was moderate to high (25-30 kts) around the system centre. It was increasing to 30-40 kts at north of 23°N along the expected track. The upper tropospheric ridge was at north and now lay near 22.0°N over Bay of Bengal. At this period the system was moving north-northeastward along the periphery of the anticyclone which lay over Myanmar.

Similar trend continued and the system weakened into a cyclonic storm at 2100 UTC of 20th, into a deep depression at 0600 UTC of 21st, into a depression at 1200 UTC of 20th and into a well marked low pressure area at 1800 UTC of 21st.

The total precipitable water (TPW) imageries (Source: TC Forecaster Website: https://rammb-data.cira.colostate.edu/tc_realtime/index.asp) during life cycle of SUCS Amphan are presented in Fig. 2.2.3. These imageries indicate excessive increase in warm moist air around the system centre on 1330 UTC of 16th May. The warm moist air supply continued till 1800 UTC of 18th May. Thereafter, it gradually decreased. The system also exhibited decrease in intensity on 19th & 20th prior to landfall.

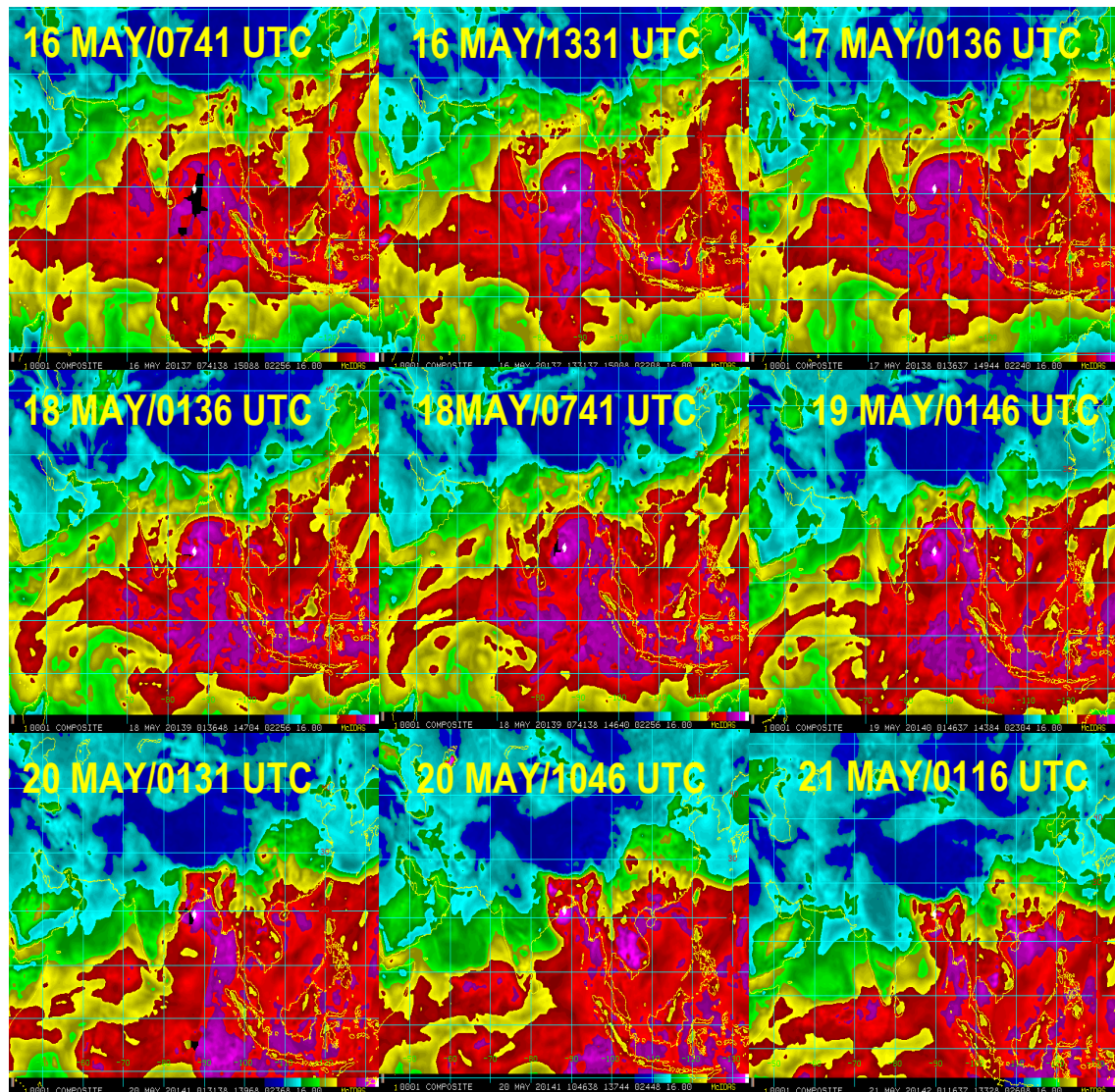


Fig.2.2.3: Typical total precipitable water imageries during life cycle of SuCS Amphan (16th-21st May, 2020).

The mean wind speed and wind shear in middle and deep layer is presented in Fig. 4. The mean wind shear speed in the deep layer was low to moderate (10-20 knot) during the entire life period of the system. The mean wind shear was low in the middle layer. The mean wind speed in the deep and middle layer was low (05-10 knot) till 1200 UTC of 19th May. The mean wind direction in the deep layer represented the near northward movement of the system.

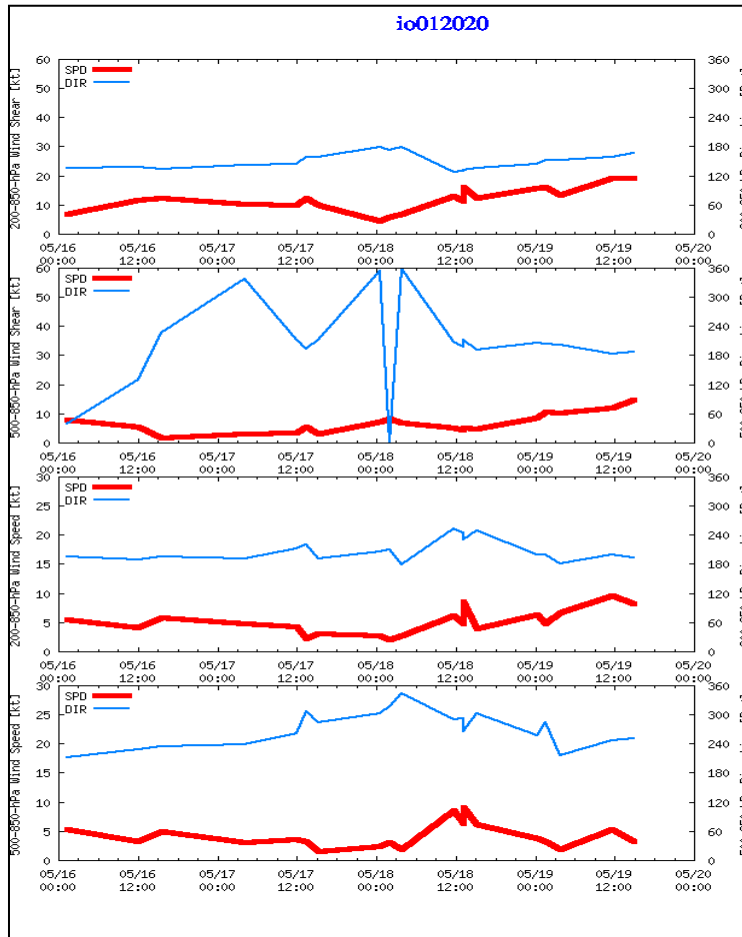


Fig.2.2.4: Wind shear and wind speed in the middle and deep layer around the system during SuCS AMPHAN (16-21 May, 2020)

It moved with 12 hour average translational speed of 13.9 kmph against LPA (1990-2013) of 14.7 kmph for VSCS category over the north Indian Ocean (Fig.5). During initial stages of it's development (0000 UTC of 16th to 1200 UTC of 18th May), AMPHAN moved slower than the average. Thereafter the speed increased and reached the maximum (29 kmph at 0600 UTC of 20th May) just prior to landfall.

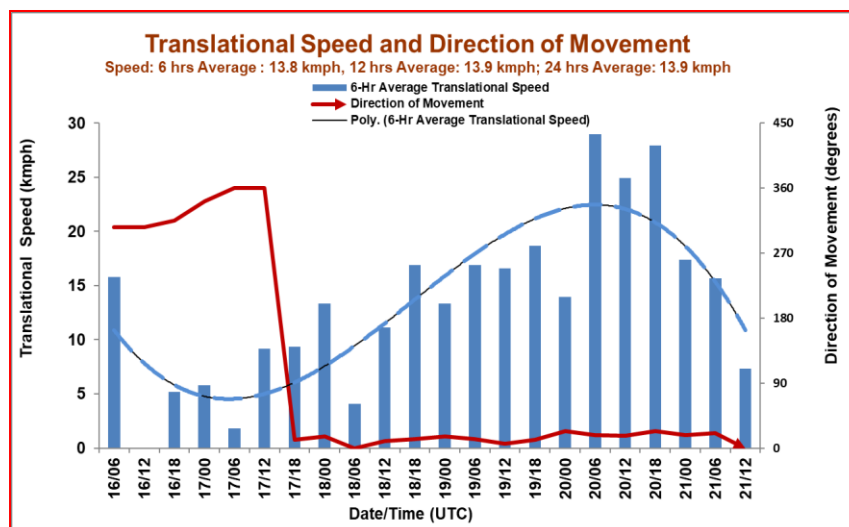


Fig. 2.2.5: Six hourly mean translational speed & direction of movement

2.2.2.3 Maximum Sustained Surface Wind speed and estimated central pressure

The six hourly average translational speed during the life cycle of SuCS Amphan is presented in Fig. 2.2.5. The six hourly maximum sustained wind speed and estimated central pressure is presented in Fig. 2.2.6. After landfall, the system exhibited rapid weakening during 1500 UTC of 20th to 0600 UTC of 21st May.

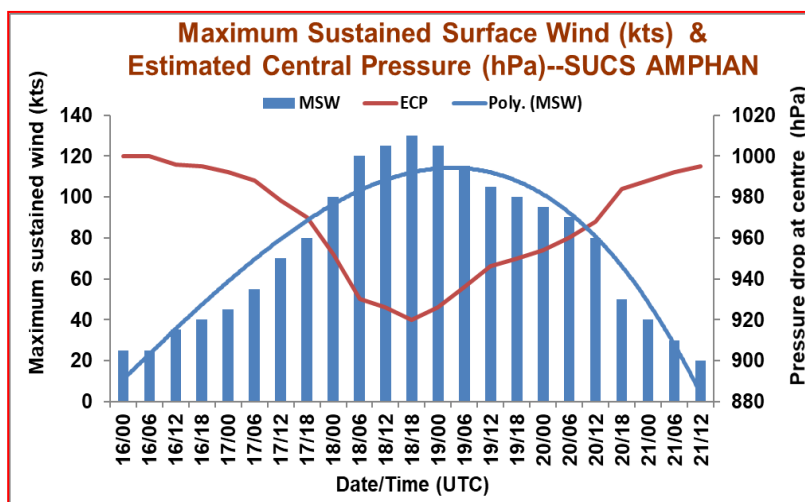


Fig.2.2.6: Maximum sustained surface winds (kts) & Estimated Central Pressure

2.2.3 Monitoring of SuCS, 'AMPHAN'

India Meteorological Department (IMD) maintained round the clock watch over the north Indian Ocean and the system was monitored since 23rd April about three weeks prior to the formation of the Low Pressure Area over the southeast BoB on 13th May. A Low Pressure Area formed over south Andaman Sea and adjoining southeast Bay of Bengal on 1st May. It meandered over the region for next 5 days and became less marked on 6th. However, associated cyclonic circulation persisted over the region till 12th. In the extended range outlook issued on 7th May, IMD indicated possible Cyclogenesis during the second week over south Andaman Sea and adjoining southeast Bay of Bengal. Accordingly, continuous watch of this circulation was maintained. On 9th May, it was indicated that a Low Pressure Area would form over the region on 13th May (96 hours prior to formation of the system) under the influence of the remnant cyclonic circulation persisting over the region during 6th-12th. On 11th, it was indicated that cyclogenesis (formation of depression) would occur around 16th May (48 hours prior to formation of the Low Pressure Area and 120 hours prior to formation of depression) over the BoB.

The cyclone was monitored with the help of available satellite observations from INSAT 3D and 3DR, polar orbiting satellites including SCATSAT, ASCAT etc. and available ships & buoy observations in the region. From 18th May midnight (1800 UTC) onwards till 20th May, the system was tracked gradually by IMD Doppler Weather Radars (DWRs) at Visakhapatnam, Gopalpur, Paradip, Kolkata and Agartala as it moved from south to north. IMD also utilised DWR products from 'DRDO Integrated Test Range', Chandipur, Balasore for tracking the system. Various numerical weather prediction models run by Ministry of Earth Sciences (MoES) institutions, various global models and IMD's dynamical-statistical models developed in-house were utilized to predict the genesis, track, landfall and intensity of the cyclone. A digitized forecasting system of IMD was utilized for analysis and comparison of guidance from various

models, decision making process and warning product generation. Typical satellite and radar imageries are presented in **Fig. 2.2.7**

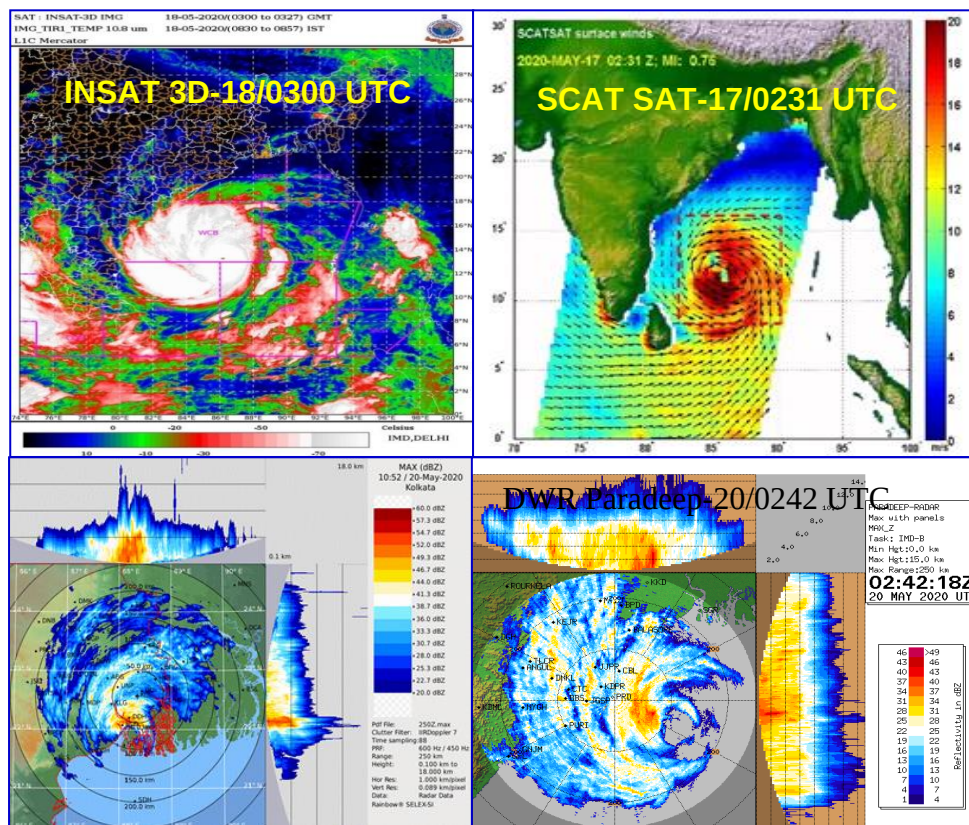


Fig. 2.2.7: Typical satellite and radar imageries of SuCS Amphan

2.2.3.1 Features observed through satellite

At 0000 UTC of 16th, the intensity of the system was T1.5. Associated broken low to medium clouds with embedded intense to very intense convection lay over Bay of Bengal between 6.0°N to 13.0°N longitude 83.0°E to 90.0°E. Minimum CTT was minus 93°C. Convection and organization had increased further.

At 0900 UTC of 16th, the intensity of the system was T 2.0. Broken low to medium clouds with embedded intense to very intense convection lay over Bay of Bengal between Latitudes 5.0°N & 13.5°N and Longitudes 82.0°E & 90.0°E. Minimum CTT minus 93°C

At 1200 UTC of 16th, vortex over south east Bay & neighborhood had further intensified rapidly. The intensity of the system was T 2.5 associated with CDO pattern. Minimum CTT minus 93°C. Associated broken low to medium clouds with embedded intense to very intense convection over Bay between latitude 6.0°N to 16.0°N long 81.0°E to 91.0°E.

At 0300 UTC of 17th, the intensity of the system was T3.0 associated with curved band pattern. Minimum CTT was minus 93°C. Associated broken low to medium clouds with embedded intense to very intense convection lay over Bay between latitude 7.5°N to

14.0°N long 81.0°E to 89.0°E. The SCAT SAT imagery at 1411 UTC of 16th May was indicating winds around 40 kts to the south of system centre with matching index of 0.79.

At 0900 UTC of 17th, it further intensified and the current intensity of the system was T4.0 associated with a banding eye pattern in the visible imagery. Minimum CTT was minus 93°C. Associated broken low to medium clouds with embedded intense to very intense convection over Bay between latitude 7.5°N to 14.0°N long 81.0°E to 89.0°E.

At 2100 UTC of 17th, the system continued to maintain the intensity T6.5. Wall cloud temperature was minus 93°C. Associated broken low to medium clouds with embedded intense to very intense convection prevails between latitude 10.1°N to 21.5°N long 81.5°E to 92.5°E.

At 0600 UTC of 18th, the system further intensified and the current intensity of the system was T6.5. Eye clearly visible with circular pattern and it was continuing with a diameter of 15 km. Eye had become colder with temperature minus 21.0°C. Wall cloud temperature was minus 93°C. Minimum cloud top temperature was minus 93°C. Associated broken low to medium clouds with embedded intense to very intense convection prevails between latitude 10.0°N to 18.0°N long 81.0°E to 90.0°E.

At 0600 UTC of 19th, the system intensity was T5.5/6.0 with ragged eye of diameter around 25 km visible. Wall cloud top temperature was minus 93.1°C. Associated broken low to medium clouds with embedded intense to very intense convection prevailed between latitude 13.0°N to 19.5°N long 83.5°E to 90.0°E.

At 1200 UTC of 20th, the vortex lay over the land close to West Bengal coast. Associated broken low to medium clouds with embedded intense to very intense convection lay over Bay between latitude 19.0°N & 27.0°N longitude 85.0°E & 92.5°E. Wall clouds' minimum cloud top temperature was minus 93°C.

At 1800 UTC of 20th, the vortex lay over the land close to West Bengal coast. Associated broken low to medium clouds with embedded intense to very intense convection lay over the Bay between latitude 19.0°N to 27.0°N longitude 85.0°E to 92.5°E. Wall clouds' minimum cloud top temperature was minus 93°C.

At 0000 UTC of 21st, the vortex lay over the land close to West Bengal coast associated broken low to medium clouds with embedded intense to very intense convection lay over Bay between latitude 20.0°N to 28.0°N longitude 85.0°E to 92.5°E. Wall clouds minimum cloud top temperature minus 83°C.

At 0600 UTC of 21st, the vortex lay over the land in areas of central parts of Bangladesh. Centre was not clearly visible in satellite imagery. Higher clouds had sheared away towards north-east from the system centre. Associated broken low to medium clouds with embedded intense to very intense convection lay over Bangladesh and west Assam Meghalaya. Minimum cloud top temperature was minus 68°C.

At 1200 UTC of 21st, the remnant vortex lay over central parts of Bangladesh & neighbourhood. The vortex center was not clearly defined. Associated scattered low to medium clouds with embedded isolated weak to moderate convection lay over Bangladesh, Assam, Meghalaya, Tripura and Mizoram.

Typical INSAT-3D imageries during entire life cycle of SuCS APHAN (16th-21st May) are presented in Fig. 2.2.8(a)-Fig 2.2.8(e).

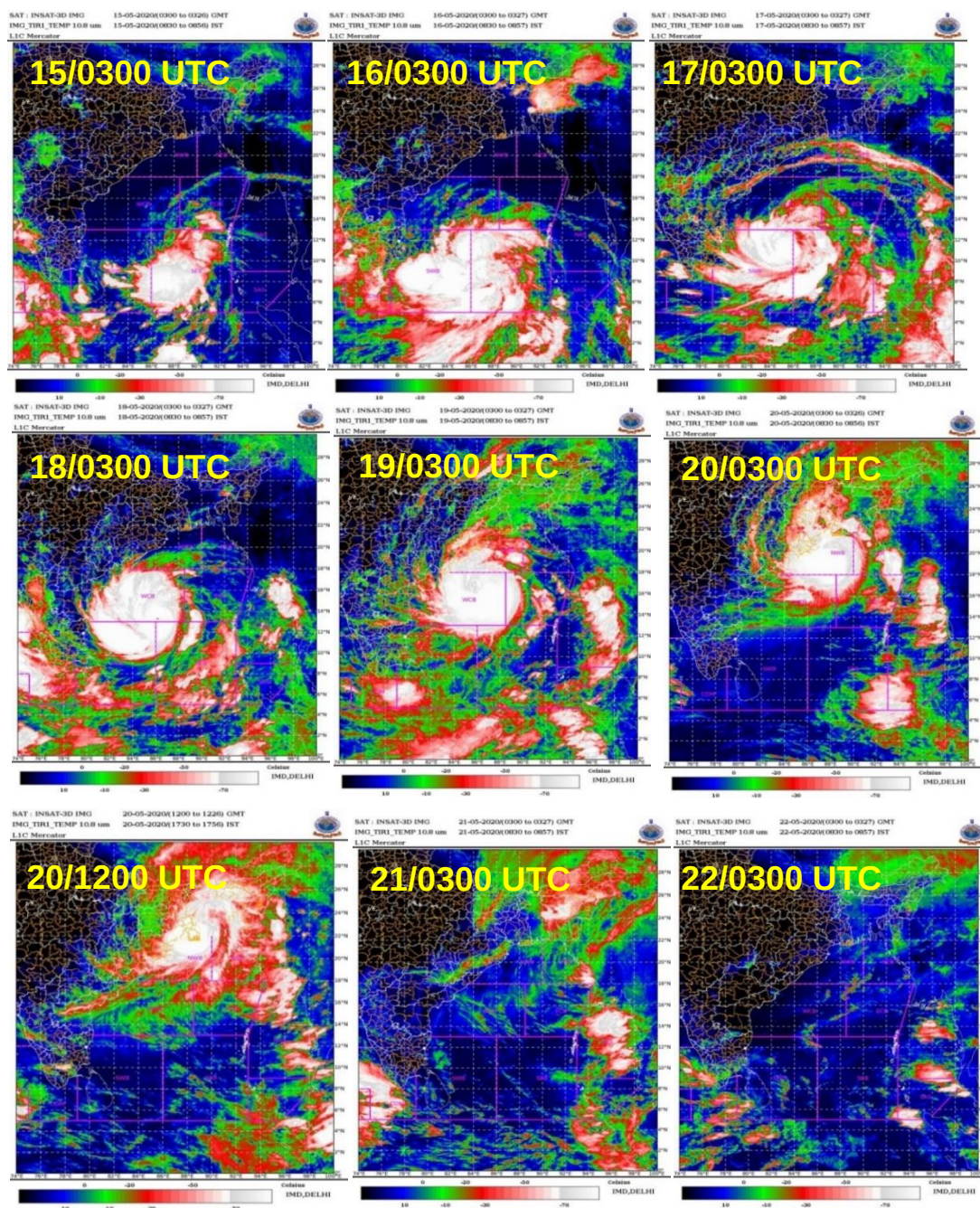


Fig.2.2.8(a): INSAT-3D enhanced colour imageries during life cycle of SuCS AMPHAN (15-21 May, 2020)

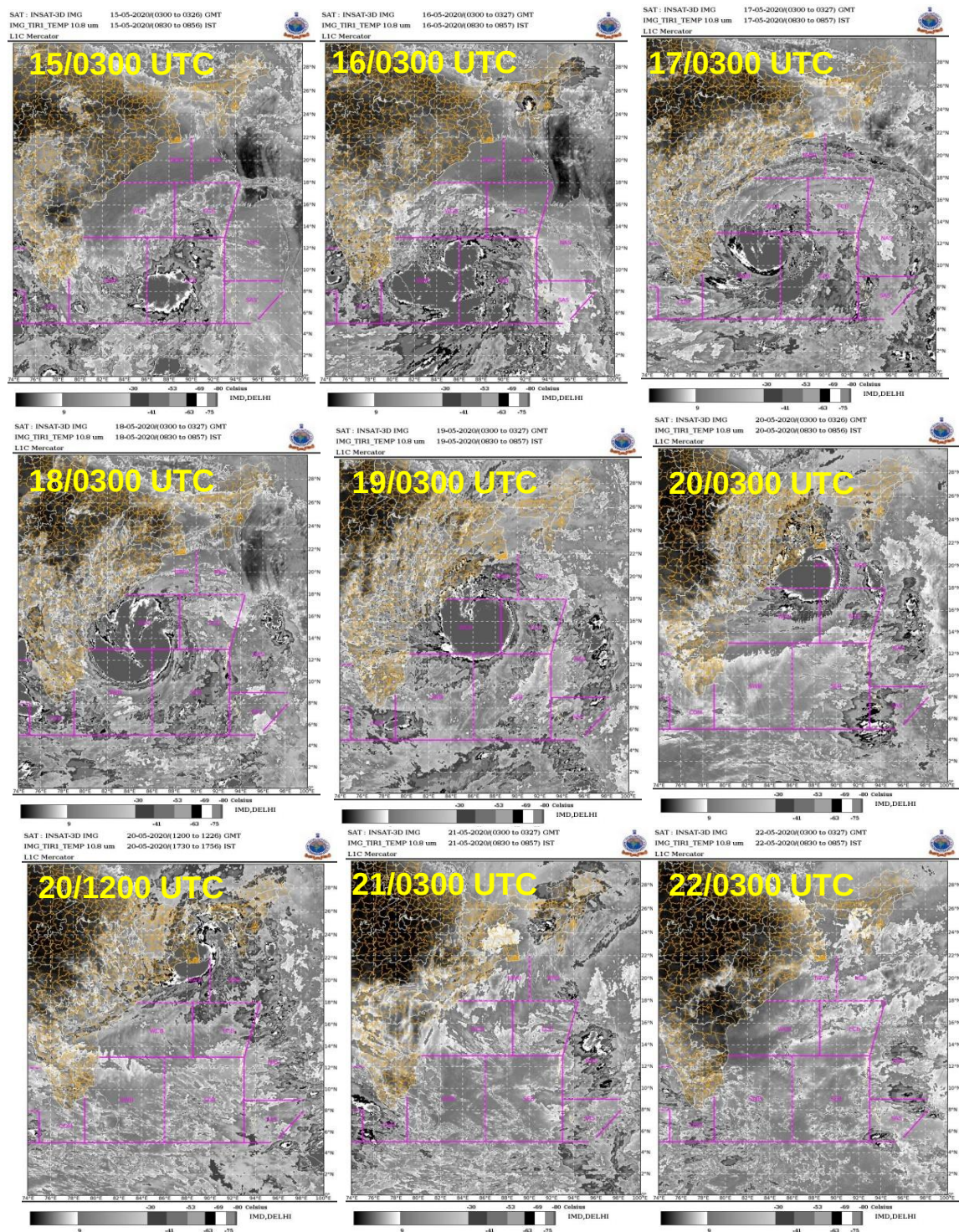


Fig.2.2.8(b): INSAT-3D BD imageries during life cycle of SuCS AMPHAN (15-22 May, 2020)

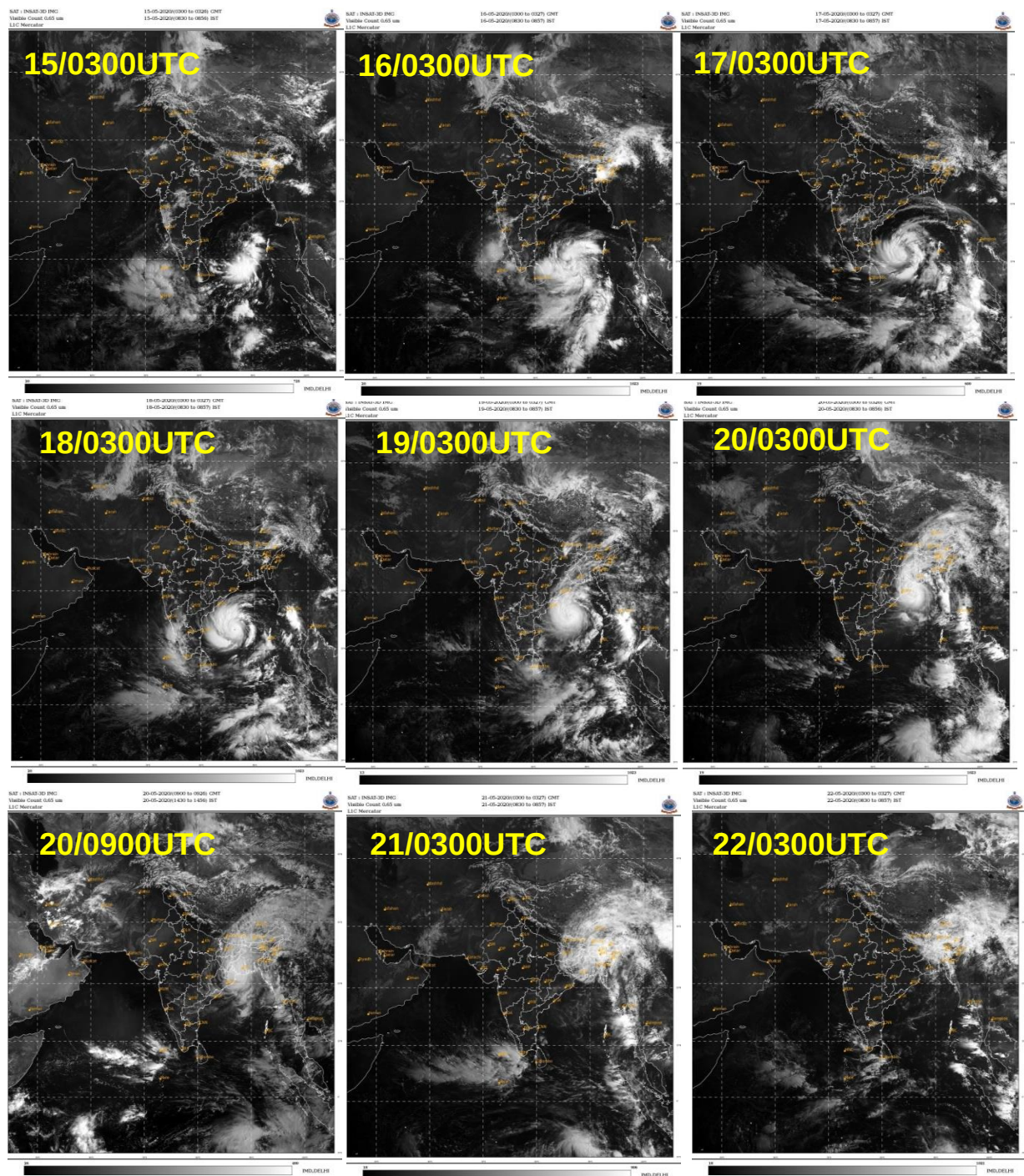


Fig. 2.2.8(c): INSAT-3D Visible imageries during life cycle of SuCS AMPHAN (15-22 May, 2020)

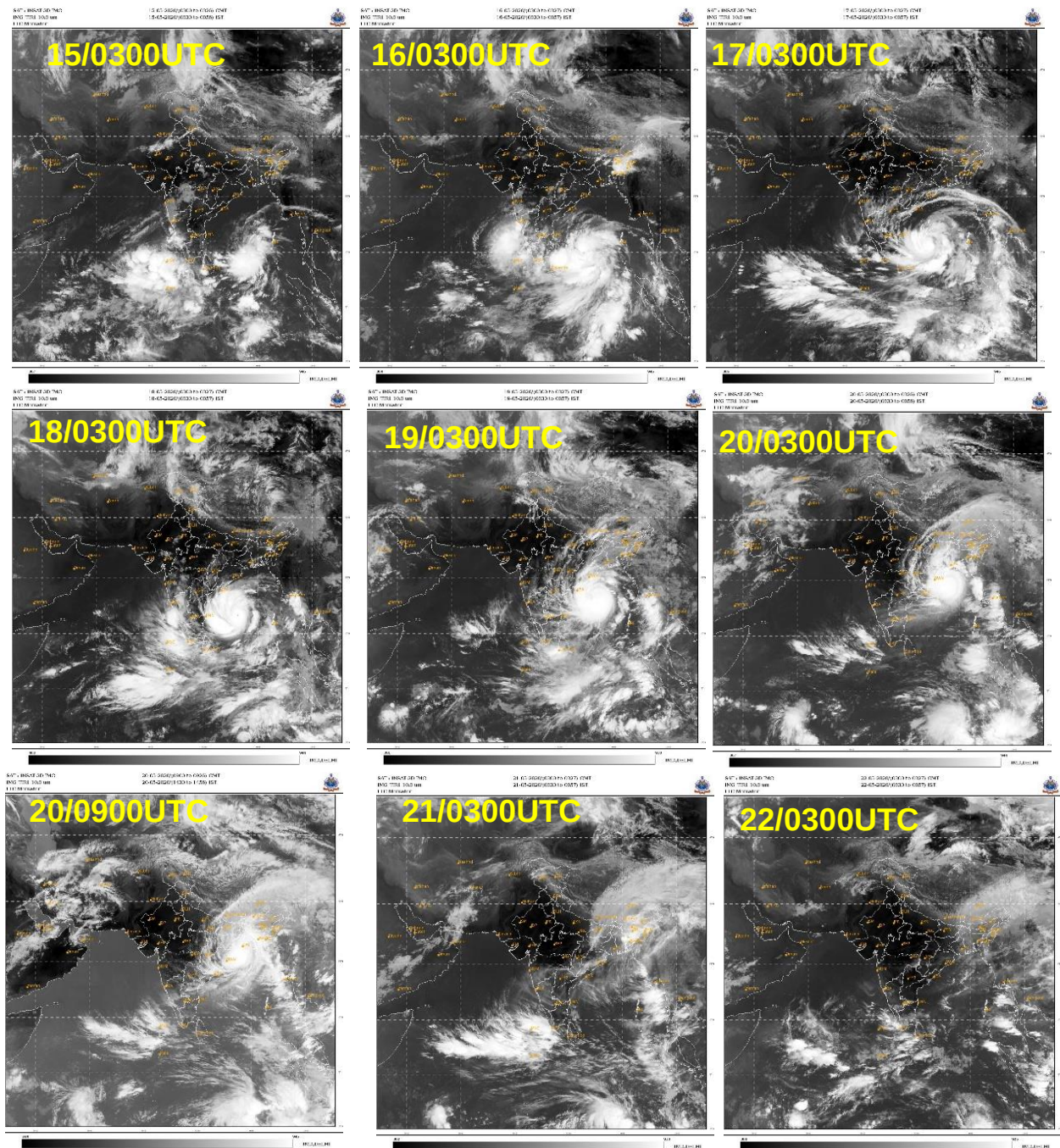


Fig.2.2.8(d): INSAT-3D IR imageries during life cycle of SuCS AMPHAN (15-22 May, 2020)

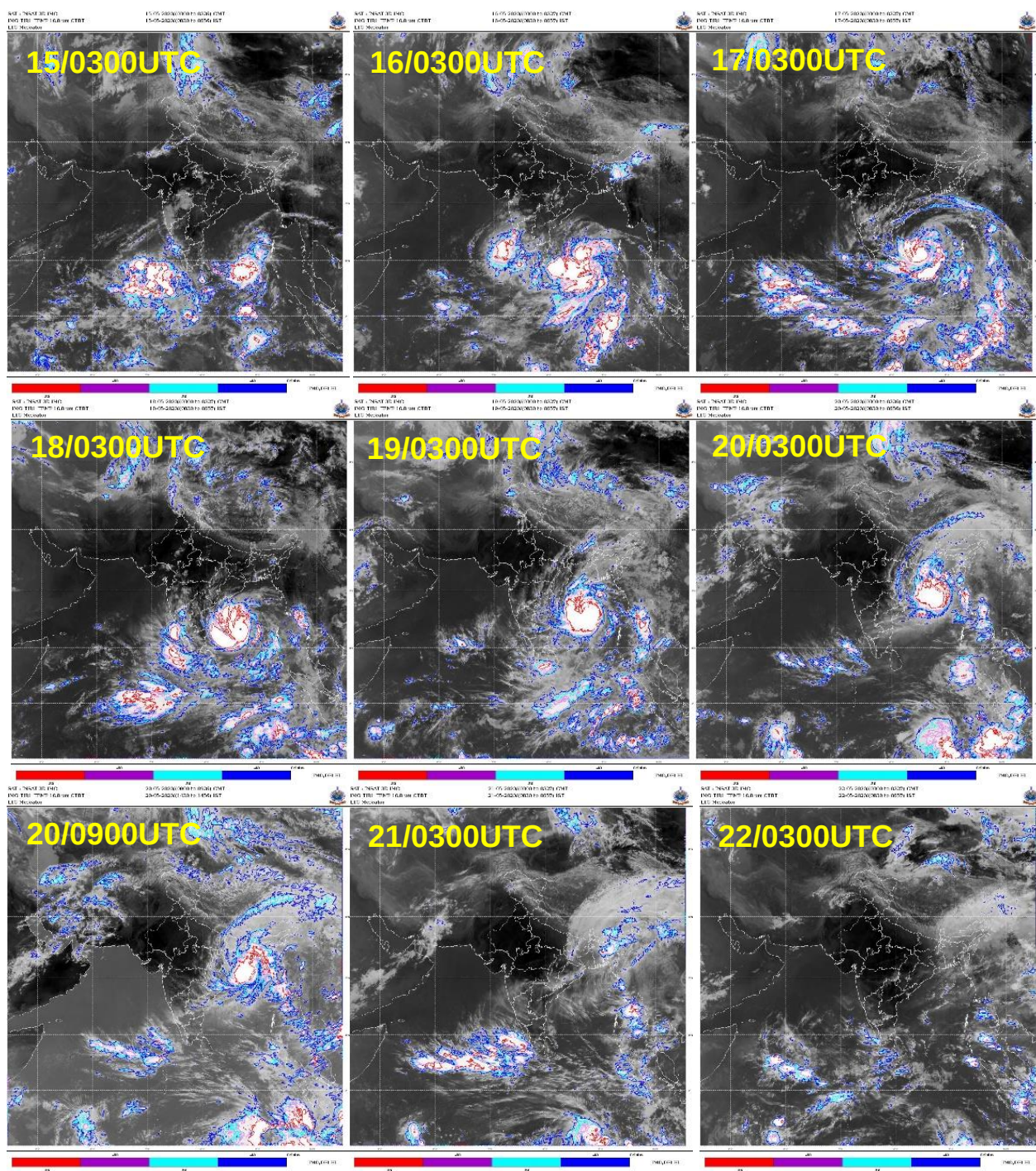


Fig. 2.2.8(e): INSAT-3D Cloud Top Brightness Temperature (CTBT) imageries during life cycle of SuCS AMPHAN (15-22 May, 2020)

Typical SCAT SAT imageries during life cycle of SUCS Amphan (13th May-20th May) since inception as low pressure area are presented in Fig. 2.2.9.

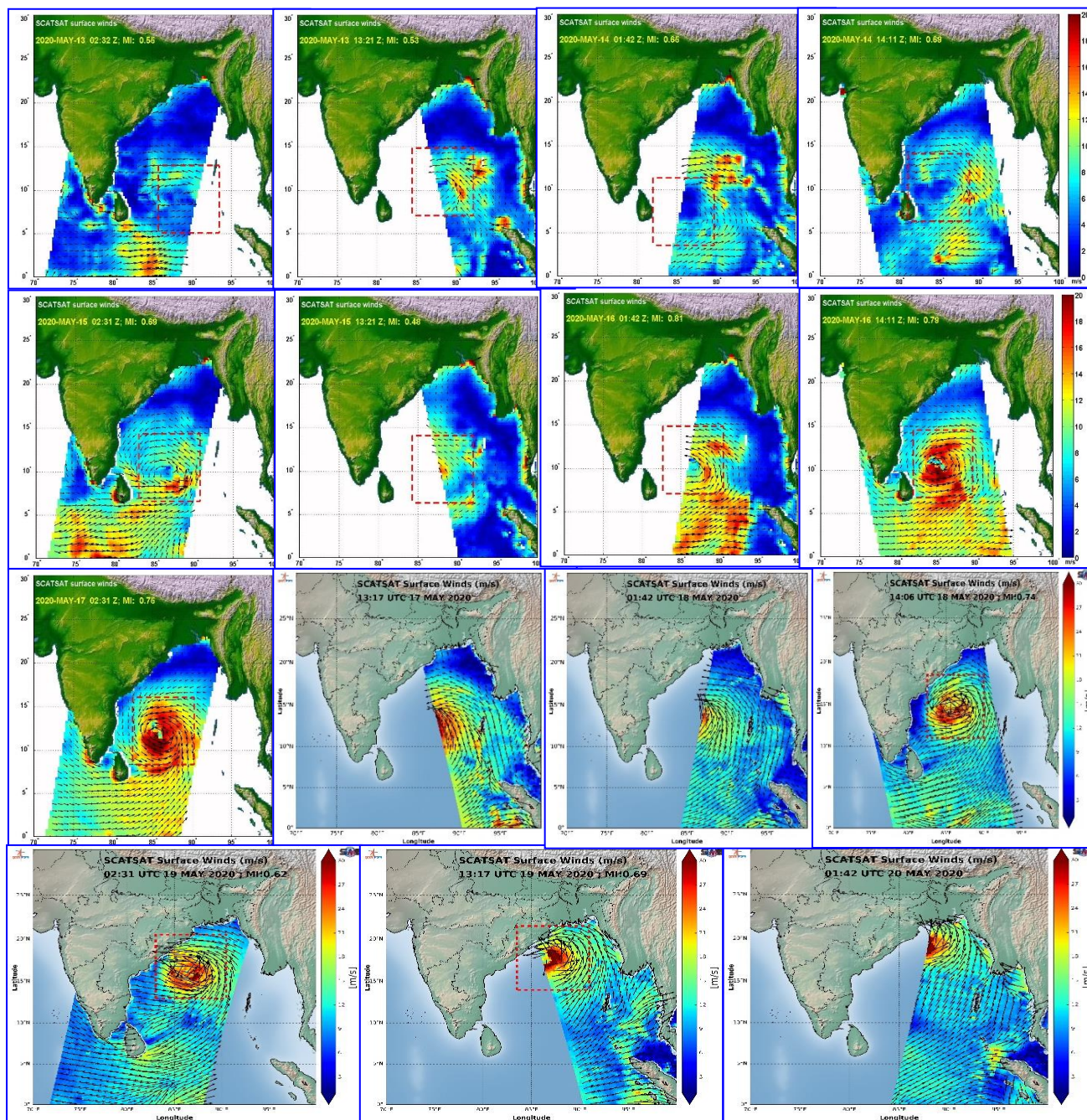


Fig. 2.2.9: SCAT SAT imageries during life cycle of SuCS AMPHAN (13-20 May, 2020)

Typical ASCAT imageries during life cycle of SuCS Amphan (13th -20th May), since inception as low pressure area are presented in Fig. 2.2.10.

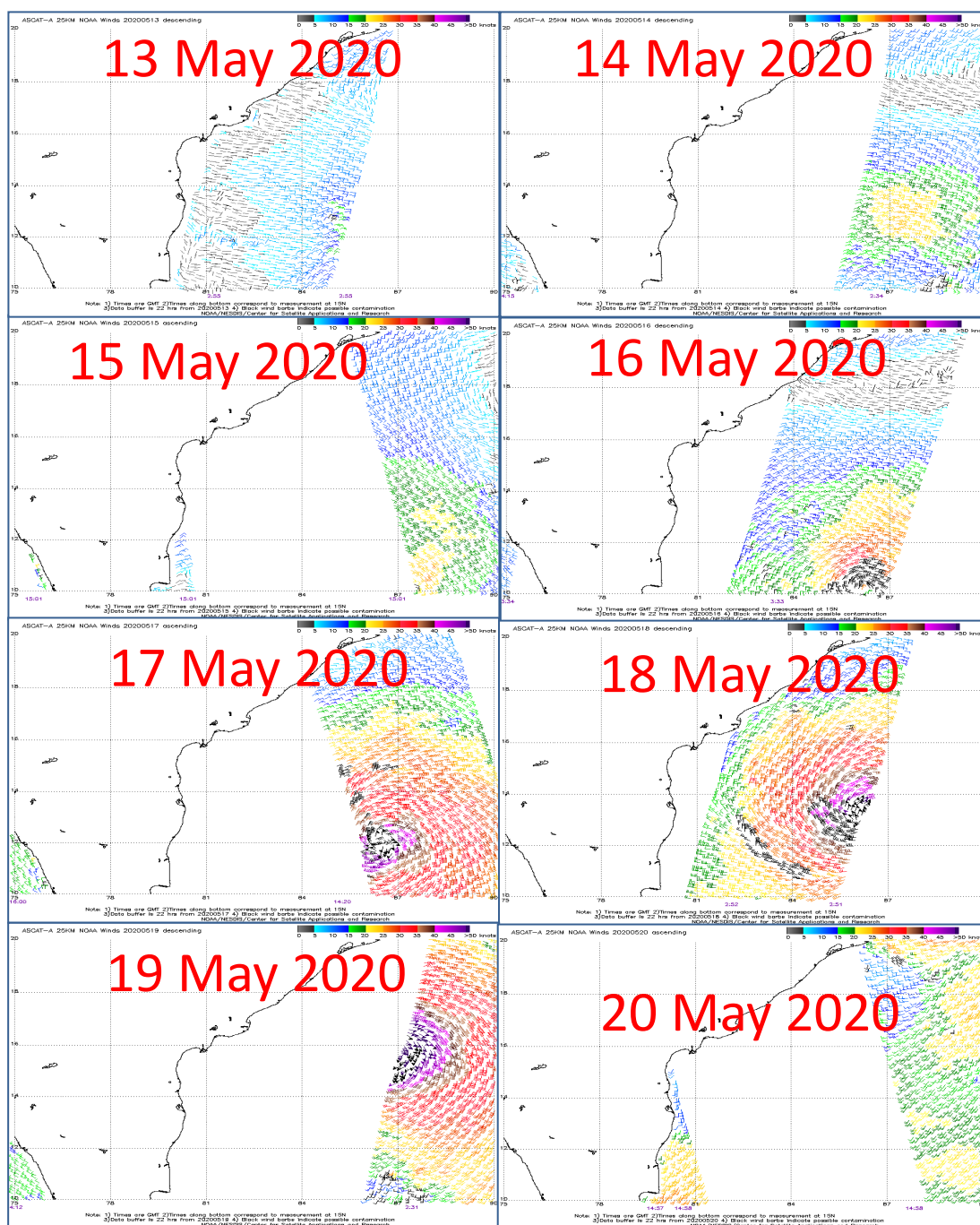


Fig.2.2.10: ASCAT imageries during life cycle of SuCS AMPHAN (13-20 May, 2020)

SuCS Amphan was continuously monitored by IMD's Doppler Weather Radars at Visakhapatnam, Gopalpur, Paradip, Chandipur, Kolkata and Agartala while moving from westcentral BoB to northeast India. Typical radar imageries from Visakhapatnam, Gopalpur, Paradip, Chandipur and Kolkata radar centres are presented in Fig. 2.2.11(a)-Fig 2.2.11(f).

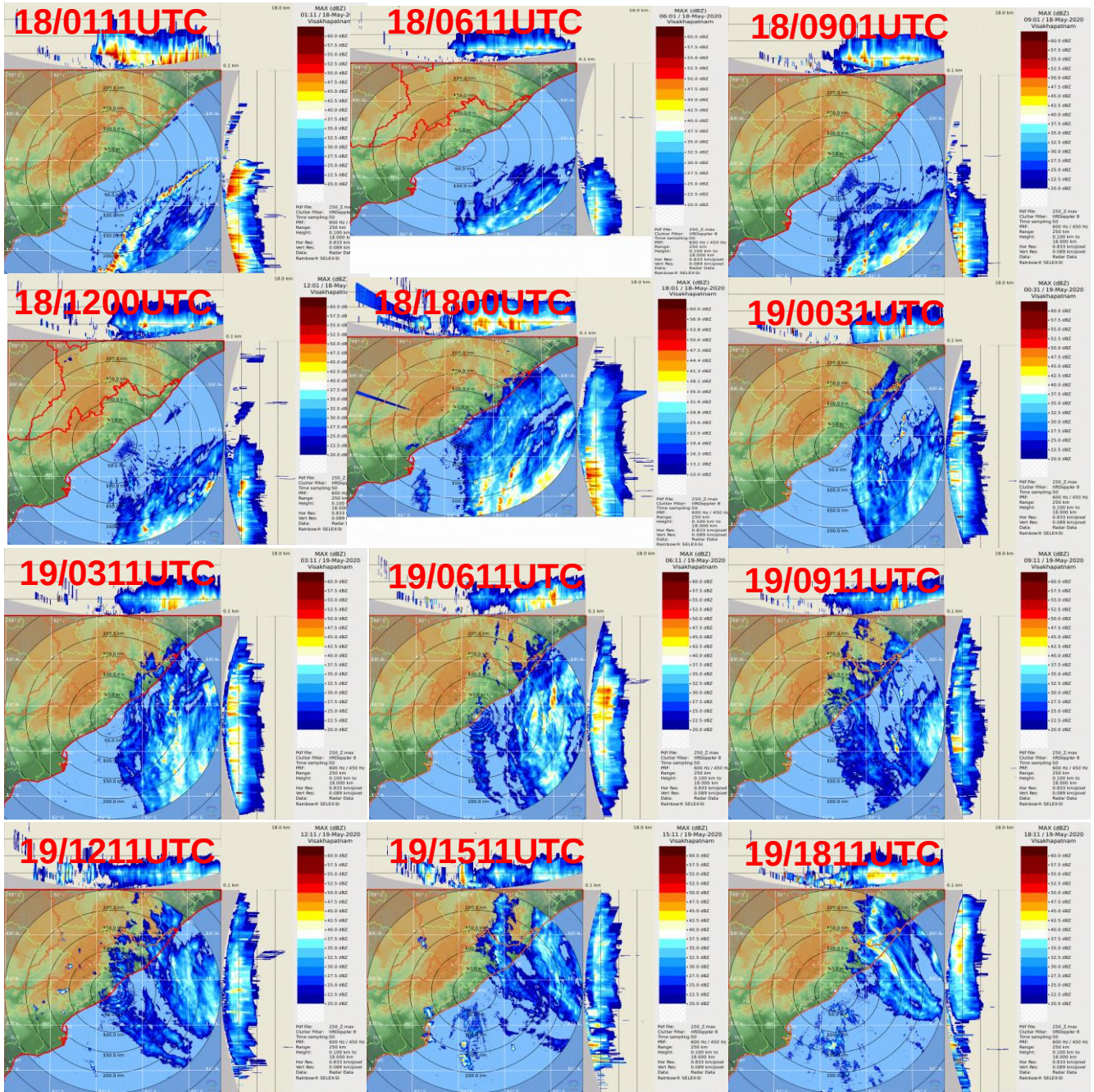


Fig. 2.2.11(a): Typical Radar Max dBZ imageries from DWR Visakhapatnam during 18-19 May, 2020

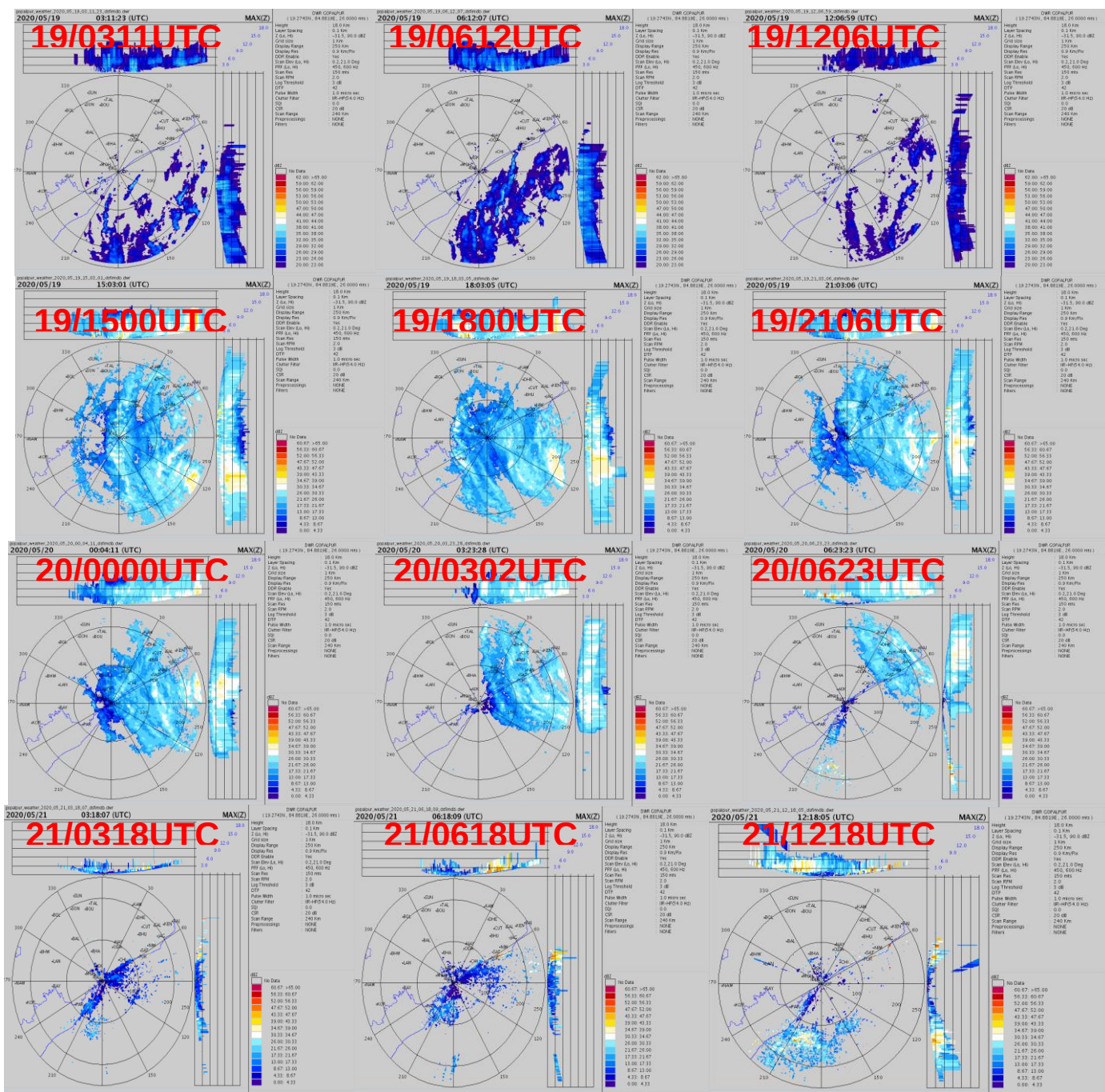


Fig. 2.2.11(b): Typical Radar Max Z imagery from DWR Gopalpur during 19-21 May, 2020

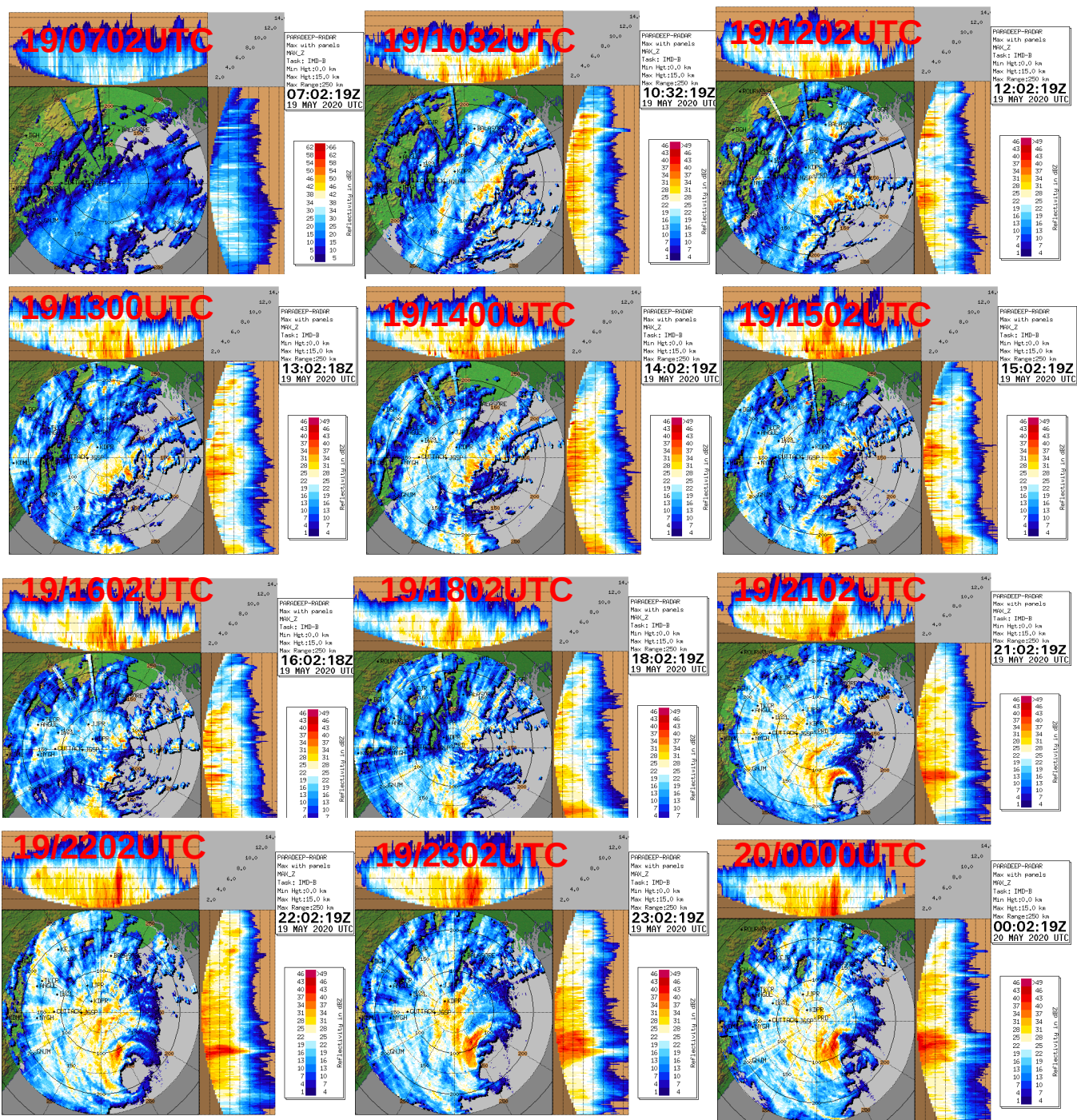


Fig. 2.2.11 (c): Typical Radar Max Z imageries of DWR Paradip during during 19-20 May, 2020

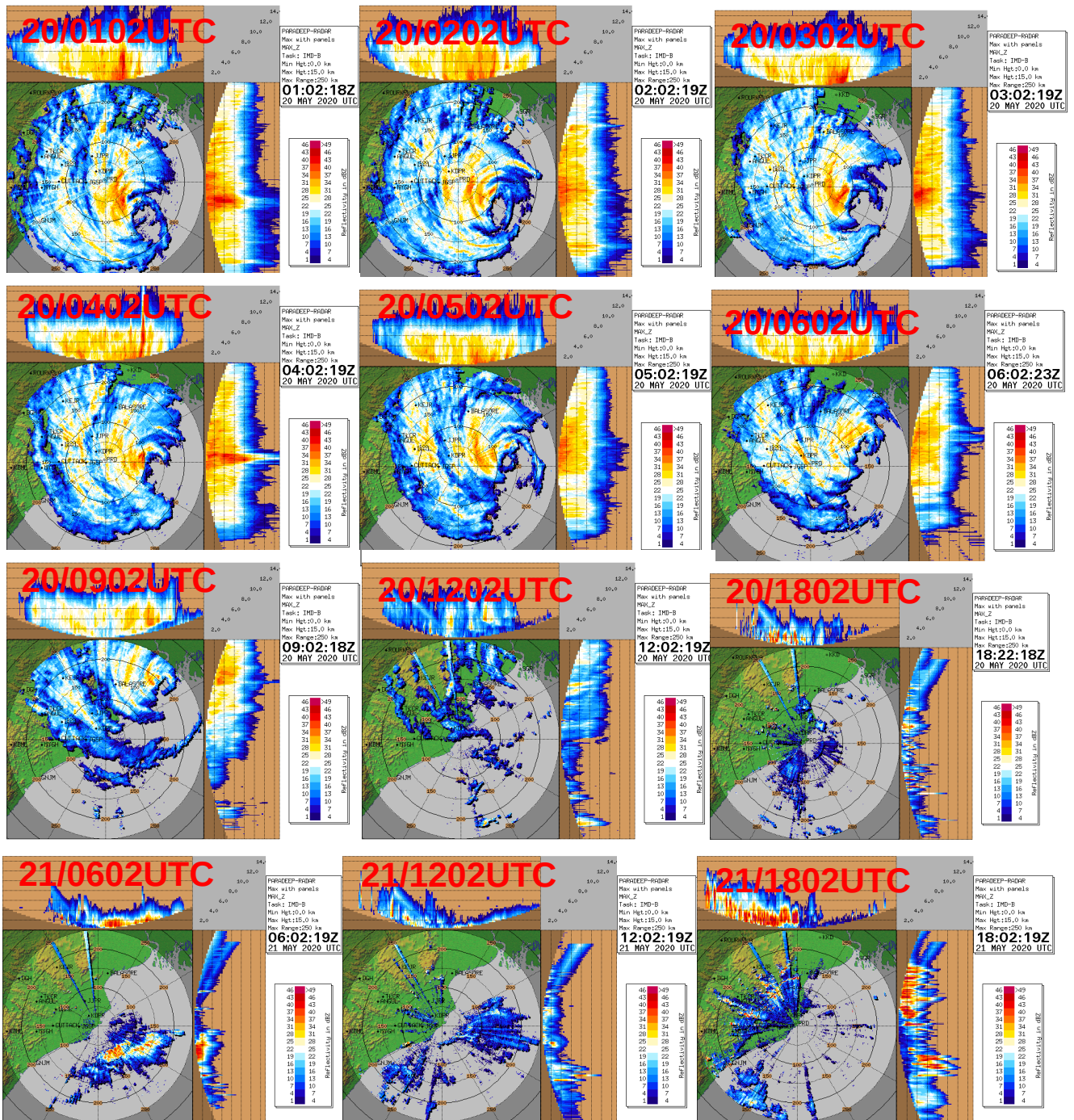


Fig. 2.2.11(d): Typical Radar Max Z imageries of DWR Paradip during during 20-21 May, 2020

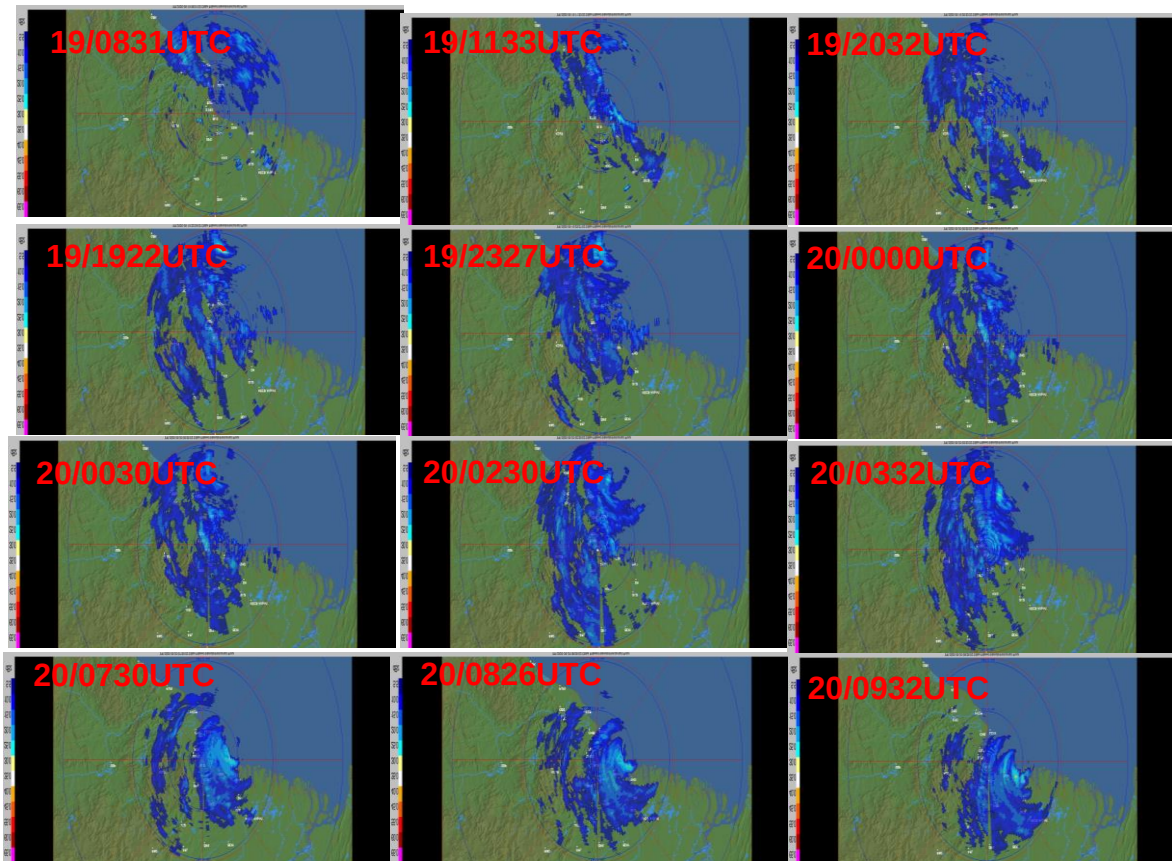


Fig. 2.2.11 (e): Typical Radar MaxZ imageries of ‘DRDO Integrated Test Range’, Chandipur during 19-20 May, 2020

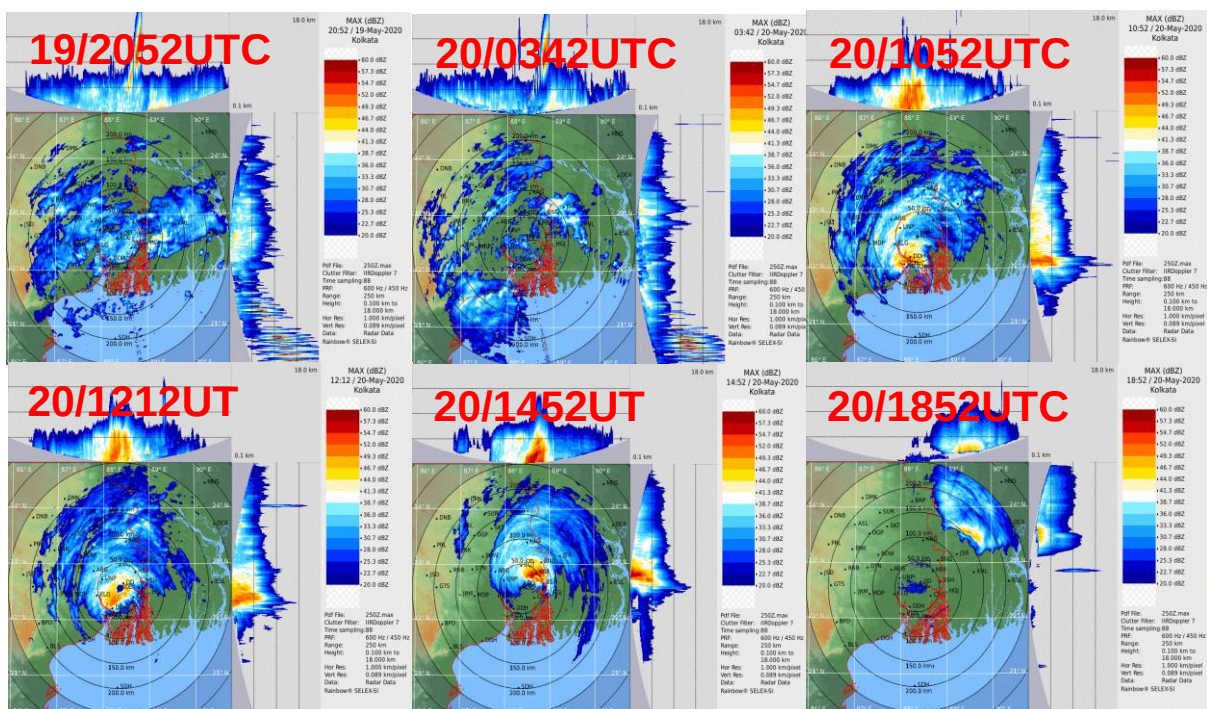


Fig. 2.2.11(f) : Typical Radar Max dBZ imageries from DWR Kolkata during during 19-20 May, 2020

2.2.4 Dynamical features

IMD GFS analysis of mean sea level pressure, winds at 10m, 850 hPa, 500 hPa and 200 hPa levels based on 0000 UTC during 13th -21st May, 2020 are presented in Fig. 2.2.12. On 13th May, IMD GFS indicated a low pressure area over southeast BOB with vertical extension of the cyclonic circulation upto 500 hPa level.

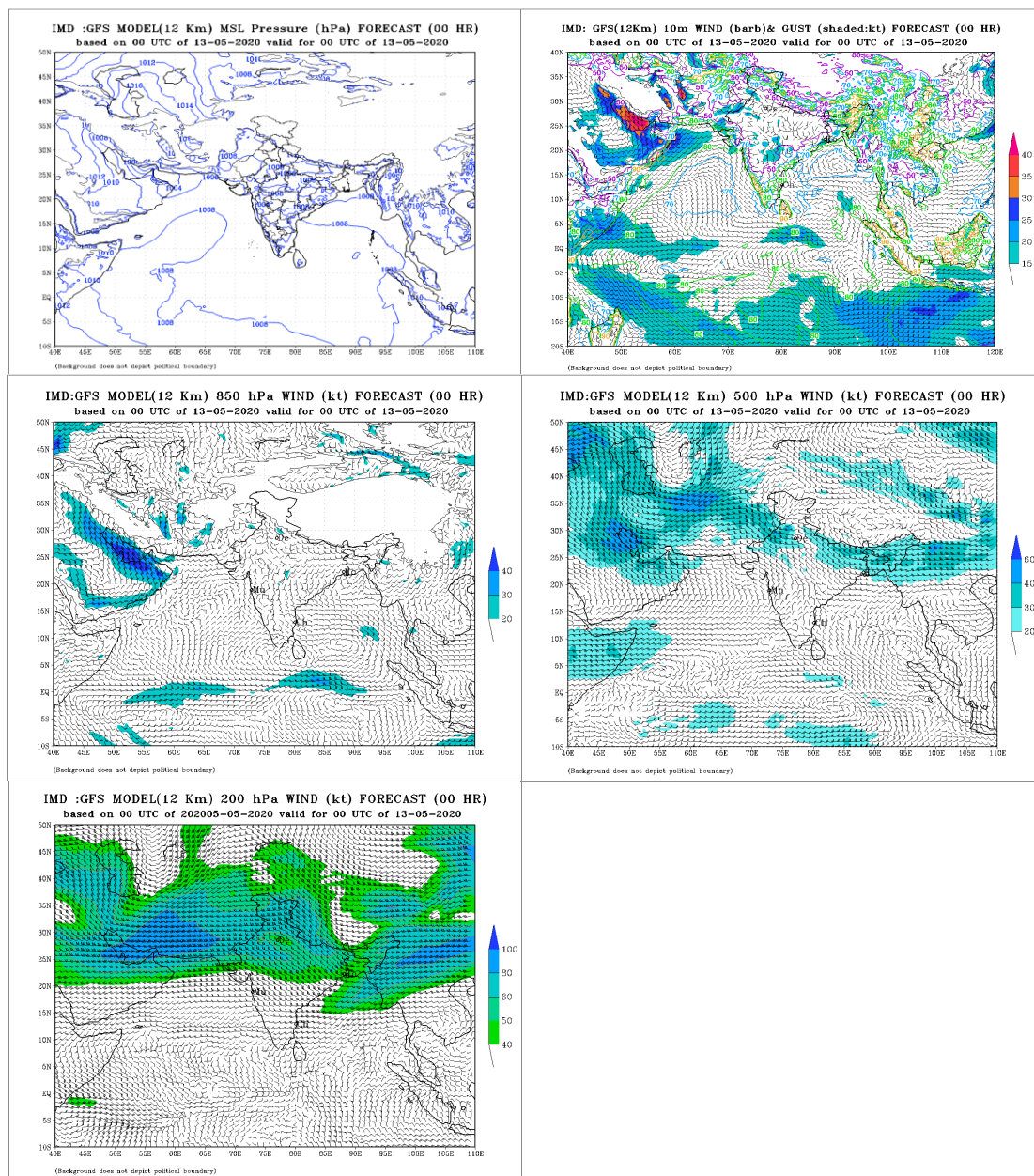


Fig. 2.2.12 (a): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 13th May, 2020

On 14th May, IMD GFS indicated a low pressure area over southwest & adjoining southeast BOB with vertical extension of the cyclonic circulation upto 500 hPa level.

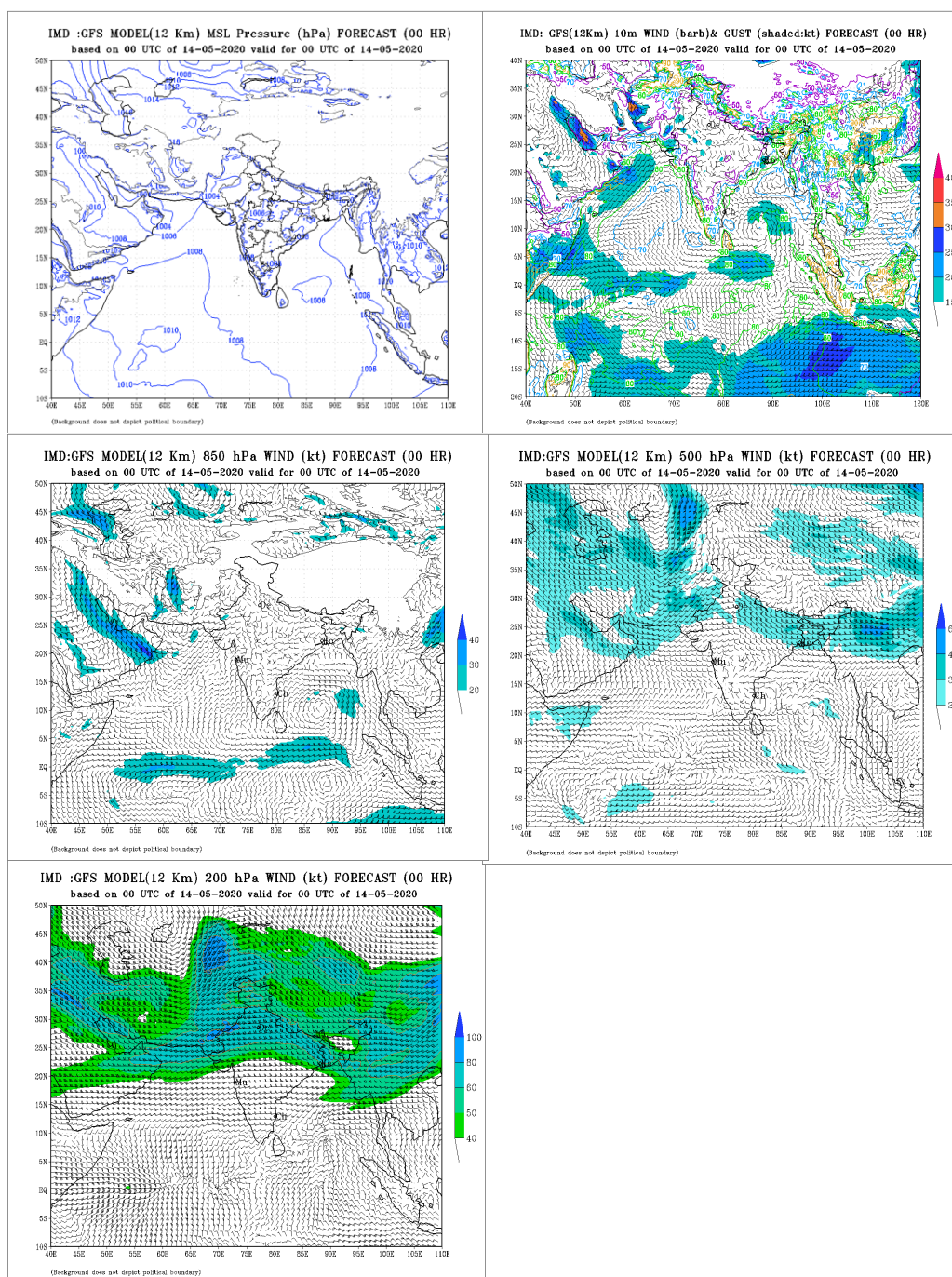


Fig. 2.2.12 (b): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 14th May,2020

On 15th May, IMD GFS indicated a well marked low pressure area over southwest BOB with vertical extension of the cyclonic circulation upto 200 hPa level.

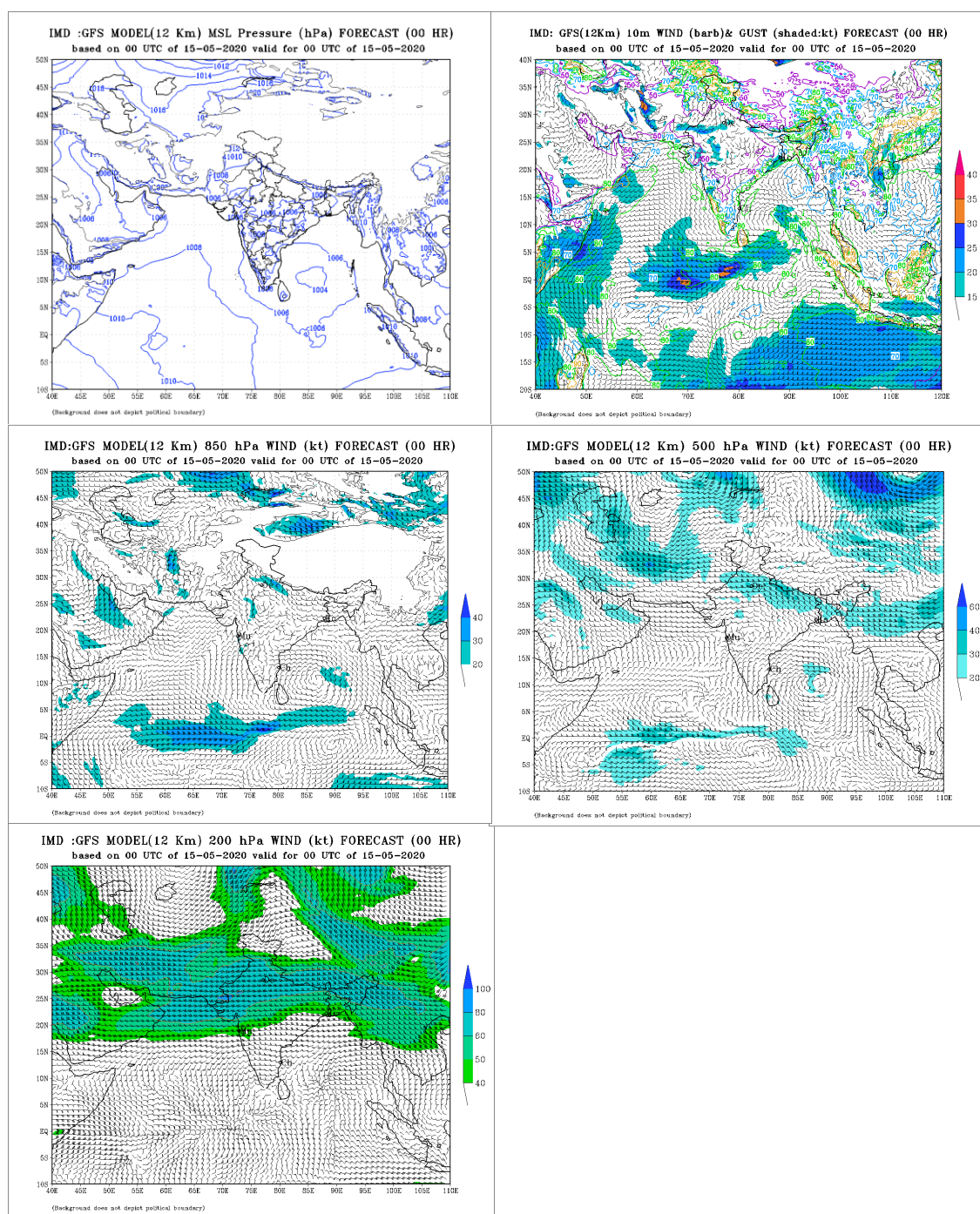


Fig. 2.2.12 (c): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 15th May, 2020

On 16th May, IMD GFS indicated a deep depression over southwest BOB with vertical extension of the cyclonic circulation upto 500 hPa level. Actually, it was a depression on 16th May over southeast BoB. IMD GFS slightly over estimated the intensity of the system.

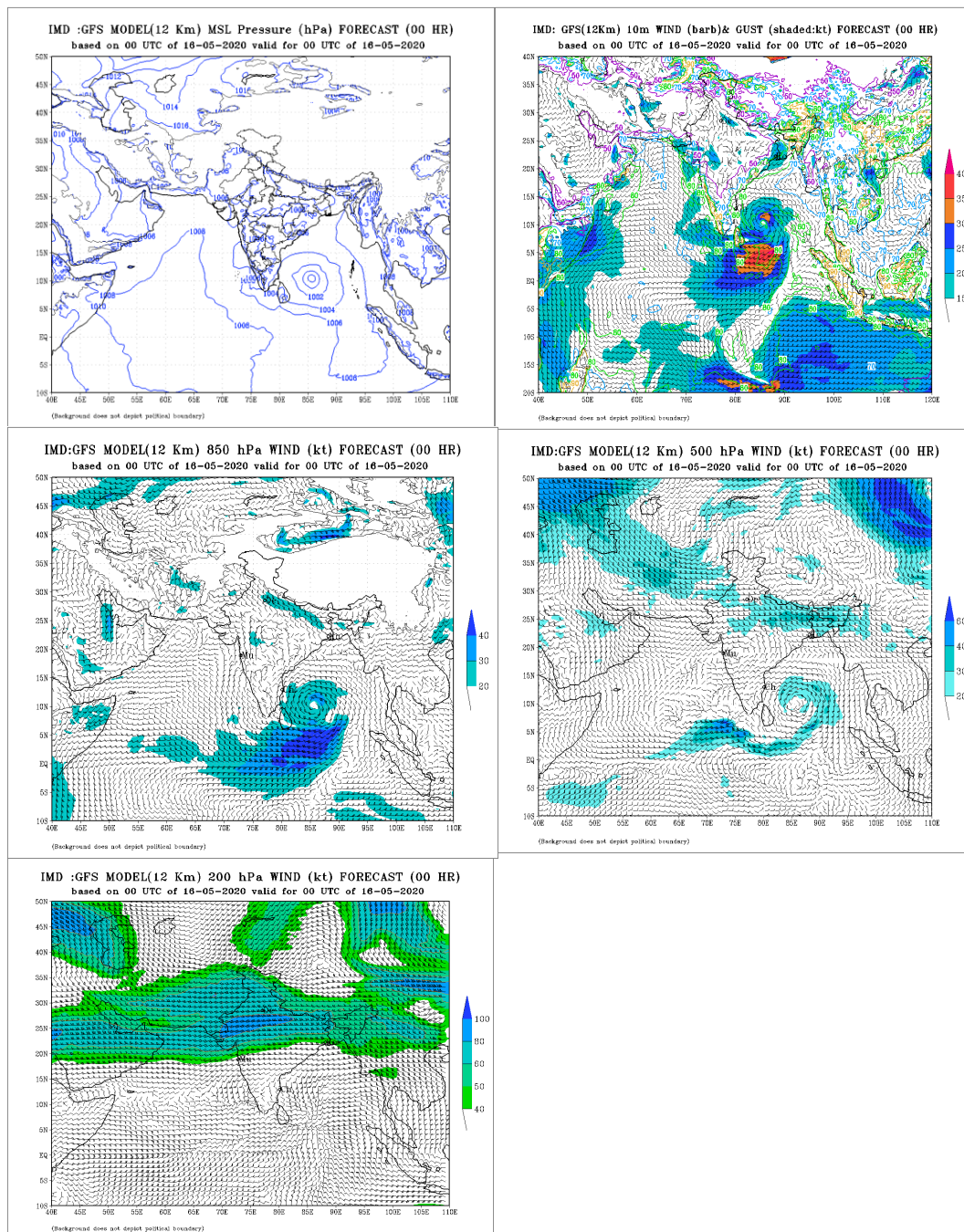


Fig. 2.2.12 (d): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 16th May,2020

On 17th May, IMD GFS indicated rapid intensification of the system. It lay as a severe cyclonic storm over southwest BoB with vertical extension of the cyclonic circulation upto 200 hPa level. GFS also indicated near northwards movement of the system. Actually, it was a cyclonic storm at 0000 UTC of 17th May over southeast BoB. IMD GFS over estimated the intensity of the system.

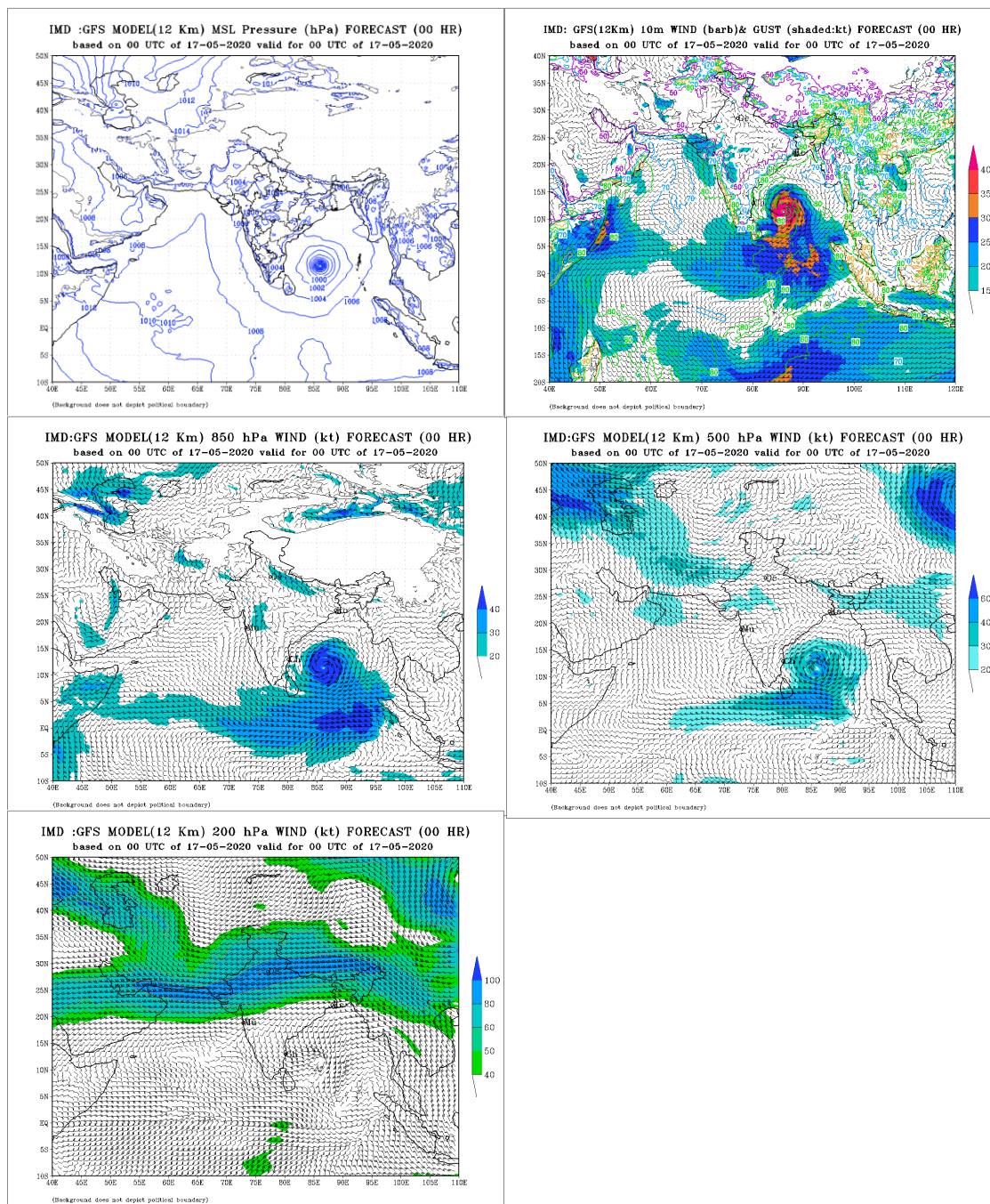


Fig. 2.2.12 (e): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 17 May,2020

On 18th May, IMD GFS indicated further intensification of the system. It lay as a very severe cyclonic storm over westcentral BOB with vertical extension of the cyclonic circulation upto 200 hPa level. GFS also indicated near northwards movement of the system. Actually, it was an extremely severe cyclonic storm at 0000 UTC of 18th May over westcentral BoB. IMD GFS correctly picked up intensity and movement of the system.

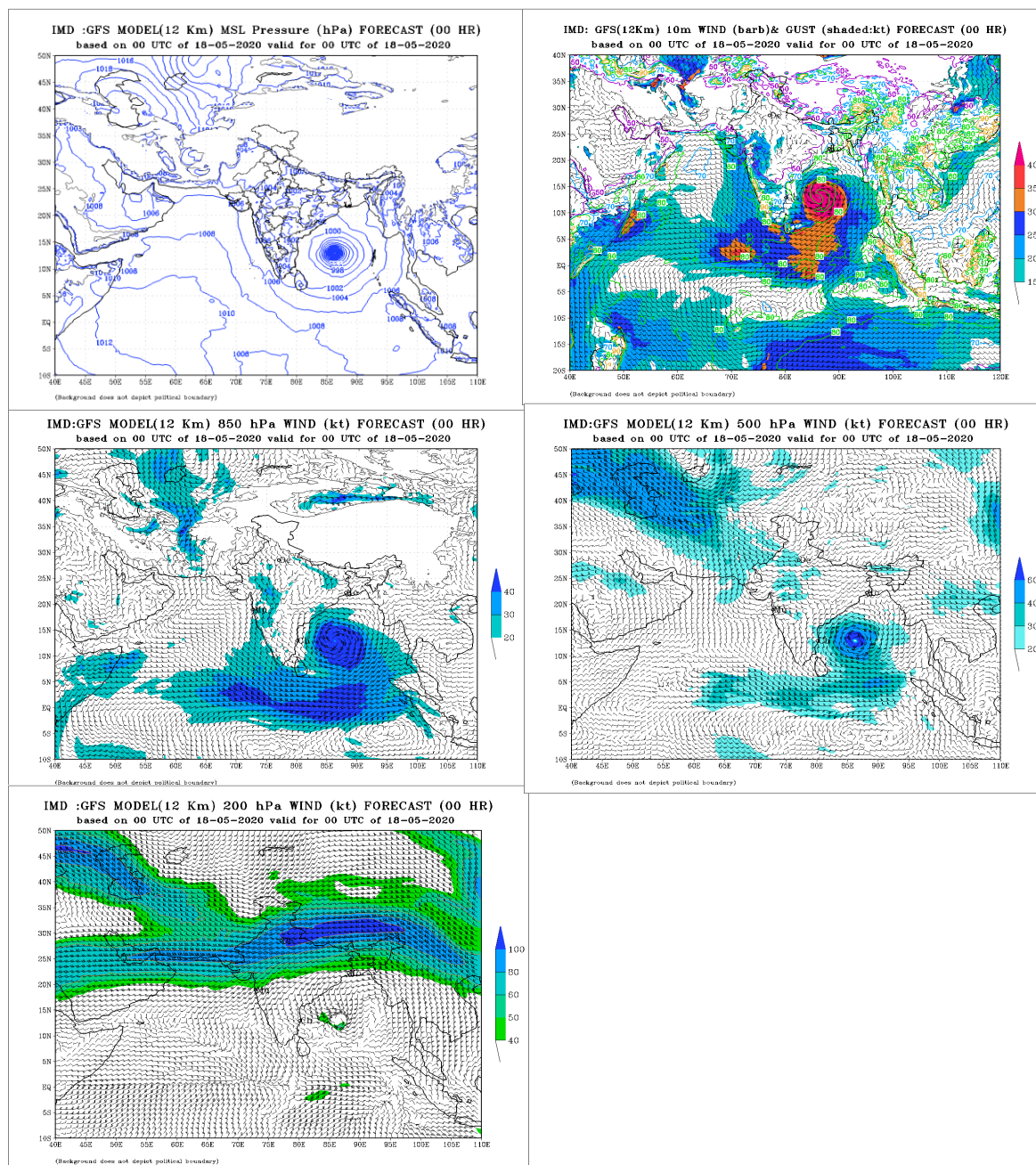


Fig. 2.2.12 (f): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 18th May,2020

On 19th May, IMD GFS indicated a very intense system over westcentral BoB with vertical extension of the cyclonic circulation upto 200 hPa level. GFS also indicated northeastwards movement of the system. Actually, it was a super cyclonic at 0000 UTC of 19th May over westcentral BoB. IMD GFS correctly picked up intensity and movement of the system.

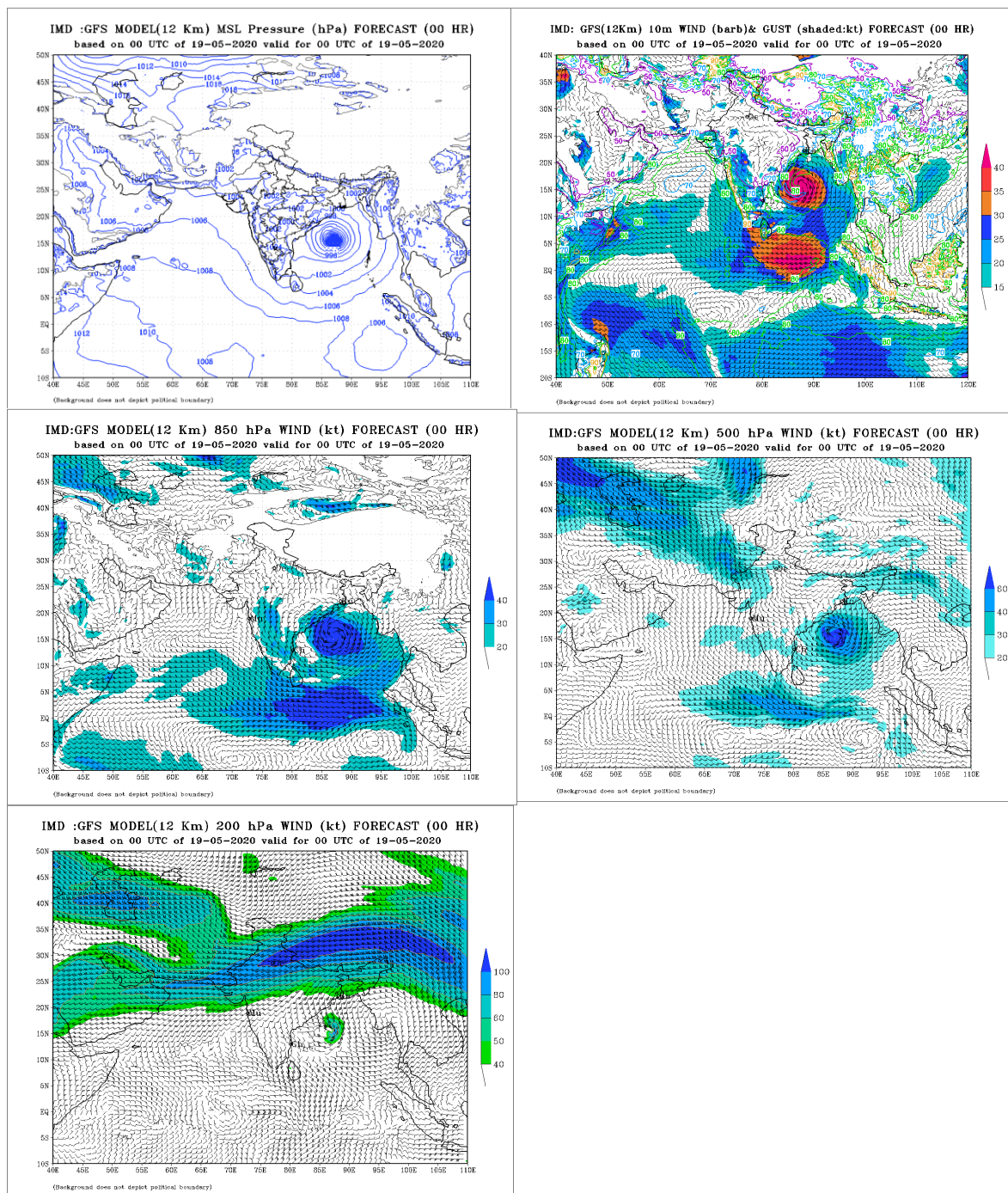


Fig.2.2.12 (g): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 19th May,2020

On 20th May, IMD GFS indicated slight weakening of the system. It lay as a very severe cyclonic storm over northwest BoB off Odisha coast. The system extended vertically upto 200 hPa level. GFS also indicated northeastwards movement of the system. Actually, it was an extremely severe cyclonic storm cyclonic storm at 0000 UTC of 20th May over northwest BoB. GFS also picked up an anticyclone over Myanmar to the west of system and strong westerlies in the upper level indicating steering of the system in northeastwards direction. IMD GFS correctly picked up intensity and movement of the system.

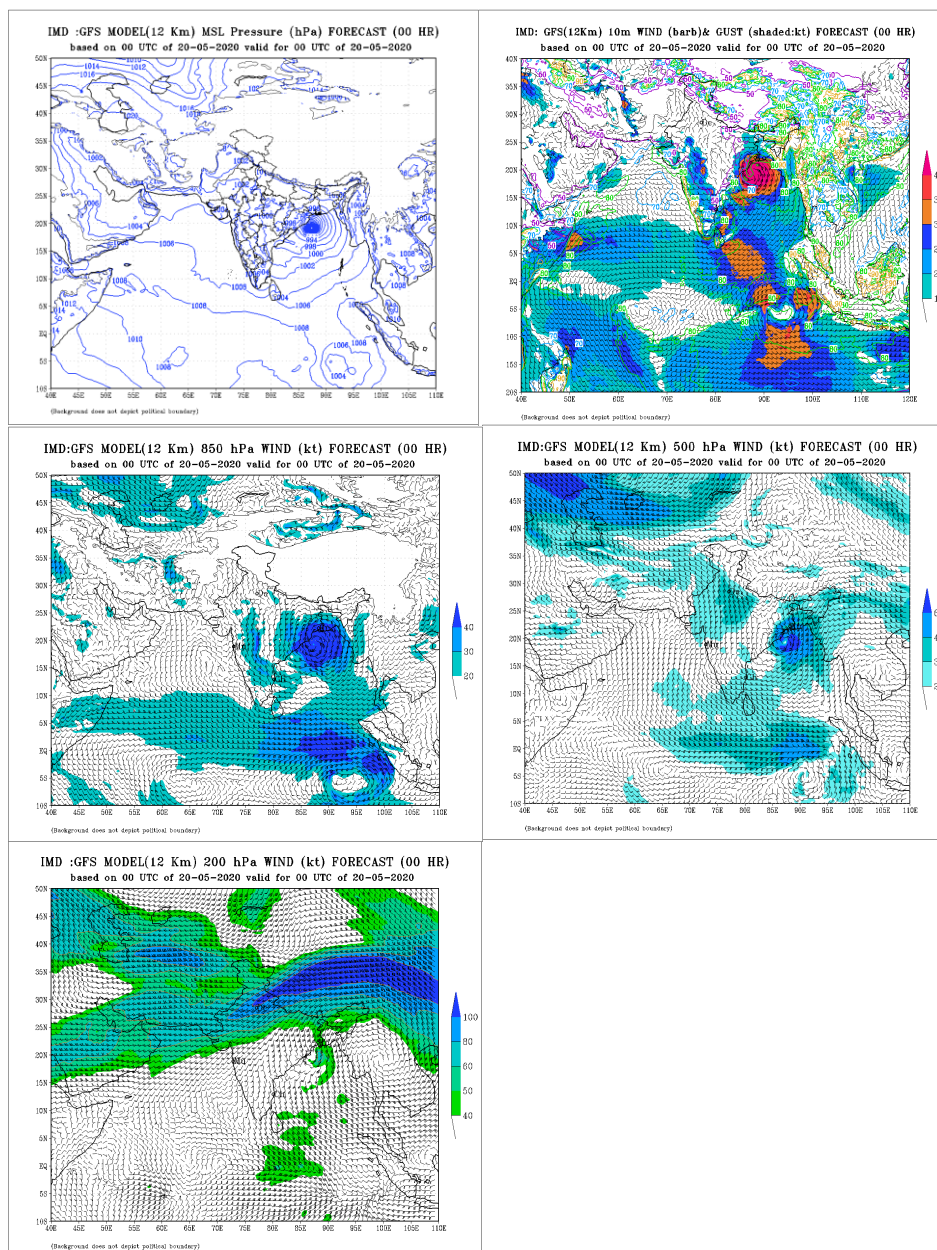


Fig. 2.2.12 (h): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 20th May, 2020

On 21st May, IMD GFS indicated a cyclonic storm over Bangladesh and adjoining Gangetic West Bengal.

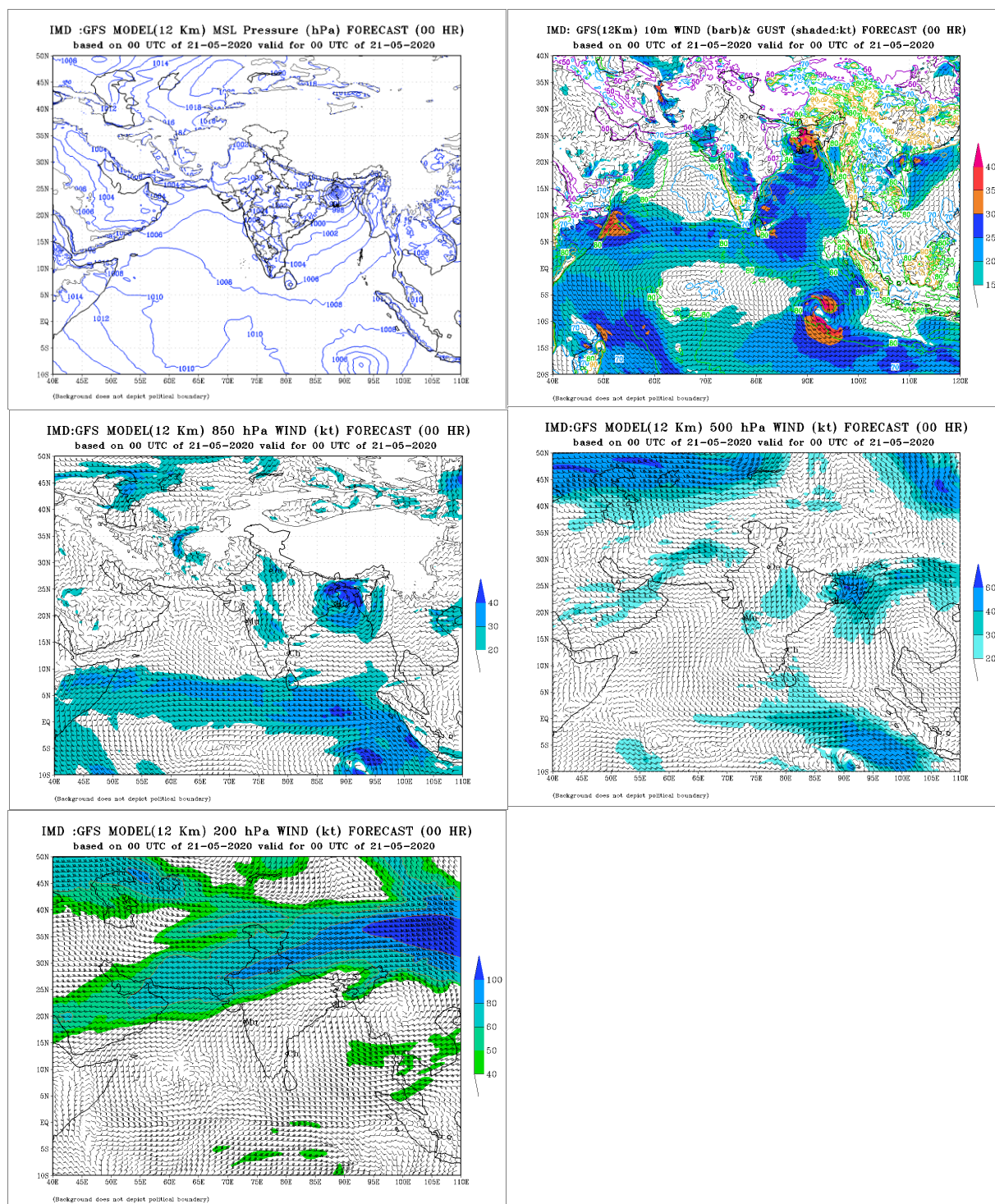


Fig. 2.2.12 (i): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 21st May,2020

IMD GFS thus correctly picked up intensification, movement and weakening of the system.

2.2.5 Realized Weather:

2.2.5.1. Realised rainfall

Rainfall associated with SuCS AMPHAN based on IMD-NCMRWF GPM merged gauge 24 hours cumulative rainfall ending at 0830 IST of date is depicted in **Fig. 2.2.13**.

It indicates occurrence of heavy to very heavy rainfall at a few places over coastal Odisha & Gangetic West Bengal on 20th May, heavy rainfall at isolated places over Gangetic West Bengal & adjoining Bangladesh and Assam, Meghalaya & Arunachal Pradesh on 21st May and heavy rainfall at isolated places over Assam, Meghalaya, Arunachal Pradesh, Sikkim, Nagaland, Manipur & Mizoram on 22nd May.

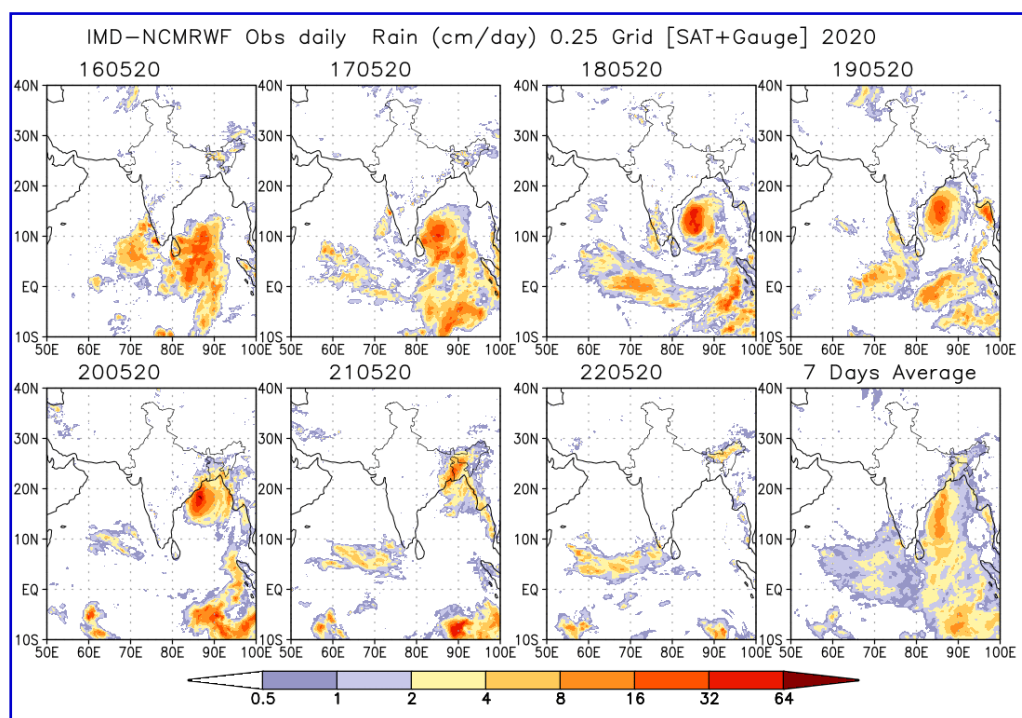


Fig. 2.2.13: IMD-NCMRWF GPM merged gauge 24 hr cumulative rainfall (cm) ending at 0830 IST of date during 16th May – 22nd May and 7 days average rainfall (cm/day)

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

20 May 2020

Gangetic West Bengal: Contai-11, Digha-9,
Odisha: Paradip-21, Balikuda-18, Kakatpur & Kujanga-16 each, Astaranga & Alipingal-14 each, Niali-12, Raghunathpur, Puri, Marsaghai, Nilgiri, Kantapada & Garadapur-9 each, Gop, Chandanpur, Betanati, Rajkanika, Jagatsinghpur, Tirtol & Baripada-8 each and Binjharpur, Satyabadi, Nischintakoili, Chandbali, Bhograi, Jajpur, Dhamnagar, Soro, Tihidi, Bari & Basudevpur-7 each,

21 May 2020

Assam & Meghalaya: Williamnagar-23, Mawsynram-15, Sohra (RKM)-13, Bhaghmara-11 and Sohra & Shillong-9 each
SHWB & Sikkim: Sevoke-7,

Gangetic West Bengal: Alipore-24, Dum Dum-20, Harinkhola & Debagram-13 each, Burdwan-10, Manteswar & Digha-9 each and Mohanpur, Kharagpur, Suri, Mangalkote, Bankura, Lalgarh & Midnapore-7 each, Odisha: Bhograi-13, Rajghat & Jaleswar-12 each and Chandanpur & Bangiriposi-11 each, Paradip, Samakhunta, Betanati & Baripada-9 each and Chandikhol, Joshipur & Danagadi-7 each

22 May 2020

Arunachal Pradesh: Bhalukpong-12, Bomdila-10, Itanagar & Ziro-9 each, Roing-8, Pasighat Aero-7, Assam & Meghalaya: Cherrapunji (RKM)-25, Mawsynram-22, Sohra -21, Khliehriat-15, Goalpara-12, Nongstein, Dhubri & Mela bazar -10 each, Goibargaon, N.Lakhimpur/Lilabari & Shillong-8 each and Tamulpur, Barapani, Williamnagar, DRF & Tezpur-7 each, Nagaland, Manipur, Mizoram & Tripura: Sabroom-13, SHWB & Sikkim: Buxaduar-8,

2.2.5.2. Realised wind:

Kolkata (Dum Dum) reported 130 kmph at 1855 hrs IST (1325 UTC) and Kolkata (Alipore) 112 kmph at 1752 hrs IST (1222 UTC) of 20th May.

Also Paradip reported 106 kmph at 0630 hrs IST (0100 UTC) , Chandbali, 80 kmph at 0830 hrs.IST (0300 UTC) and Balasore 91 kmph during 1330 – 1430 hrs. IST (0800 & 0900 UTC) of 20th May.

Maximum sustained wind speed recordings from Automated Weather Stations (AWS) at Canning, Nimpith and Sagar Islands on 20th May are shown in Fig. 2.2.14.

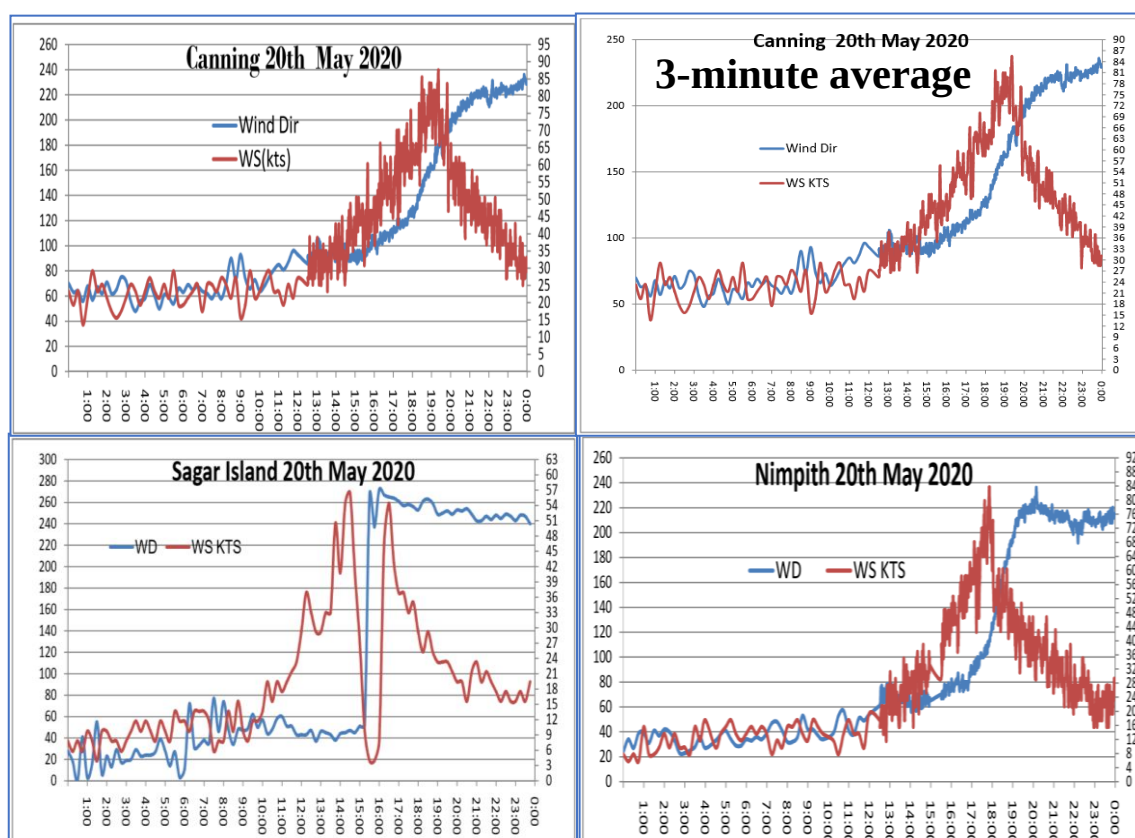


Fig. 2.2.14: AWS data from Canning, Sagar Island & Nimpith on 20th May 2020

Five hours period during 1600-2100 hrs IST witnessed wind speed 60-80 kmph with many gusts of 100 kmph (with maximum of 114 kmph) over Kolkata. Fig. 2.2.15 indicates the wind recorded at Alipore (Kolkata) on 20th May 2020.

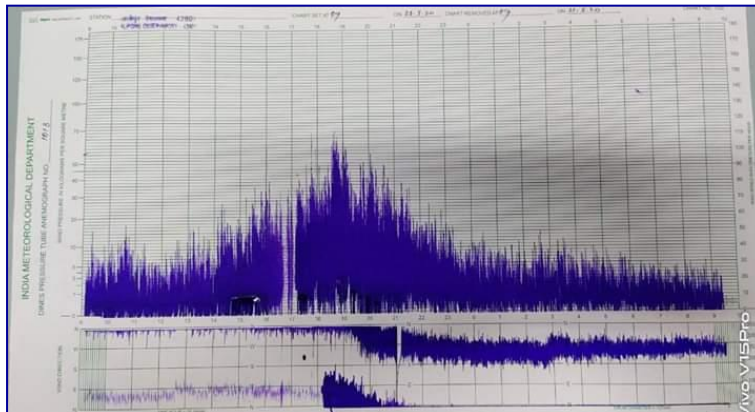


Fig. 2.2.15: Wind anemograph recordings at Kolkata (Alipore) on 20th May 2020

2.2.5.3. Realised storm surge:

As per the Post Cyclone landfall survey conducted by Area Cyclone Warning Centre (ACWC) Kolkata, Tidal waves of 15 Feet height inundated low lying areas of South & North 24 Parganas and adjoining areas of east Medinipur Districts of West Bengal.

2.2.6 Damage due to SuCS, AMPHAN

98 persons lost their lives in West Bengal due to Amphan. No death was reported from Odisha.



Fig. 2.2.16: (a)Hanging electric pole(The Hindu,23rd May) (b)Flooded Kolkata Airport (NDTV,4TH June) (c) Damaged homes (outlookindia.com,22nd May) (d) Flooded area of West Bengal (cnn.com,22nd May)



Fig.2.2.16(e): A bus crashed after a tree fell on it in Kolkata (The Hindu, 22nd May)
(f) Uprooted trees (dnaindia.com,21st,May)

Damages caused by the Super Cyclonic Storm AMPHAN



IMPACT & DAMAGES

Extent of Damages:

The damages caused by the Extremely Severe Cyclone AMPHAN were mainly due to gusting action of wind, heavy rainfall and the storm surge. Detailed reports have been collected from the District Magistrates of the affected areas as well as the Departments that were affected. 99 people lost their lives while around 221 people were injured in 16 Districts. Major damage was caused in infrastructure, agriculture, horticulture, irrigation, power sector, water supply, drainage system, education & health sector. Roads were damaged and also blocked by lakhas of uprooted trees. Agriculture and horticulture crops including orchards covering 19.5 lakh hectares were reportedly damaged. The fishing community has been severely affected and major infrastructural damage reported besides huge losses to public properties. The reported losses are tabulated below:

EXTENT OF DAMAGE DUE TO NATURAL CALAMITIES

APPENDIX - II

State: West Bengal

Nature and period of natural Calamity Super Cyclone AMPHAN on 20th May 2020

Sl. No.	Item	Details
1	Total number of districts in the State	23
2	Number and names of districts affected	16 (South 24 Parganas, North 24 Parganas, Kolkata, Purba Medinipur, Howrah, Hooghly, Paschim Medinipur, Nadia, Purba Bardhaman, Paschim Bardhaman, Bankura, Birbhum, Purulia, Jhargram, Murshidabad, Malda)
3	Number of villages affected	25245
4	Population affected	60% of state population
5	Cropped area affected	
	(i) Total cropped area affected (in lakh ha)	19.68777
	(ii) Estimated loss to crops (Rs. In lakh)	15,84,445.80
	(iii) Area where cropped damage was more than 33% (in lakh ha)	19.68777
6	Percentage of area held by SMF :	
	(i) In the State as a whole	80.72 (As per 2010-11)
	(ii) In the affected districts	95.0
7	Houses damaged :	
	(a) No. of houses damaged :	
	(i) Fully damaged pucca houses	2,668
	(ii) Fully damaged kutcha houses	15,61,492
	(iii) Severely damaged pucca houses	1,06,286
	(iv) Severely damaged Kutcha houses	2,29,685
	(v) Partly damaged houses (Pucca + Kutcha)	4,99,348
	(vi) No. of huts damaged	29,507
	(b) Estimated value of damage to houses (Rs. In lakh)	18,14,004.28
8	No. of human lives lost	98
9	No. of persons with grievous injuries	177
10	No. of persons with minor injuries	Nil
11	Animals lost :-	
	(a) No. of big animals lost	2,831
	(b) No. of small animals lost	21,096
	(c) No. of Poultry (birds) lost	20,97,710
12	Damage to public properties :-	
	In physical terms (sector wise details should be given - e.g. length of State roads damaged. Length of district roads damaged, length of village roads damaged. No. of bridges damaged, No. of culverts damaged. No. of school buildings damaged etc.)	Total length of damaged PWD road = 2148 km No. of Damaged culvert / bridge under BGSY & RIDF = 651 nos. Length of Damaged BGSY Road = 2991.05 km. Length of damaged RIDF Road = 909.62 km. Length damaged other Road = 6109.50km Total no. of PWSS affected = 1192 Total no. of Schools Building affected = 14,640 Total No. of College Building affected = 301 No. of AWC Damaged: 12678 Damaged: HT Pole : 98018 nos. LT Pole : 351156 nos. DTR Damaged : 10280 Conductor in Km.: 189169.08
13	Estimated total damage to houses, crops and public properties. (Rs. In lakh)	Rs.102442 Crore

Synopsis of Sector wise Damages & losses as on 06/06/2020

Sl. No.	Sector	Extent of assessed damage so far	Quantum of Damages (INR crores)
1	Dwelling Houses	28.56 lakhs houses damaged	28,560
2	Agriculture	17 lakh hectares agriculture land Crops - Boro paddy/Moong/Til/Jute, Groundnut/Sugarcane/Maize /Cotton	15,860
3	Horticulture	Area – 2,50,556.17 Ha Betel vine, Litchi, Mango etc	6,581
4	Fisheries	Boats- 8007, Huts-1.48 Lakh	2,000
5	ARD	Animals lost -21.22 lakhs	452
6	Drinking Water	Piped Water Schemes affected-1192	2,060
7	Roads, including rural roads and culverts/bridges	Roads - 2148.22 Km, Bridge & Culverts — 355, Rural Road – 10091.17 Km	2,237
8	Irrigation canals / Ponds	Embankments -244.73Kms, Sea Dykes – 3.6 Km	2,944
9	Power	Power Sub Stations Damaged: 273 Poles - 4,49,174	3,230
10	Forest	Forest area affected 1.58 lakh hectares	1,033
11	Education infrastructure	14,640 schools, 301 colleges	793
12	Health infrastructure	PHC-563,BPHC/RH-169,Sub Centre-5142, SDH/SGH-37, DH-24	1,270
13	Anganwadi infrastructure	ICDS Centre damaged - 12678	342
14	Urban infrastructure	Municipal Roads, Street Lights, Underground Sewerage system, Storm Water drainage, Water supply schemes, roads etc.	6,750
15	Industries including MSME	Industrial ware house/raw material/ Industrial Infrastructure/sheds	26,790
16	Miscellaneous	Transport, Fire & Emergency infrastructure, SHG, Trees, Godowns, Housing, Correctional Homes, Labour, BCW etc.	1,540
		TOTAL LOSSES	1,02,442

Table-1; Report on Death & Injury i.c.w. Cyclone "AMPHAN"

Sl No.	District	Death	Seriously Injured
1	South 24 Parganas	25	68
2	North 24 Parganas	22	44
3	Kolkata	19	0
4	Howrah	13	26
5	Nadia	7	62
6	Purba Medinipur	6	2
7	Hooghly	4	19
8	Paschim Medinipur	2	0
9	Paschim Burdwan	1	0
	Total	99	221

Table-2; District – wise Report of Human Casualties:

Details of Death Report due to Super Cyclone AMPHAN											
Sl. No.	District	Total Death	Tree Falling	Electrocution	Wall Collapsed	Roof Top Falling	House Collapsed	Fall of Electric Pole	Drowning	Death Due to Fear / Cardiac arrest	Others
1	North 24 Parganas	22	7	2	8	2	1	2			
2	South 24 Parganas	24	9	4	5	3				1	3
3	KMC	19		12	2	1			3		1
4	Howrah	13	2	5	5		1	0			
5	Nadia	7	4	0	1	1	0	0	0	1	
6	Purba Medinipur	6	6	0							
7	Paschim Medinipur	2	1							1	
8	Hooghly	4	2	2							
9	Purba Bardhaman	1			1						
	Total	99	31	25	22	7	2	2	3	3	4

A. POST AMPHAN MEASURES FOR RELIEF AND RESTORATION:

The Honourable Chief Minister and Chief Secretary held a review meeting and videoconference with districts on 21st May to assess relief and restoration work. The Honourable Prime Minister of India and Honourable Chief Minister of West Bengal did an aerial survey of North and South 24 Parganas on 22nd May 2020 and held a review meeting at Basirhat. There an announcement that Rs 1000 crore as SDRF fund will be allotted to West Bengal was made .The fund was received from Ministry of Home Affairs, soon thereafter.

The route of the aerial survey was Pather pratima, Namkhana, Diamond Harbour II block (Sarisa) in South 24 Parganas and Basirhat,Minakhan, Hasnabad, Sandeshkhali and Hingalganj in North 24 Parganas district.

Indian Army was requisition and involved in clearing roads and restoring essential services. Additional NDRF teams were rushed and also teams of Odisha RAF and firemen were deployed for road clearance and power restoration.

The State Government opened Special Amphan account West Bengal State Disaster Management Authority for receiving financial donation for Super Cyclone AMPHAN relief and also made arrangements for receiving and distributing relief articles in kind from civil society and other agencies across the nation. Requests for donations in kind could be emailed to: wbsdmadon@gmail.com

The state govt allotted Rs 6500 crores for House building, agriculture, roads, drinking water, electricity, repair of embankments etc.

B. Visit of IMCT team for AMPHAN

The Inter Ministerial Central Team on Super Cyclone Amphan visited West Bengal from 4th to 6th June 2020. The team visited the Amphan devastated areas in South 24 Pargans and North 24 parganas. They formed into two teams and one team did an aerial survey by helicopter on 5th June and visited South 24 Parganas, while the other team went by road to North 24 Parganas to Sandeshkhali in Basirhat.

The Central Team constituted of following members:

Sl. No.	Name	Designation
1	Shri Anuj Sharma	Joint Secretary (CIS), Ministry of Home Affairs, New Delhi Team Leader
2	Shri Narendra Kumar	Director, Ministry of Agriculture & Farmers Welfare
3	Shri R.P.Debey	Assistant Commissioner, Department of Fisheries
4	Shri S.C. Meena	Director (FCD), Department of Expenditure
5	Shri Sidhartha Mitra	Sup. Engineer (Coord), Ministry of Jal Shakti
6	Ms Rishika Sharan	Director, Ministry of Power
7	Shri Samiran Saha	Executive Engineer (SG), Ministry of Road Transport & Highways

- The Inter Ministerial Central Team met Chief Secretary and heads of different departments like – Home, Finance, Agriculture, Fisheries, PWD, Irrigation & Waterways, Food & Supplies, Power, Forest, Transport, Panchayat & Rural Development & Animal Resource Department at Nabanna, Howrah on 06th June 2020 at 3 PM.



Table-3: District wise affected Blocks, Municipalities, GP & Villages

District Wise Damage Details					
Sl. No.	Name of District	No. of Blocks affected	No. of Municipalities / MCs affected	No. of GP Affected	No. of villages affected
1	South 24 Parganas	29	7	310	3079
2	North 24 Parganas	22	26	199	1527
3	Purba Medinipur	25	5	223	3109
4	Kolkata	0	1	0	0
5	Paschim Medinipur	21	7	290	4250
6	Howrah	14	2	157	734
7	Hooghly	18	13	210	1886
8	Nadia	18	11	187	2142
9	Bankura	22	3	190	1589
10	Birbhum	18	6	131	931
11	Purulia	19	1	17	82
12	Purba Bardhaman	23	6	215	1518
13	Paschim Bardhaman	8	2	62	414
14	Jhargram	8	1	79	2605
15	Murshidabad	26	7	250	1270
16	Malda	9	1	34	109
	Total	280	99	2554	25245

Table-3A: District wise details of Damaged Blocks & Municipalities

Details of District-wise Damages – Overview							
Sl. No	Name of District	Blocks Affected		Municipalities/MCs Affected		Human Casualty & Injury	
		Nos	Name	Nos	Name	Dead	Injured
1	South 24 Pgs	29	All Blocks	7	All Municipalities	25	68
2	North 24 Parganas	22	1) Hingalganj, 2) Sandeshkhali-I, 3) Sandeshkhali-II, 4) Hasnabad, 5) Minakhamb, 6) Basirhat-I 7) Basirhat-II, 8) Haroa, 9) Baduria, 10) Swarupnagar, 11) Bongaon, 12) Bagda, 13) Gaighata, 14) Barasat-I, 15) Barasat-II, 16) Habra-I 17) Habra-II, 18) Deganga, 19) Amdanga, 20) Rajarhat, 21) Barrackpore-I & 22) Barrackpore-II	26	1) Basirhat, 2) Baduria, 3) Taki, 4) Bongaon, 5) Barasat, 6) Madhyamgram, 7) Habra, 8) Ashoknagar Kalyangarh, 9) Gobardanga, 10) Halisahar, 11) Kancharapar, 12) Naihati, 13) Bhatpara, 14) Garulia, 15) North Barrackpore, 16) Barrackpore, 17) Titagarh, 18) Khardah, 19) Panihati, 20) New Barrackpore, 21) North Dum Dum, 22) Kamarhati, 23) Baranagar, 24) South Dum Dum, 25) Dum Dum & 26) Bidhannagar MC	22	44
3	Purba Medinipur	25	All Blocks	5	All Municipalities	6	2
4	Kolkata	0	0	1	All 144 wards	19	0
5	Paschim Medinipur	21	Midnapur Sadar, Keshpur, Salboni, Garhbeta-I, Garhbeta-II, Garhbeta-III, Kharagpur-I, Kharagpur-II, Sabang, Pingla, Narayangarh, Debra, Keshiary, Dantan-I, Dantan-II, Mohanpur, Ghatal, Daspur-I, Daspur-II, Chandrakona-I, Chandrakona-II	7	Medinipur, Kharagpur, Ghatal, Kharar, Khirpai, Chandrakona, Ramjibanpur	2	0
6	Howrah	14	Amta-I, Amta-II, Bagnan-I, Bagnan-II, Shyampur-I, Shyampur-II, Uluberia-I, Uluberia-II, Udaynarayanpur UDER Uluberia Sub-Division and Bally-Jagacha, Domjur, Jagatballavpur, Panchla & Sankrail under Howrah(Sadar) Sub-Division.	2	Uluberia Municipality & Howrah Municipal Corporation	13	26
7	Hooghly	18	Balagarh, Chinsurah-Mogra, Pandua, Dhaniakhali, Polba-Dadpur, Singur, Tarakeswar, Haripal, Jangipara, Serampur-Uttarpara, Chanditala-I, Chanditala-II, Arambagh, Goghat-I, Goghat-II, Khanaku-I, Khanakul-II, Purusurah.	13	1) Arambagh, 2) Hooghly-Chinsurah, 3) Bansberia, 4) Bhadreswar, 5) Champdani, 6) Chandannagar Municipal Corporation, 7) Tarakeshwar, 8) Baidyabati, 9) Serampore, 10) Rishra, 11) Dankuni, 12) Uttarpara-Kotrung 13) Konnagar	4	19

Details of District-wise Damages – Overview						
Sl. No	Name of District	Blocks Affected		Municipalities/MCs Affected	Human Casualty & Injury	
		Nos	Name		Dead	Injured
8	Nadia	18	1. Krishnagar-I, 2. Krishnagar-II, 3. Nabadwip, 4. Nakashipara, 5. Kaliganj, 6. Chapra, 7. Krishnagaj, 8. Tehatta-I, 9. Tehatta-II, 10. Karimpur-I, 11. Karimpur-II, 12. Santipur, 13. Hanskhali, 14. Ranaghat-I, 15. Ranaghat-II, 16. Haringhata 17. Kalyani, 18. Chakdaha	11 1. Santipur(M), 2. Ranaghat(M), 3. Taherpur(NAA), 4. Birnagar (M), 5. Coopers (NAA), 6. Kalyani(M), 7. Gayeshpur(M), 8. Chakdaha(M), 9. Haringhata(M), 10. Krishnagar(M), 11. Nabadwip(M)	7	62
9	Bankura	22	Bankura-I, Bankura-II, Chhatna,Onda, Mejhia, Gangajalghati, Saltora, Barjora, Bishnupur, Kotulpur, Joypur, Sonamukhi, Indas, Patrasayer, Khatra, Indpur, Raipur, Hirbandh, Ranibandh, Sarenga, Simlapal, Taldangra,	3 Bankura, Bisnupur, Sonamukhi	0	0
10	Birbhum	18	Srui-I, Suri-II, Md. Bazar, Sainthia, Dubrajpur, Rajnagar, Khoyrasole, Bolpur-Sriniketan, Nanoor, Illambazar, Rampurhat-I, Rampurhat-II, Murarai-I, Murarai-II, Nalhati-I, Nalhati-II, Mayureswar-I, Mayureswar-II,	6 Suri, Sainthia, Dubrajpur, Bolpur, Nalhati, Rampurhat	0	0
11	Purulia	19	Purulia-I, Purulia-II, Hura, Balarampur, Arsha, Pancha, Manbazar-I, Manbazar-II, Bandwan, Barabazar, Baghmundi, Jhalda-I, Jhalda-II, Joypur, Para, Raghunathpur-I, Raghunathpur-II, Kashipur & Santuri	1 Jhalda Municipality	0	0
12	Purba Bardhaman	23	Ausgram-I, Ausgram-II, Bhatar, Burdwan-I, Burdwan-II, Galsi-I, Galsi-II, Memari-I, Memari-II, Jamalpur, Raina-I, Raina-II, Khandoghosh, Kalna-I, Kalna-II, Monteswar, Purbasthali-I, Purbasthali-II, Katwa-I, Katwa-II, Mongalkote, Ketugram-I, Ketugram-II	6 Burdwan, Guskara, Memari, Kalna, Katwa, Dainhat	1	0
13	Paschim Bardhaman	8	Jamuria, Raniganj, Salanpur, Barabani, Pandebswar, Andal, Kanksa, Durgapur, Faridpur	2 Asansol Municipal Corporation Durgapur Municipal Corporation	0	0
14	Jhargram	8	Jhargram , Binpur- I, Binpur-II, Gopiballavpur-I, Gopiballavpur-II, Nayagram, Sankrail, Jamboni	1 Jhargram Municipality	0	0

Details of District-wise Damages – Overview							
Sl. No	Name of District	Blocks Affected		Municipalities/MCs Affected		Human Casualty & Injury	
		Nos	Name	Nos	Name	Dead	Injured
15	Murshidabad	26	Berhampore, Beldanga-I&II, Hariharpara, Nowda, Domkal, Raninagar-I&II, Jalangi, Kandi, Bharatpur-I&II Burwan, Khargram, Lalgola, Bhagwangola-I&II Nabagram, Murshidabad-Jiaganj, Farakka, Suti-I&II, Samserganj, Raghunathganj-I&II, Sagardighi	7	Berhampore, Domkal, Kandi, Beldanga, Jiaganj-Azim-ganj, Murshidabad, Dhulyan,	0	0
16	Malda	9	Kaliachak-I, Kaliachak-II, Kaliachak-III, Manikchak, Bamongola, Gazole, Old Malda, Englishbazar, Habibpur	1	Englishbazar	0	0
	Total-	280		99		99	221



ANNEXURES

Annexure-I

The devastating Super Cyclone AMPHAN made severe damage to dwelling houses in following districts:

1. South 24 Parganas	9. Murshidabad
2. North 24 Parganas	10. Jhargram
3. Purba Medinipur	11. Malda
4. Paschim Medinipur	12. Bankura
5. Kolkata	13. Birbhum
6. Nadia	14. Paschim Bardhaman
7. Howrah	15. Purba Bardhaman
8. Hooghly	16. Purulia

Total cost of House damaged reported so far: 28.56 Lakhs.





Annexure II

Agricultural Sector

Crops Damaged	Boro Paddy, Moong, Till, Jute, Groundnut, Sugarcane, Cotton & Maize
Total (Area in ha)	17 lakh
Money Value Loss (Rupees in crores)	15,860.00



Annexure-III

Horticultural Damage

Crops Damaged	Betel vine (lakh mote), Litchi, Mango etc.
Total (Area in ha)	250556.17
Money Value Loss (Rs. in Crore)	6,581.00



Annexure-IV

Damage to Fisheries

No of Damaged Boat	8,007
Number of Damage Hut	1.48 Lakhs
Approx. Loss (Rs. In Crore)	2,000.00



Annexure-V

Damage to Animal Resources

Loss of animal (Number)	21,21,637
Total Loss (Rs. In Crore)	452.00



Annexure-VI

Damage to Drinking Water

Piped Water Supply Schemes Damaged	1192
Total Estimated Damage (in Crore)	2060.00



Annexure-VII

Damage to Roads including Rural Roads & Culverts / Bridges

Road Damaged (Km)	2148.22
No. of Damaged Bridges / Culvert	355
Length of Damaged Rural Road (Km)	10091.17
Total Approximate cost of damage (Rs. in Crore)	2,237.00



Annexure-VIII

Damage to Irrigation Canals / Ponds

Embankments damaged across 37 Blocks and 01 Municipality, erosion in many islands	
Length of Damaged embankments (Km)	244.73
Damage to Sea Dykes (KM)	3.6
Total Assessed cost of damage on the basis of primary survey (Rs. In Crore)	2944.00



Annexure-IX

Damage to Power Sector

Power Sub- Station Damaged	273
Electric Pole Damaged	449174
Total Restoration Cost (Rs. In Crore)	3,230.00



Annexure-X

Damage to Forest

Damaged Forest Area (Ha)	1.58 Lakh
Total Assessed Loss (Rs. in Crore)	1033.00



Pre & Post AMPHAN Views of Botanical Gardens, Shibpur, Howrah



Annexure-XI

Damage to Educational Infrastructure

School Damaged	14640
Colleges Damaged (Govt. & Govt. Aided Colleges, Engineering Colleges)	301
Total Estimated Damage (in Crore)	793.00



Annexure-XII

Damage to Health Infrastructure

Sub Centre Damaged	5142
PHC Damaged	563
BPHC/RH Damaged	169
SDH / SGH Damaged	37
District Hospital Damaged (Including Health Districts)	24
Total Estimated Damage (Rs. in Crore)	1270.00

Annexure-XIII

Damage to Anganwadi Infrastructure

AWCs Damaged	12678
Total Estimated Damage (Rs. in Crore)	342.00

Annexure-XIV

Urban Infrastructure

Municipal Roads, Street Lighting,Sewerage,water supply etc.	
Quantum of Loss (Rs. in Crore)	6,750



Annexure-XV

Damage to Industries including MSME

Damaged caused to Industrial ware house/raw material / Industrial Infrastructure/sheds etc.	
Quantum of Loss (Rs. in Crore)	26,790.00



Annexure-XVI

Miscellaneous Damages

Total Estimated Amount (Rs.in Crore)	1,540
Assessed Loss of Transport, Fire & Emergency infrastructure, Godowns, Housing, SHG,Trees, Correctional Homes, BCW etc.	



2.3. Depression over the south coastal Oman and adjoining Yemen (29th May – 01st June, 2020)

2.3.1 Introduction:

- A cyclonic circulation developed over westcentral and adjoining southwest Arabian Sea (AS) on 27th May. Under its influence, a low pressure area formed over westcentral AS in the morning (0300 UTC) of 28th May.
- It lay as a Well Marked Low pressure area (WML) over westcentral AS off south Oman-east Yemen coasts in the morning (0300 UTC) of 29th May.
- Under favourable environmental conditions, it concentrated into a depression (D) over south coastal Oman and adjoining Yemen in the afternoon (0900 UTC) of 29th May.
- It moved slightly westwards till the morning (0300 UTC) of 30th May over south coastal Oman and adjoining Yemen.
- Thereafter, it moved southwestwards and weakened into a WML over south coastal Oman and adjoining Yemen in the early morning (0000 UTC) of 1st June 2020.
- The observed track of the system during 29th May to 1st June is presented in **Fig. 2.3.1**. Best Track parameters associated with the system are presented in **Table 2.3.1**.

2.3.2 Salient Features:

The salient features of the system were as follows:

- i. It was the first cyclonic disturbance over the Arabian Sea during the year 2020.
- ii. Climatologically, during the period 1891-2018, a total of 17 cyclonic disturbances (including depressions and cyclonic storms) developed over AS during May-June (**Fig. 2.3.2a**). Out of these, 13 crossed Oman coast and 4 crossed Yemen coast. Out of the 13 cyclonic disturbances, 4 crossed Oman as depression ((intensity 27-33 kt) and 9 crossed Oman as cyclonic storms (intensity $\geq$ 34 kt). Out of these 4 cyclonic disturbances, there was only 1 system that maintained the intensity of depression throughout its life period (**Fig. 2.3.2b**).
- iii. It had an anti-clockwise recurving track as it moved initially westwards till 0300 UTC of 30th over south coastal Oman and adjoining Yemen. Thereafter, it moved southwestwards and weakened into a well marked low pressure area over south coastal Oman and adjoining Yemen in the morning of 1st June.
- iv. Constant moisture feed occurred all through the life period of the system owing to the cross equatorial south westerly winds in association with the monsoon surge. This factor, along with the low to moderate vertical wind shear aided the

system to maintain the Depression stage intensity over the coastal belt of Oman and adjoining Yemen for 3 days.

v. The life period (D to D) of the system was 85 hours (3 days & 15 hours).

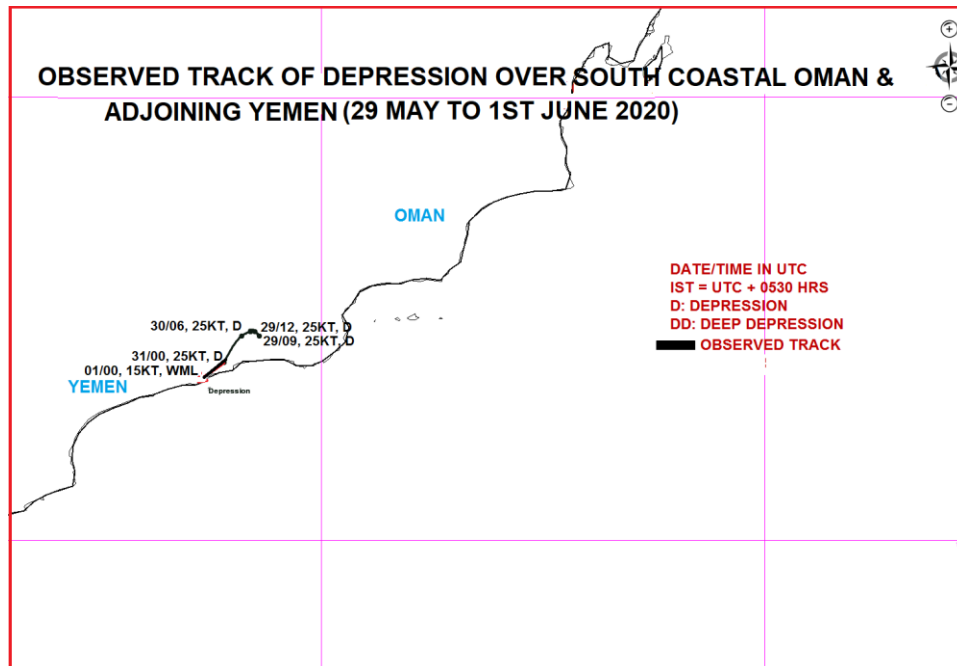


Fig. 2.3.1: Observed track of depression over the south Oman and east Yemen (29 May-01 June, 2020)

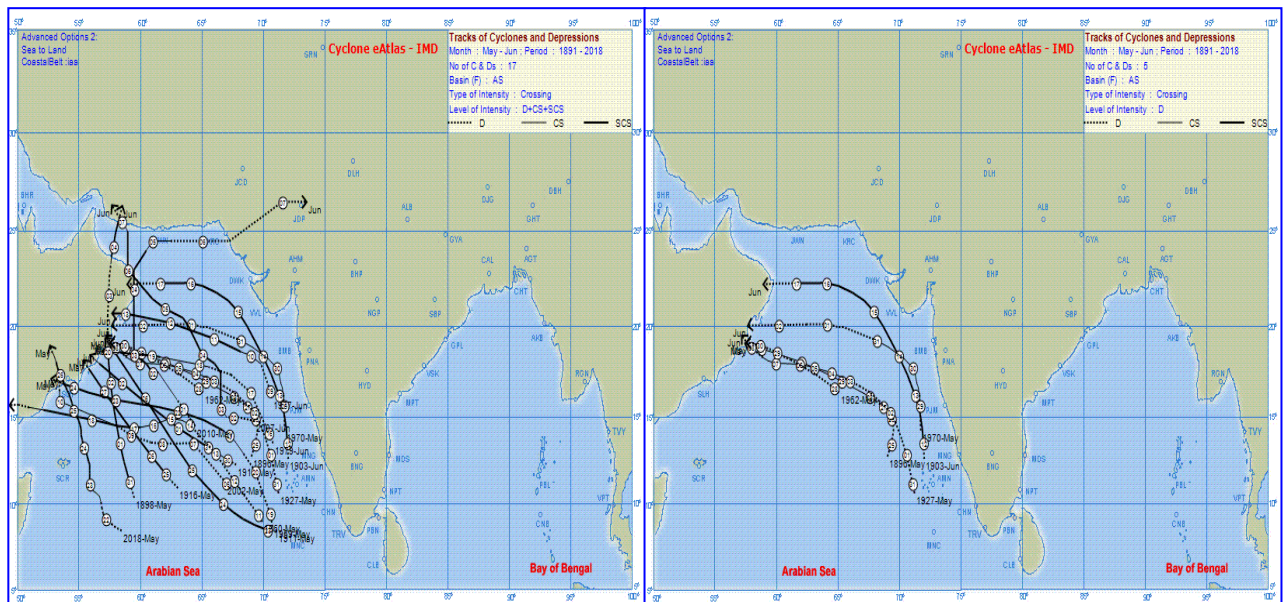


Fig.2.3.2: Tracks of (a) cyclonic disturbances (including depression & cyclones) and (b) depressions crossing Oman & Yemen coasts in the months of May & June during 1891-2018

Table2.3.2: Best track positions and other parameters of the Depression, over the Arabian Sea during 29 May- 01 June, 2020

Date	Time (UTC)	Centre lat. ^o N/ long. ^o E		C.I. NO	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
29/05/2020	0900	17.3	54.3	-	1000	25	3	D
	1200	17.3	54.3	-	1000	25	3	D
	1800	17.3	54.3	-	1000	25	3	D
30/05/2020	0000	17.3	54.2	-	1000	25	3	D
	0300	17.3	54.2	-	1000	25	3	D
	0600	17.2	54.0	-	1000	25	3	D
	1200	17.2	54.0	-	1000	25	3	D
	1800	17.2	54.0	-	1000	25	3	D
31/05/2020	0000	17.1	53.8	-	1000	25	3	D
	0300	17.1	53.8	-	1000	25	3	D
	0600	17.0	53.5	-	1000	25	3	D
	1200	16.9	53.1	-	1000	25	3	D
	1800	16.8	52.9	-	1000	25	3	D
01/06/2020	0000	Weakened into well marked low pressure area over south coastal Oman and adjoining Yemen						

2.3.3. Monitoring and Prediction:

India Meteorological Department (IMD) maintained round the clock watch over the north Indian Ocean and the system was monitored since 27th May with the development of cyclonic circulation over westcentral and adjoining southwest AS.

The Depression was monitored with the help of available satellite observations from INSAT 3D and 3DR, polar orbiting satellites including SCATSAT, ASCAT etc. and available ships & buoy observations in the region. Various numerical weather prediction models run by the Ministry of Earth Sciences (MoES) institutions, various global models and IMD's dynamical-statistical models developed in-house were utilized to predict the genesis, track, landfall and intensity of the Depression. A digitized forecasting system of IMD was utilized for analysis and comparison of various Numerical models' guidance, decision making process and warning product generation. Typical INSAT-3D imageries are presented in **Fig. 2.3.3.**

At 0300 UTC of 27th May, scattered low and medium clouds with embedded intense to very intense convection lay over westcentral and adjoining southwest AS. Scattered low and medium clouds with embedded moderate to intense convection lay over southeast AS. At 0300 UTC of 28th May, scattered low and medium clouds

with embedded intense to very intense convection lay over southeast and westcentral AS. Scattered low and medium clouds with embedded isolated weak to moderate convection lay over eastcentral AS. At 0300 UTC of 29th May, the cloud mass over westcentral AS further organised. The vortex lay over westcentral AS & neighbourhood centered within half a degree of 15.7°N/54.8°E. The intensity of the system was T 1.0. Broken low and medium clouds with embedded intense to very intense convection lay over westcentral AS between latitude 13.0°N to 21.0°N & longitude 51.0°E to 57.0°E and south Oman and adjoining east Yemen. Minimum cloud top temperature (CTT) was minus 93°C. Scattered low and medium clouds with embedded intense to very intense convection also lay over southeast and westcentral AS. At 0900 UTC of 29th May, broken low and medium clouds with embedded intense to very intense convection lay over westcentral AS between latitude 14.0°N to 17.5°N longitude 51.0°E to 56.0°E and south Oman adjoining north Yemen. Minimum CTT was minus 93°C. At 0300 UTC of 30th May, broken low and medium clouds with embedded intense to very intense convection lay over westcentral AS between latitude 13.5°N to 19.0°N longitude 52.5°E to 57.0°E and south Oman adjoining north Yemen. At 0300 UTC of 31st May, broken low and medium clouds with embedded intense to very intense convection lay over south coastal Oman and adjoining Yemen and westcentral AS between latitude 15.0°N to 19.0°N longitude 52.0°E to 56.0°E. Minimum CTT was minus 93°C.

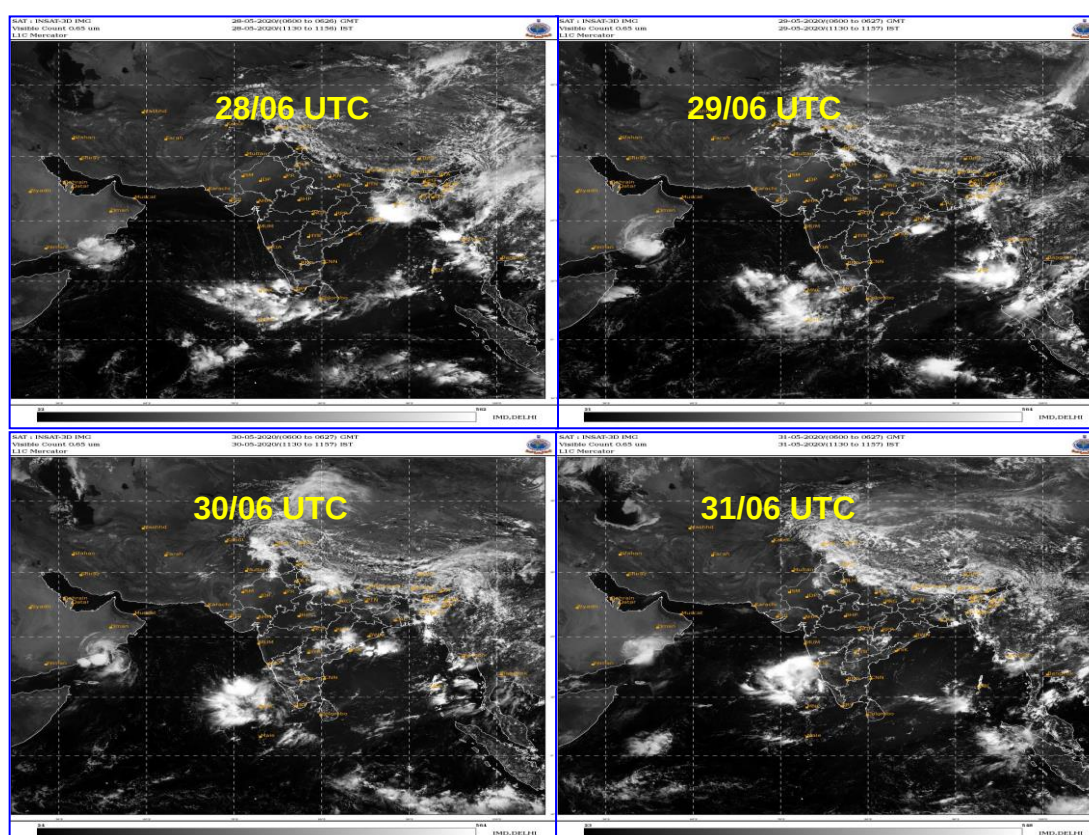


Fig. 2.3.3 (a): INSAT-3D visible imageries during 28th-31st May, 2020

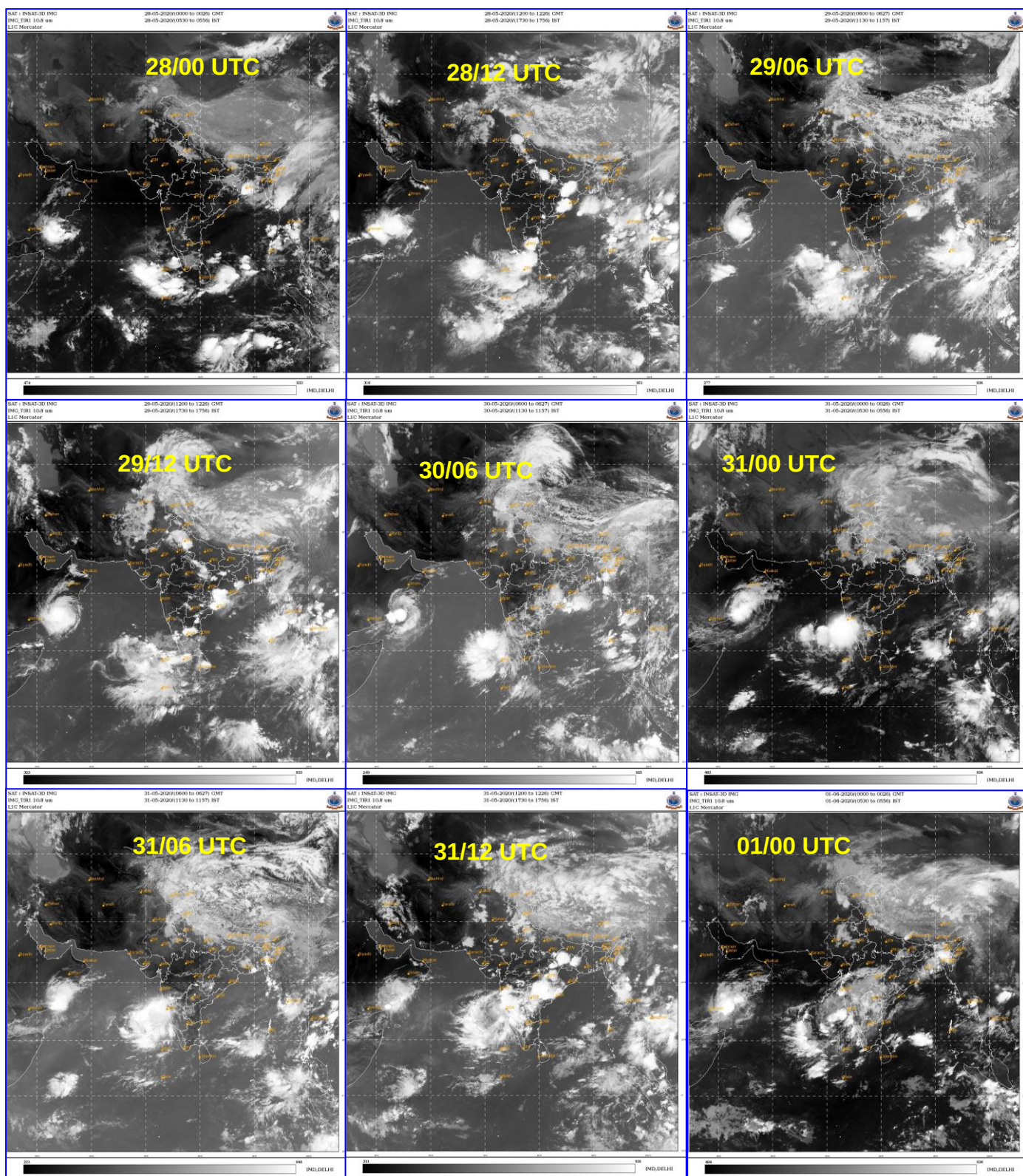


Fig. 2.3.3(b): INSAT-3D IR imageries during 28th May – 1st June, 2020

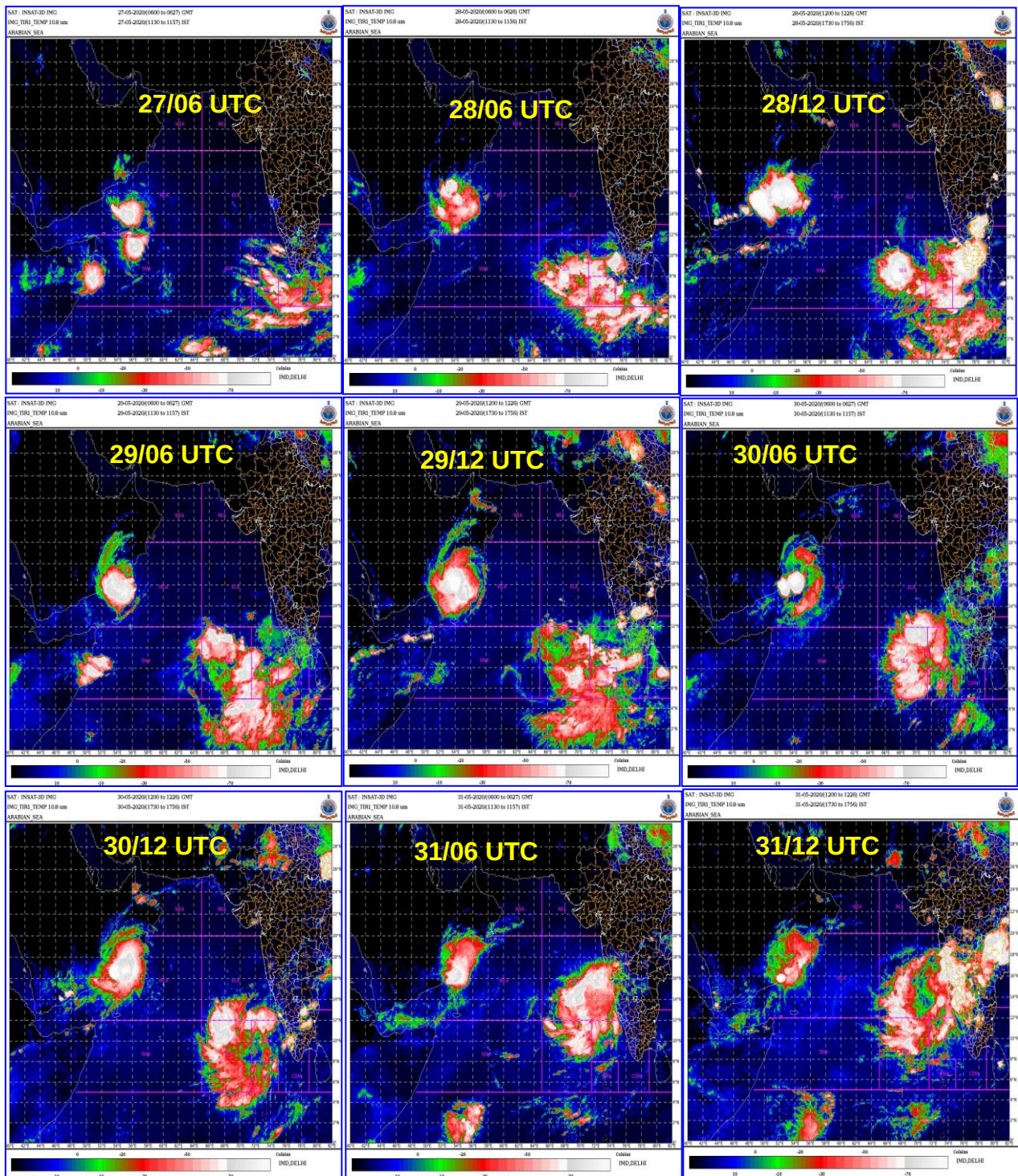


Fig. 2.3.3(c): INSAT-3D enhanced colour imageries during 27th May – 31st May, 2020

2.3.4. NWP Model forecast

IMD GFS analysis of mean sea level pressure, 10m wind, winds at 850, 500 and 200 hPa levels based on 0000 UTC during 29th May to 1st June is presented in Fig.4. On 29th May, IMD GFS predicted a cyclonic circulation over westcentral AS off south coastal Oman and adjoining Yemen coasts. The circulation extended upto 500 hPa level.

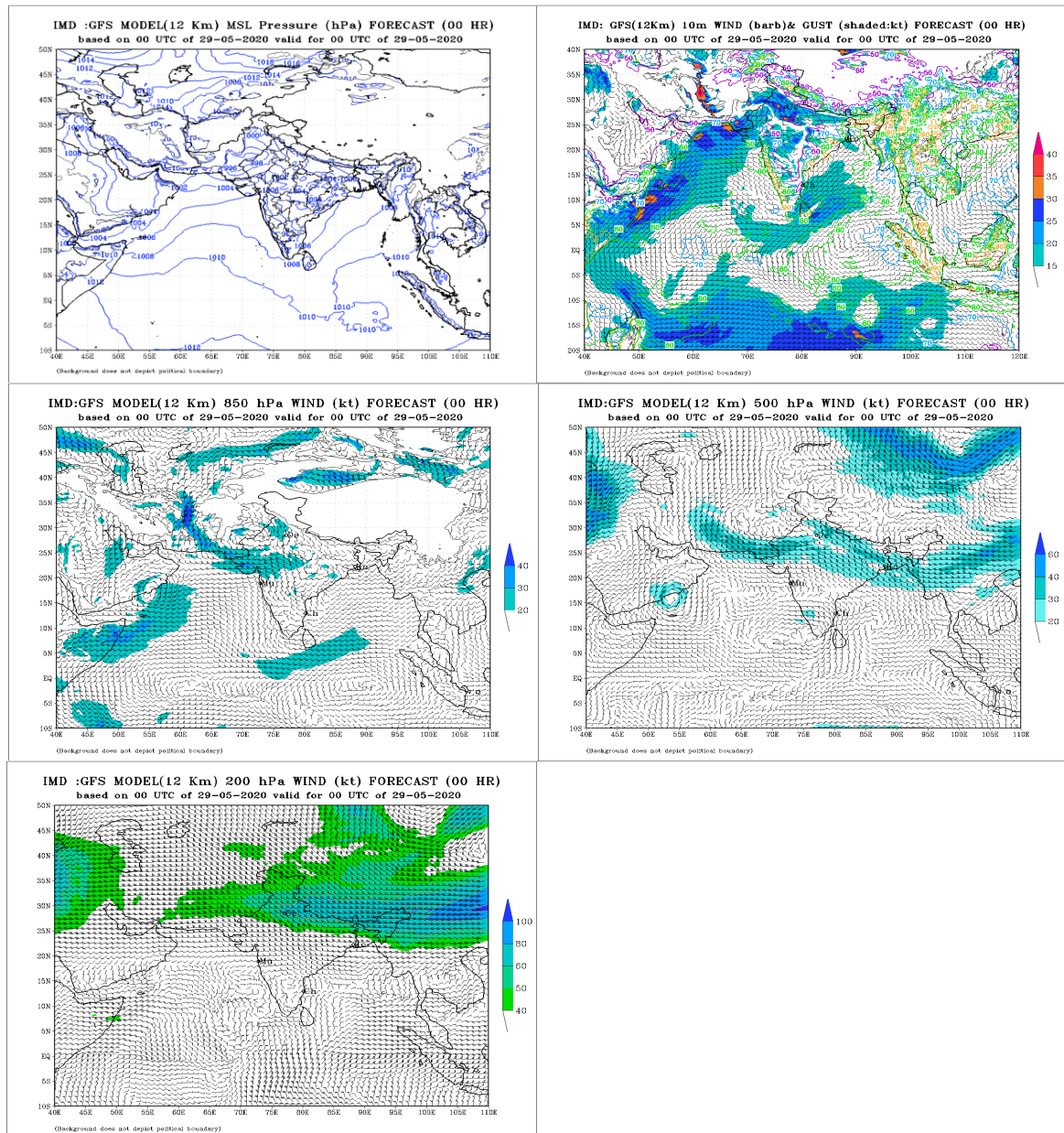


Fig. 2.3.4a: IMD GFS analysis of mean sea level pressure (hPa), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 29th May.

On 30th May, IMD GFS predicted a depression over south coastal Oman and adjoining Yemen coasts. The circulation extended upto 200 hPa level.

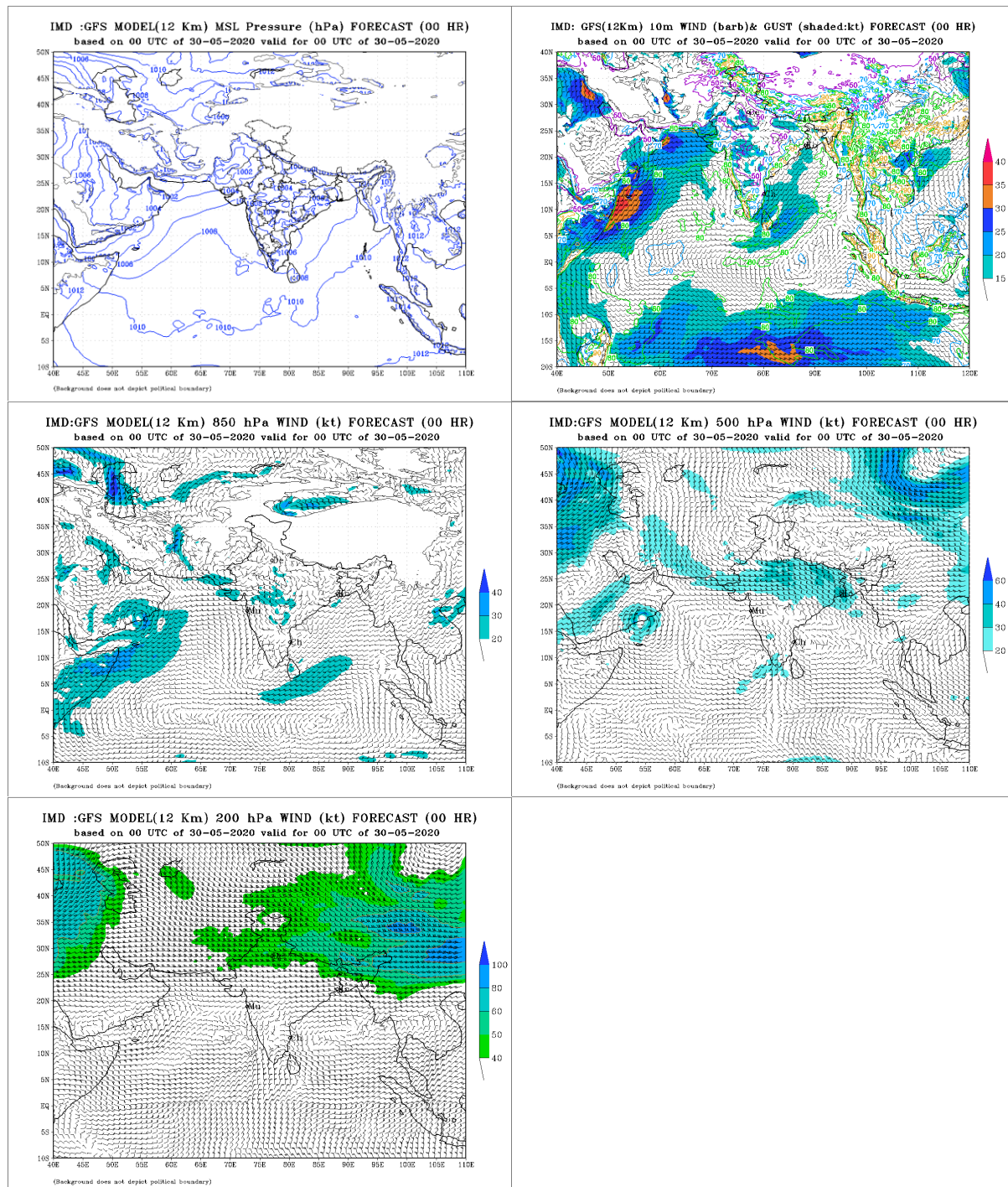


Fig. 2.3.4b: IMD GFS analysis of mean sea level pressure (hPa), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 30th May.

On 31st May, IMD GFS predicted a cyclonic circulation over south coastal Oman and adjoining Yemen coasts. The circulation extended upto 200 hPa level.

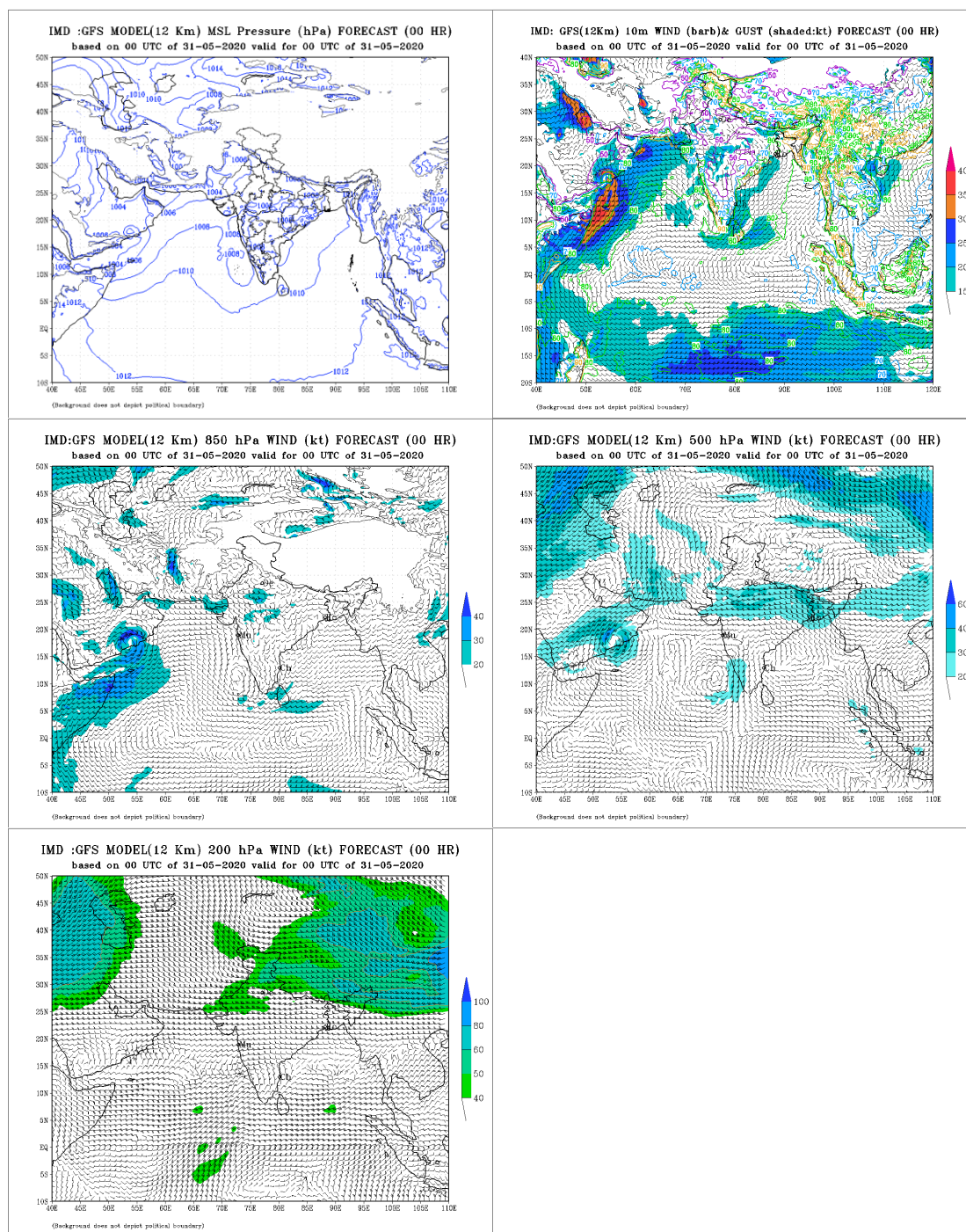


Fig. 2.3.4c: IMD GFS analysis of mean sea level pressure (hPa), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 31st May.

On 1st June, IMD GFS predicted a well marked low pressure area over south coastal Oman and adjoining Yemen coasts with west-southwestwards movement. The circulation extended upto 500 hPa level.

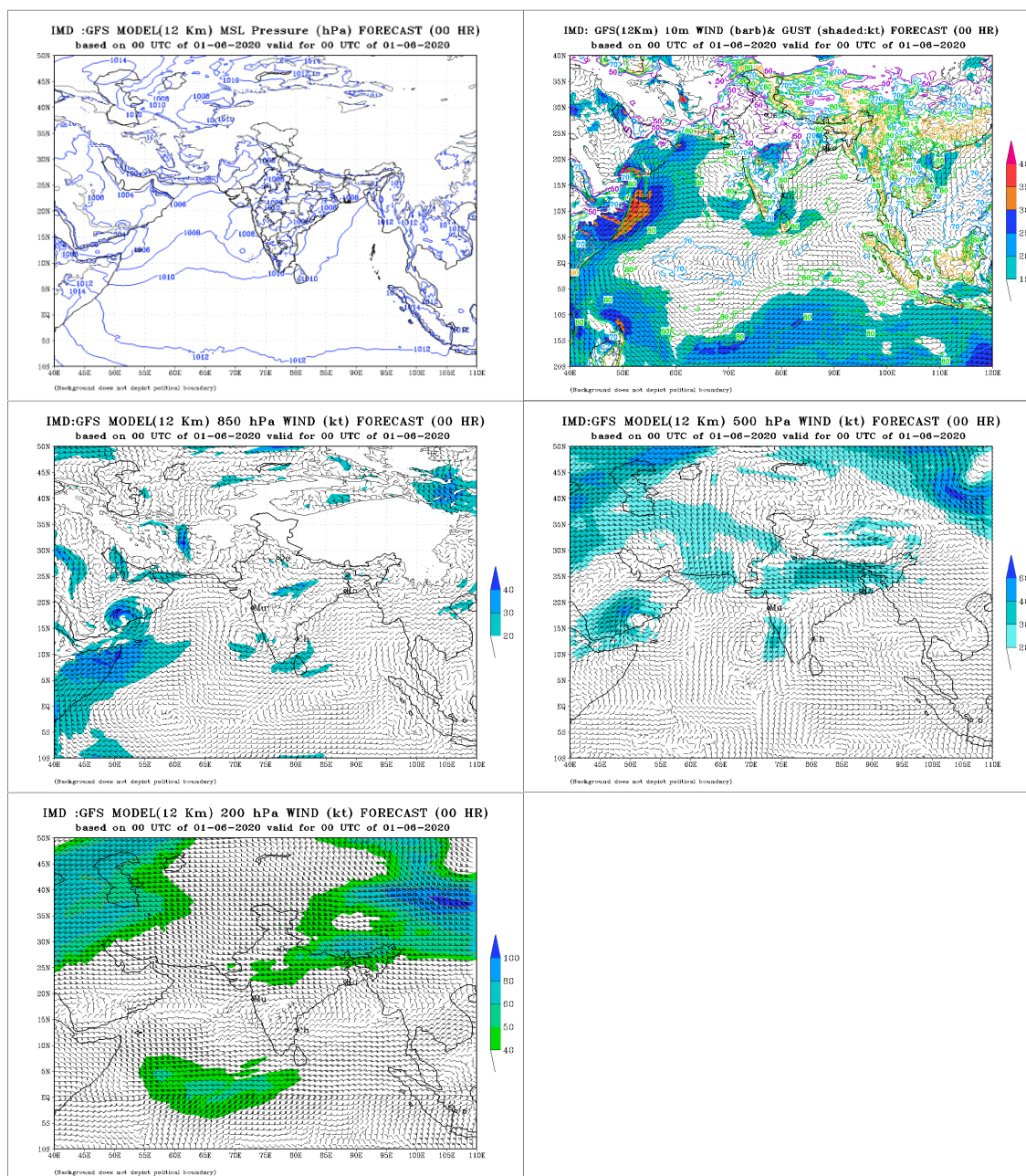


Fig. 2.3.4d: IMD GFS analysis of mean sea level pressure (hPa), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 1st June.

2.3.5. Realized Weather:

2.3.5.1 Realised rainfall

Rainfall associated with depression over coastal Oman and Yemen based on IMD-NCMRWF GPM merged gauge 24 hours cumulative rainfall ending at 0300 UTC of date is depicted in **Fig 2.3.5**.

It indicates occurrence of heavy to very heavy rainfall at few places with extremely heavy falls at isolated places during 29th-31st May and heavy to very heavy rainfall at isolated places on 1st June over south coastal Oman and adjoining Yemen.

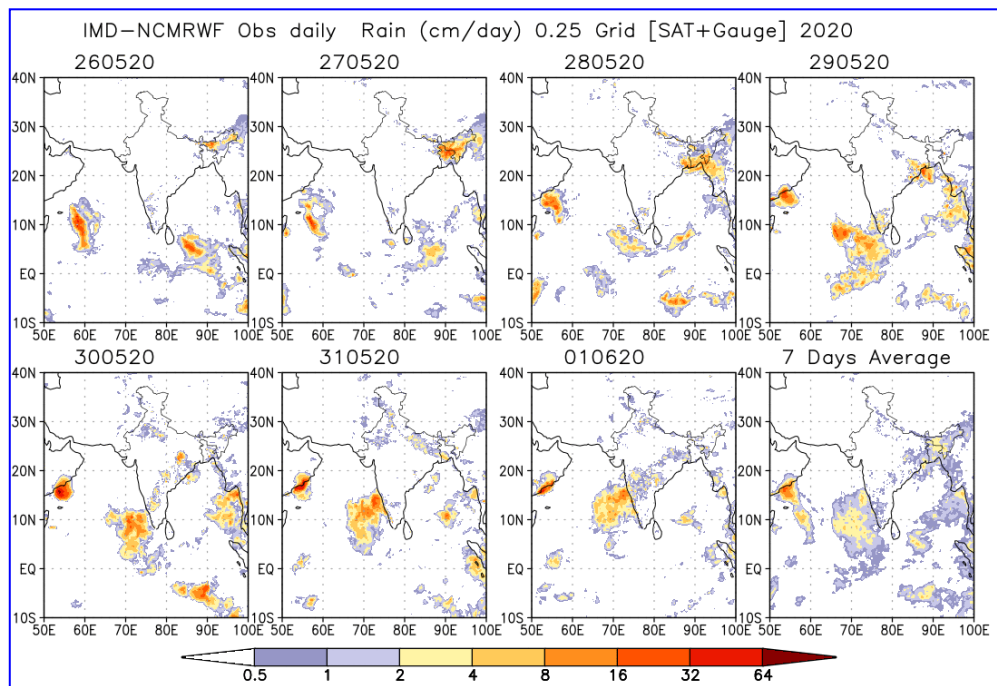


Fig. 2.3.5: IMD-NCMRWF GPM merged gauge 24 hr cumulative rainfall (cm) ending at 0830 IST of date during 16th May – 22nd May and 7 days average rainfall (cm/day)

2.3.5.2. Realised wind:

As per satellite data maximum sustained winds of the order of 20 – 25 kts prevailed over south coastal Oman and adjoining Yemen during 29th-31st May.

2.3.5.3. Realised storm surge:

No storm surge was reported in association with the system.

2.4. Severe Cyclonic Storm “NISARGA” over the eastcentral and adjoining southeast Arabian Sea (01st-04th June, 2020)

2.4.1. Introduction

A Low-pressure area formed over southeast & adjoining eastcentral Arabian Sea and Lakshadweep area in the early morning (0000 UTC) of 31st May 2020. Under favorable environmental conditions, it concentrated into a depression over eastcentral and adjoining southeast Arabian Sea in the early morning (0000 UTC) of 1st June 2020. It intensified into deep depression over eastcentral Arabian Sea in the early morning (0000 UTC) and into cyclonic storm “NISARGA” in the noon (0600 UTC) of 2nd June. It moved northwards till evening (1200 UTC) of 2nd June. Thereafter, it gradually recurved northeastwards and intensified into a severe cyclonic storm in the early morning (0000 UTC) of 3rd June 2020. Further moving northeastwards, it crossed Maharashtra coast close to south of Alibag as a severe cyclonic storm with a maximum sustained wind speed of 110-120 kmph gusting to 130 kmph during 0700-0900 UTC of 03rd June. Continuing to move northeastwards after landfall, it weakened into a cyclonic storm in the evening (1200 UTC) over north Madhya Maharashtra and into a deep depression in the mid-night (1800 UTC) of 3rd June 2020 over the same region. It further weakened into a depression over western parts of Vidarbha and neighbourhood in the early morning (0000 UTC) and into a well-marked low-pressure area in the evening (1200 UTC) of 4th June over central parts of Madhya Pradesh. It lay as a low-pressure area over southeast Uttar Pradesh and adjoining Bihar in the afternoon (0900 UTC) of 5th June. The observed track of the system during 1st - 4th June is presented in Fig. 2.4.1. The best track parameters associated with the system are presented in **Table 2.4.1**.

2.4.2. Salient Features:

The salient features of the system were as follows:

- i. It was the first cyclonic storm over the AS during 2020. The last cyclone, which crossed Maharashtra coast was cyclonic storm, Phyan which crossed coast on 11th Nov., 2009. Prior to the SCS, Nisarga, an SCS crossed Maharashtra coast on 24th May, 1961. It was also the fourth cyclone crossing Maharashtra coast during the 1961-2020 (Fig. 2.4.2a).
- ii. Climatologically, during the period 1891-2018, a total of 6 cyclonic storms and above intensity storms developed within the grid 11-15°N and 70-74°E about $\pm 2.0^\circ$ of the genesis point (13.0°N/71.4°E) of Nisarga. Out of these only 1 crossed Maharashtra coast as a severe cyclonic storm in May 1961, 3 crossed Oman coast and 1 weakened over northeast AS (Fig. 2.4.2b).
- iii. It had a clockwise recurving track as it moved initially northwards till 1200 UTC of 2nd June and thereafter recurved northeastwards. The total track length of the system was 1294 km. It was mainly steered by an anticyclonic circulation in middle & upper tropospheric levels to the east of the system centre.
- iv. It moved with a 12-hour average translational speed of 15.8 kmph against the Long Period Average (LPA) (1990-2013) of 10.5 kmph for SCS category over the AS during monsoon season (Fig. 2.4.5a).

- v. The peak MSW of the cyclone was 110-120 kmph (60 knots) gusting to 130 kmph (70 knots) during 0600 UTC of 3rd to 0900 UTC of 3rd June over the eastcentral AS. The lowest estimated central pressure was 984 hPa during the same period (Fig. 2.4.5b).
- vi. The system crossed Maharashtra coast close to south of Alibag near 18.35°N/72.95°E, as an SCS with maximum sustained wind speed of 110-120 kmph (60 knots) gusting to 130 kmph (70 knots) between 1230-1430 hrs IST (0700-0900 UTC) of 3rd June.
- vii. The system maintained the cyclonic storm intensity for almost 7 hours after landfall till 1500 UTC of 3rd June.
- viii. The life period (D to D) of the system was 84 hours (3 days & 12 hours) against long period average (LPA) (1990-2013) of 85 hours (3 days & 13 hrs) for SCS category over the AS during monsoon season.
- ix. The Velocity Flux, Accumulated Cyclone Energy (a measure of damage potential) and Power Dissipation Index (a measure of loss) were 2.65×10^2 knots, 1.21×10^4 knots² and 0.58×10^6 knots³ respectively against the long period average during 1990-2013 of 2.12×10^2 knots, 1.4×10^4 knots² and 1.0×10^6 knots³ respectively for tropical cyclones over the AS during monsoon season.

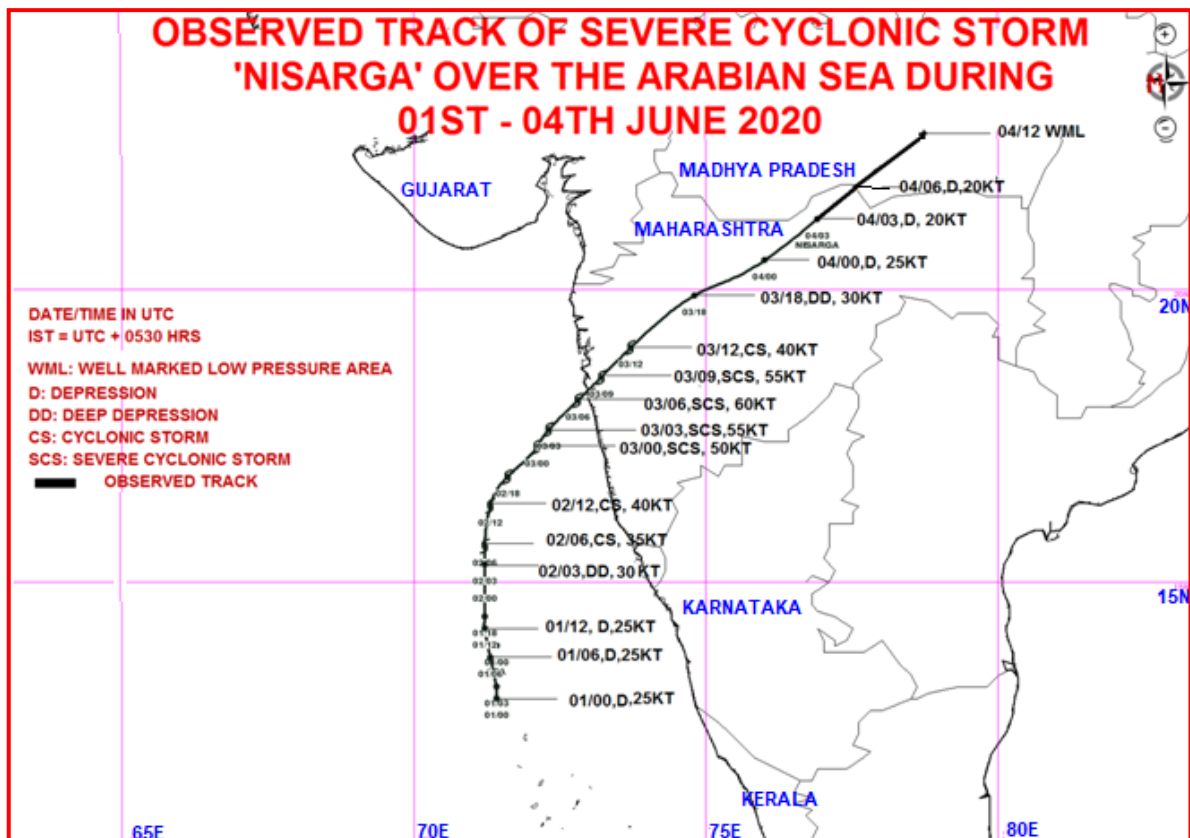


Fig. 2.4.1: Observed track of SCS 'NISARGA' over the eastcentral and adjoining southeast Arabian Sea (1st-4th June, 2020)

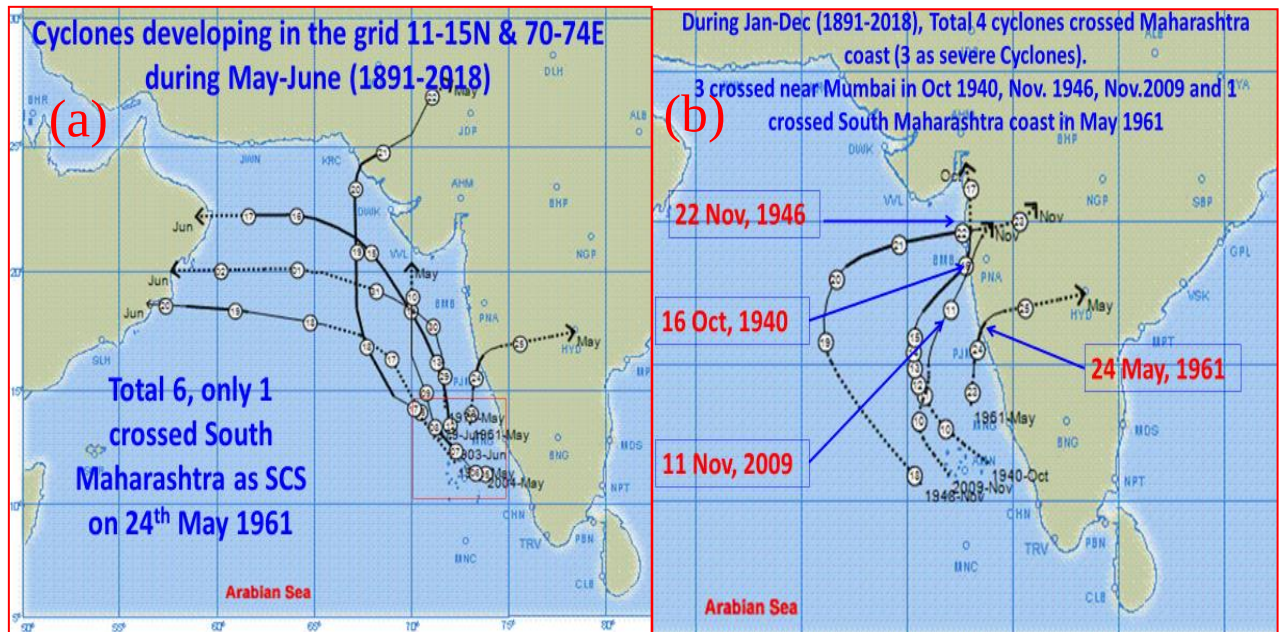


Fig. 2.4.2: Past Tracks of severe cyclonic storms and above intensity storms (a) developing in the grid $\pm 2.5^\circ$ of genesis point and (b) crossing Maharashtra coast in the month of May and June during 1891-2018

Table 2.4.1: Best track positions and other parameters of the Severe Cyclonic Storm, 'NISARGA' over the eastcentral and adjoining southeast Arabian Sea during 1st – 4th June, 2020

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
01/06/2020	0000	13.0	71.4	1.5	1004	25	3	D
	0300	13.2	71.4	1.5	1004	25	3	D
	0600	13.7	71.3	1.5	1004	25	3	D
	1200	14.2	71.2	1.5	1003	25	4	D
	1800	14.4	71.2	1.5	1003	25	4	D
02/06/2020	0000	15.0	71.2	2.0	1000	30	6	DD
	0300	15.3	71.2	2.0	1000	30	6	DD
	0600	15.6	71.2	2.5	999	35	7	CS
	0900	16.0	71.2	2.5	999	35	7	CS
	1200	16.3	71.3	2.5	996	40	8	CS
	1500	16.0	71.4	2.5	996	40	8	CS
	1800	16.8	71.6	2.5	996	40	8	CS
	2100	17.1	71.8	3.0	994	45	10	CS
03/06/2020	0000	17.3	72.1	3.0	992	50	12	SCS
	0300	17.6	72.3	3.5	988	55	16	SCS
	0600	18.1	72.8	4.0	984	60	20	SCS

		Crossed Maharashtra coast close to south of Alibag near 18.35°N/72.95°E, as Severe Cyclonic Storm with maximum sustained wind speed of 60 kt gusting to 70 kt between 0700-0900 UTC of 03 rd June						
	0900	18.5	73.2	-	992	55	14	SCS
	1200	19.0	73.7	-	998	40	8	CS
	1500	19.6	74.0	-	1000	30	6	DD
	1800	19.8	74.8	-	1001	30	5	DD
04/06/2020	0000	20.5	76.0	-	1004	25	4	D
	0300	21.2	76.9	-	1005	20	3	D
	0600	21.8	77.6	-	1005	20	3	D
	1200	Weakened into a well marked low pressure area over central parts of Madhya Pradesh						

2.2.3. Brief life history

2.4.3.1 Genesis

At 0300 UTC of 31st May, it lay an LPA. The Madden Julian Oscillation (MJO) index lay in phase 1 with amplitude more than 1. MJO was supporting enhancement of convective activity over the west AS. The sea surface temperature (SST) was 30-32°C over the entire AS. The tropical cyclone heat potential (TCHP) was more than 100 KJ/cm² over major parts of south and westcentral AS. It was about 60-80 KJ/cm² over central AS and was becoming negative over extreme north AS off Oman coast. Positive lower level positive vorticity ($100 \times 10^{-6} \text{ sec}^{-1}$) lay over Comorin-Lakshadweep areas. It was extending upto 200 hPa level. The lower level convergence was around $30 \times 10^{-5} \text{ sec}^{-1}$ over southeast Arabian Sea. The upper level divergence was $50 \times 10^{-5} \text{ sec}^{-1}$ over southeast Arabian sea. Vertical wind shear (VWS) was moderate to high (20-30 kts) over the system centre. The upper tropospheric ridge lay near 12.0°N over the southeast Arabian Sea.

At 1500 UTC of 31st May, the system lay as a well marked low pressure area. The MJO index lay in phase 1 with amplitude more than 1. It was forecast to remain in same phase during next 7 days with amplitude remaining more than 1. Thus MJO was supporting enhancement of convective activity over the west AS. The sea surface temperature (SST) was 30-32°C over the entire AS. The tropical cyclone heat potential was more than 100 KJ/cm² over major parts of south and westcentral AS. It was about 60-80 KJ/cm² over central AS and was becoming negative over extreme north AS off Oman coast. Positive lower level vorticity was about $100 \times 10^{-6} \text{ sec}^{-1}$ over Lakshadweep area. It was extending upto 500 hPa level tilting southwards. The lower level convergence was around $15 \times 10^{-5} \text{ sec}^{-1}$ over southeast AS. The upper level divergence was $30 \times 10^{-5} \text{ sec}^{-1}$ over southeast Arabian Sea. Vertical wind shear (VWS) was moderate to high (25-30 kts) over the system centre and was low to moderate to the east of the system.

At 0000 UTC of 1st June, similar Sea conditions prevailed. Positive lower level vorticity was about $100 \times 10^{-6} \text{ sec}^{-1}$ over eastcentral Arabian Sea. It was extending upto 500 hPa level tilting southwards. The lower level convergence was around $10 \times 10^{-5} \text{ sec}^{-1}$ over southeast AS. The upper level divergence was $10 \times 10^{-5} \text{ sec}^{-1}$ over southeast Arabian sea. Vertical wind shear (VWS) was moderate to high (10-15 kts) over the system centre and was low to moderate to the southwest of the system.

Under these conditions, it intensified into a depression over eastcentral and adjoining southeast Arabian Sea.

2.4.3.2 Intensification and movement

At 0000 UTC of 2nd June, it intensified into a **deep depression**. the MJO index lay in phase 1 with amplitude more than 1. The sea surface temperature (SST) was 30-31°C over eastcentral Arabian sea. The tropical cyclone heat potential was 100-120 KJ/cm² over eastcentral Arabian sea and becoming 80-100 KJ/cm² near Karnataka, Maharashtra and Gujarat coast. Positive lower level vorticity was about $100 \times 10^{-5} \text{ sec}^{-1}$ over eastcentral Arabian Sea. The lower level convergence was around $10 \times 10^{-5} \text{ sec}^{-1}$ over the system center. The upper level divergence was $20 \times 10^{-5} \text{ sec}^{-1}$ to the southwest of the system center. Vertical wind shear (VWS) was low to moderate (05-10 KTS) around the system centre and was moderate (15-20 KTS) along the forecast track.

At 0600 UTC of 2nd June, the system intensified into the **cyclonic storm 'NISARGA'**. Similar Sea conditions prevailed. The lower level vorticity was about $100-150 \times 10^{-5} \text{ sec}^{-1}$ over eastcentral AS. The lower level convergence and the upper level divergence around the system centre were $40 \times 10^{-5} \text{ sec}^{-1}$ each. Vertical wind shear was low to moderate (15-20 kts) around the system centre and was moderate (20-30 kts) along the forecast track. All these environmental and dynamical conditions were favouring further intensification of the system into a severe cyclonic storm during next 12-hours.

At 0000 UTC of 3rd June, it intensified into a **severe cyclonic storm**. Similar Sea conditions prevailed. The lower level vorticity was about 200 to $250 \times 10^{-6} \text{ sec}^{-1}$ around the system center. The lower level convergence increased and was about $40 \times 10^{-5} \text{ sec}^{-1}$ to the south of the system centre. The upper level divergence also increased and was about $30 \times 10^{-5} \text{ sec}^{-1}$ to the south of the system center. The vertical wind shear was low (10-15 kts) around the system centre and also along the forecast track. Under these favourable environmental and dynamical conditions, the system had intensified into a severe cyclonic storm. The system was steered by an anticyclonic circulation to the east of the system center over peninsular India. Under it's influence, it was forecast to move gradually north-northeastwards across north-Maharashtra coast.

The system crossed Maharashtra coast as a severe cyclonic storm during 0700 to 0900 UTC of 3rd June. Thereafter, it weakened into a cyclonic storm at 1200 UTC of 3rd June, into a deep depression at 1500 UTC of 3rd June. Moving north-northeastwards, it further weakened into a depression at 0000 UTC of 4th June and further into a WML over central parts of Madhya Pradesh.

The total precipitable water (TPW) imageries (Source: TC Forecaster Website: https://rammb-data.cira.colostate.edu/tc_realtime/index.asp) during life cycle of SCS Nisarga are presented in Fig. 2.4.3. These imageries indicate excessive increase in warm moist around the system centre till 0436 UTC of 3rd June. Thereafter, the system crossed Maharashtra coast.

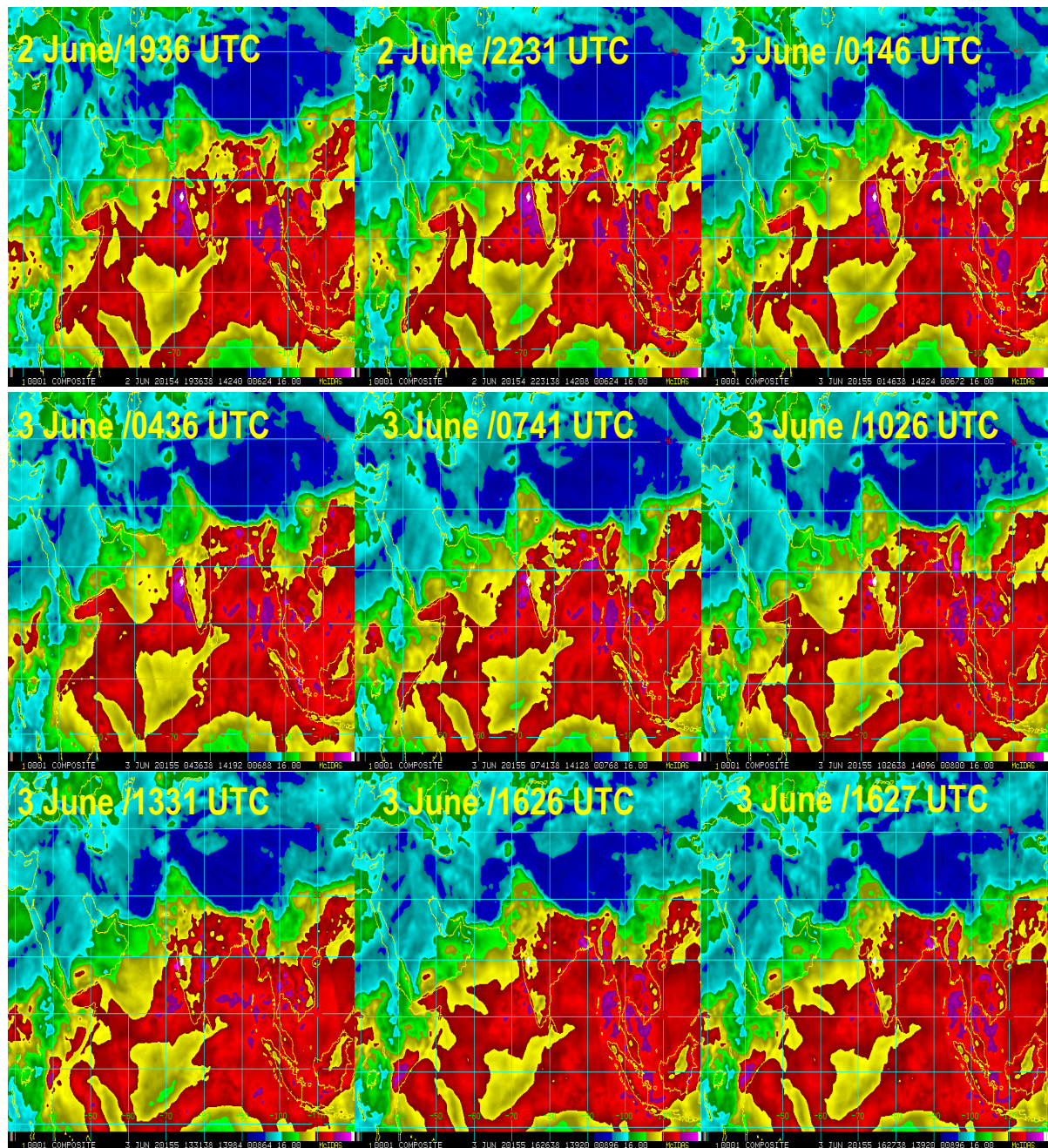


Fig.2.4.3: Total precipitable water vapour imagery during 2-3 June in association with SCS Nisarga

The mean wind speed and wind shear in middle and deep layer is presented in Fig. 2.4.4. The mean wind shear speed in the deep layer was low (10 knot) during the entire life period of the system. The mean wind shear was low (05 kt) in the middle layer during entire life cycle. The mean wind shear direction in the deep layer was east-northeastwards, thereby shearing the cloud mass to the northeast of system centre. The mean wind speed in the deep and middle layer was low (05-10 knot) during entire life cycle. The mean wind speed direction was southwesterly in both the deep and middle layer.

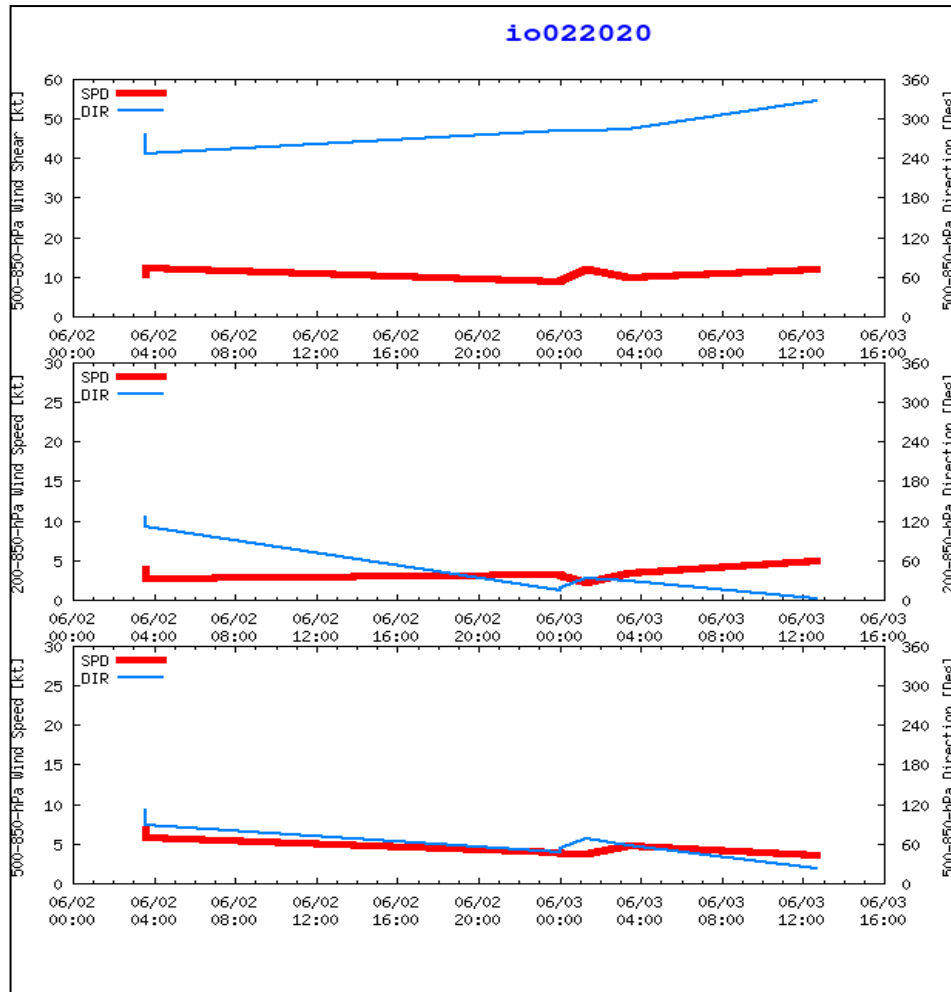


Fig. 2.4.4: Wind shear and wind speed in the middle and deep layer around the system during SCS NISARGA (1st – 4th June), 2020

The six hourly average translational speed during the life cycle of SCS Nisarga is presented in Fig. 2.4.5a. During initial stages of its development (0000 UTC to 1800 UTC of 1st June), Nisarga moved slower than the average (1990-2013) speed of 10.5 kmph for SCS category over the AS during monsoon season. Thereafter the speed increased gradually till morning (0000 UTC) of 3rd June. Subsequently, it increased sharply during landfall till it's weakening into a WML at 1200 UTC of 4th June. The six hourly maximum sustained wind speed and estimated central pressure is presented in Fig. 2.4.5b. The intensity of the system increased gradually till 1800 UTC of 2nd. Thereafter, intensity increased sharply and reached it's peak of 60 kts at 0600 UTC of 3rd June. The landfall process had already started by that time and the system crossed Maharashtra coast during 0700 to 0900 UTC of 3rd with peak intensity of 60 kts gusting to 70 kts. Thereafter, due to land interactions, cut in moisture supply and increased translational speed, the system rapidly weakened into a WML at 1200 UTC of 4th June.

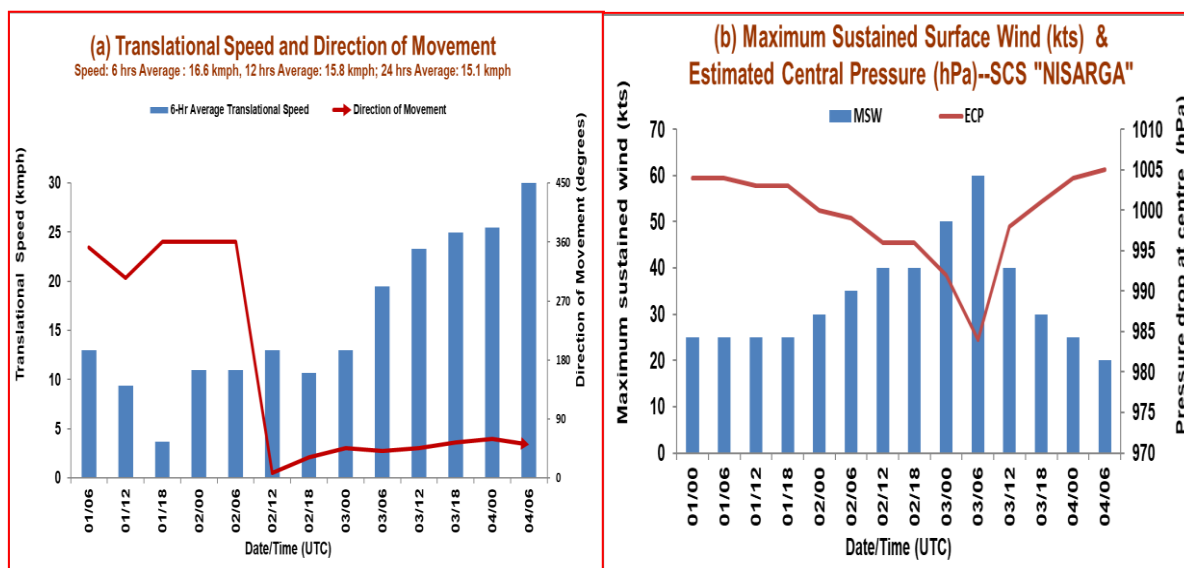


Fig. 2.4.5: (a) Translational speed & direction of movement and (b) Maximum sustained surface winds (kts) & Estimated Central Pressure

2.4.4. Monitoring and Prediction of SCS NISARGA:

India Meteorological Department (IMD) maintained round the clock watch over the north Indian Ocean and the genesis was monitored since 21st May, about 10 days prior to the formation of low pressure area over the southeast & adjoining eastcentral Arabian Sea and Lakshadweep on 31st May. The cyclone was monitored with the help of available satellite observations from INSAT 3D and 3DR, SCAT SAT, polar orbiting satellites and available ships & buoy observations in the region. The system was also monitored by Doppler Weather RADARs (DWRs) Goa and Mumbai. Various numerical weather prediction models run by Ministry of Earth Sciences (MoES) institutions, global models and dynamical-statistical models were utilized to predict the genesis, track, landfall and intensity of the cyclone. A digitized forecasting system of IMD was utilized for analysis and comparison of various models' guidance, decision making process and warning products generation. The satellite and RADAR imageries during entire life cycle of the system are presented in Fig. 2.4.6 & 7 respectively.

2.4.5. Features observed through Satellite and Radar

2.4.5.1. Features observed through satellite

As per satellite imagery based on 0300 UTC of today, the 29th May, the cloud mass over westcentral Arabian Sea further organized. The vortex lay over westcentral Arabian Sea & neighborhood centered within half a degree of 15.7°N/54.8°E. The intensity of the system was T1.0. In association with this system, broken low and medium clouds with embedded intense to very intense convection lay over westcentral Arabian Sea between latitude 13.0°N to 21.0°N & longitude 51.0°E to 57.0°E and south Oman and adjoining east Yemen. Minimum cloud top temperature is minus 93°C. Scattered low and medium clouds with embedded

intense to very intense convection also lay over southeast and westcentral Arabian Sea.

At 1200 UTC of 29th May, broken low/medium clouds with embedded intense to Very intense convection lay over westcentral Arabian Sea between Latitude 13.5°N to 19.5°N longitude 50.5°E to 57.5°E, south Oman Adjoining north Yemen. Minimum CTT is minus 93°C.

At 1200 UTC of 30th May, associated Broken low and medium clouds with embedded intense to very intense Convection lay over westcentral Arabian sea between latitude 14.5°N To 19.0°N and longitude 52.5°E to 57.0°E. Minimum cloud top temperature was minus 93°C.

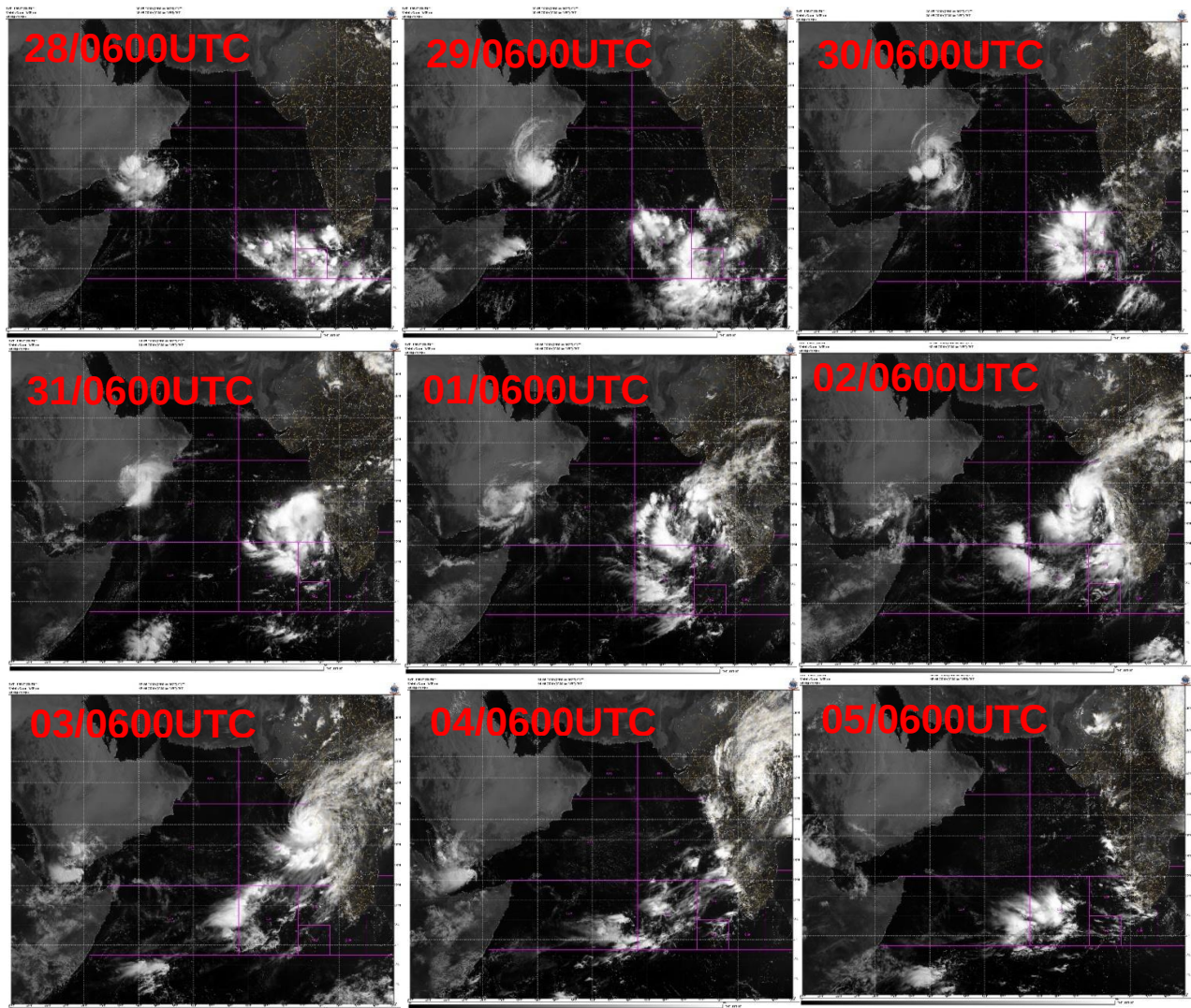


Fig. 2.4.6a: INSAT-3D Visible imageries during life cycle of SCS NISARGA (28 MAY-5 JUNE, 2020)

At 0000 UTC of 31st May, associated broken low and medium clouds with embedded intense to very intense convection lay over Lakshadweep, south east & eastcentral Arabian Sea between latitude 10.0°N to 15.0°N and longitude 68.0°E. Minimum cloud top temperature was minus 93°C.

At 1200 UTC of 31st May, associated broken low and medium clouds with embedded intense to very intense convection lay over Lakshadweep, south east & eastcentral Arabian sea between latitude 09.0°N to 16.5°N and LONGITUDE 66.0°E to 74.5°E. Minimum cloud top temperature was minus 84°C.

At 0000 UTC of 01st June, the intensity of the system was T1.5. Associated scattered to broken low/medium clouds with embedded intense to very intense convection lay over southeast and adjoining eastcentral Arabian sea between latitude 7.5°N TO 17.0°N and longitude 65.0°E to 74.5°E. Minimum cloud top temperature (CTT) was minus 93°C.

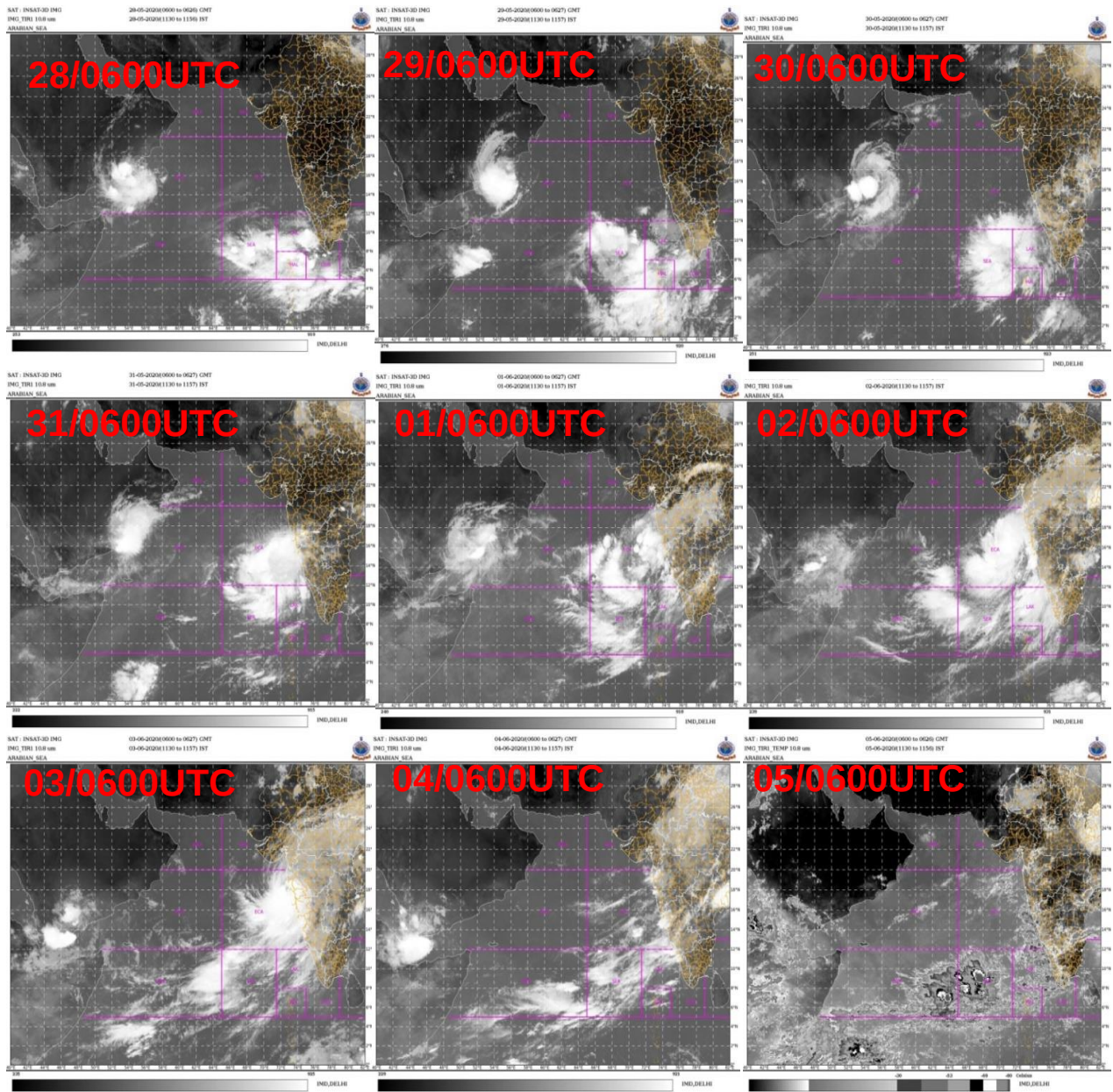


Fig. 2.4.6 b: INSAT-3D IR imageries during life cycle of SCS NISARGA (28 MAY-5 JUNE, 2020)

As per INSAT-3D satellite imagery based on 0000 UTC of 02nd June, the intensity of the system intensity is T2.0. Associated scattered to broken low/medium clouds with embedded intense to very intense convection observed over eastcentral Arabian sea between latitude 12.5°N to 18.0°N and longitude 67.0°E TO 74.5°E . Minimum cloud top temperature (CTT) was minus 93°C .

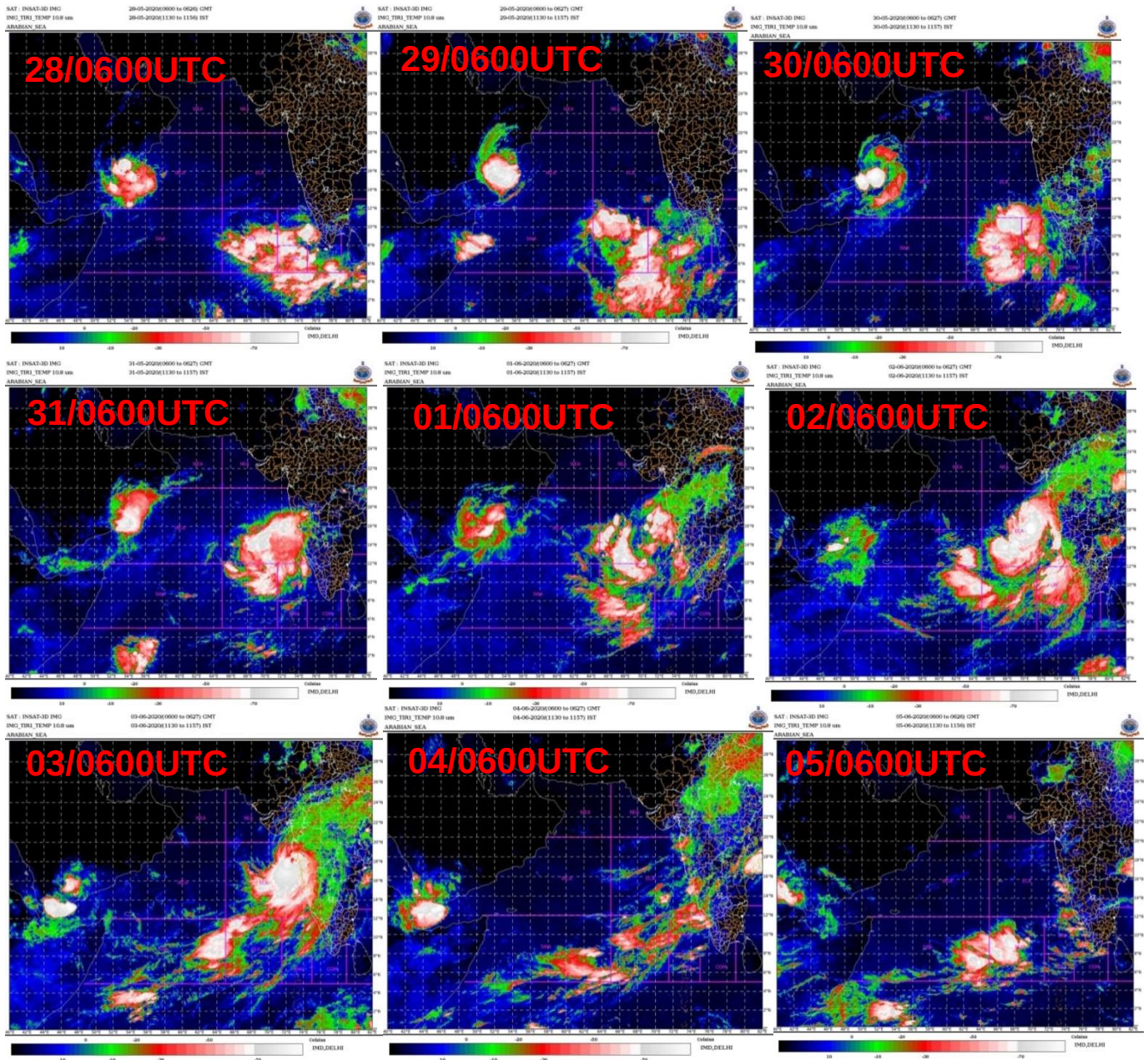


Fig. 2.4.6c: INSAT-3D enhanced color imageries during life cycle of SCS NISARGA (28 MAY-5 JUNE, 2020)

At 0600 UTC of 02nd June, the vortex further intensified. The current intensity of the system was T 2.5 associated with irregular CDO pattern. The system became further organized in last 3-hours. Associated broken low/medium clouds with

embedded intense to very intense convection observed over eastcentral Arabian sea between latitude 11.1°N TO 18.0°N and longitude 66.0°E to 74.5°E . Minimum cloud top temperature (CTT) was minus 93°C .

At 0000 UTC of 03rd June, the current intensity of the system was T 3.0 associated with curved band pattern with wrap 0.5 on 10° log spiral. The system continued to organise in last 3-hours. Associated broken low/medium clouds with embedded intense to very intense convection observed over eastcentral Arabian sea between latitude 11.5°N TO 19.0°N and longitude 66.5°E TO 75.0°E . Minimum cloud top temperature (CTT) is minus 93°C .

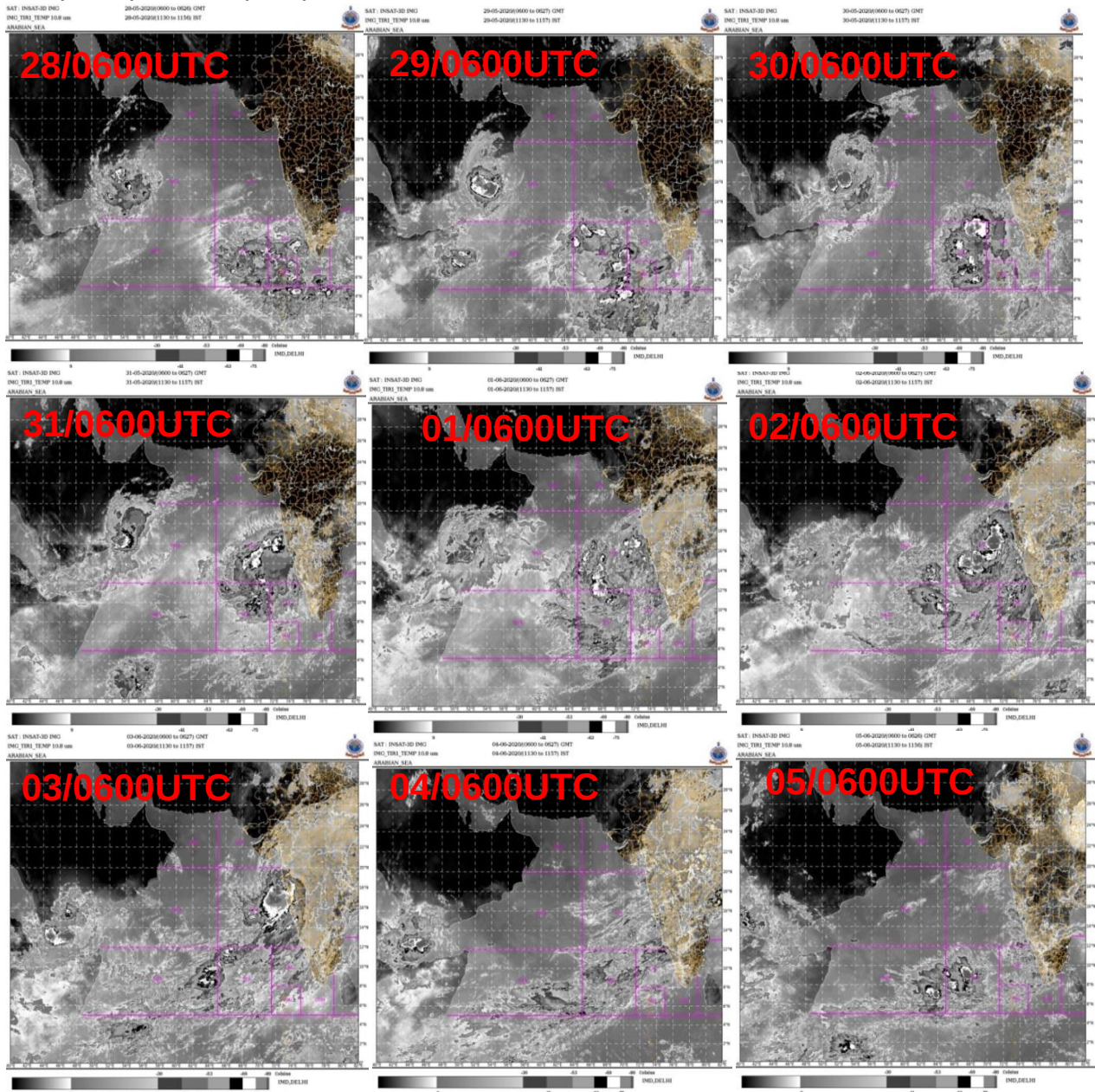


Fig. 2.4.6d: INSAT-3D BD imageries during life cycle of SCS NISARGA (28MAY-5 JUNE, 2020)

The system crossed Maharashtra coast during 0700 to 0900 UTC of 3rd June. AT 1200 UTC of 03rd June, the system further weakened over the land. Broken low/medium clouds with embedded intense to very intense convection over eastcentral Arabian Sea between latitude 13.0⁰ NTO 20.0⁰ N and longitude 70.0⁰ E & 75.0⁰.E Minimum cloud top temperature (CTT) was -86°C.

At 1500 UTC of 03rd June, the system further weakened over the land. Associated broken low/medium clouds with embedded intense to very intense convection over eastcentral Arabian Sea between latitude 13.0⁰N to 20.0⁰N and longitude 70.0⁰E TO 75.0⁰E. Minimum cloud top temperature (CTT) was -86°C.

At 0000 UTC of 04th June, the system continued to weaken over the land. INSAT 3D further showed associated broken low/medium clouds with embedded intense to very intense convection between latitude 18⁰N to 22.0⁰N and longitude 73.0⁰E TO 75.0⁰E. Minimum cloud top temperature (CTT) was minus 50°C.

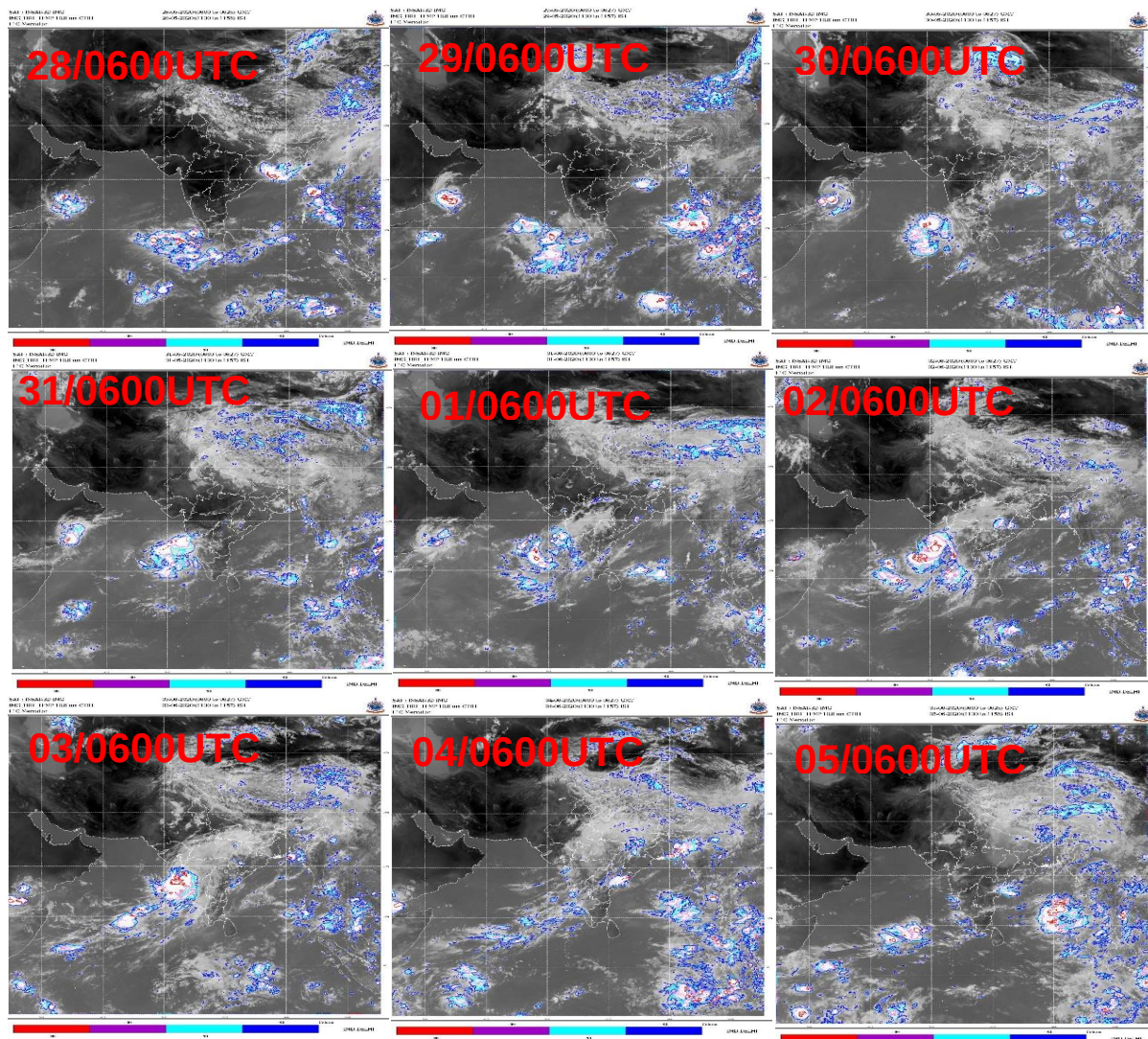


Fig. 2.4.6e: INSAT-3D cloud top brightness temperature imageries during life cycle of SCS NISARGA (28MAY-5 JUNE, 2020)

Typical microwave imageries during life cycle of SCS Nisarga are presented in Fig. 2.4.6 f.

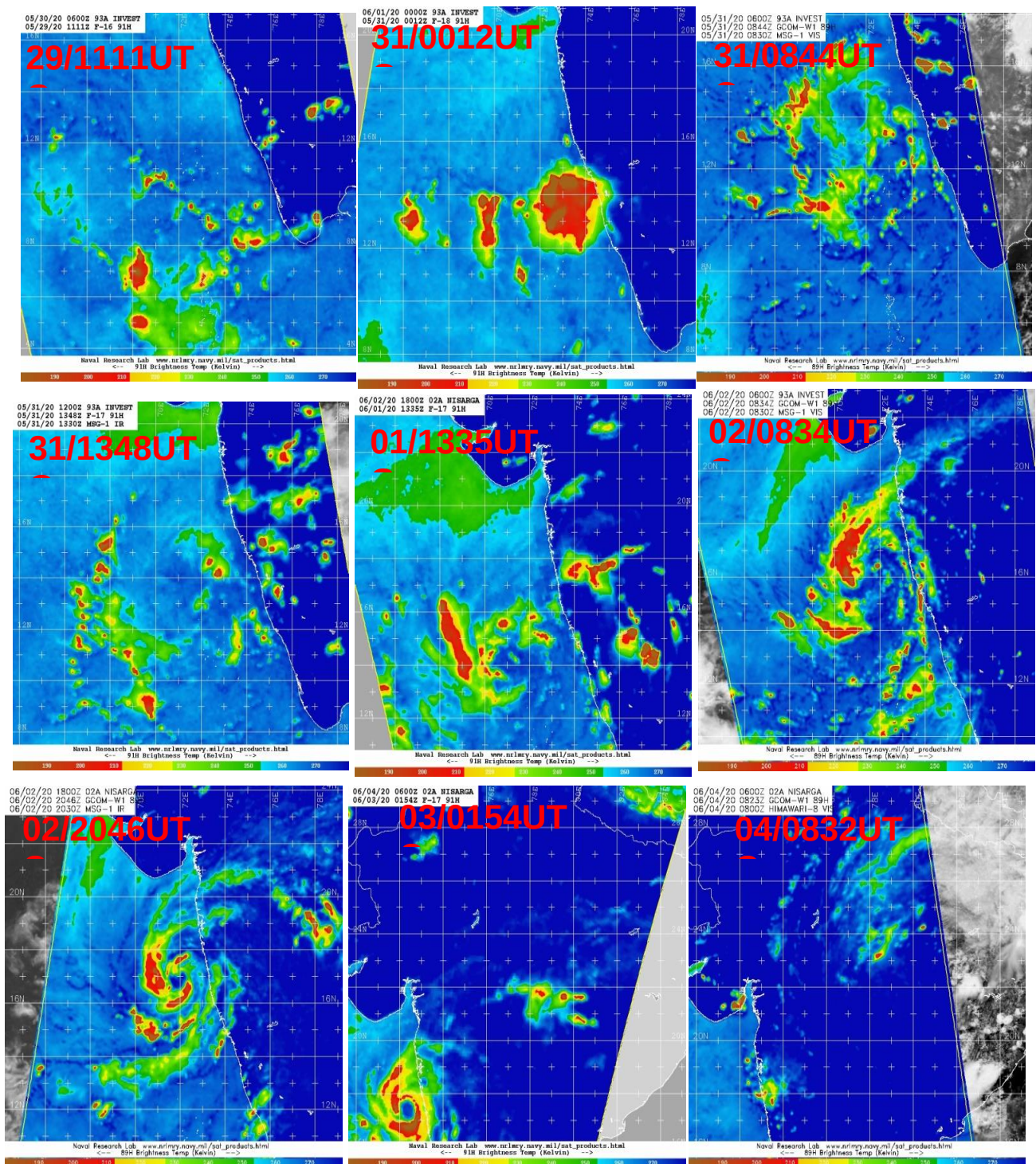


Fig. 2.4.6 f: Microwave imageries during life cycle of SCS NISARGA (29MAY-4 JUNE, 2020)

Typical ASCAT imageries during life cycle of SCS NISARGA (29MAY-4 JUNE, 2020), since inception as low pressure area are presented in 6 g.

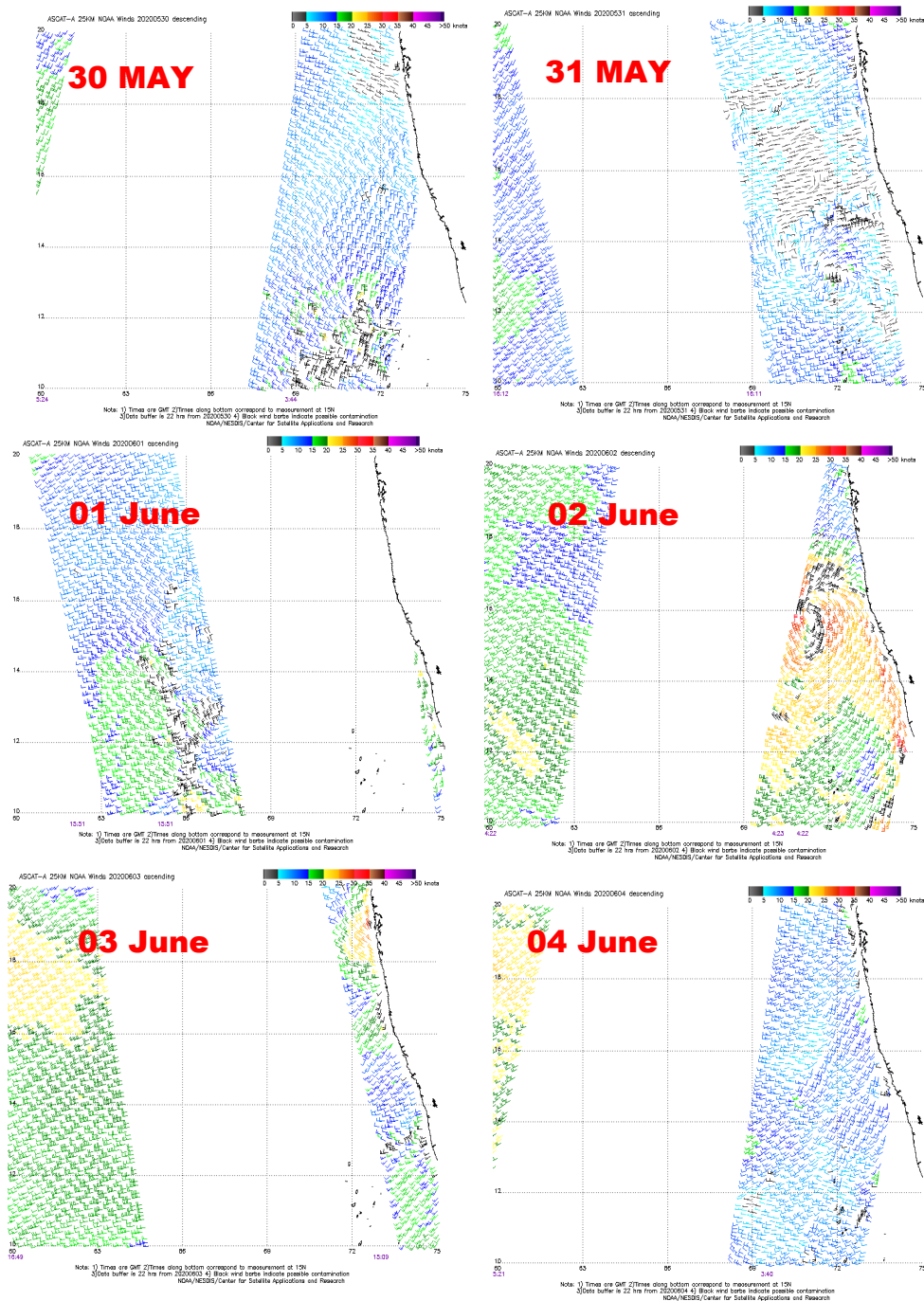


Fig. 2.4.6g: ASCAT imageries during life cycle of SCS NISARGA (29MAY-4 JUNE, 2020)

Typical SCAT SAT imageries are presented in Fig. 2.4.6h.

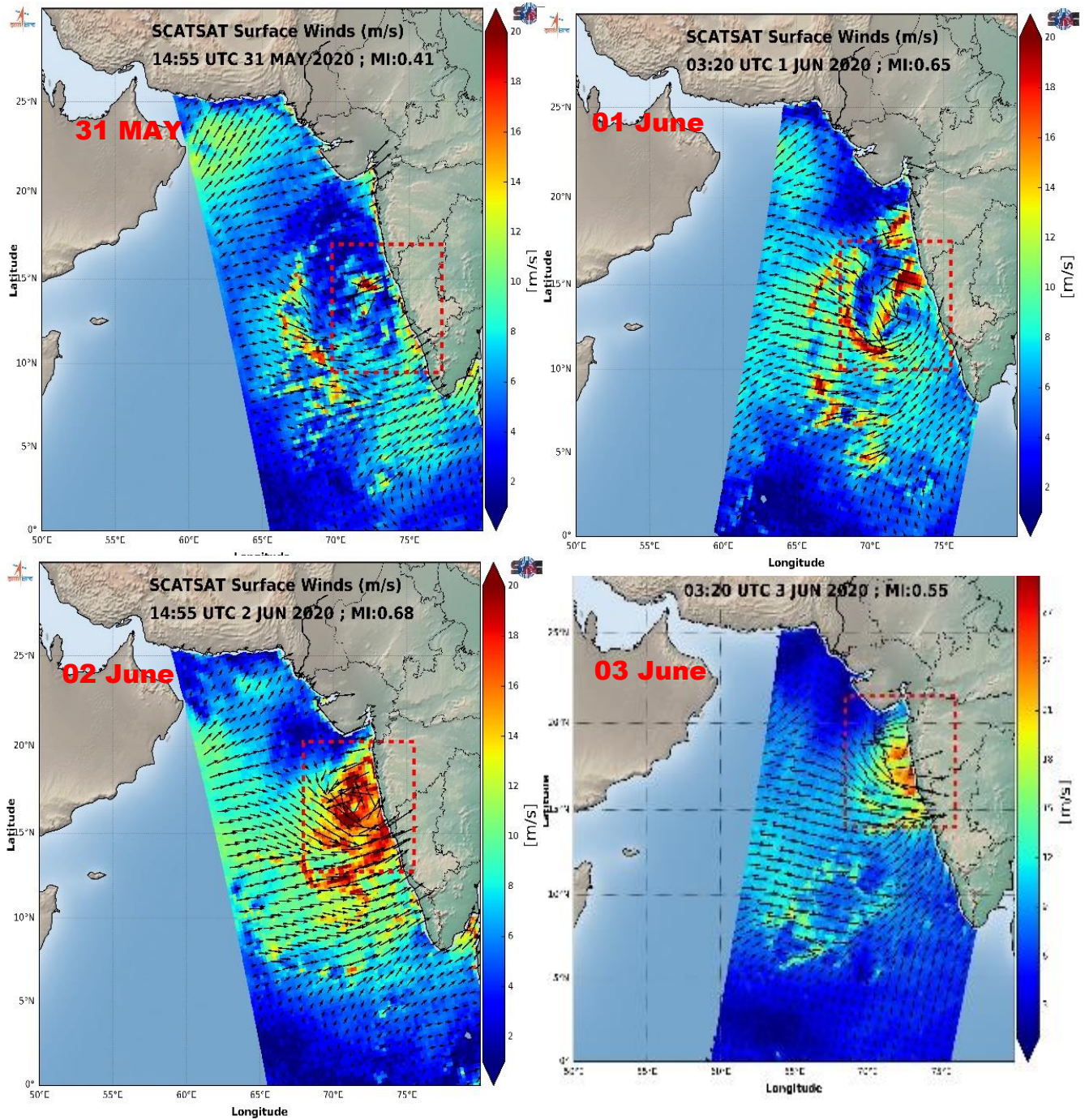


Fig. 2.4.6h: SCAT SAT imageries during life cycle of SCS NISARGA (31MAY-3 JUNE, 2020)

2.4.5.2. Features observed through Radar

The SCS NISARGA was tracked by DWRs Mumbai, GOA during its movement from southwest to north BoB. Typical DWR imageries from these radars are presented in Fig. 2.4.6.

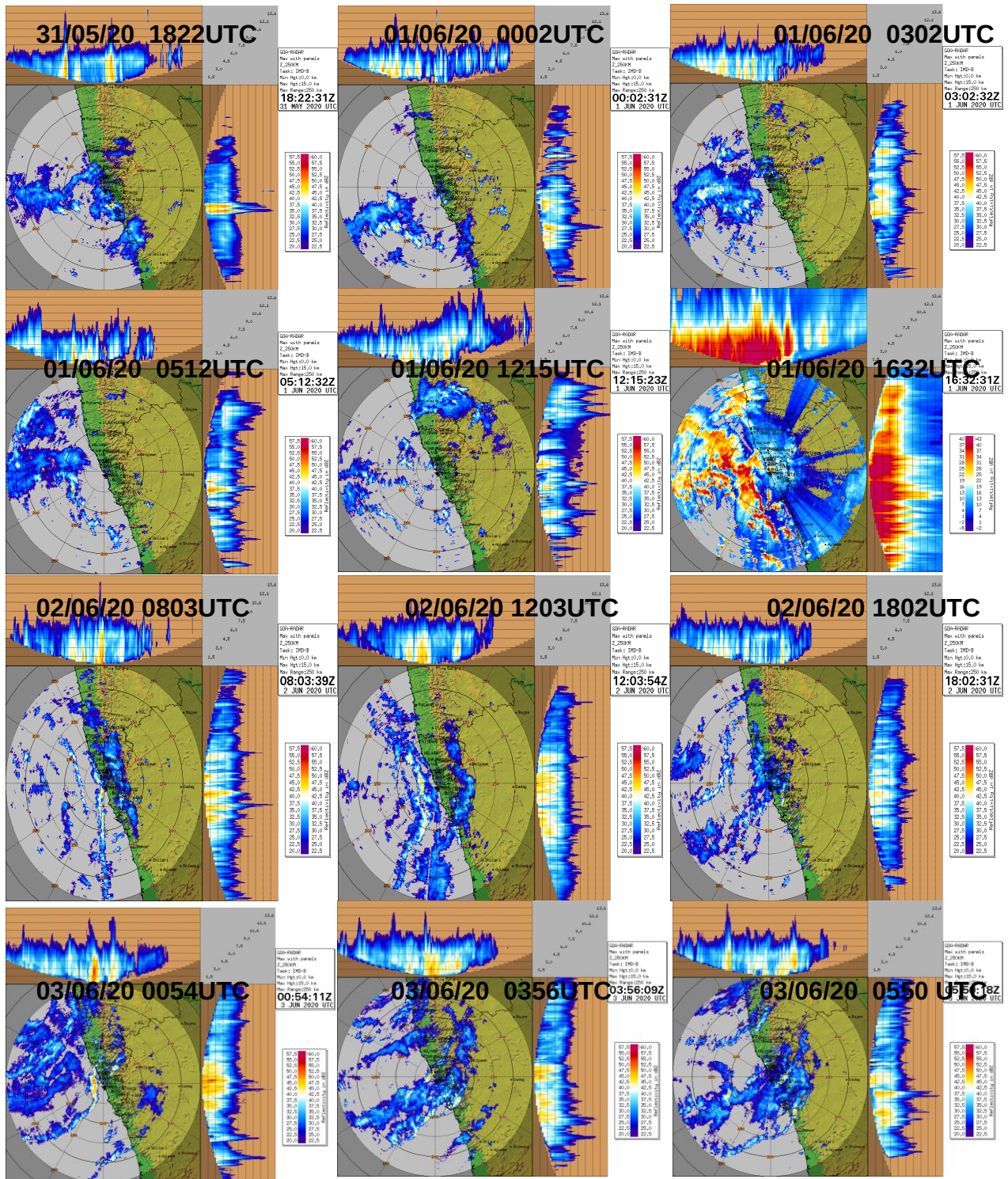


Fig. 2.4.7b: Typical Radar imagery from DWR Goa during 31May- 03 June of SCS NISARGA

2.4.6. Dynamical features

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels during 01st-05th June are presented in Fig. 2.4.8. At 0000 UTC of 01st June, IMD GFS was indicating a low pressure area over southeast Arabian Sea with vertical extension upto 500 hPa level. The model underestimated the intensity of the system on 1st June. However, location was correctly estimated.

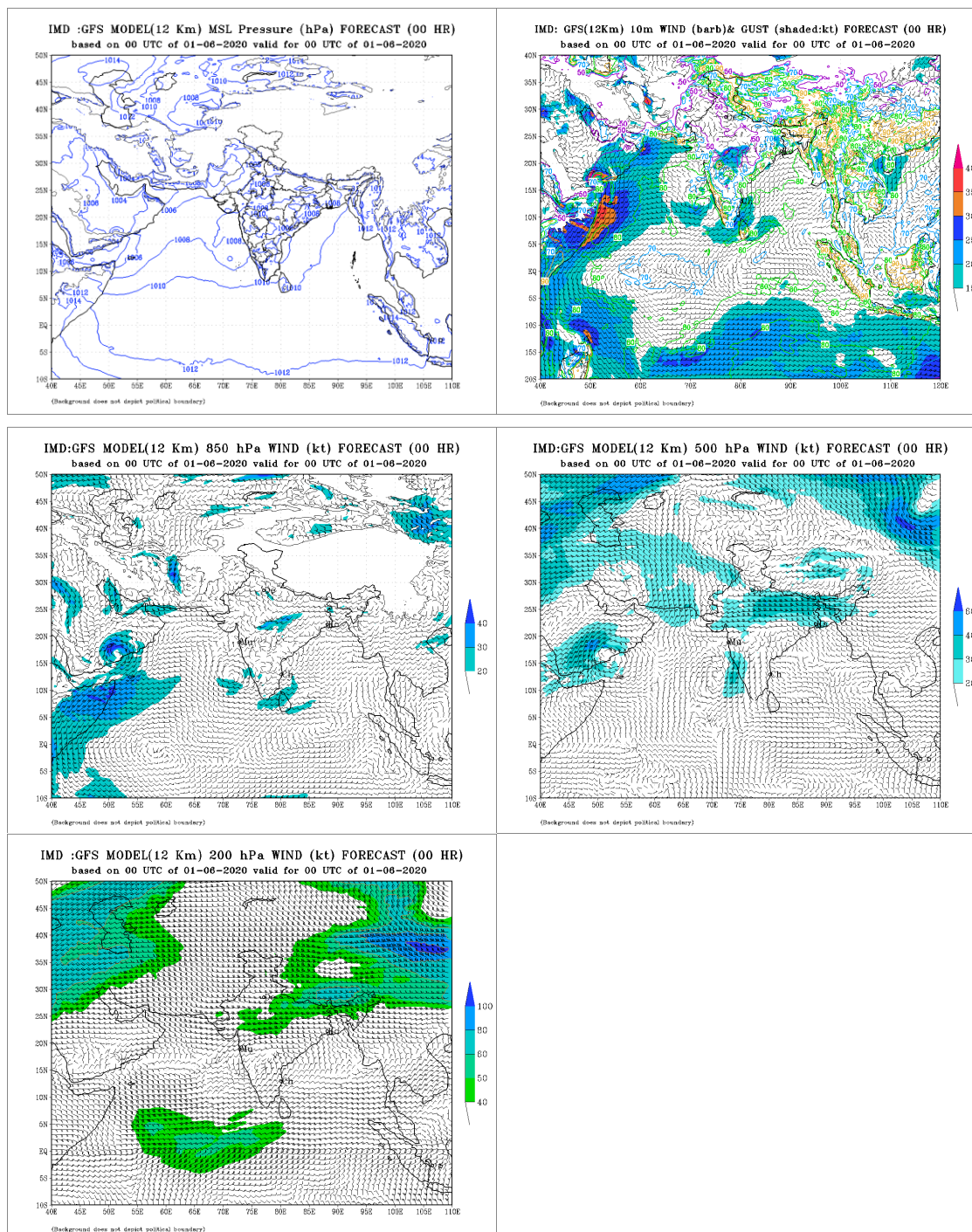


Fig 2.4.8(a): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 01st June 2020

At 0000 UTC of 2nd June, IMD GFS was indicating a deep depression over eastcentral Arabian Sea with vertical extension upto 500 hPa level. The model correctly estimated the location and intensity of the system on 2nd June.

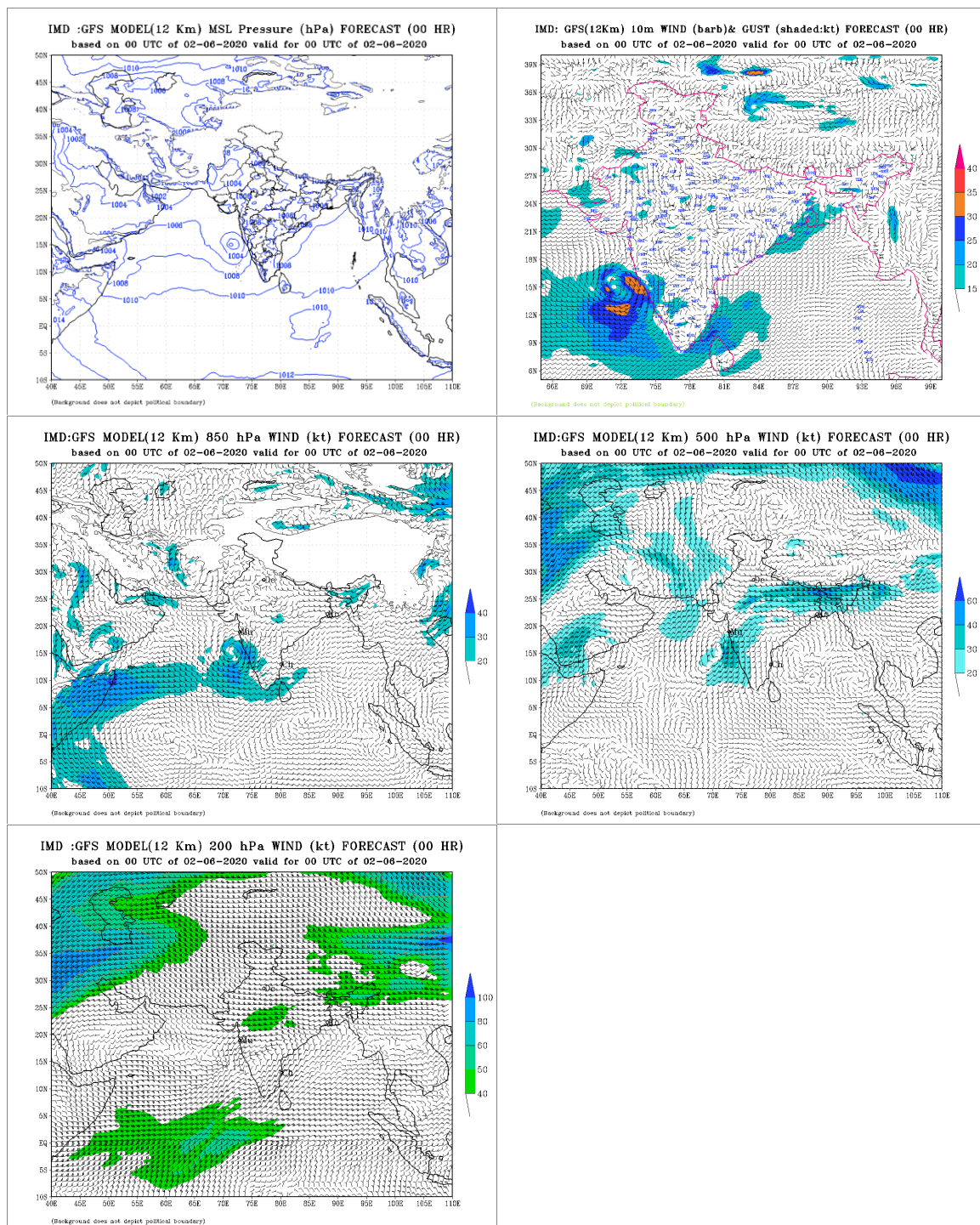


Fig 2.4.8(b): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 02nd June 2020

At 0000 UTC of 3rd June, IMD GFS was indicating a severe cyclonic storm over eastcentral Arabian Sea with vertical extension upto 500 hPa level. The model correctly estimated the location and intensity of the system on 3rd June.

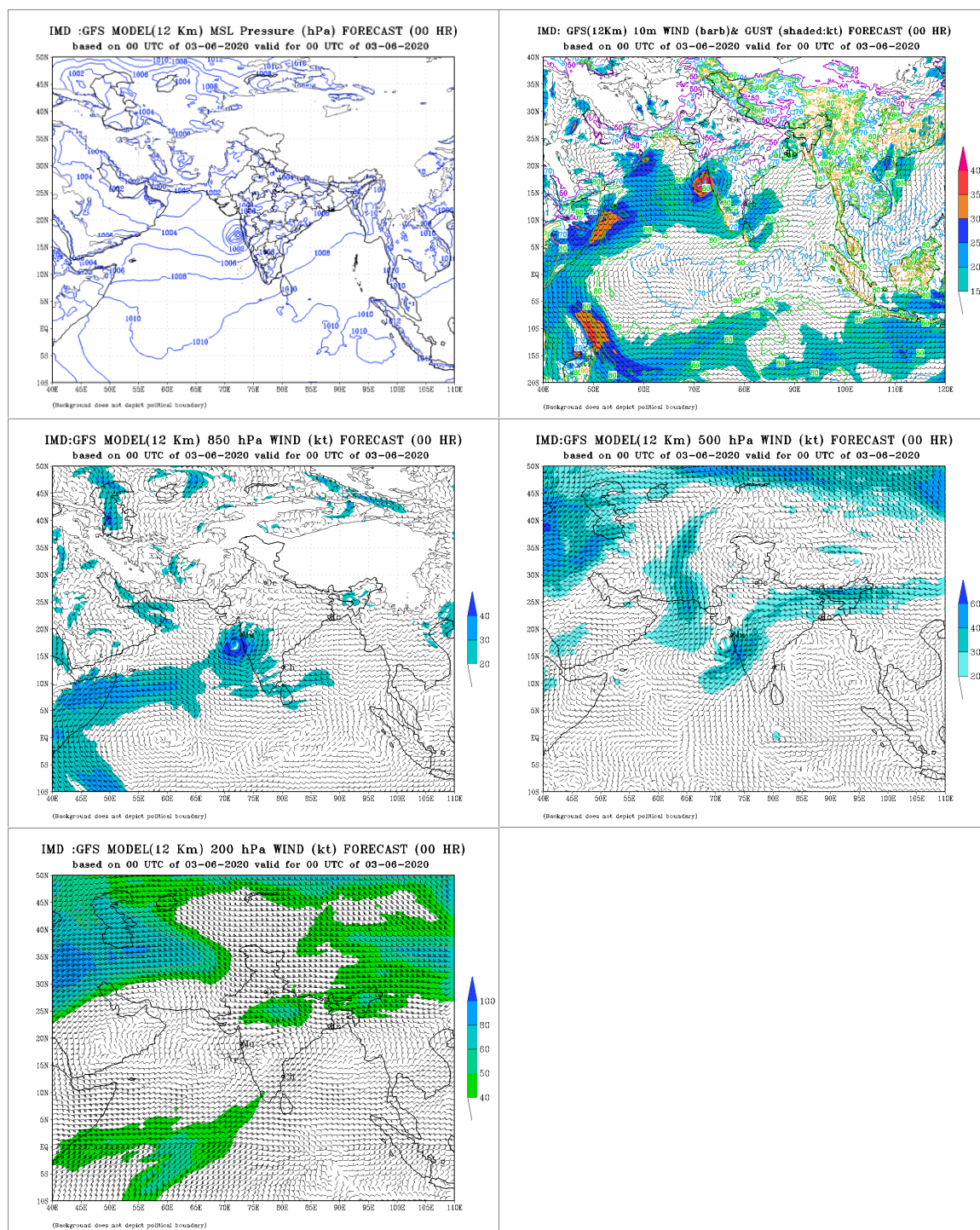


Fig. 2.4.8(c): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 03rd June 2020

At 0000 UTC of 4th June, IMD GFS was indicating a deep depression over interior Maharashtra and adjoining Madhya Pradesh with vertical extension upto 500 hPa level. The model correctly estimated the location of the system. However, intensity was slightly over estimated. At that time, system lay as a depression over Maharashtra and adjoining Madhya Pradesh.

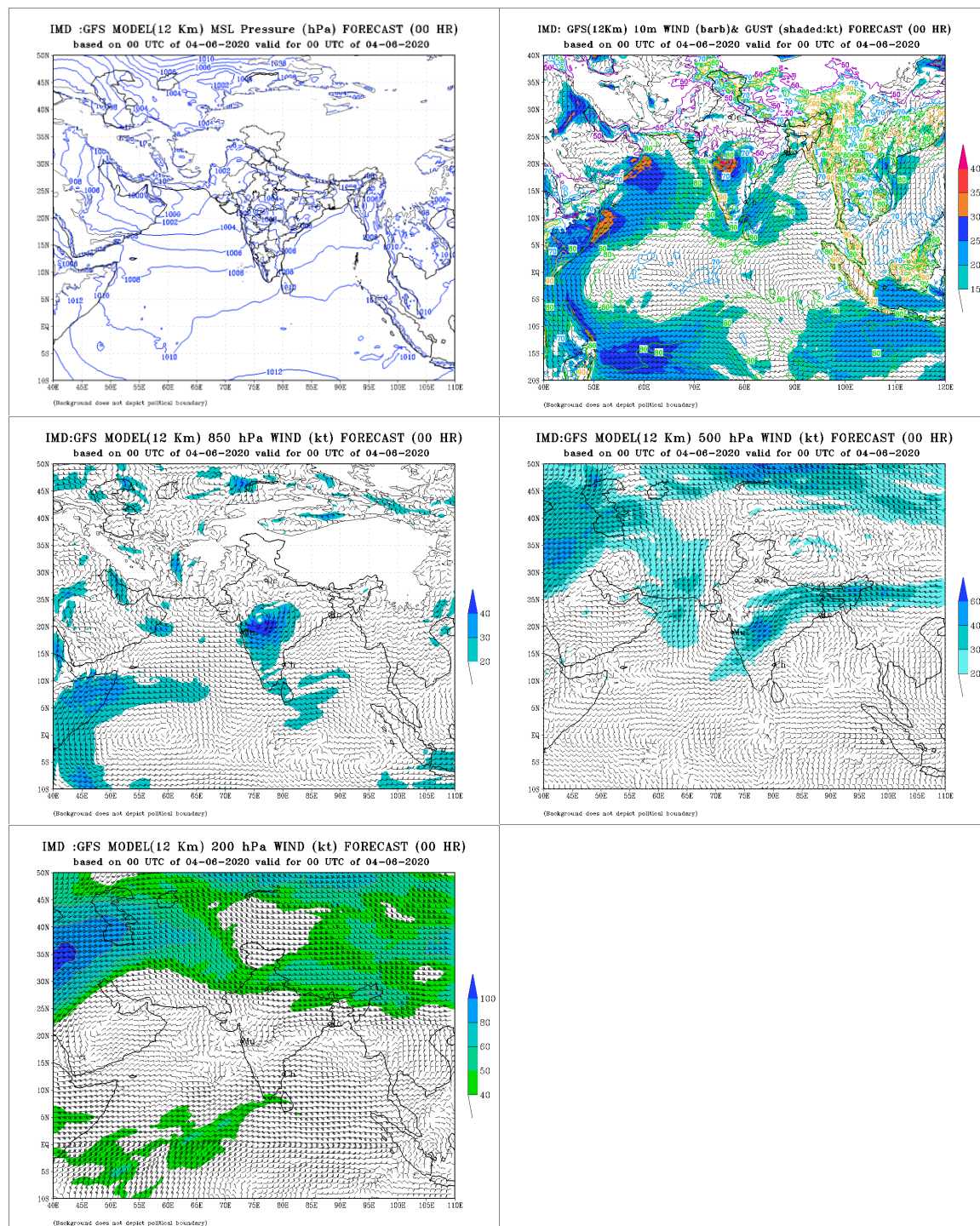


Fig. 2.4.8(d): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 04th June 2020

IMD GFS thus correctly picked up intensification, movement and weakening of the system.

2.4.7. Realized Weather:

2.4.7.1 Realized rainfall

Rainfall associated with SCS NISARGA based on IMD-NCMRWF GPM merged gauge 24 hours cumulative rainfall ending at 0300 UTC of date is depicted in Fig. 2.4.9.

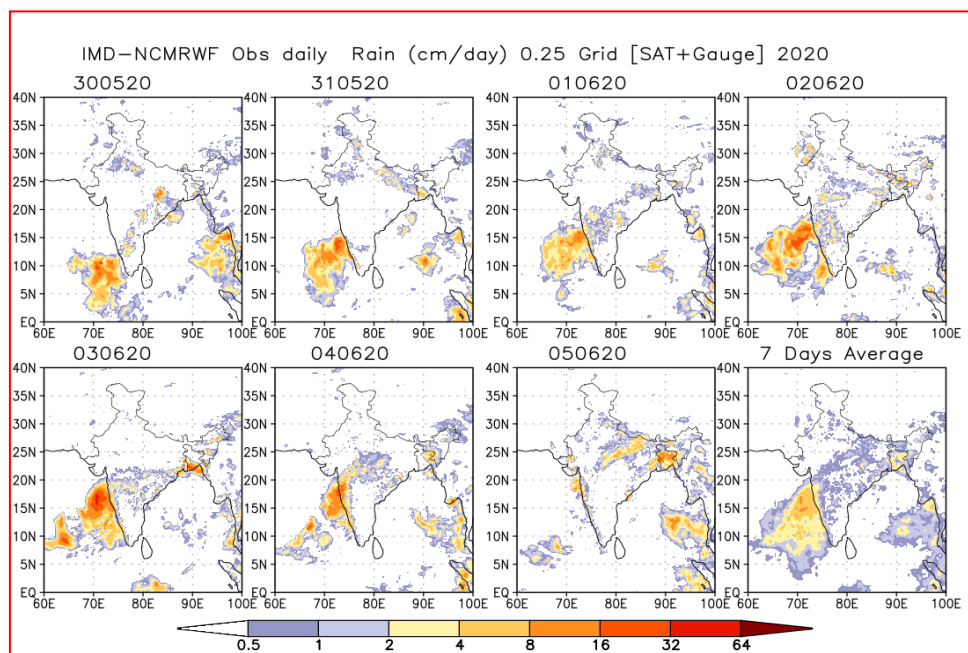


Fig. 2.4.9: IMD-NCMRWF GPM merged gauge 24 hr cumulative rainfall (cm) ending at 0300 UTC of date during 30th May – 05th June and 7 days average rainfall (cm/day)

It indicates occurrence of heavy rainfall at isolated places over coastal Karnataka, Madhya Maharashtra & Marathwada on 1st June, heavy to very heavy rainfall at many places over Goa & at isolated places over Madhya Maharashtra on 3rd June, heavy to very heavy rainfall at many places over coastal Maharashtra & Goa and at isolated places over interior Maharashtra on 4th June and moderate rainfall at few places over Madhya Pradesh on 5th June.

Realized 24 hrs accumulated rainfall (≥ 7 cm) ending at 0300 UTC of date during the life cycle of the system is presented below.

1 June 2020

Coastal Karnataka: Kota-10 and Kundapur-7

3 June 2020

Konkan & Goa: Mormugao & Panjim-13 each, Quepem & Malvan-11 each, Valpoi & Sanguem-9 each, Sawantwadi, Dodamarg, Canacona & Devgad-8 each and Kudal-7

Madhya Maharashtra: Khed Rajgurunagar-7

4 June 2020

Konkan & Goa: Pen-16, Poladpur-15, Mangaon-14, Lanja, Mandangad & Dapoli -13 each, Tala-12, Vaibhavwadi & Alibag-11 each, Chiplun-10, Roha, Rajapur & Harnai -9 each, Guhagarh & Khed-8 each and Shahapur, Murud, Sangameshwar Devrukh, Khalapur, Jawhar & Ulhasnagar-7 each

Madhya Maharashtra: Mahabaleshwar-19, Gaganbawada-15, Nashik-14, Sinnar, Bhusawal & Igatpuri-11 each, Akole, Devla, Satna Baglan & Chandgad-9 each, Javali Medha, Patan & Khed Rajgurunagar-8 each and Girnadam, Malegaon Camp, Sakri, Kalvan, Dindori, Yaval, Shahuwadi, Surgana & Radhanagari-7 each
Vidarbha: Mangrulpir, Karanjlad, Jalgaon Jamod & Washim-8 each and Manora & Malegaon-7 each

2.4.7.2. Realized wind:

Peak wind speed (kmph) recorded by the meteorological observatories of IMD in association with the passage of NISARGA is presented in **Table 2.4.2**.

Table 2.4.2: Peak maximum sustained wind speed (kmph) reported by various observatories in Maharashtra on 3rd June

Station	Wind speed (kmph)	Time of observation (IST / UTC) of 3 rd June 2020
Devgad	92	0530 / 0000
Ratnagiri	110	1330 / 0800
Harnai	74	1230 / 0700
Alibag	102	1430 / 0900
Mumbai (Colaba)	92	1330 / 0800
Thane	75	2200 / 1700
Rajgurunagar (Pune)	65	1600 / 1030
Ahmadnagar	50	2030 / 1500
Satara	59	1730 / 1200

2.4.8. Damage and death tolls due to SCS, NISARGA

As per media reports Damage and death tolls due to SCS NISARGA in affected states are as follows -

a) **Maharashtra:** (<https://en.gaonconnection.com/tag/helping-villagers-rebuild-their-houses-destroyed-by-cyclone-nisarga/>)

A joint survey conducted by the National Fishworkers' Forum and Maharashtra Machhimar Kriti Samiti has recorded extensive damage to plantations, houses and fishing boats incurring loss of about Rs 1,000 crore in the coastal districts of Raigad and Ratnagiri. But, timely warning and evacuation helped save lives. Impact on Fishermen: (SOURCE: - Gaon connection June 18th, 2020). The damages to fishing boats alone was Rs 25 crore.

Impact on Farmers:

People living along the coast of Raigad and Ratnagiri have suffered huge losses. Majority of the houses went roofless and some houses suffered wall and slab collapse. A large number of plantations of coconut, betel, mango were flattened. Official survey by the Raigad district collector has estimated Rs 200 crore losses due to Cyclone Nisarga in 13 tehsils of the district. These include damages to 1.4 lakh houses, 1.6 lakh trees uprooted, and over 20,000 hectares farmland affected. (SOURCE: - Gaon connection dated 18th June, 2020)

b) **Gujarat:**

No major damage was reported.



Fig 2.4.10 (a) Uprooted trees from a road following rains and strong winds triggered by Cyclone Nisarga, at Alibag in Navi Mumbai, Wednesday, June 3, 2020. (PTI Photo) (b) & (c) Cyclone Nisarga: Strong winds pull down trees, damage property across Mumbai (Source:Deccanherald)



Fig 2.4.10 (d-g): Maharashtra: Many trees were uprooted in the Raigad district due to strong winds in view of #CycloneNisarga. The cyclone is expected to make landfall in an hour in the state and the process will be completed during the next 3 hours, as per IMD. (Source: @ANI, Twitter 3 June 12:32pm)



Fig. 2.4.10 (h-i) Houses damaged from Sindhudurg Dist. Maharashtra (Source: NDRF)

2.5. Deep Depression over the Bay of Bengal during 11-14 October, 2020

2.5.1 Introduction

- ❖ The Deep Depression originated from a low pressure area which developed over north Andaman Sea & neighbourhood in the early morning (0000 UTC) of 9th October 2020, it lay as a Well Marked Low Pressure Area over East Central Bay of Bengal and adjoining north Andaman Sea in the early morning of 10th October.
- ❖ It concentrated into a **Depression** over West Central Bay of Bengal in the early morning (0000 UTC) of 11th October.
- ❖ It intensified into **Deep Depression** in the forenoon (0600 UTC) of 12th October, 2020 and lay at a distance of about 250 km to the south-southeast of Vishakhapatnam.
- ❖ Moving west-northwestwards, it **crossed north Andhra Pradesh coast close to Kakinada (near Lat. 17.0°N & Long 82.4° E) between 0630 & 0730 hrs IST (0100 & 0200 UTC) of 13th October 2020, as a Deep Depression with a maximum sustained wind speed of 55-65 kmph gusting to 75 kmph.**
- ❖ Continuing to move west-northwestwards, it weakened into a **Depression** over Telengana in the forenoon (0600 UTC) of 13th October. It moved west-northwestwards as a Depression across Telangana and North Interior Karnataka to Maharashtra till evening of 14th October.
- ❖ It weakened into a Well Marked Low pressure area and lay centred over South Madhya Maharashtra and neighbourhood in the evening (1200 UTC) of 14th October 2020.
- ❖ It moved across Maharashtra and emerged as a well marked low pressure area over east-central Arabian Sea off Maharashtra coast on 16th morning. (Subsequently it re-intensified once again into a Depression over the Arabian Sea and moved away westwards during 17th – 19th October).
- ❖ The Deep Depression had impacts over Odisha, Andhra Pradesh, Telangana, Karnataka & Maharashtra in terms of heavy to extremely heavy rainfall and squally winds.

The salient features of the system were as follows:

- (i) It had an initial west-northwestward followed by near westward moving track.
- (ii) It had a life period of nearly 84 hours.
- (iii) It had a track length of 1150 km.
- (iv) Under the influence of this system and its remnant low pressure area, fairly widespread to widespread rainfall with heavy to very heavy and extremely heavy rainfall at isolated places occurred over Andhra Pradesh & south Odisha for a day, Telangana on 3 days and over Karnataka and Maharashtra on 2 days each.

IMD mobilised all its resources to track the system and regular warnings w.r.t. track, intensity, crossing point & time, associated severe weather and adverse impacts & suggested actions 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. Its genesis, movement and associated adverse weather could be predicted with actionable accuracy by IMD. The brief life history, associated weather and forecast performance of IMD/RSMC, New Delhi are presented in following sections.

2.5.2. Brief Life History:

The observed track of Deep Depression over west-central BoB is presented in Fig.1. The best track parameters of the system are presented in Table 1.

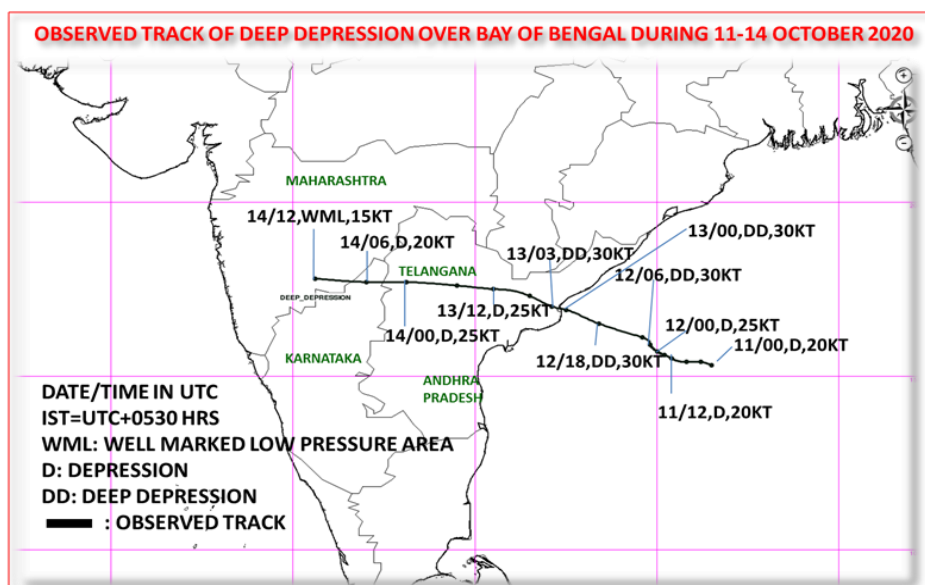


Fig.2.5.1. Observed track of deep depression over west-central Bay of Bengal (11-14 October, 2020)

Table 2.5.1: Best track positions and other parameters of the observed track of Deep Depression over west-central Bay of Bengal (11-14 October, 2020)

Date	Time (UTC)	Centre lat. ^o N/ long. ^o E		C.I NO	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
11/10/2020	0000	15.3	86.5	1.5	999	20	3	D
	0300	15.4	86.2	1.5	998	25	4	D
	0600	15.4	85.8	1.5	998	25	4	D
	1200	15.5	85.4	1.5	998	25	4	D
	1800	15.6	85.2	1.5	998	25	4	D
12/10/2020	0000	15.7	85	1.5	998	25	4	D
	0300	15.7	85	2.0	997	30	5	DD

	0600	15.9	84.8	2.0	997	30	5	DD
	1200	16.1	84.6	2.0	997	30	5	DD
	1800	16.5	83.4	2.0	997	30	5	DD
13/10/2020	0000	16.9	82.5	-	997	30	5	DD
	crossed north Andhra Pradesh coast close to Kakinada (near Lat. 17.0°N & Long 82.4° E) between 0100 & 0200 UTC of 13th October 2020, as a Deep Depression							
	0300	17	82.1	-	996	30	6	DD
	0600	17.3	81.5	-	998	25	4	D
	1200	17.5	80.5	-	998	25	4	D
	1800	17.6	79.5	-	998	25	4	D
14/10/2020	0000	17.7	78.1	-	1000	20	3	D
	0300	17.7	77.5	-	1000	20	3	D
	0600	17.7	77.0	-	1000	20	3	D
	1200	Weakened into well marked low pressure area over south Madhya Maharashtra & neighbourhood						

Fig.2.5.2 depicts the hourly coastal observations recorded by the surface meteorological observatories located along Andhra Pradesh coast during 1600 UTC of 12th October to 0600 UTC of 13th October denoting the changes in wind direction and mean sea level pressure in association with the approach & crossing of the Deep Depression across Andhra Pradesh coast. Kakinada and Tuni reported the lowest mean sea level pressure of 995.2 hPa & 996.8 hPa respectively at 0100 UTC of 13th. The wind direction of Tuni had changed from northerly to southeasterly between 0100 & 0200 UTC, indicating that the system crossed close to Kakinada during this time period. Both the stations reported continuous rain as the present weather during the time of crossing.

Hourly data plot - Coastal stations of Andhrapradesh 12-13 Oct 2020

CWC Visakhapatnam

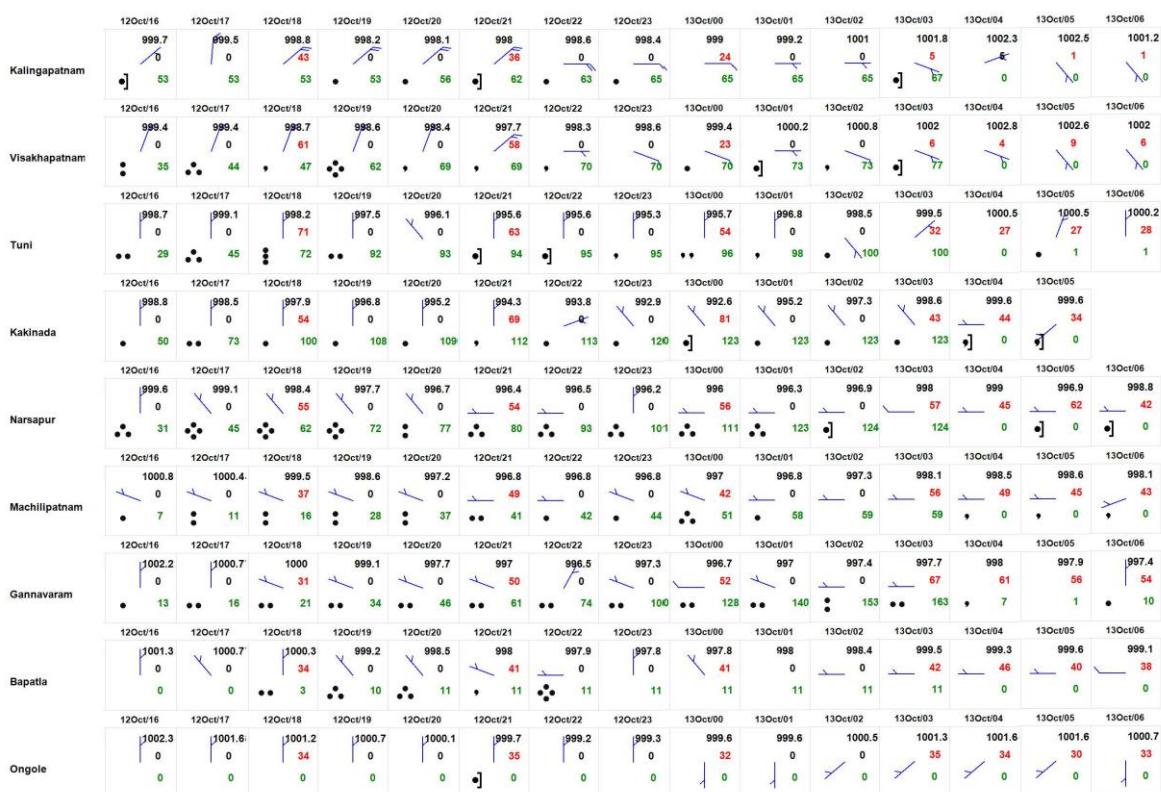


Fig.2.5.2. Hourly wind, mean Sea level & current weather observations recorded at the coastal surface meteorological observatories of coastal Andhra Pradesh during the passage of the Deep Depression over west-central Bay of Bengal (11-14 October, 2020)

2.5.3 Features observed through Satellites and Radar:

India Meteorological Department (IMD) maintained round the clock watch over the north Indian Ocean and the development of the system was monitored since 01st October, about 8 days prior to the formation of low pressure area over north Andaman Sea & neighbourhood on 9th October. The **Deep Depression** was monitored with the help of available satellite observations from INSAT 3D and 3DR, SCAT SAT, polar orbiting satellites and available ships & buoy observations in the region. The system was also monitored by Doppler Weather RADARs (DWRs) Machilipatnam, Vishakhapatnam and Gopalpur. Various numerical weather prediction models run by Ministry of Earth Sciences (MoES) institutions, models run by other Global centres and dynamical-statistical models were utilized to predict the genesis, track, landfall and intensity of the Deep Depression. A digitized forecasting system of IMD was utilized for analysis and comparison of various models' guidance, decision making process and warning products generation. The heavy rainfall and wind warning at district and meteorological subdivision level along with expected impact, suggested actions and fishermen warnings were issued by IMD well in advance to all concerned states, media and stakeholders.

Typical satellite imageries are presented in Fig.2.5.3. From the system centre as evidenced by the SCATSAT derived near surface winds and the cloud organization based on the INSAT derived cloud imagery it may be noted that the clouds were sheared to the west of system centre.

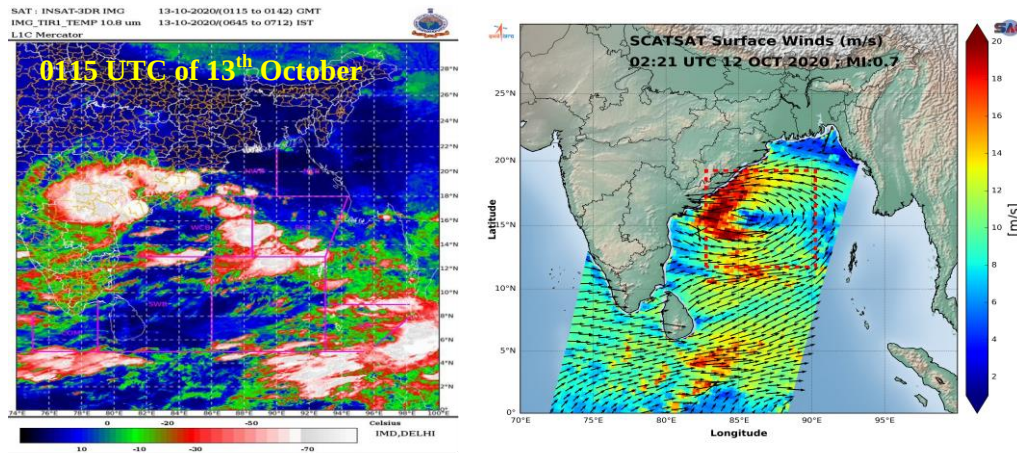


Fig. 2.5.3: Typical satellite imagery from INSAT-3D and SCATSAT

Fig.2.5.4 presents the ASCAT derived winds, **Fig. 2.5.5**, the INSAT based cloud imageries and Fig.6 the SCATSAT winds. All through the system period, the convection was organized in a shear pattern and the minimum Cloud Top Temperature reported had been minus 93°C, when the system was over the Sea.

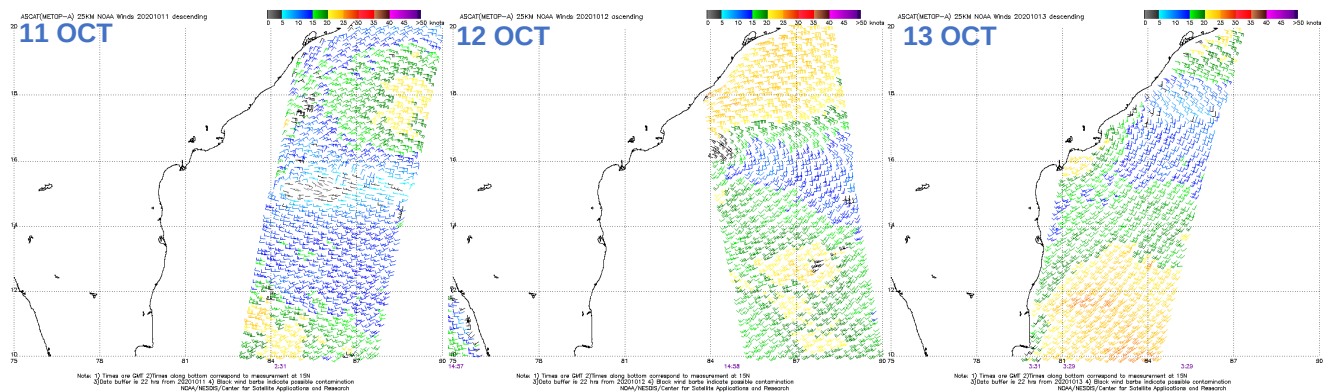


Fig. 2.5.4: ASCAT images during life cycle of Deep Depression (11-14 October, 2020)

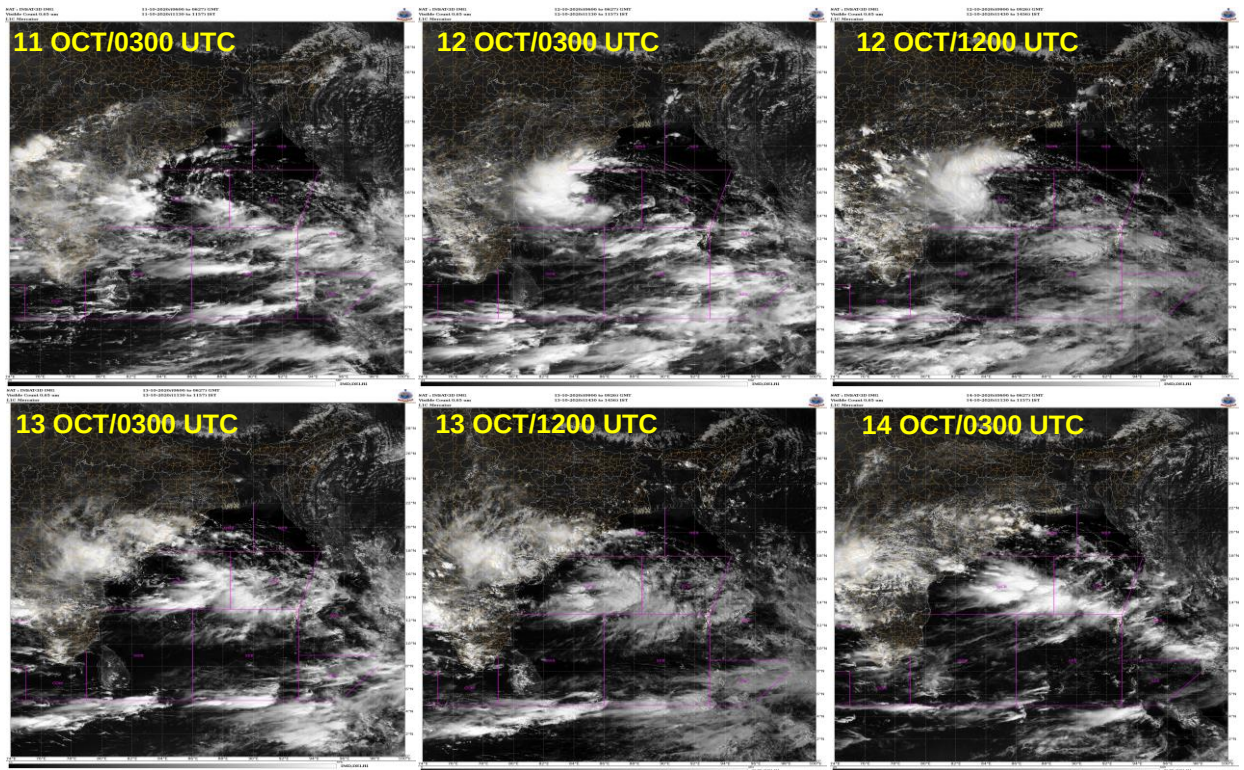


Fig. 2.5.5a: INSAT-3D IR imageries during life cycle of Deep Depression (11-14 October, 2020)

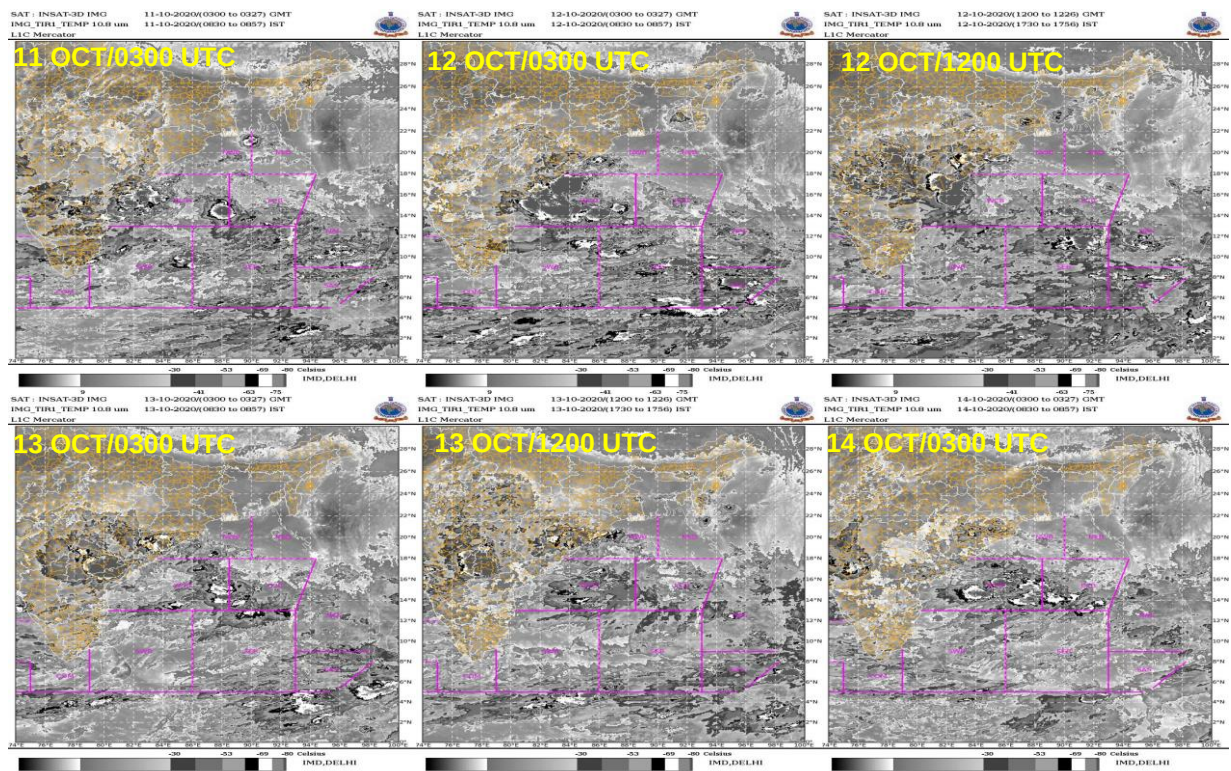


Fig. 2.5.5b: INSAT-3D cloud top brightness imageries during life cycle of Deep Depression (11-14 October, 2020)

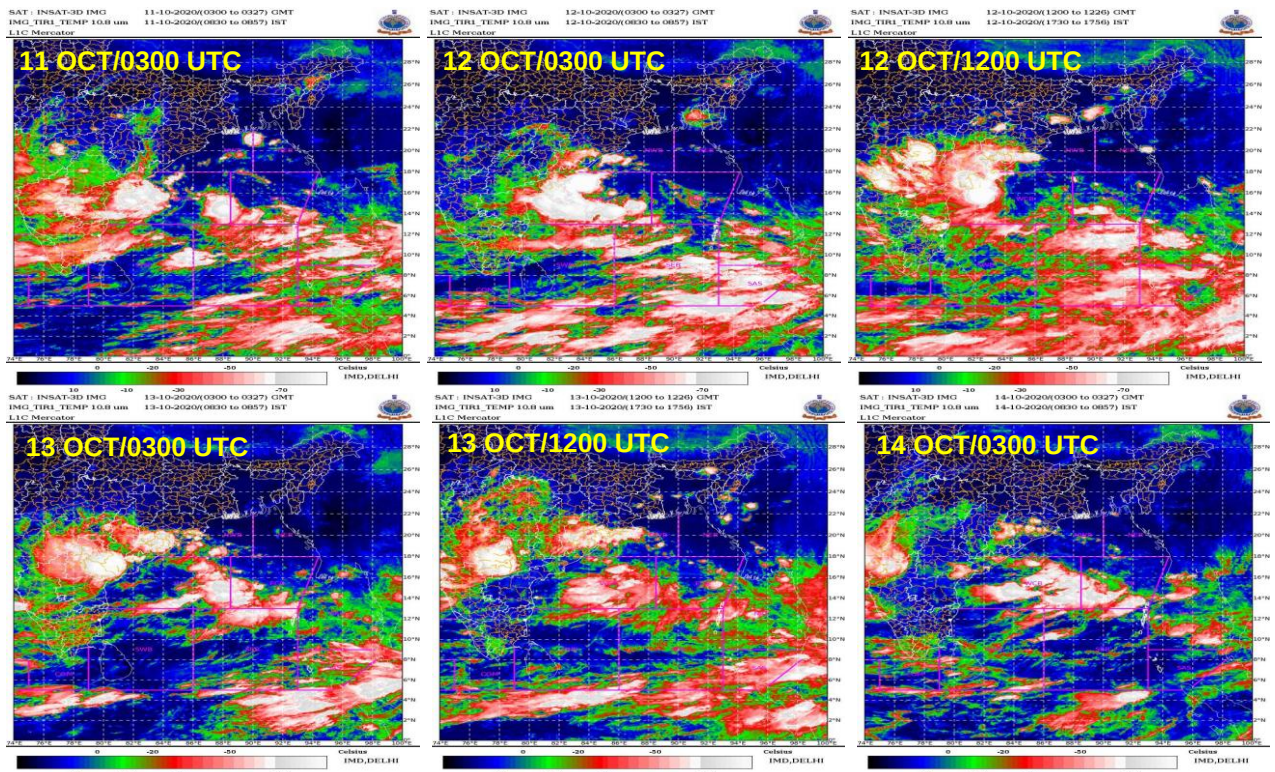


Fig. 2.5.5c: INSAT-3D enhanced colored imageries during life cycle of Deep Depression (11-14 October, 2020)

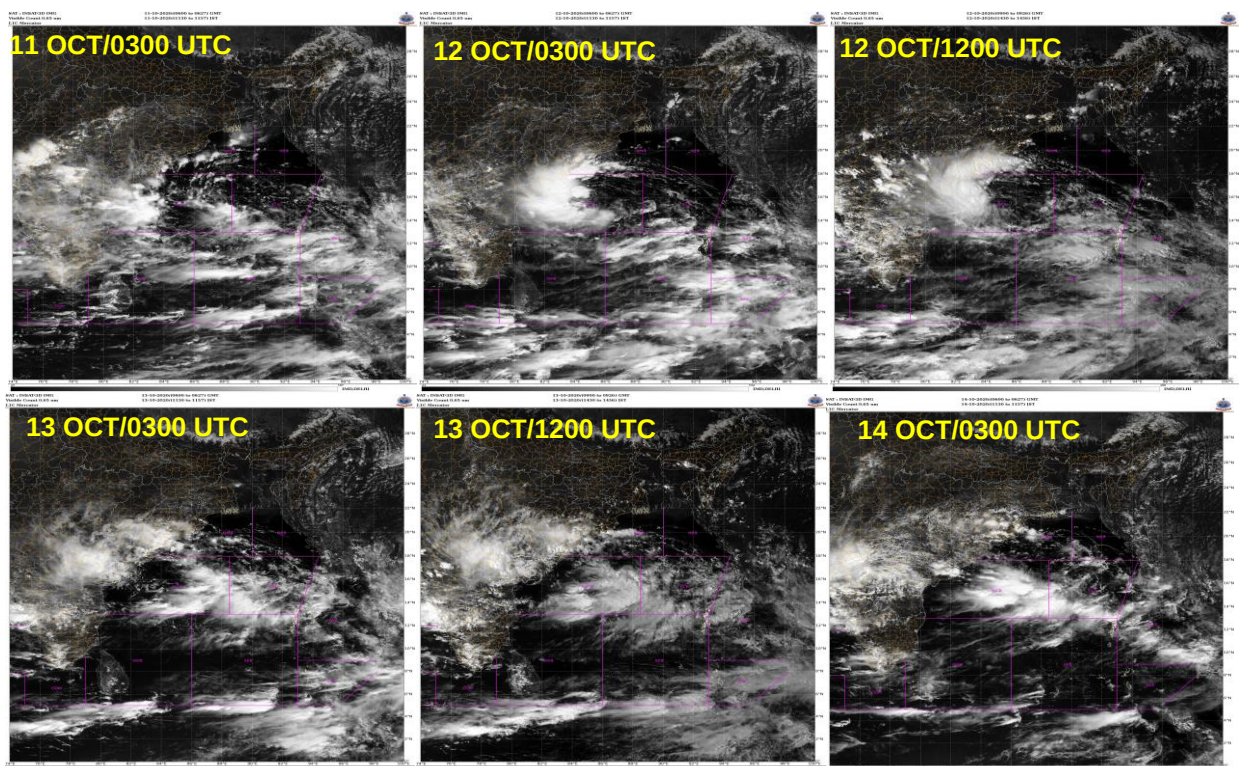


Fig. 2.5.5d: INSAT-3D visible imageries during life cycle of Deep Depression (11-14 October, 2020)

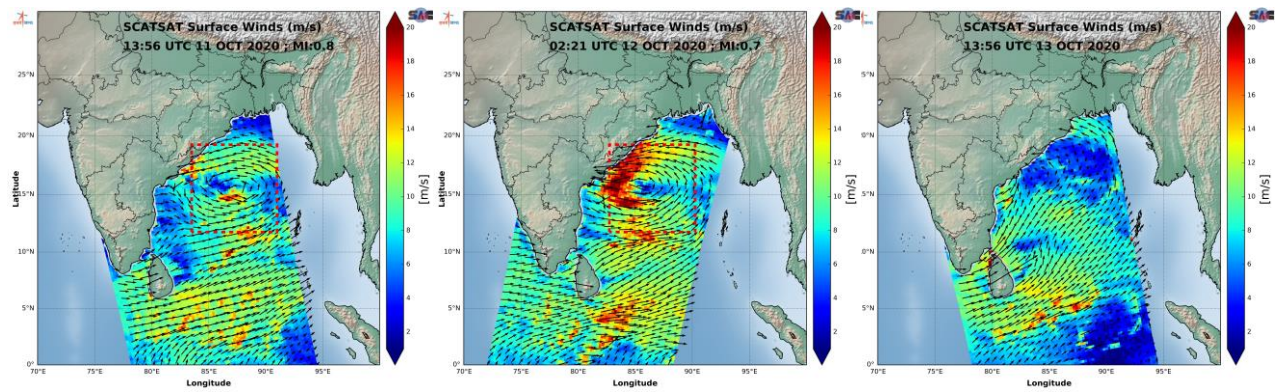


Fig. 2.5.6: SCAT SAT based sea surface winds during life cycle of Deep Depression (11-14 October, 2020)

Fig. 2.5.7 shows the RADAR imageries from Doppler Weather RADARs (a) Hyderabad (b) Visakhapatnam (c) Machilipatnam and (d) Mumbai in association with the system.

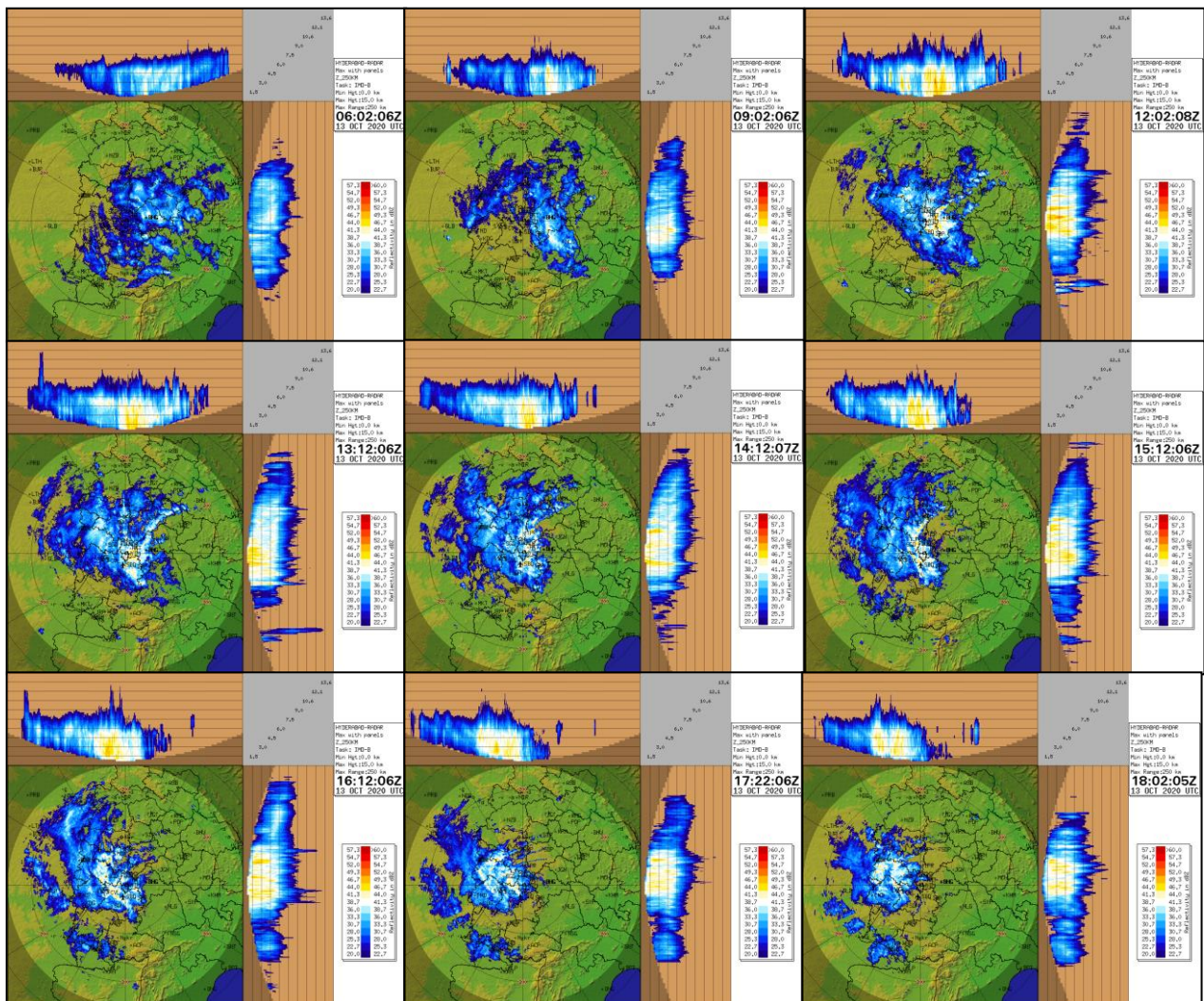


Fig 2.5.7a: Typical Max Z Radar imageries of DWR Hyderabad during 11-14 October, 2020

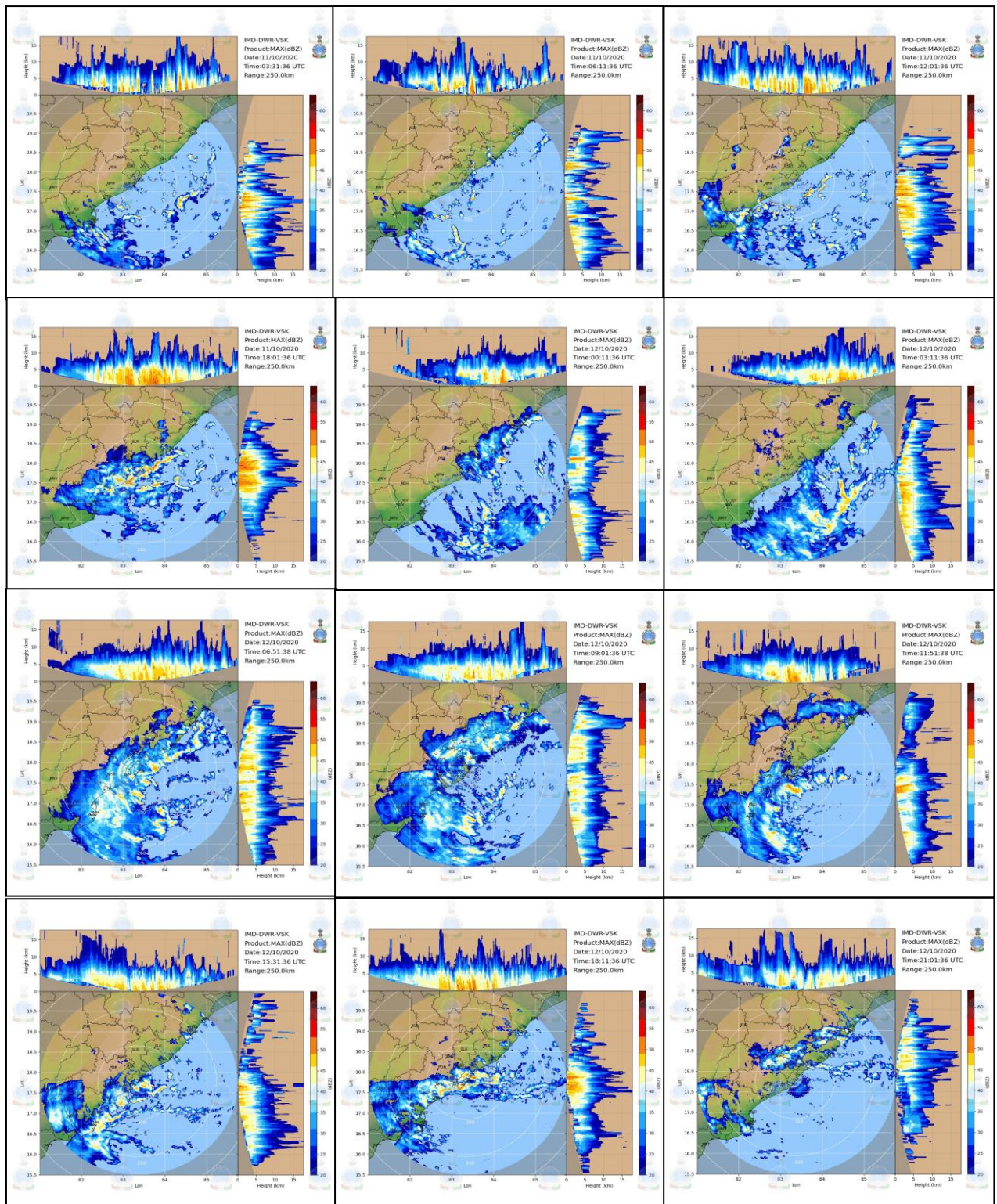


Fig 2.5.7b: Typical Max Z Radar imageries of DWR Visakhapatnam during 11-14 October, 2020

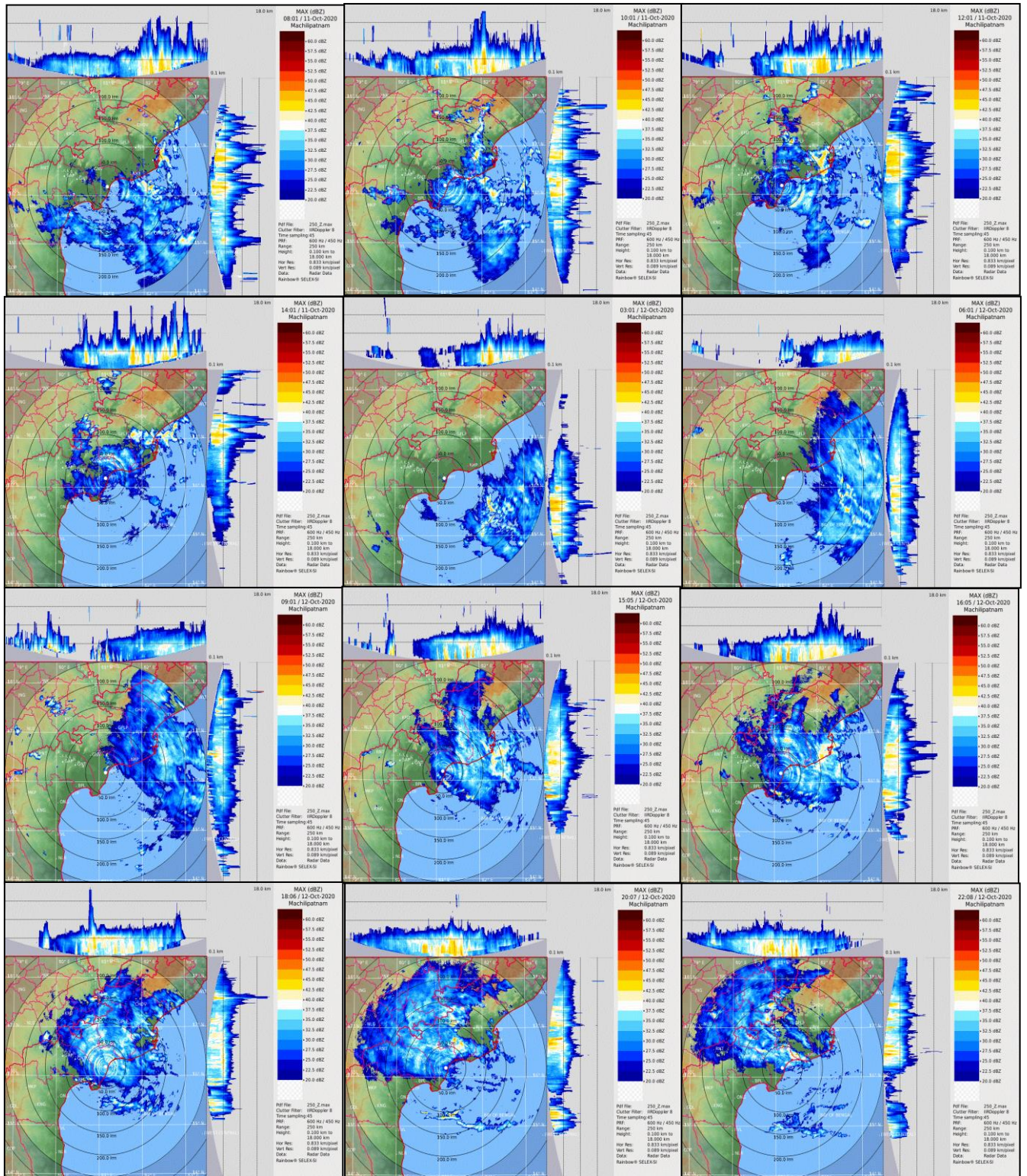


Fig 2.5.7c: Typical Max Z Radar imageries of DWR Machilipatnam during 11-14 October, 2020

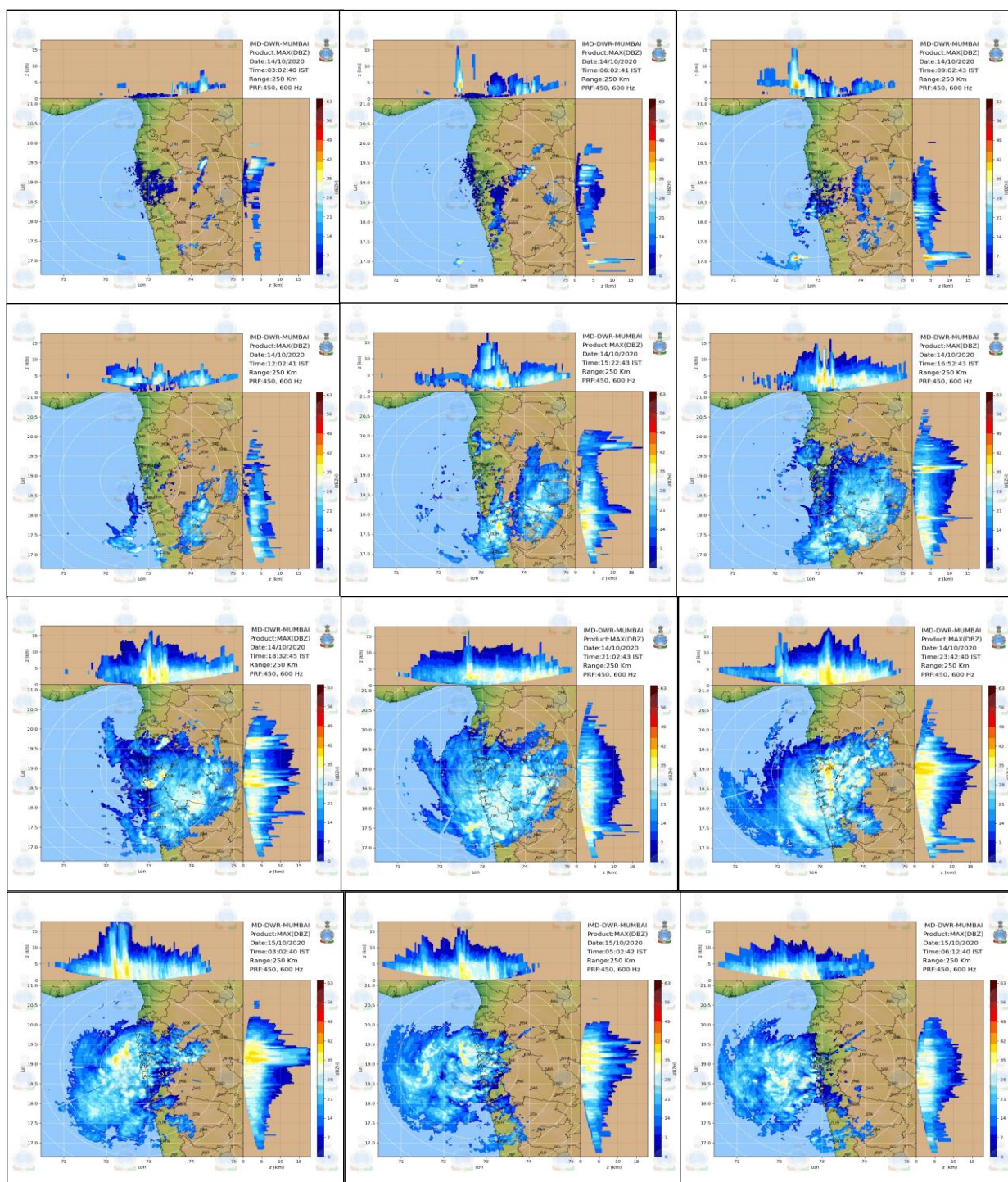


Fig 2.5.7d: Typical Max Z Radar imageries of DWR Mumbai during 11-14 October, 2020

2.5.4. Dynamical features

IMD GFS (T1534) analysis fields of mean sea level pressure (MSLP), winds at 10 m, 850, 500 and 200 hPa levels are presented in Fig. **2.5.8 (a) – 8(d)**.

At 0000 UTC of 11th October, it indicated a Depression over central BoB. The circulation was seen extending upto 500 hPa level. Also another cyclonic circulation lay over south peninsular India to the west of this system and a trough in the wind field linked the two cyclonic vortices at 500 hPa. At 200 hPa level east-southeasterly winds prevailed over the system area and easterly flow to the west, indicating the likely direction of movement. Overall model simulated the system quite well.

At 0000 UTC of 12th October, it indicated a Deep Depression over west-central BoB. The circulation was seen extending upto 500 hPa level. The other cyclonic circulation over south peninsular India to the west of this system and the trough in the wind field linking the two cyclonic vortices at 500 hPa persisted. At 200 hPa level easterly winds prevailed over the system area indicating the likely direction of movement. The system intensity at 0000 UTC remained that of a Depression. However it intensified into a Deep Depression by 0300 UTC.

At 0000 UTC of 13th October, the model indicated the system as a Deep Depression over west-central BoB, close to north Andhra Pradesh coast. The circulation was seen extending upto 500 hPa level. The other cyclonic circulation over south peninsular India to the west of this system had merged with the trough in the wind field which extended westwards across south peninsula at 500 hPa. Easterly flow prevailed at 200 hPa level. The system as a Deep Depression lay very close to north Andhra Pradesh coast and was beginning the process of crossing coast at this time.

At 0000 UTC of 14th October, the model located the system as a Depression centered over Telangana and adjoining north interior Karnataka. The circulation was seen extending upto 500 hPa level. Easterly flow prevailed at 200 hPa level. The system after crossing north Andhra Pradesh coast had weakened into a Depression by 0600 UTC of 13th October. Further moving west-northwestwards it lay over North Interior Karnataka & adjoining areas of Maharashtra and Telangana as a Depression, at this point of time.

Hence IMD GFS provided reliable guidance in forecasting the intensity & movement of the system all through its life period.

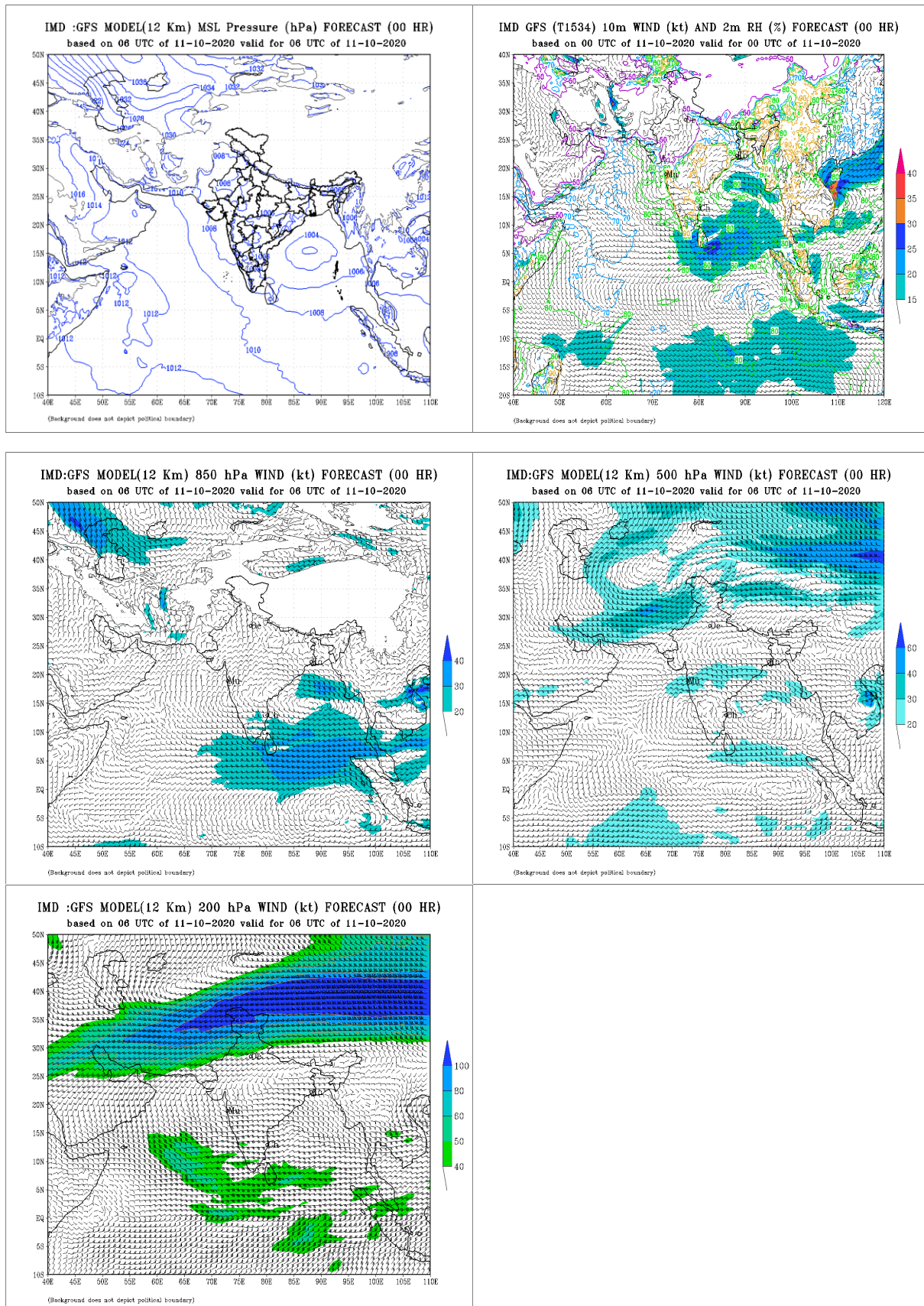


Fig. 2.5.8 (a): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 11th October 2020

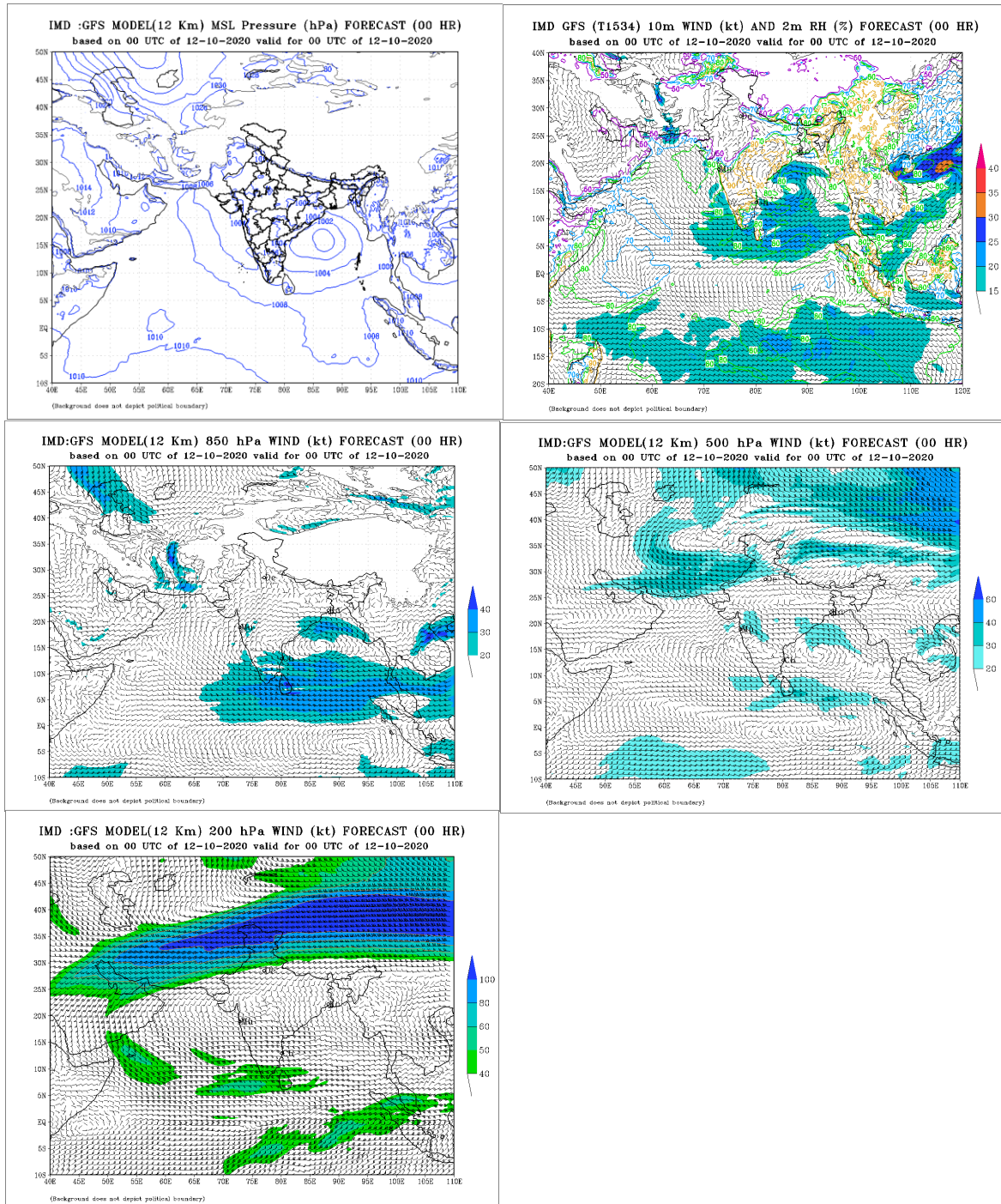


Fig. 2.5.8 (b): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 12th October 2020

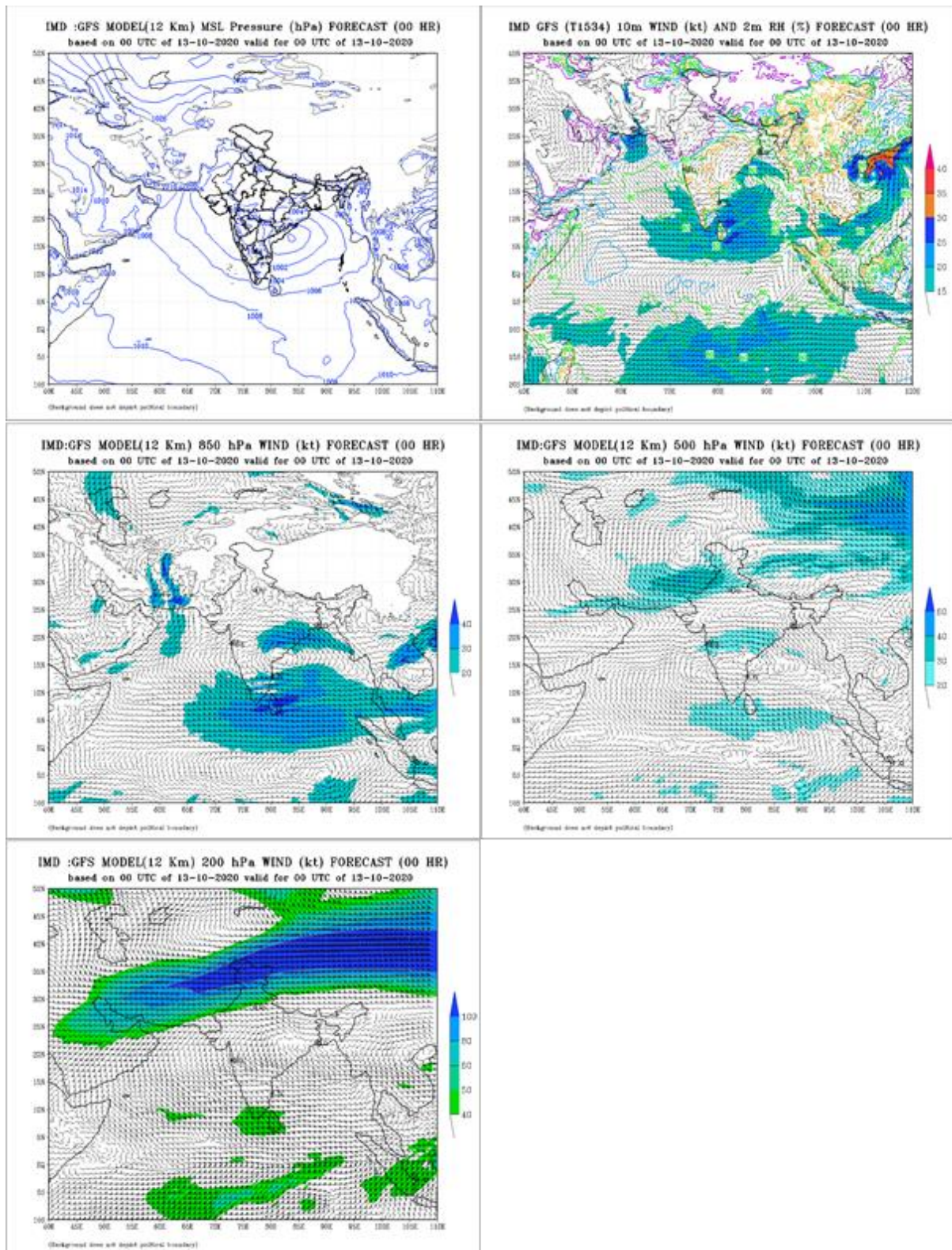


Fig. 2.5.8 (c): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 13th October 2020

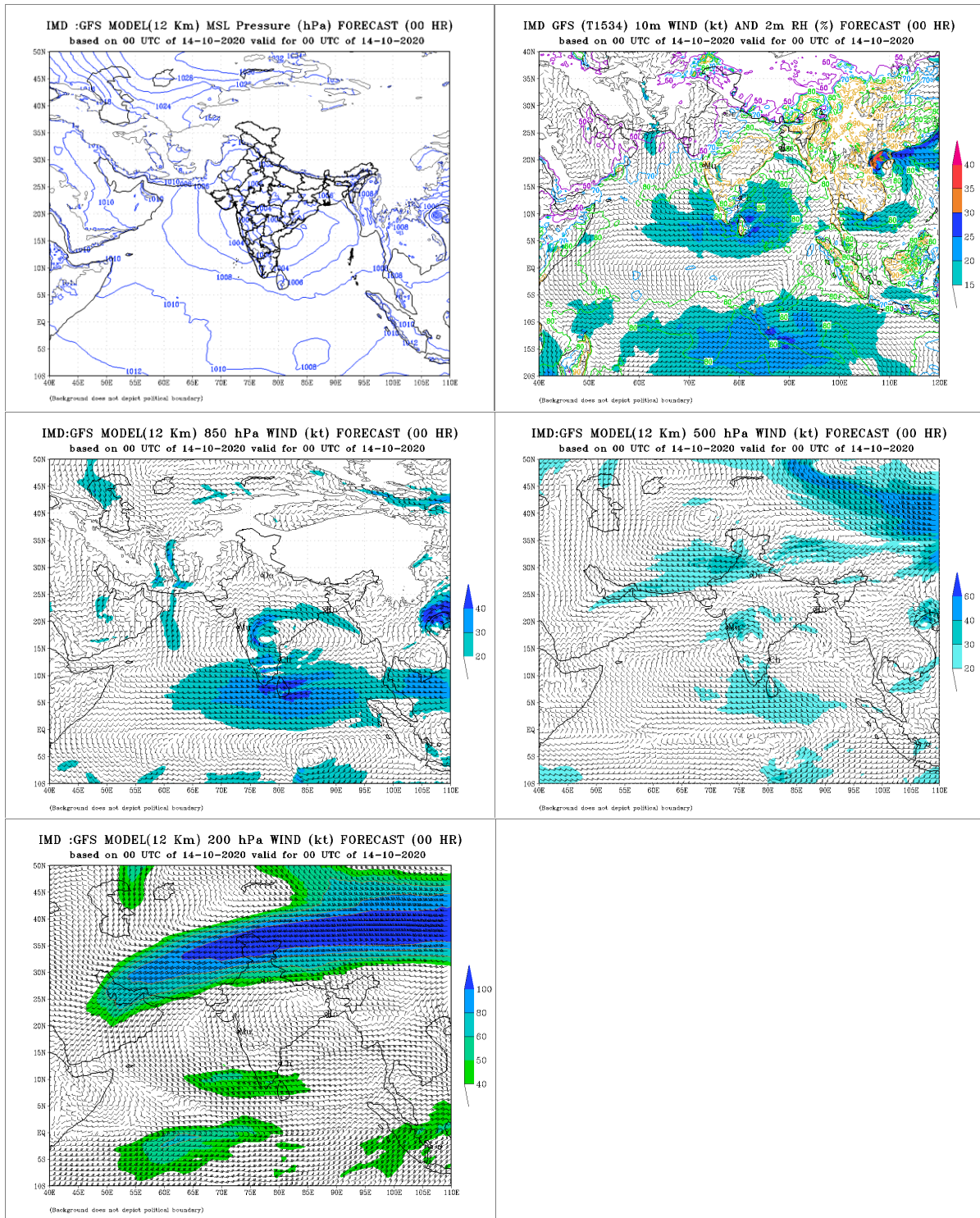


Fig. 2.5.8 (d): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 14th October 2020

2.5.5. Realized Weather:

Under the influence of this system, light to moderate rainfall at many places with heavy to very heavy & extremely heavy rainfall at isolated places occurred over Odisha, Coastal Andhra Pradesh & Yanam, Telangana and Coastal Karnataka on one day each, Heavy to very heavy rainfall at isolated places over Telangana on three days; over North & South Interior Karnataka and Marathwada on two days each; over Madhya Maharashtra, Coastal Andhra Pradesh & Yanam, Rayalaseema and Coastal Karnataka on one day each.

The daily rainfall distribution ending at 0300 UTC of each date during 09-15 October, 2020 based on merged gridded rainfall data of IMD/NCMRWF is shown in Fig. 2.5.9. It may be noted that the rainfall over the mainland had started even 2 days prior to the system crossing Andhra Pradesh coast owing to the sheared nature of the convection associated with the system.

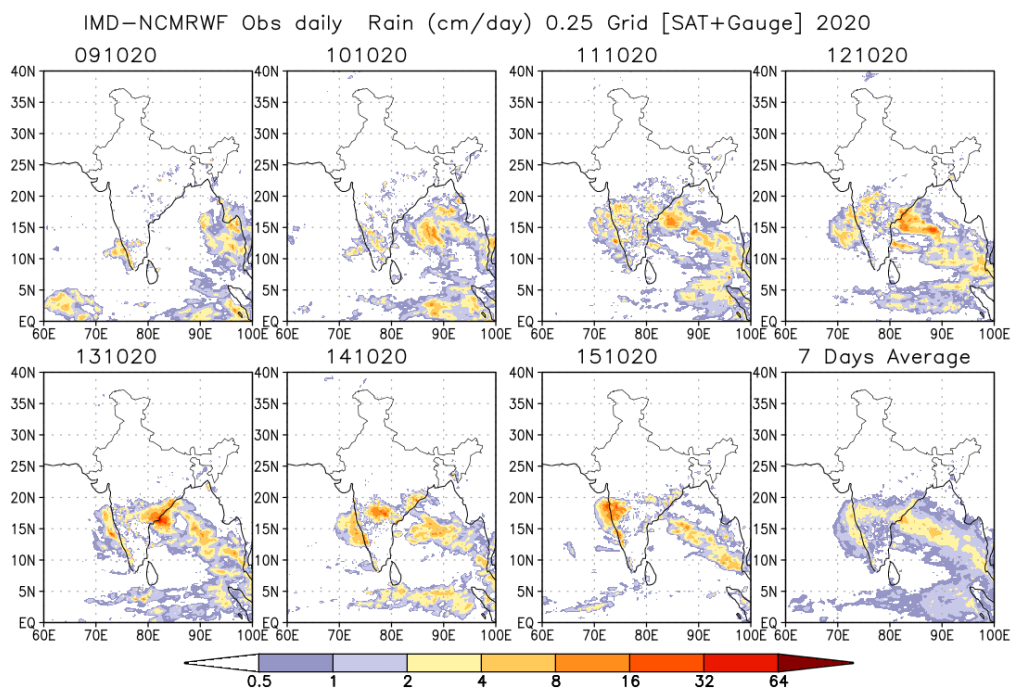


Fig. 2.5.9: Daily rainfall distribution based on merged gridded rainfall data of IMD/ NCMRWF during 09-15 October, 2020

(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 0300 UTC (0830 hours IST) of date during 11th – 15th October 2020 is presented below:

11th October

Coastal Andhra Pradesh (A.P) & Yanam: Rancherla-10, Velairpad-8

Telangana: Kothagudam -14

Rayalaseema: Chinnamandem-13, Pakala-12, Badvel-10, Uravakonda-9, Orvakal-9, Atmakur (District: Kurnool) - 9, Kurnool -8, Gurramkonda-9, Atlur-8, Penagaluru-8, Pamidi-8, Sambepalle-8, Lepakshi-7

12th October

Coastal A.P. & Yanam: Bheemunipatnam-17, Visakhapatnam-15, Visakhapatnam AP-14, Kakinada-14, Peddapuram-14, Yanam-11, Anakapalle-10, Amalapuram-10, Marripudi-8, Tuni-8, Prathipadu-7, Dowleshwaram-7, Yelamanchili-7

Telangana: Kondapak-10, Ramayampet-10, Ghattu-7, Mirdoddi-7, Bhiknur-7, Sarangapur-7, Domakonda-7.

Rayalaseema: Simhadripuram-7

North interior Karnataka: Hukkeri-13, Hungund-10, Khajuri-9, Bevoor-9

13th October

Odisha: Mohana-14, Paralakhemundi-12, Nuagada-11, Berhampur-10, Aska-10, Kashinagar-9, Purushottampur-9, Mahendragarh-8, Chhatrapur-8, R.Udaigiri-7, Gunupur-7

Coastal A.P. & Yanam: Yanam-25, Amalapuram-19, Tanuku-19, Nuzvid-19, Tadepalligudem-18, Vijayawada A.P.-16, Bheemunipatnam-16, Kaikalur-15, Palasa-15, Ichchapuram-15, Tiruvuru-15, Yelamanchili-14, Chintalapudi-13, Sompeta-13, Gudivada-13, Mandasa-13, Narsapuram-12, Kakinada-12, Prathipadu-12, Koyyalagudem-12, Palakoderu-12, Bheemavaram-12, Dowleshwaram-11, Peddapuram-11, Bhimadole-11, Rajahmundry-11, Narsipatnam-11, Eluru-11, Vijayawada(ARG)-10, Tuni-10, Prakasam Barrage-9, Nandigama-9, Bondapalle-9, Anakapalle-9, Chodavaram-9, Vepada-9, Visakhapatnam A.P.-8, Vararamachandrapur-8, Therlam-8, Kukunoor-8, Paderu-8, Pathapatnam-8, Pusapatirega-8, Visakhapatnam-8, Velairpad-7, Denkada-7, Palakonda-7, Ranastalam-7, Parvathipuram-7, Mangalagiri-7, Nellimarla-7, Mentada-7, Nandigama (ARG)-7, Paleru Bridge-7, Koida-7, Gajapathinagaram-7, Garugubilli-7, Polavaram-7, Merakamudidam-7, Kalingapatnam-7, Garividi-7, Kunavaram-7.

Telangana: Sathupalle-19, Mahabubabad-13, Madhira-11, Mulakalapalle-11, Aswaraopeta-11, Bayyaram-10, Chandrugonda-9, Thimmajipeta-9, Thollada-8, Tupran (ARG) -8, Suryapet-7, Devarakonda-7, Wanaparthy-7, Chandur-7, Kusumanchi-7

North interior Karnataka: Badami-8, Kushtagi-7.

South interior Karnataka: Sandur-10, Agumbe EMO-7, Hagaribommanahalli-7

14th October

Odisha: Aska-21, Purushottampur-19, Daspalla-10, Sorada-10, Daitari-9, Berhampur-7, Daringibadi-7, R.Udaigiri-7, Digapahandi-7, Brahmagiri-7, Mohana-7, Raikia-7.

Coastal A.P. & Yanam: Avanigada-10, Nandigama (ARG) -10, Sattenapalle-10, Therlam-10, Macherla-9, Sompeta-9, Machilipatnam CDR -9, Narsapuram-9, Nandigama-8, Jangamaheswarapuram-8, Repalle-7, Bheemavaram-7.

Telangana: Hayathnagar-30, Jogipet-24, Ibrahimpatnam-23, Hakimpet IAF- 20, Hyderabad A.P.-19, Golkonda-18, Manchal-18, Warangal-18, Tekmal-17, Marpalle-17, Nalgonda-16, Kondapur-16, Sangareddy-15, Kohir-15, Mominpet-15, Medchal-15, Dindigul-15, Chandur-15, Maheswaram-15, Shamirpet-15, Hathanoora-15, Narsapur-15, Nidamanur-14, Yacharam-14, Saroornagar-14, Munipalli-13, Naykal-13, Raikode-13, Peddemul-12, Doultabad-12, Medak-12, Sadasivpet-11, Palakurthi-11, Nawabpet-11, Alladurg-11, Chevella-11, Narmetta-11, Gajwel-11, Regode-11, Chegunta-10, Ghanpur-10, Kondapak-10, Kowdipalle-10, Ramayampet-10, Jagadevpur-10, Mahabubabad-9, Zaffergadh-9, Vicarabad-9, Aswaraopeta-9, Mirdoddi-9, Tandur-9, Dubbak-9, Nanganur-9, Jangaon-8, Bejjanki-8, Marriguda-8, Huzurabad-8, Nagareddipet-8, Kamareddy-8, Sathupalle-7, Jukkal-7, Bhiknur-7, Doma-7, Mustabad-7, Jajireddigudem-7, Papannapet-7, Noothankal-7, Narayankhed-7.

Marathwada: Nilanga-13, Deoni-8, Umarga-8, Chakur-7, Ausa-7.

Konkan & Goa: Malvan-9, Dodamarg-7.

North interior Karnataka: Manthala-15, Basavakalyan-15, Humnabad-13, Kalaburgi obsy-13, Bidar PTO-13, Kalaburgi AWS-13, Chincholi-11, Khajuri-11, Aland-9, Aurad-8, Afzalpur HMS-7, Raddewadgi ARG-7.

South interior Karnataka: Agumbe EMO-14, Kottigehara-9, Arasalu-7

Coastal Karnataka: Kollur-24, Kota-17, Mulki-17, Mani-15, Mangaluru A.P obsy-15, Mudubidre-13, Brahmavar AWS-13, Karkala-13, Udupi-13, Kundapur-12, Belthangadi-12, Puttur HMS-12, Mangaluru-12, Panambur obsy-12, Vitla ARG-12, Dharmasthala-11, Bhatkal-10, Sulya-10, Shirali PTO -9, Siddhapura ARG-8, Siddhapura-8, Subramanya-8, Uppinangadi-7.

15th October

Marathwada: Paranda-18, Tuljapur-14, Lohara-10, Shirur Kasar-7, Georai-7.

Madhya Maharashtra: Gaganbawada-17, Indapur-16, Barshi-16, Pandharpur-16, Jeur IMD Part time-16, Baramati-15, Sangli IMD obsy-15, Panhala-14, Malshiras-14, Mangalvedha-13, Mahabaleshwar- IMD obsy-13, Kolhapur/Karvir IMD-13, Vita-11, Pune city IMD obsy-11, Bhor-11, Karad-11, Ambegaon Ghodegaon-11, Patan-10, Palus-10, Lonavala agri-10, Shirala-10, Karmala-10, Tasgaon-9, Miraj-9, Kavathe Mahakal-9, Atpadi-9, Dahiwadi man-9, Khandala Bavda-9, Kagal-9, Daund-9, Wai-9, Kadegaon-9, Madha-9, Satara IMD obsy-9, Khatav Vaduj-9, Jat-9, Shirur Ghodnadi-9, Sholapur IMD obsy-8, Shirol-8, Purandar Sasvad-8, Khed Rajgurunagar-8, Phaltan-7, Javali Medha-7, Junnar-7, Hatkanangale-7, Mohol-7, Velhe-7, Akole-7, Vadgaon maval-7

Konkan & Goa: Alibag IMD part time-15, Lanja-15, Khed-14, Murud-13, Karjat agri-12, Vaibhavwadi-12, Khalapur-12, Pen-12, Ratnagiri IMD obsy-12, Matheran-12, Colaba IMD obsy-12, Rajapur-11, Sangameshwar Devrukh-11, Poladpur-10, Panvel agri-10, Mandangad-9, Sudhagad Pali-9, Bhira IMD part time - 9, Santacruz IMD obsy-9, Roha-9, Malvan-8, Chiplun-8, Tbia IMD part time-8, Shriwardhan-7, Mahad-7, Mhasla-7, Guhagarh-7, Tala-7, Dodamarg-7, Uran-7.

2.6 Depression over the Arabian Sea during 17-19 October, 2020

2.6.1 Introduction

- ❖ The Depression originated from the remnant well marked low pressure area of the last Deep Depression which moved across south Peninsular India during 11th – 14th October.
- ❖ Last Deep Depression had weakened into a Well Marked Low pressure area and lay centred over South Madhya Maharashtra and neighbourhood in the evening (1200 UTC) of 14th October 2020.
- ❖ It moved across Maharashtra and emerged as a well marked low pressure area over east-central Arabian Sea (AS) off Maharashtra coast on 16th early morning (0000 UTC).
- ❖ Subsequently it re-intensified into a **Depression** over the same region (east-central AS off Maharashtra coast) on 17th morning (0300 UTC).
- ❖ It maintained its intensity of depression till 19th early morning (0000 UTC) while moving westwards, away from Indian coast and weakened into a well marked low pressure area in the early morning of 19th October.
- ❖ As it moved away from the Indian coast, it had no impact along Indian coast from 18th October 2020.

The salient features of the system were as follows:

- (i) It had a straight westward track.
- (ii) It had a life period of nearly 45 hours.
- (iii) It had a track length of nearly 500 km.
- (iv) Under the influence of this system there had been rough to very rough Seas and squally weather over east-central & adjoining northeast AS off north Maharashtra – south Gujarat coasts on 17th October and over east-central and adjoining northeast AS on 18th October.

IMD mobilised all its resources to track the system and regular warnings w.r.t. track, intensity, associated severe weather and adverse impacts & suggested actions 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. Its genesis, movement and associated adverse weather could be predicted with actionable accuracy by IMD.

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

The observed track of the Depression over east-central AS is presented in Fig.2.6.1. The best track parameters of the system are presented in Table 2.6.1.

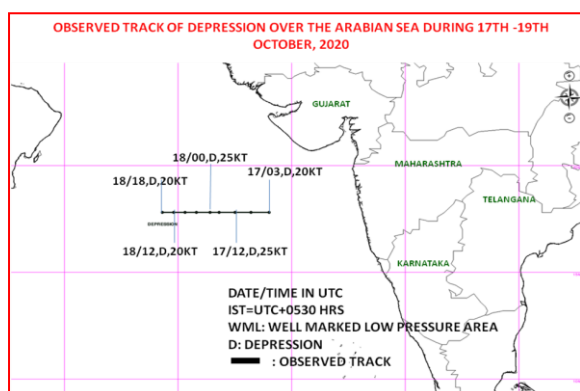


Fig. 2.6.1. Observed track of Depression over the Arabian Sea (17-19 October, 2020)

Table 2.6.1: Best track positions and other parameters of the observed track of Deep Depression over west-central Bay of Bengal (11-14 October, 2020)

Date	Time (UTC)	Centre lat. ^o N/ long. ^o E		C.I. NO	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
17/10/2020	0300	17.8	69.0	1.5	1004	20	3	D
	0600	17.8	68.2	1.5	1004	20	3	D
	1200	17.8	67.5	1.5	1003	25	4	D
	1800	17.8	66.8	1.5	1003	25	4	D
18/10/2020	0000	17.8	66.4	1.5	1003	25	4	D
	0300	17.8	65.8	1.5	1004	20	3	D
	0600	17.8	65.3	1.5	1004	20	3	D
	1200	17.8	64.8	1.5	1004	20	3	D
19/10/2020	1800	17.8	64.3	1.5	1004	20	3	D
	0000	Weakened into well marked low pressure area over westcentral Arabian Sea and neighbourhood						

2.6.1 Monitoring of the system:

India Meteorological Department (IMD) maintained round the clock watch over the north Indian Ocean and the development of the system was monitored since 08th October, about 9 days prior to the formation of the Depression over eastcentral AS on 17th October. The **Depression** was monitored with the help of available satellite observations from INSAT 3D and 3DR, SCAT SAT, polar orbiting satellites and available ships & buoy observations in the region. The system in its initial stage was

also monitored by Doppler Weather RADAR (DWR) Mumbai. Various numerical weather prediction models run by Ministry of Earth Sciences (MoES) institutions, models run by other Global centres and dynamical-statistical models were utilized to predict the genesis, track, landfall and intensity of the Depression. A digitized forecasting system of IMD was utilized for analysis and comparison of various models' guidance, decision making process and warning products generation.

As the system was expected to move away from the Indian coast, no heavy rainfall warning was issued in association with the system. However, necessary Sea area warnings & fishermen warnings with suggested actions were issued by IMD well in advance to all concerned states, media and stakeholders.

2.6.2 Genesis, intensification and movement

Typical satellite imageries are presented in **Fig. 2.6.2**.

Some of the favourable environmental features which aided in the formation of the Depression and its westward track and dissipation over the Sea are as follows:

The convectively active phase of Madden Julian Oscillation (MJO) remained in Phase 5 with amplitude more than 1. This supported convection over the north Indian Ocean during the period.

The Sea Surface Temperature (SST) remained to be around 28-29°C over most parts of Arabian Sea (AS). It was slightly higher (30-32°C) over Gulf of Oman and cooler (26- 24°C) all along Oman – Yemen and Arabian coasts and 26 -27°C over west-central & southwest AS during 17th -19th October. The Tropical Cyclone Heat Potential (TCHP) was less than 50KJ/cm² to the west of 55°E over the AS and 100 – 120 kJ/cm² over south AS. Over north AS, it was between 50-70 kJ/cm², to the east of 55°E, except over south Gujarat coast where it was less than 50KJ/cm² during 17th – 19th October.

The relative vorticity at 850 hPa was around $100 \times 10^{-6} \text{s}^{-1}$ over east-central AS & adjoining northeast AS and extended upto 200 hPa on 17th October, around $50 - 70 \times 10^{-6} \text{s}^{-1}$ over west-central AS & adjoining northeast AS extending upto 500 hPa on 18th and around $50 - 60 \times 10^{-6} \text{s}^{-1}$ over west-central AS extending upto 500 hPa on 19th October.

Low level convergence of $(5 \times 10^{-5} \text{s}^{-1})$ prevailed over east-central AS on 17th October, $(5 \times 10^{-5} \text{s}^{-1})$ over west-central AS on 18th and isolated small areas of positive convergence zone $(5 \times 10^{-5} \text{s}^{-1})$ over north & west-central AS on 19th October. Upper level divergence of $(20 \times 10^{-5} \text{s}^{-1})$ prevailed over east-central AS on 17th October, $(05-10 \times 10^{-5} \text{s}^{-1})$ over west-central AS on 18th and isolated pockets of divergence zones $(05 \times 10^{-5} \text{s}^{-1})$ over west-central AS on 19th October.

Moderate (10-20 kts) vertical wind shear (VWS) prevailed over east-central & adjoining northeast AS with a decreasing wind shear tendency on 17th October, low to moderate (05-15 kts) over north AS and high (40-50 kts) over remaining parts of Arabian Sea with a decreasing wind shear tendency over northern parts of the AS and increasing tendency over south & central parts on 18th and low to moderate (05-20 kts) over north & adjoining central AS and high (40-50 kts) over remaining parts of Arabian Sea with decreasing wind shear tendency over northern parts of the AS and increasing or neutral tendency over south & central parts of the AS on 19th October. The upper tropospheric ridge at 200 hPa extended roughly along Lat. 22°N across

north Arabian Sea during 17th – 19th October, directing the system in a westward track. As it moved westwards, it gradually experienced colder Sea area. As a result, the system did not intensify further and weakened into a well marked low on 19th due to unfavourable vertical wind shear and colder Sea.

According to satellite imagery on 17th October, the intensity of the system was T 1.5. The convection was organised in shear pattern. Associated broken low and medium clouds with embedded intense to very intense convection lay over east-central and adjoining northeast AS between latitude 16.5°N & 22.0°N & longitude 62.5°E & 68.0°E. Minimum cloud top temperature was -90°C. According to satellite imagery on 18th October, the intensity of the system was T 1.5. The convection was organised in shear pattern. Associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over central and adjoining north AS between latitude 16.5°N - 22.5°N & longitude 60.0°E - 65.0°E. Minimum cloud top temperature was -78°C. According to satellite imagery of 19th October, the intensity of the system has been T 1.5. The convection was organised in shear pattern. Associated scattered to broken low and medium clouds with embedded isolated moderate to intense convection lay over west-central and adjoining northwest AS between latitude 16.0°N - 21.0°N & to the west of longitude 64.0°E and adjoining coastal Oman. Minimum cloud top temperature was -82°C.

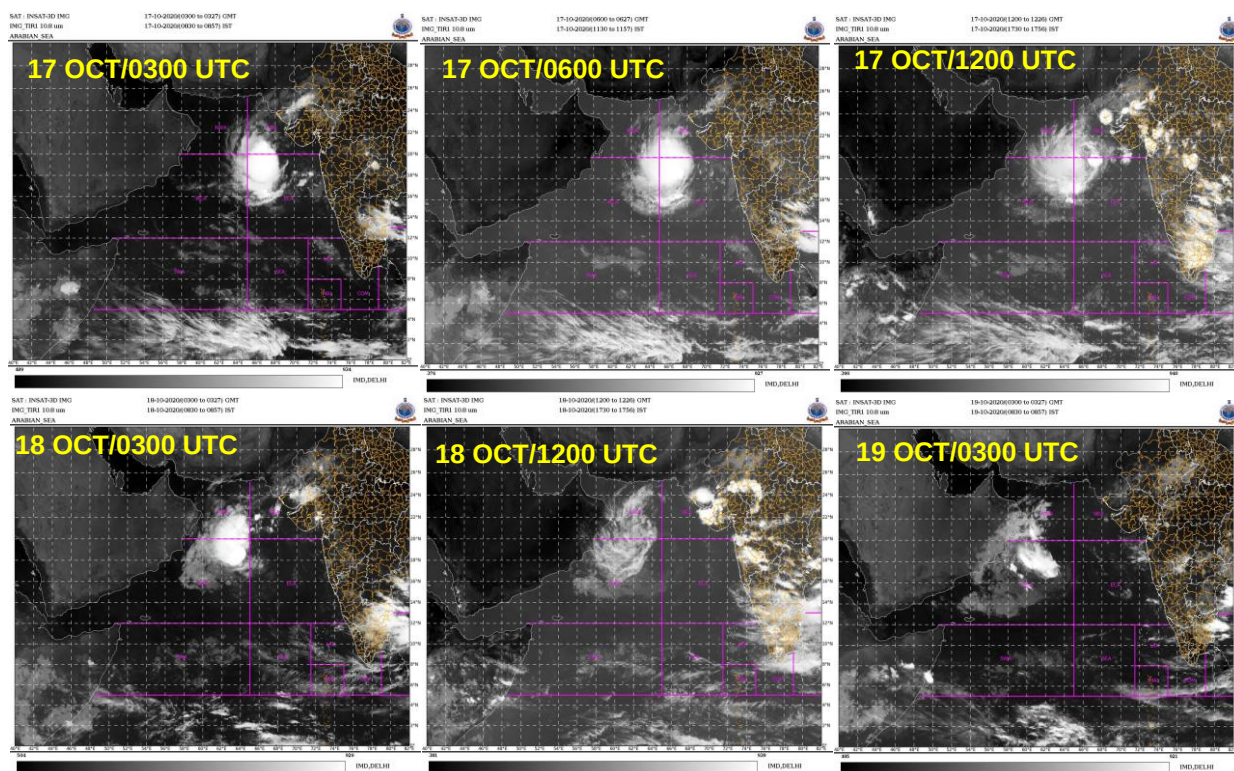


Fig. 2.6.2a: INSAT-3D IR imageries during life cycle of the Depression (17-19 October, 2020)

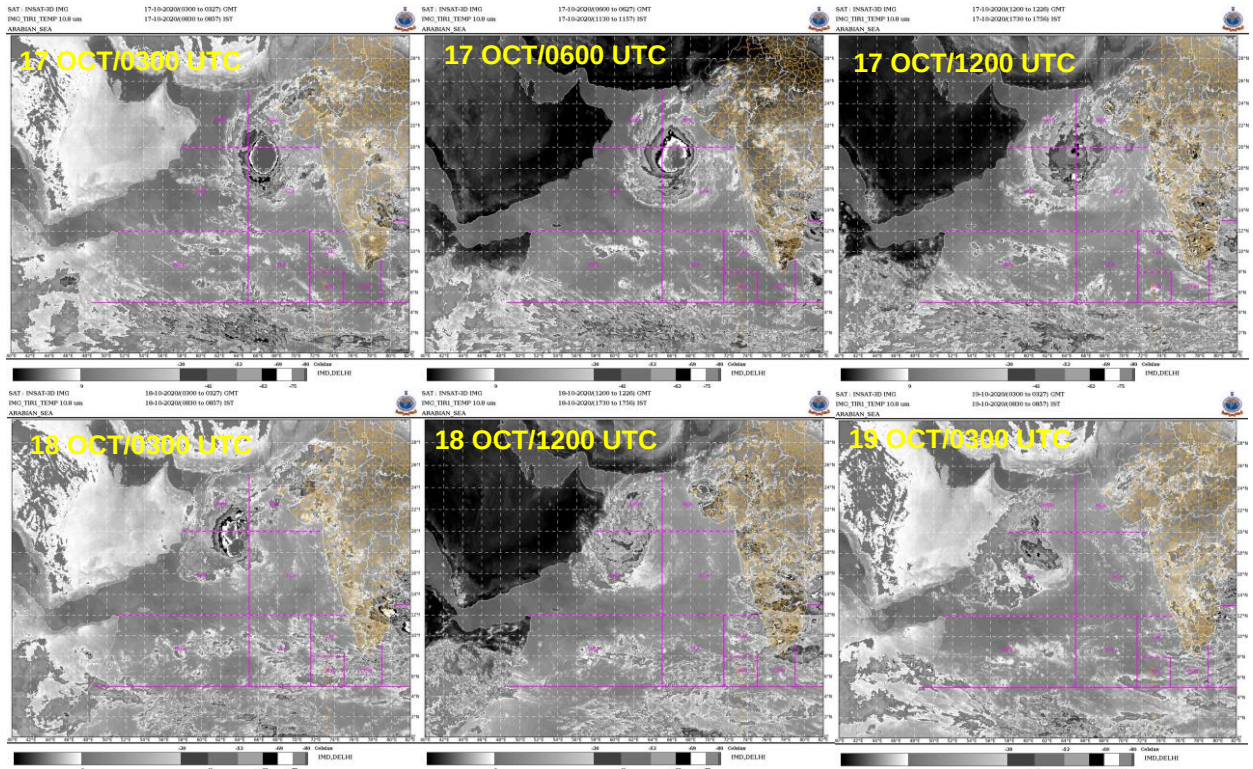


Fig. 2.6.2b: INSAT-3D cloud top brightness imageries during life cycle of the Depression (17-19 October, 2020)

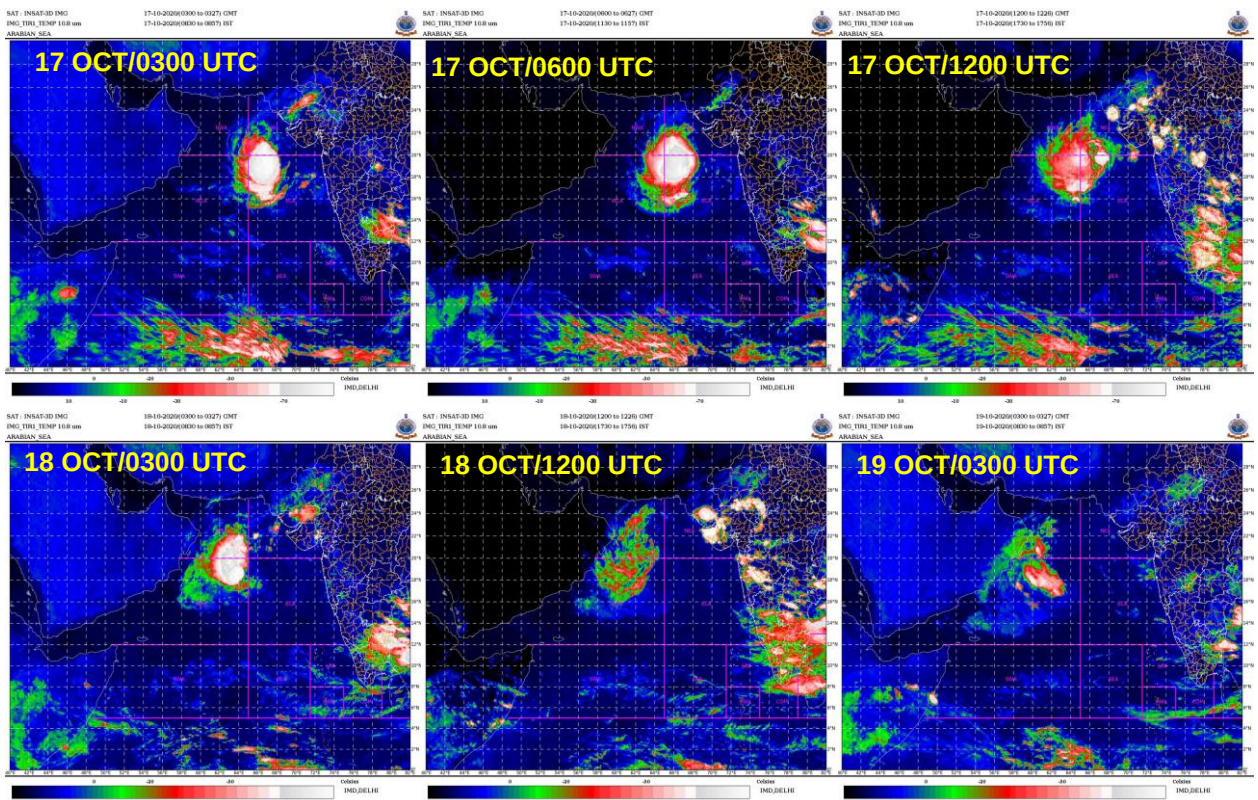


Fig. 2.6.2c: INSAT-3D enhanced colored imageries during life cycle of the Depression (17-19 October, 2020)

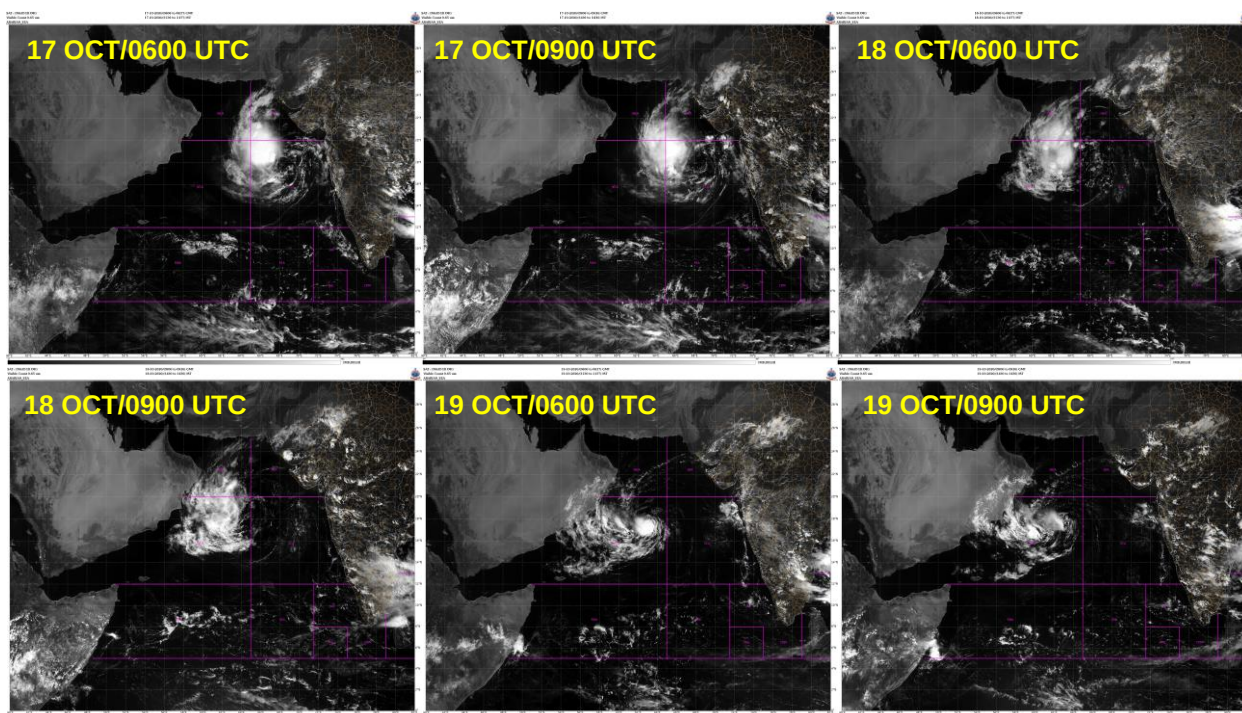


Fig. 2.6.2d: INSAT-3D visible imageries during life cycle of the Depression (17-19 October, 2020)

2.6.4. Dynamical features

IMD GFS (T1534) analysis fields of mean sea level pressure (MSLP), winds at 10 m, 850, 500 and 200 hPa levels are presented in Fig. 2.6.3 (a) – 3(c).

The model analysis field simulated the system as a Depression all through the period of its existence, with vertical extension upto 500 hPa. The analysis of IMD-GFS T-1534 model forecasts based on 0000 UTC of 17th October, 2020 showed that the Depression over east central AS would move further westwards by 18th morning, weaken into a low pressure area over west-central AS on 19th & persist there on 20th & 21st and dissipate subsequently. The analysis of IMD-GFS T-1534 model forecasts based on 0000 UTC of 18th October, 2020 showed that the Depression over east central AS & neighbourhood would move further westwards, weaken into a well marked low pressure area over west-central AS on 19th morning, persist there on 20th, as a low pressure area on 21st and dissipate subsequently. The analysis of IMD-GFS T-1534 model forecasts based on 0000 UTC of 19th October, 2020 showed the system as a Well marked low pressure area (WML) over west central AS & neighbourhood which would move further west-southwestwards and weaken into a low pressure area over west-central & adjoining south west AS on 21st morning, and dissipate on 22nd. Hence IMD GFS provided reliable guidance in forecasting the intensity & movement of the system all through its life period.

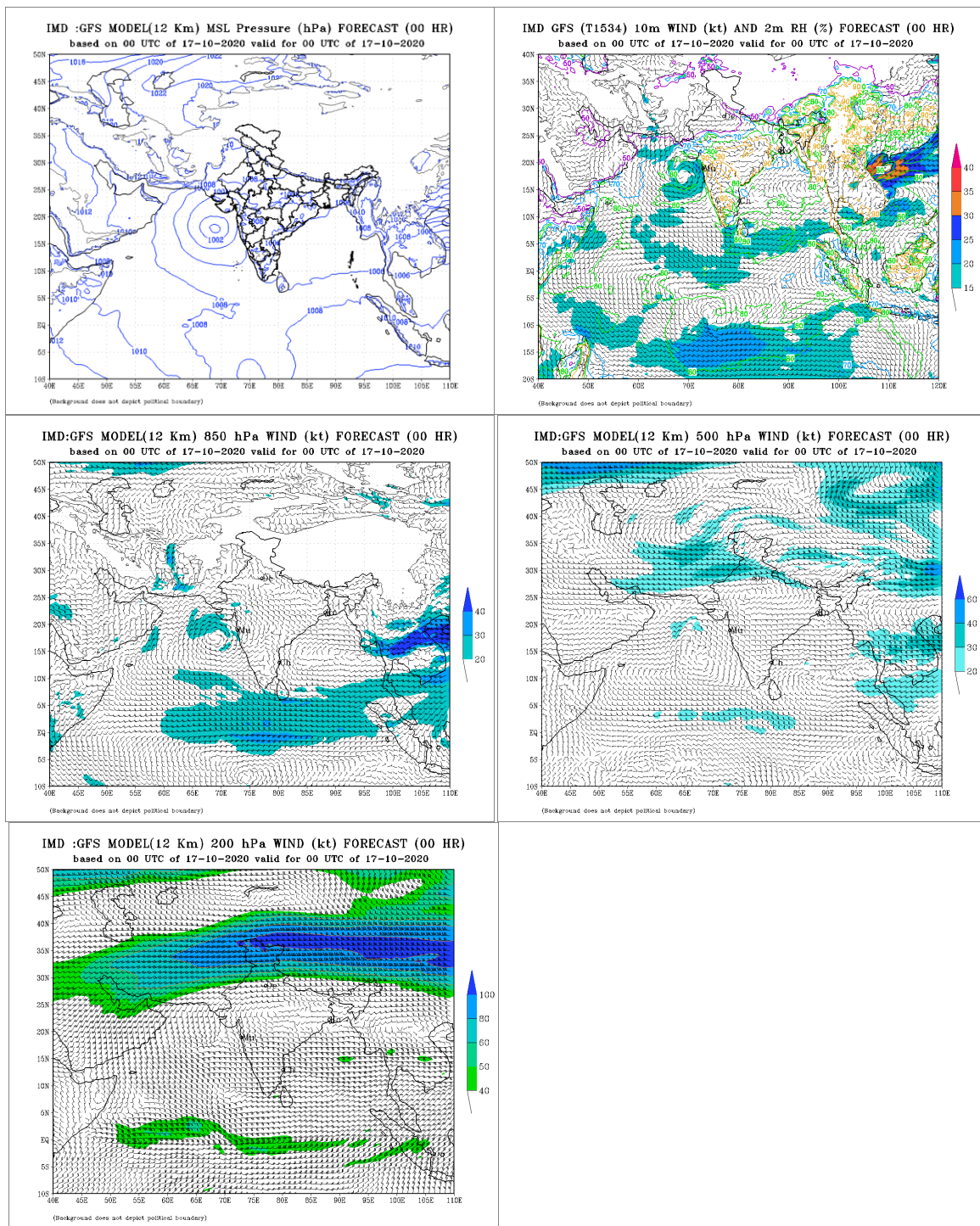


Fig. 2.6.3 (a): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 17th October 2020

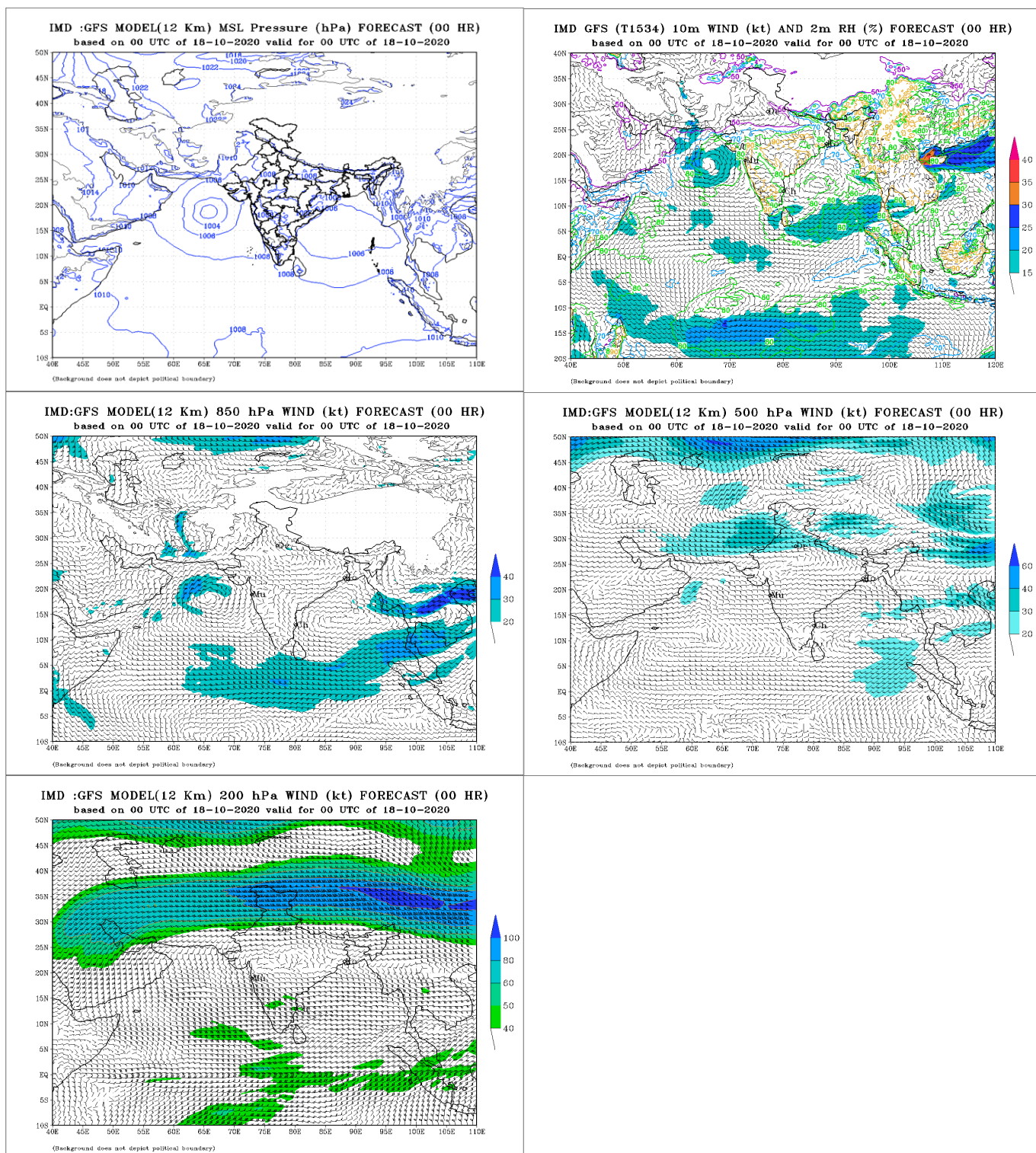


Fig. 2.6.3 (b): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 18th October 2020

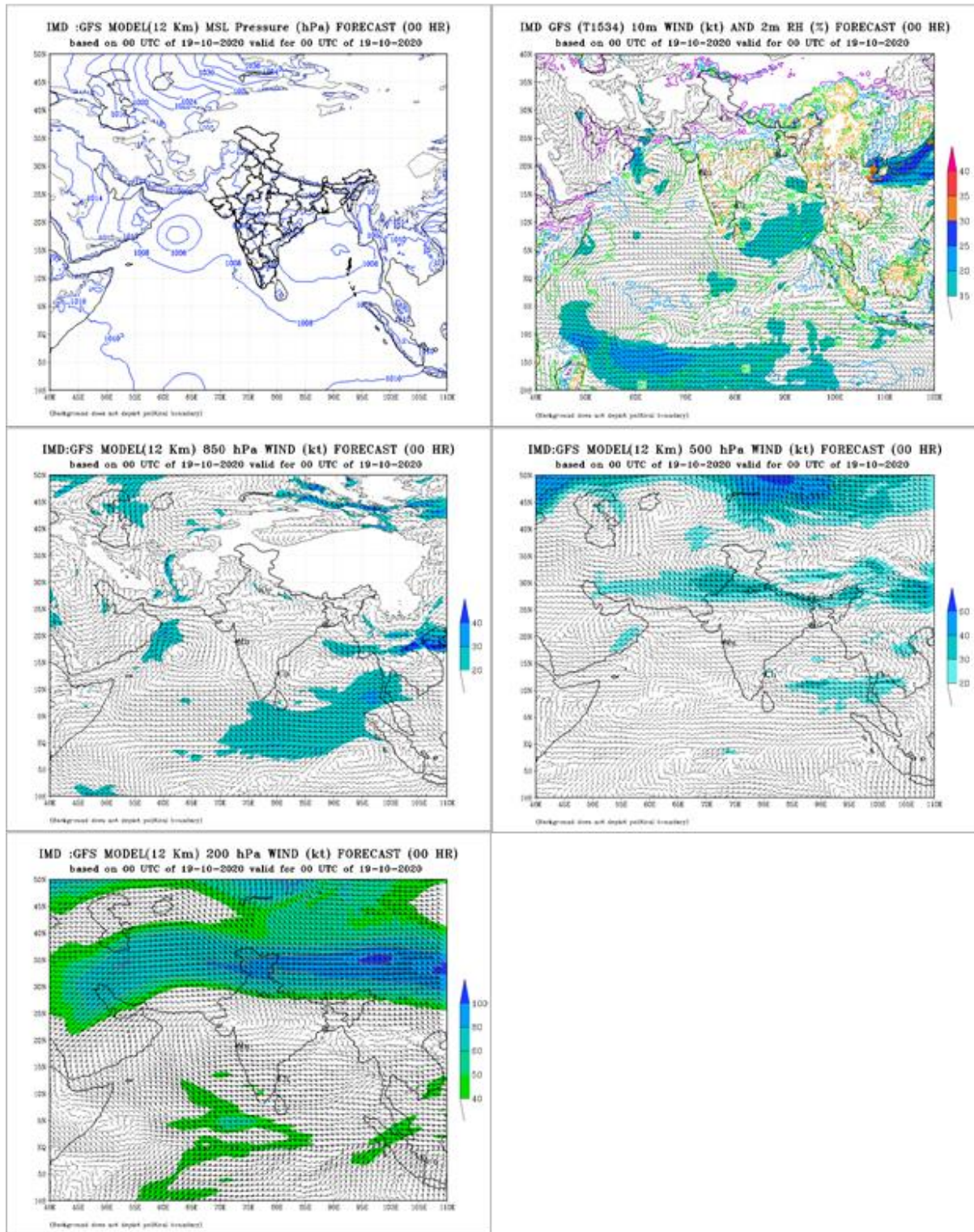


Fig. 2.6.3 (c): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 19th October 2020

2.6.5. Realized Weather:

Since the system moved away from the Indian coast it did not cause any rainfall over the land area. The daily rainfall distribution ending at 0300 UTC of each date during 15-21 October, 2020 based on merged gridded rainfall data of IMD/NCMRWF is shown in Fig.4. It may be noted that the rainfall over Maharashtra on 15th and over coastal belt of Maharashtra on 16th October happened due to the presence of the remnant as a well marked Low pressure area over the region.

The system caused heavy rainfall Heavy rainfall (64.5 – 115.5 mm) over parts of east-central & adjoining northeast AS on 17th & 18th and over northern parts of central AS on 19th October.

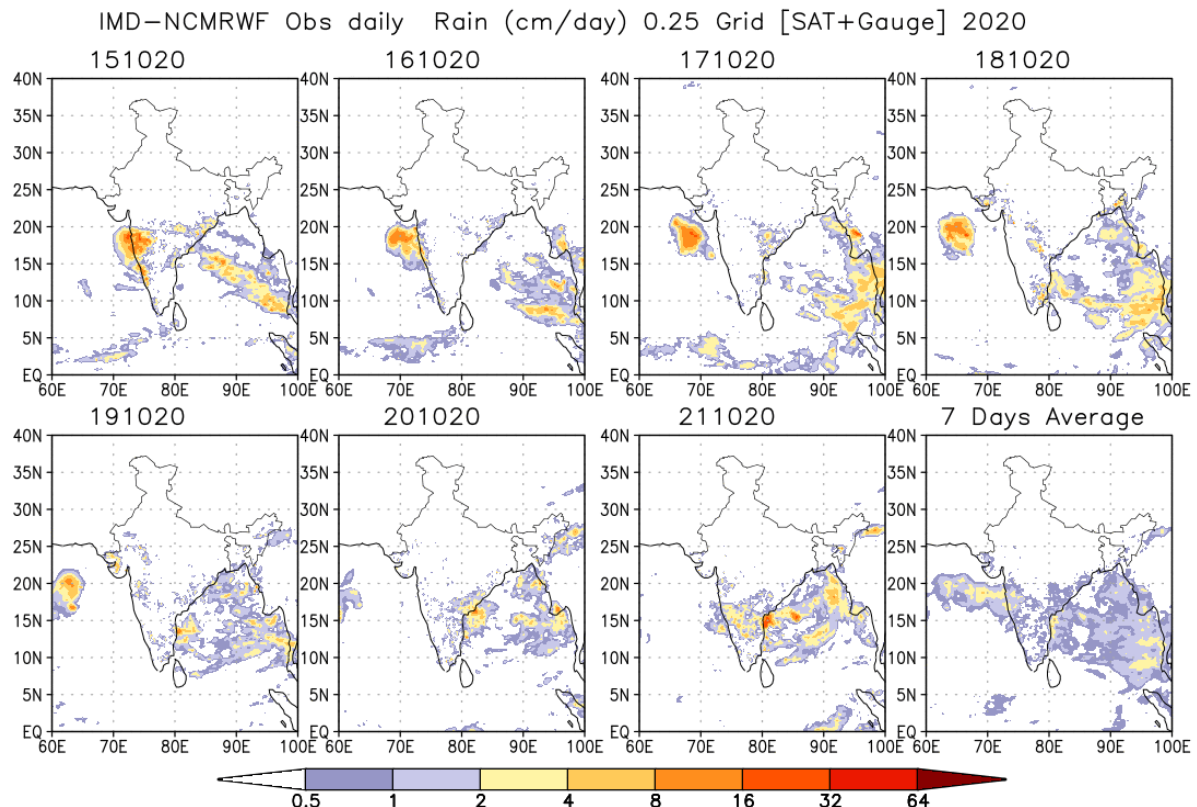


Fig. 2.6.4: Daily rainfall distribution based on merged gridded rainfall data of IMD/ NCMRWF during 15-21 October, 2020

2.7 Depression over the Bay of Bengal during 22nd – 24th October, 2020

2.7.1 Introduction

- ❖ The Depression originated as a Low Pressure Area over central parts of Bay of Bengal (BoB), in the early morning (0000 UTC) of 20th October, 2020 which became a well marked low pressure area over west-central BoB in the morning (0300 UTC) of 21st October.
- ❖ Under favourable environmental conditions, it concentrated into a **Depression over northwest & adjoining west-central BoB** in the morning (0300 UTC) of 22nd October, 2020.
- ❖ It initially moved northwards for some time and thereafter moved north-northeastwards and crossed West Bengal & adjoining Bangladesh coasts over Sundarbans near latitude 21.8°N and longitude 88.5°E around noon (between 0600 & 0700 UTC) of 23rd October 2020 as a Depression with maximum sustained wind speed of 45-55 kmph gusting to 65 kmph.
- ❖ Further moving north-northeastwards, it weakened into a well marked low pressure area over central Bangladesh & neighbourhood in the early morning (0000 UTC) of 24th October 2020.
- ❖ The system caused heavy rainfall at isolated places over Telangana, Rayalaseema & Odisha and heavy to very rainfall at few places with extremely heavy falls at isolated places over the northeastern states of India including Assam, Meghalaya, Manipur, Nagaland, Mizoram & Tripura. As a consequence of these heavy rains, Landslides also happened over north-eastern states, affecting normal life.

The salient features of the system were as follows:

- (i) It had an initial northward movement followed by north-northeastward moving track.
- (ii) It had a life period of nearly 45 hours.
- (iii) It had a track length of 662 km.
- (iv) Convection and hence the rainfall associated with the system was pronounced over the northeastern Sector and to the left of the track did not experience any heavy rainfall when the system moved inland.

IMD mobilised all its resources to track the system and regular warnings w.r.t. track, intensity, crossing point & time, associated severe weather and adverse impacts & suggested actions 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 with actionable accuracy 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:

The observed track of Depression over west-central BoB is presented in Fig. 2.7.1. The best track parameters of the system are presented in Table 2.7.1.

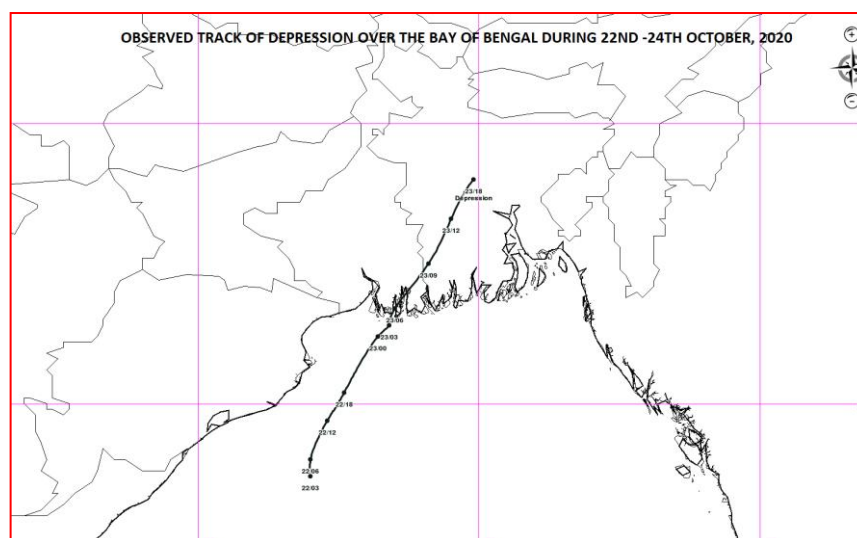


Fig. 2.7.1. Observed track of Depression over the Bay of Bengal (22-24 October, 2020)

Table 2.7.1: Best track positions and other parameters of the observed track of Depression over the Bay of Bengal (22-24 October, 2020)

Date	Time (UTC)	Centre lat. ^o N/ long. ^o E		C.I. NO	Estimat ed Central Pressu re (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
22/10/2020	0300	18.7	87.0	1.5	999	20	3	D
	0600	19.0	87.0	1.5	998	25	4	D
	1200	19.7	87.3	1.5	998	25	4	D
	1800	20.2	87.6	1.5	998	25	4	D
23/10/2020	0000	21.2	88.2	1.5	998	25	4	D
	0300	21.4	88.4	1.5	998	25	4	D
	0600	21.7	88.5	1.5	998	25	4	D
	Crossed West Bengal & adjoining Bangladesh coasts (near latitude 21.8°N & longitude 88.5° E), between 0600 & 0700 UTC of 23 rd October 2020.							
	0900	22.5	89.1	1.5	998	25	4	D
	1200	23.3	89.5	1.5	1000	20	3	D
	1800	24.0	89.9	1.5	1000	20	3	D
24/10/2020	0000	Weakened into well marked low pressure area over Central parts of Bangladesh.						

2.7.3 Features observed through Satellites and Radar:

India Meteorological Department (IMD) maintained round the clock watch over the north Indian Ocean and the development of the system was monitored since 14th October, about 8 days prior to the formation of depression over northwest BoB and adjoining westcentral BoB on 22nd October. The **Depression** was monitored with the help of available satellite observations from INSAT 3D and 3DR, SCAT SAT, polar orbiting satellites and available ships & buoy observations in the region. The system was also monitored by Doppler Weather RADARs (DWRs) Paradip, Kolkata and Agartala. Various numerical weather prediction models run by the Ministry of Earth Sciences (MoES) institutions, models run by other Global centres and dynamical-statistical models were utilized to predict the genesis, track, landfall and intensity of the Depression. A digitized forecasting system of IMD was utilized for analysis and comparison of various models' guidance, decision making process and warning products generation. The heavy rainfall and wind warning at district and meteorological subdivision level along with expected impact, suggested actions and fishermen warnings were issued by IMD well in advance to all concerned states, media and stakeholders.

All through the system period, the convection was organized in a shear pattern and the minimum Cloud Top Temperature reported had been minus 93°C. Intensity of the system remained to be T 1.5 over the Sea.

As per satellite imagery based on 0300 UTC of 22nd October, the convective clouds were sheared to the northwest of the system center. Scattered low and medium clouds with embedded intense to very intense convection lay over northwest and adjoining west-central BoB and neighbourhood. As per satellite imagery based on 0000 UTC of 23rd October, the convective clouds became sheared to the northeast of the system center, mainly under the influence of upper level westerlies. Scattered low and medium clouds with embedded intense to very intense convection lay over north BoB, coastal west Bengal and Bangladesh in association with the system. As per satellite imagery based on 1200 UTC of 23rd October, the system lay over coastal areas of south-west Bangladesh and neighborhood. Center was not clearly defined in IR/visible imageries. Broken low/medium clouds with embedded intense to very intense convection lay over north BoB, coastal west Bengal and Bangladesh, Meghalaya, south Assam, Mizoram & Tripura in association with the system.

Fig. 2.7.2 a-d depicts the INSAT based cloud imageries. The radar imageries from DWR Paradip, Kolkata and Agartala are presented in **Fig. 2.7.3a to Fig 2.7.3c**.

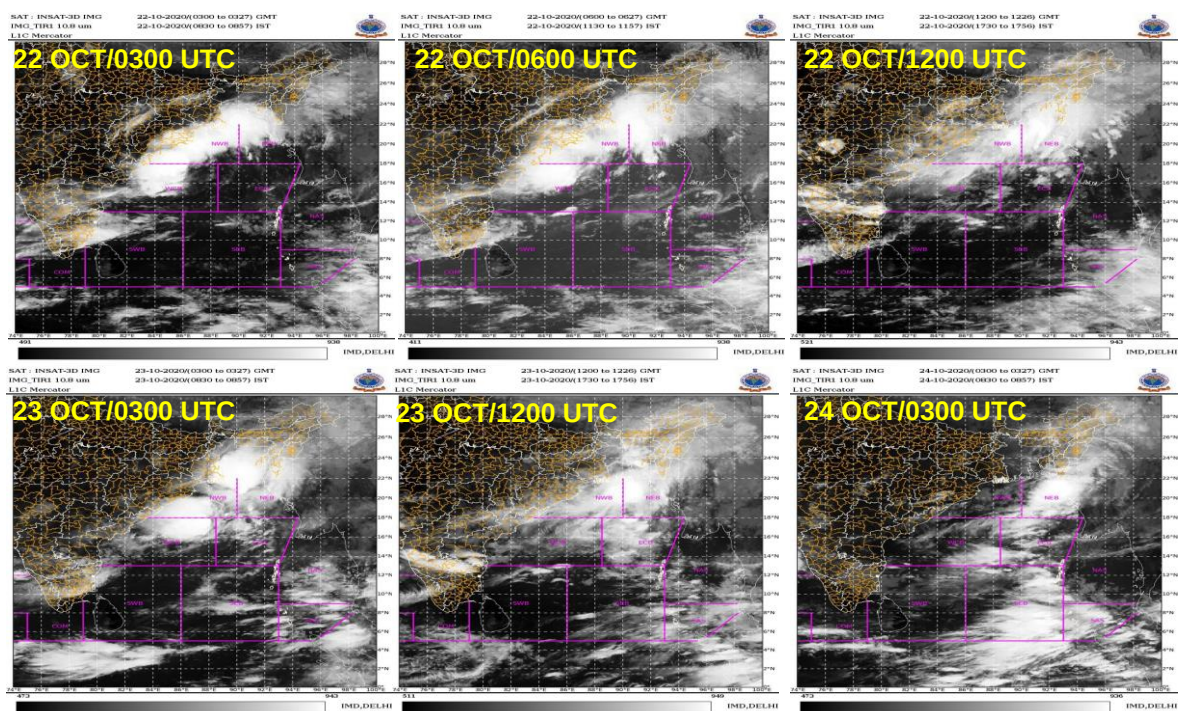


Fig. 2.7.2a: INSAT-3D IR imageries during life cycle of Depression (22-24 October, 2020)

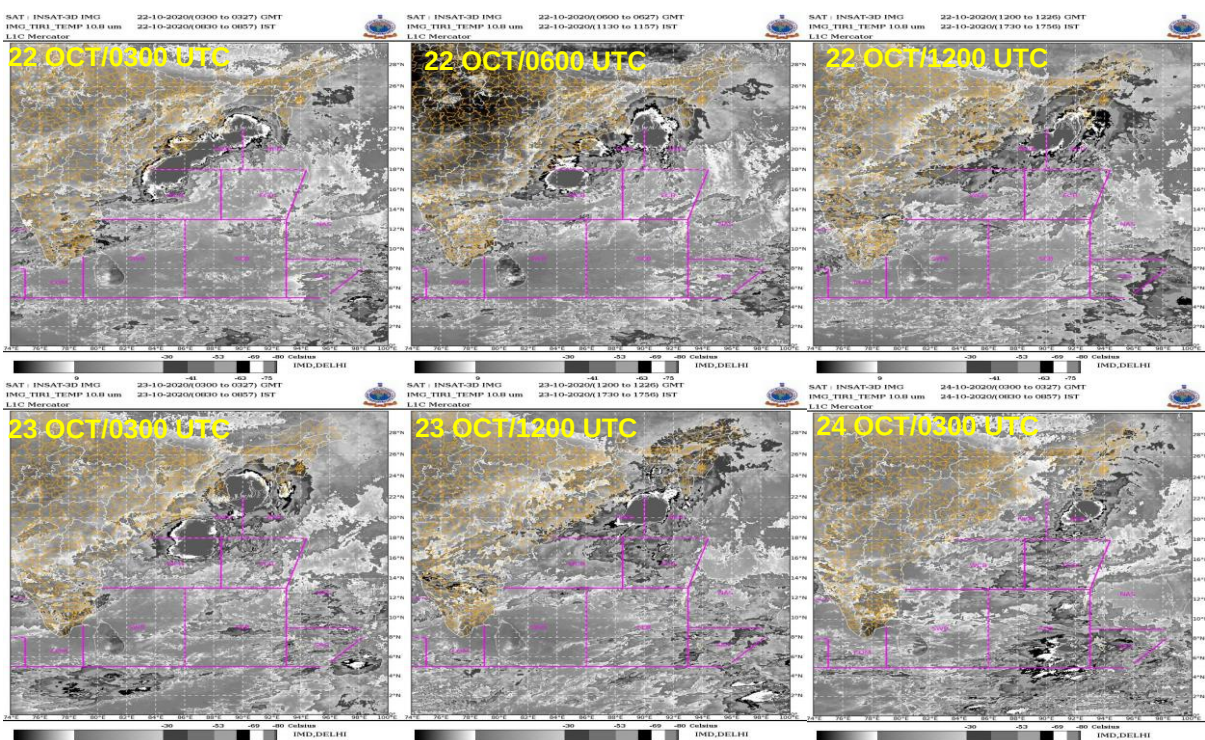


Fig. 2.7.2b: INSAT-3D cloud top brightness imageries during life cycle of Depression (22-24 October, 2020)

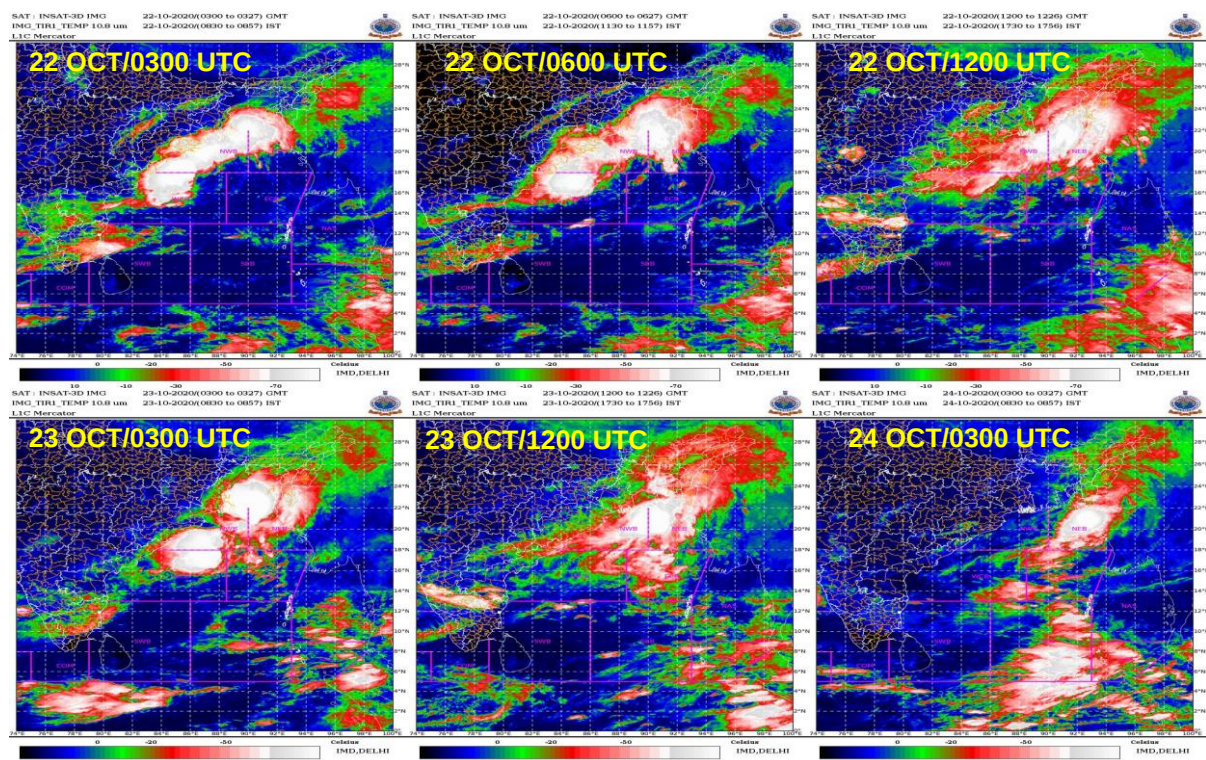


Fig. 2.7.2c: INSAT-3D enhanced colored imageries during life cycle of Depression (22-24 October, 2020)

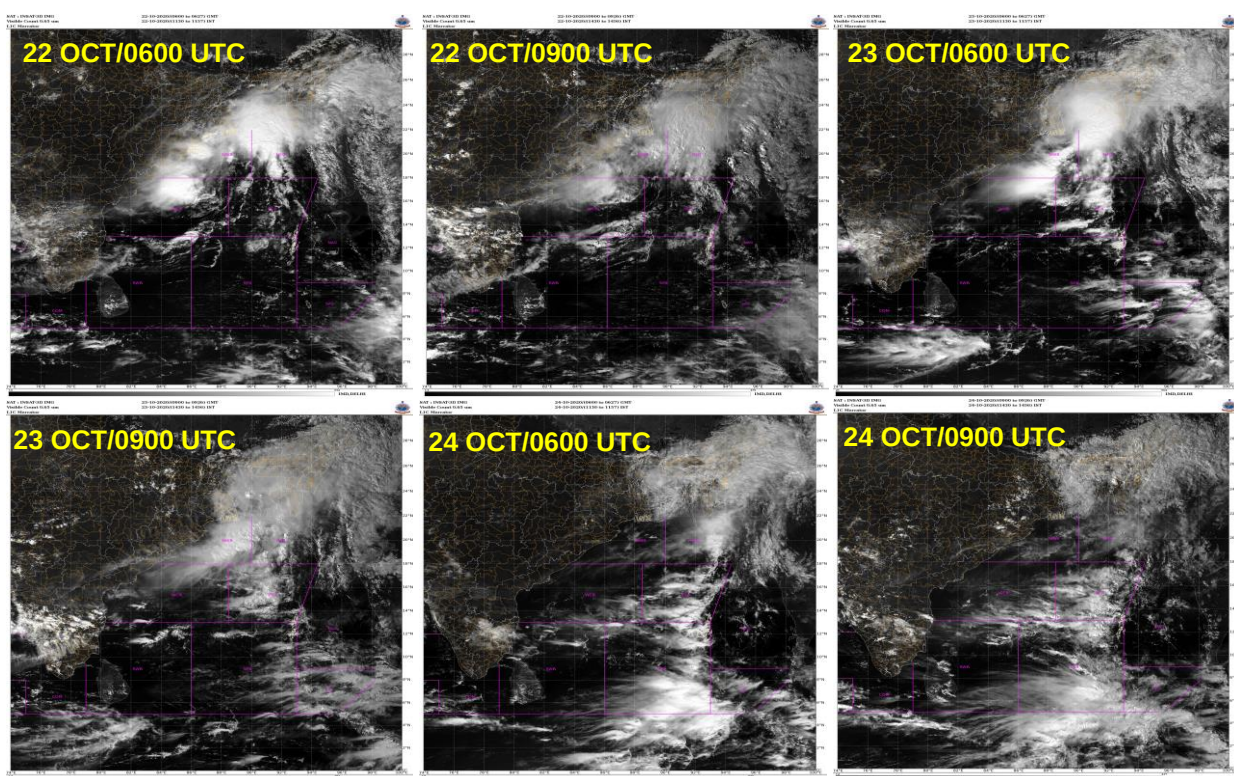


Fig. 2.7.2d: INSAT-3D visible imageries during life cycle of Depression (22-24 October, 2020)

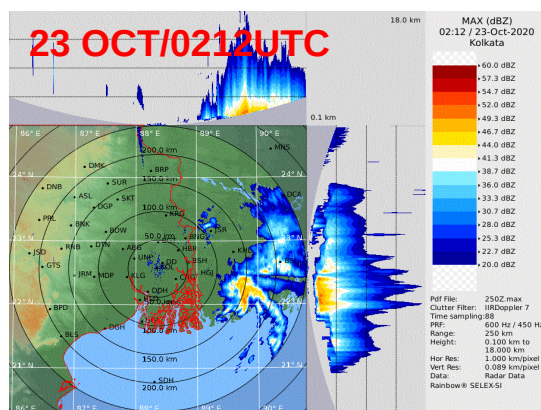


Fig 2.7.3a: Typical Max Z Radar imageries of DWR KOLKOTA during 23 October, 2020

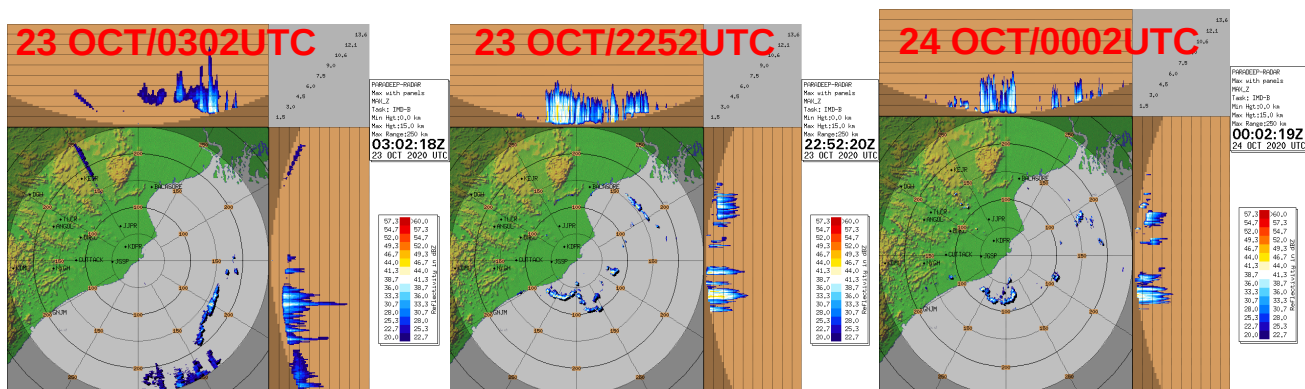


Fig 2.6.3b: Typical Max Z Radar imageries of DWR PARADIP during 22-24 October, 2020

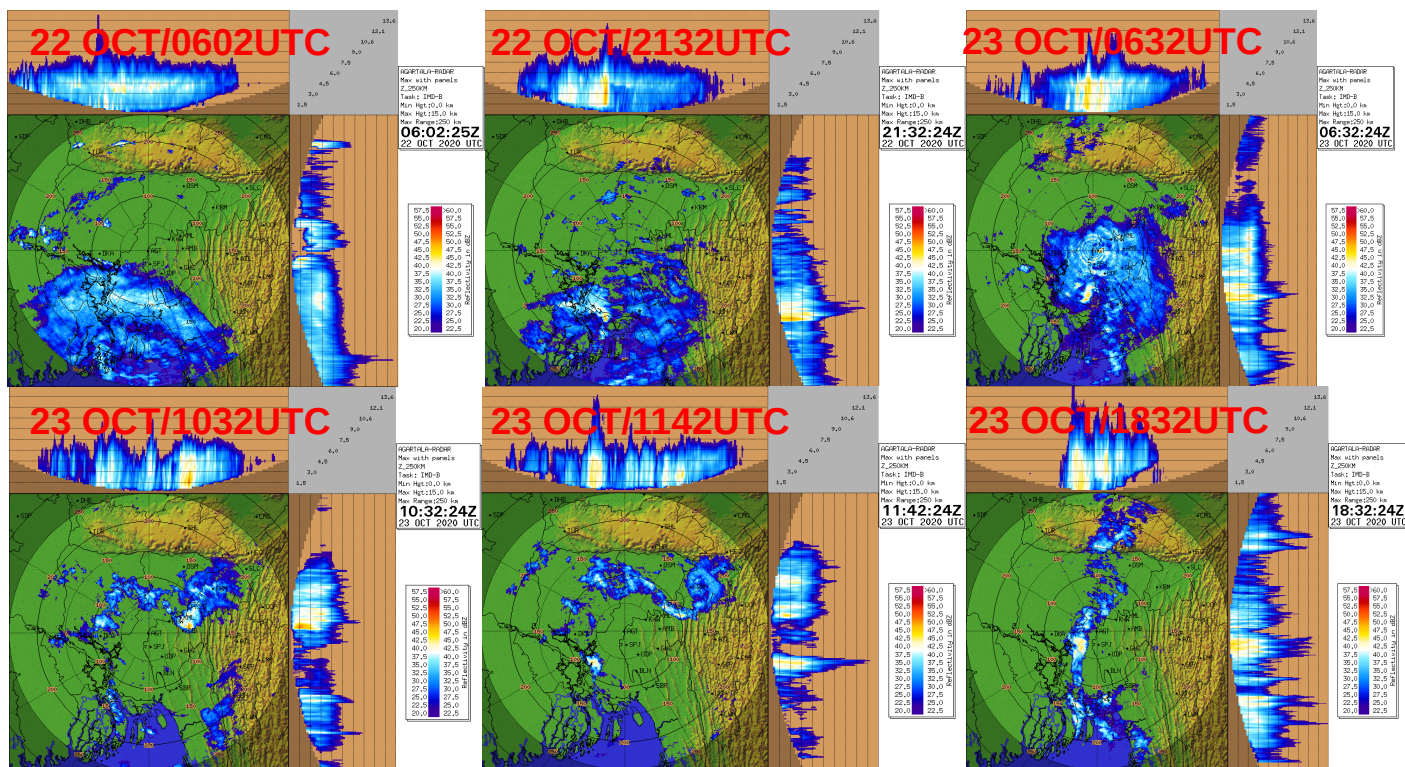


Fig 2.7.3c: Typical Max Z Radar imageries of DWR AGARTALA during 22-24 October, 2020

2.7.4. Dynamical features

IMD GFS (T1534) analysis fields of mean sea level pressure (MSLP), winds at 10 m, 850, 500 and 200 hPa levels are presented in Fig. 2.7.4 (a) – 5(d).

At 0000 UTC of 21st October, it indicated a Depression over northern parts of west-central BoB. The circulation was seen extending upto 500 hPa level. At 200 hPa level, an anti-cyclone prevailed to the northeast of the system centre, indicating the likely northeastward movement of the system. In general, the model simulated the system quite well, with slight shift in the observed location.

At 0000 UTC of 22nd October, it indicated a Depression lying over northwest BoB. The circulation was seen extending upto 500 hPa level, but with slight southward tilt. Also a trough in mid-latitude westerlies was shown to be present to the west of the system, over northwest India at 500 hPa. At 200 hPa level the anti-cyclone was located overhead the system centre, providing upper level divergence. The system intensity at 0000 UTC remained that of a Depression. Also the location was aptly simulated by the model.

At 0000 UTC of 23rd October, the model indicated the system as a Depression (with slight intensification, as compared to the previous day) over northwest BoB, close to south Bangladesh coast. The circulation was seen extending only upto 600 hPa level (Figure not shown). The westerly trough at 500 hPa had moved further eastwards & was seen over eastern India, to the west of the system. The anti-cyclone at 200 hPa level remained to be overhead the system, though its vertical extension had diminished. The system as a Depression lay close to Bangladesh coast.

At 0000 UTC of 24th October, the model located the system as a Low Pressure Area centered over Bangladesh and adjoining Assam & Meghalaya. The circulation was seen extending upto 850 hPa level. The westerly trough was seen over the system area at 500 hPa level. In reality, the system had crossed West Bengal & adjoining Bangladesh coasts (near latitude 21.8°N & longitude 88.5° E), between 0600 & 0700 UTC of 23rd October 2020. It maintained the intensity of Depression till the mid-night of 23rd October and subsequently weakened into well marked low pressure area over Central parts of Bangladesh by 0000 UTC of 24th October.

Thus IMD GFS provided reliable guidance in forecasting the intensity & movement of the system all through its life period.

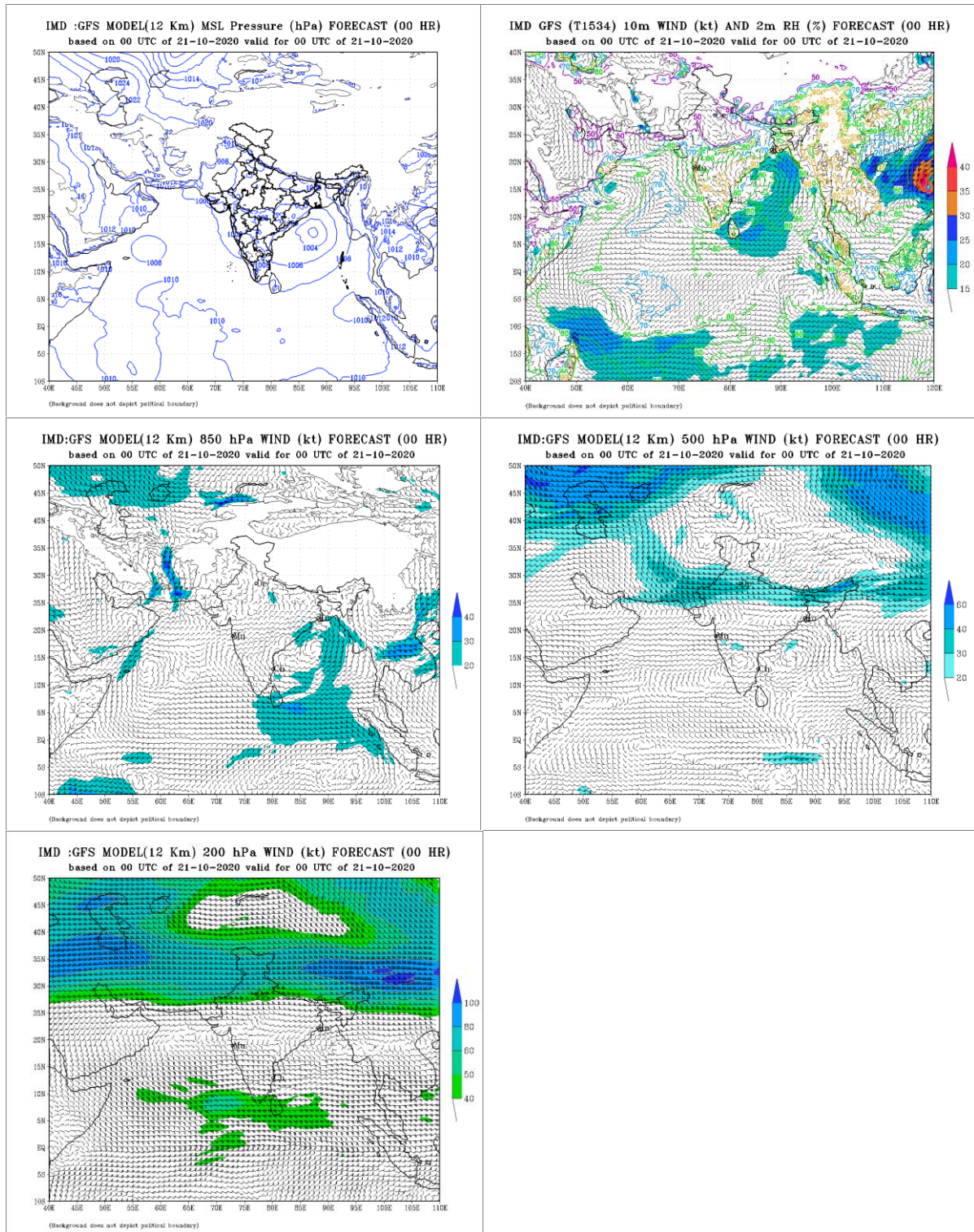


Fig. 2.7.4 (a): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 21st October 2020

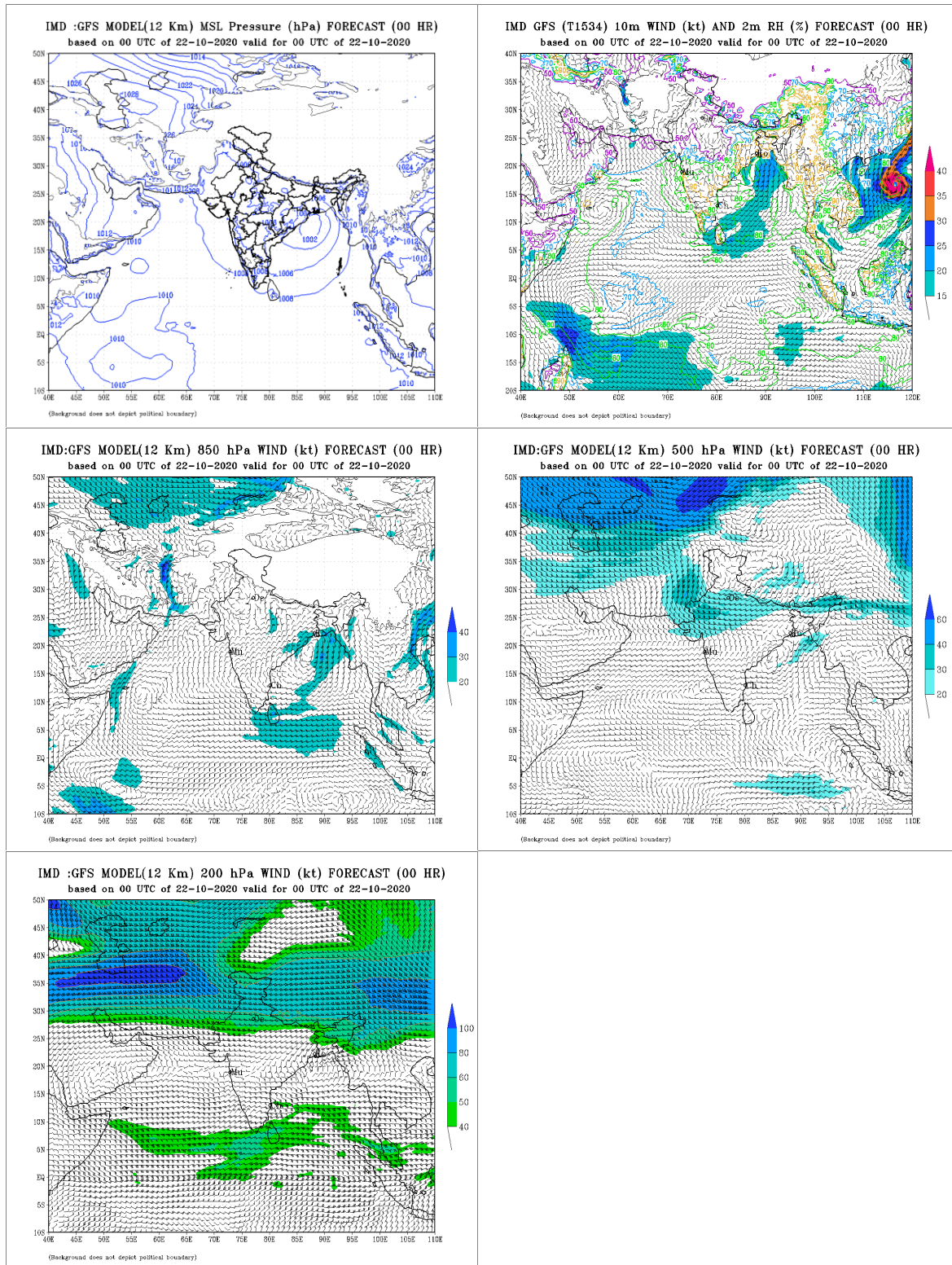


Fig. 2.7.4 (b): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 22nd October 2020

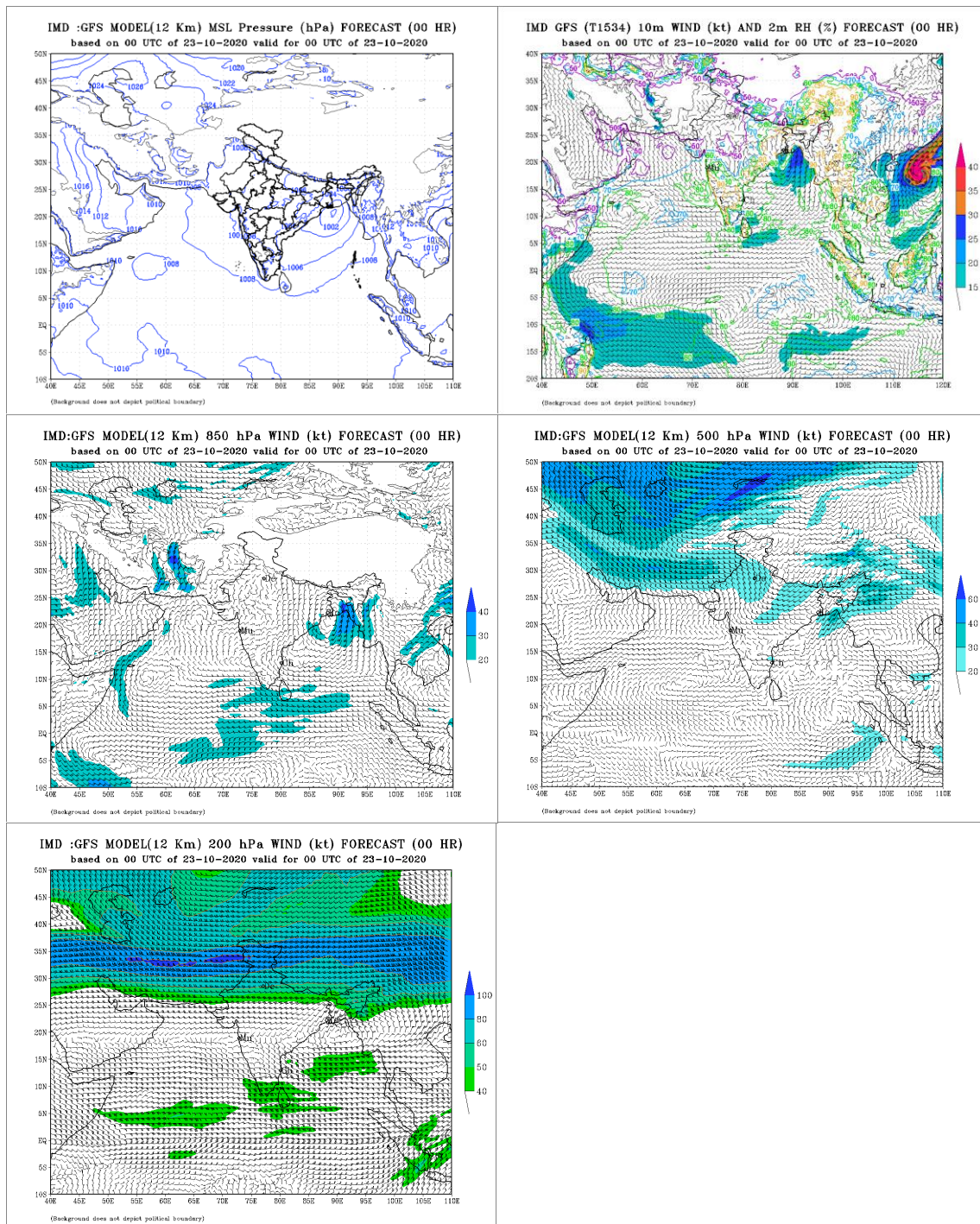


Fig. 2.7.4 (c): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 23rd October 2020

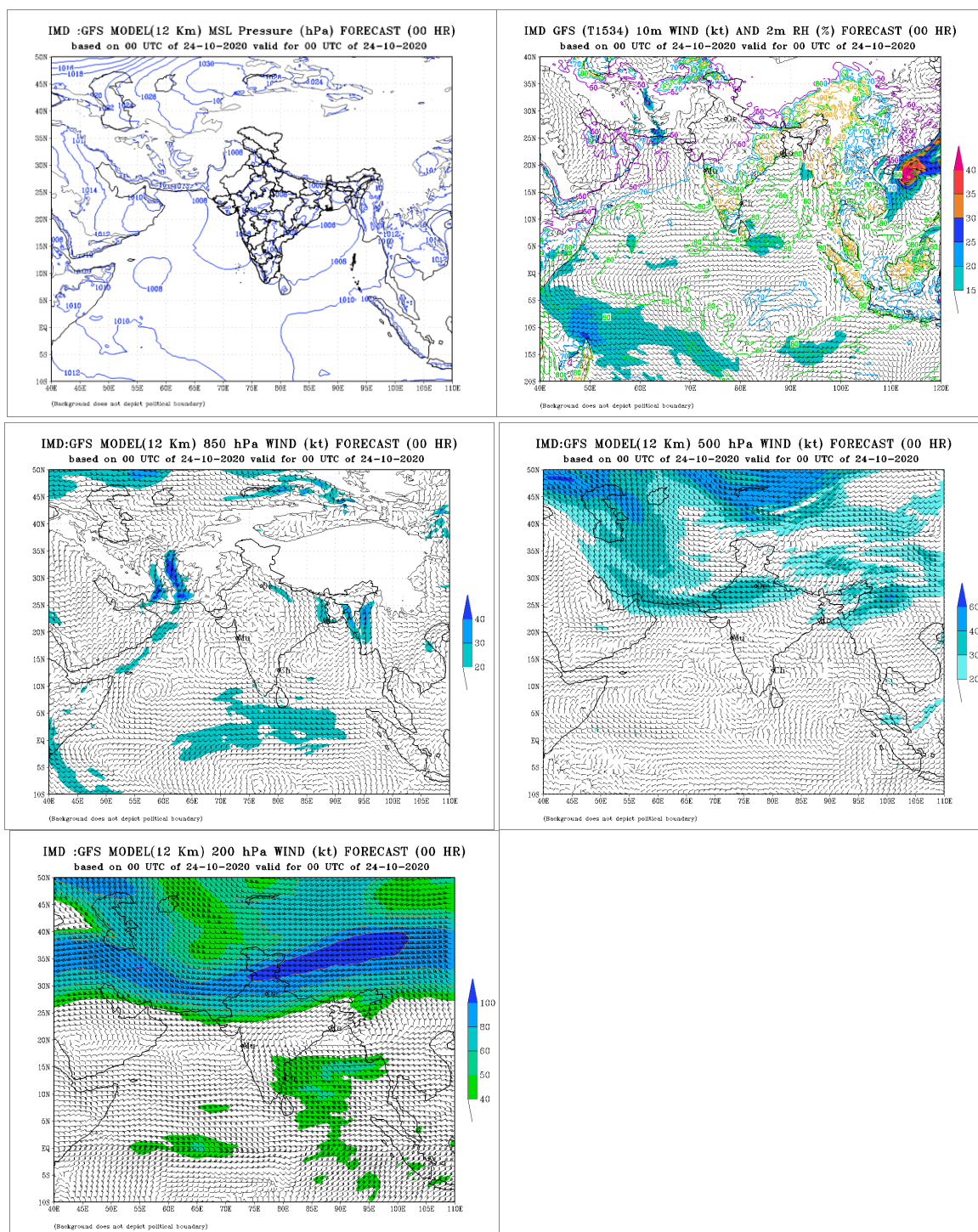


Fig. 2.7.4 (d): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 24th October 2020

2.7.5. Realized Weather:

Realised rainfall in association with the system based on IMD-NCMRWF GPM merged gauge rainfall data is depicted in Fig 2.7.5. It may be noted that the system caused heavy rainfall at few places over coastal Odisha on 22nd, heavy to very heavy rainfall with extremely heavy rainfall at a few places over coastal Bangladesh on 23rd and over Assam & Meghalaya on 24th.

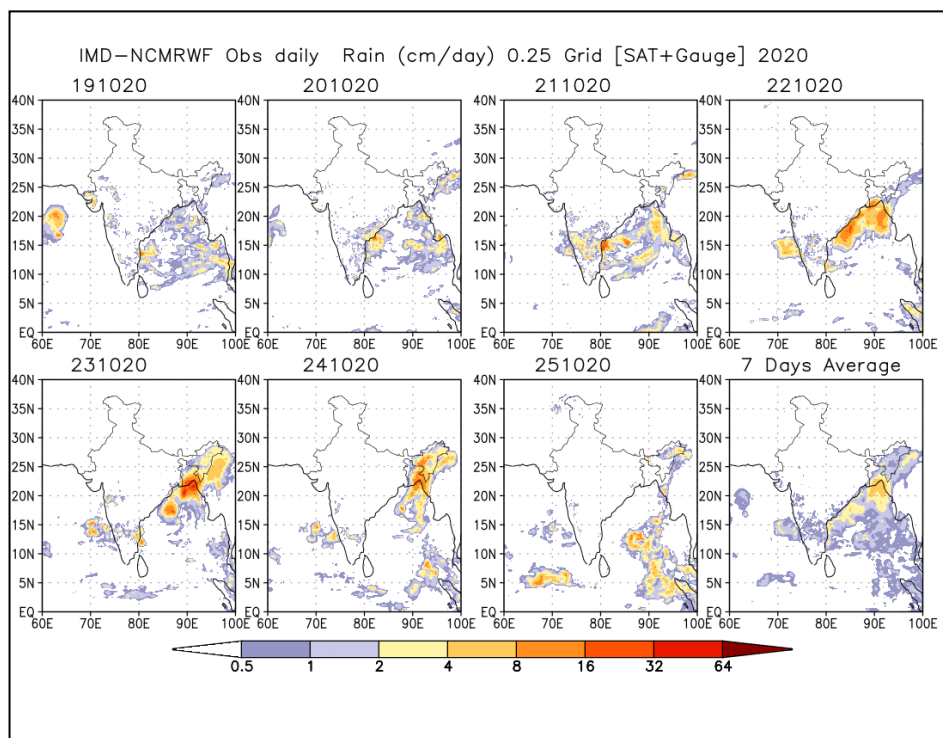


Fig. 2.7.5: Daily rainfall distribution based on merged gridded rainfall data of IMD/ NCMRWF during 19-25 October, 2020

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

(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).

22nd October

Odisha: Paradip -7, Tihidi-7.

23rd October

Assam & Meghalaya: Mawsynram-13, Sohra-12, Sohra (RKM) -11, Bakulia-8

Nagaland- Manipur – Mizoram – Tripura: Sabroom-8, Lawngtlai-7

Odisha: Kendrapara-7

24th October

Assam & Meghalaya: Mawsynram-35, Sohra (RKM) – 30, Sohra -29, Shillong C.S.O.-17, Nongstein-16, Shillong AWS-15, Barapani-13, Dharamtul-10, Kampur-10, Williamnagar-7, Numaligarh-7, Bhaghmara-7.

Nagaland- Manipur – Mizoram – Tripura: Kailashahar Aero-9, Gande cherra-7, Dharmanagar/ Panisagar-7, Sonamura-7, Udaipur-7.

2.8 Very Severe Cyclonic Storm “GATI” over the Arabian Sea (21-24 November 2020)

2.8.1 Introduction

Very Severe Cyclonic Storm (VSCS) “GATI” originated from a low pressure area formed over central parts of south Arabian Sea (AS) in the morning (0300 UTC) 19th November. It lay as a well marked low pressure area over southwest AS & neighborhood in the early morning (0000 UTC) 21st. It concentrated into a depression over the same region in the midnight (1800 UTC) of 21st. Moving west-southwestwards, it explosively intensified into a deep depression in the early morning (0000 UTC) of 22nd, further into the cyclonic storm “**GATI**” in the same morning (0300 UTC), into a severe cyclonic storm in the noon (0600 UTC) and into very severe cyclonic storm in the afternoon (0900 UTC) over southwest AS. It reached it’s peak intensity of 75 knots in the same evening (1200 UTC) over the southwest AS. Continuing to move westwards, it crossed Somalia coast near latitude 10.45°N and longitude 51.10°E between 1400 and 1500 UTC of 22nd as a very severe cyclonic storm with estimated wind speed of 130-140 kmph gusting to 155 kmph. Continuing to move nearly westwards, it weakened into a severe cyclonic storm in the early hours (2100 UTC of 22nd) of 23rd, into a cyclonic storm in the early morning (0000 UTC) and into a deep depression in the same noon (0600 UTC) over north Somalia.

Thereafter, it moved west-northwestwards and emerged into Gulf of Aden in the evening (1200 UTC) of 23rd. Continuing to move west-northwestwards, it weakened into a depression in the early morning (0000 UTC) of 24th over Gulf of Aden and adjoining north Somalia and into a well marked low pressure area in the noon (0600 UTC) of 24th over the same region. As per media reports, intense rainfall activity occurred over north Somalia. More than 20 cm rainfall occurred during the period of a day against about 10 cm of annual rainfall over this region. The observed track of the system during 21st to 24th November is presented in Fig. 2.8.1.

2.8.2 Salient Features:

The salient features of the system were as follows:

- GATI was the first very severe cyclonic storm ($MSW \geq 64$ KT) crossing Somalia coast during satellite era as per the best track data available with IMD. However it is the second severe cyclonic storm to cross Somalia after 1994. A severe cyclonic storm crossed north Somalia coast during early hours of 20th November 1994 with a wind speed of 101 kmph. Another cyclonic storm (MURJAN) crossed Somalia coast on 26th October 2012. Cyclonic storms, Sagar (in 2018) & Pawan (in 2019) respectively crossed Somalia coast in recent years. Thus though rare, Somalia gets affected by the cyclones from Arabian Sea. Looking at the above statistics, the frequency of cyclones hitting Somalia coast has increased in recent years (2010 onwards).
- Yemen and Somalia also get affected by the cyclones moving into Gulf of Aden. Like the case of cyclone, GATI.

- GATI underwent explosive intensification with an increase in maximum sustained wind speed by 45 knots in 12 hours during 0000 to 1200 UTC of 22nd.
- It moved very fast with a 6-hourly speed of about 20 kmph against the long period average of 13.6 kmph for the period 1990-2013 for cyclonic storms over the Arabian Sea. On 22nd November, it moved with a six hourly speed varying between 36-50 kmph.
- It maintained the intensity of cyclonic storm for about 15 hours after crossing Somalia coast.

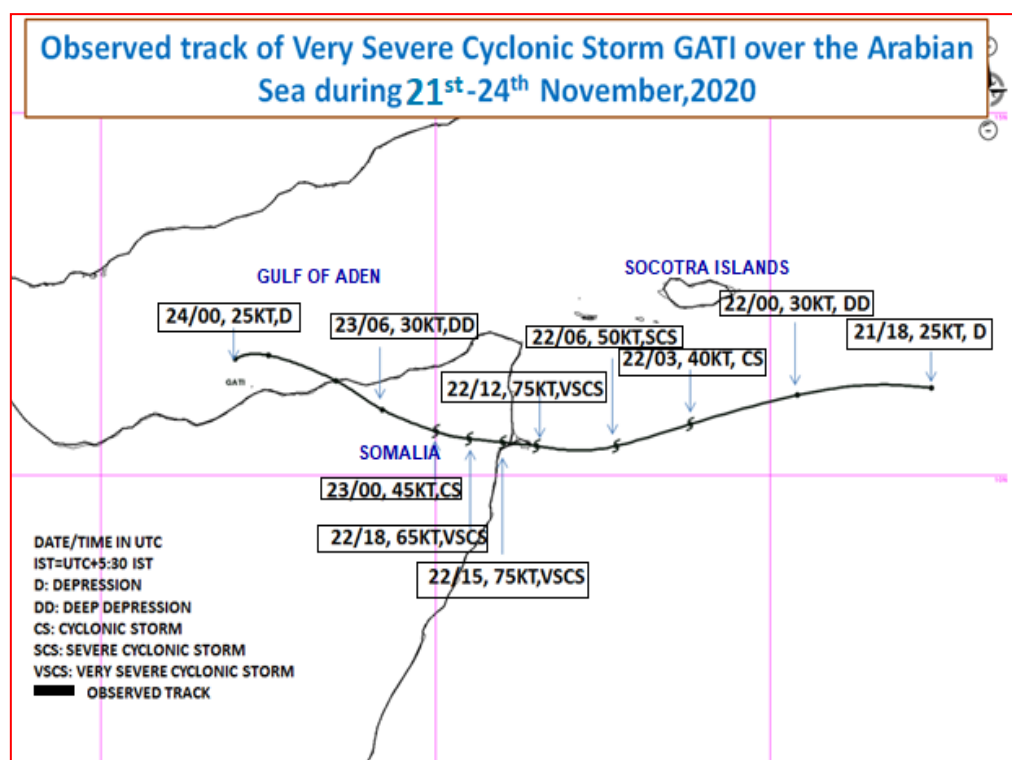


Fig.2.8.1 Observed track of VSCS GATI (21-24 November, 2020) over the Arabian Sea

Table 2.8.1: Best track positions and other parameters of the Very Severe Cyclonic Storm “GATI” over the Arabian Sea during 21-24 November, 2020

Date	Time (UTC)	Centre lat. ^o N/ long. ^o E		C.I. NO	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
21/11/2020	1800	11.2	57.4	1.5	1000	25	04	D
22/11/2020	0000	11.1	55.4	2.0	998	30	06	DD
	0300	10.7	53.8	2.5	996	40	08	CS
	0600	10.4	52.7	3.0	992	50	12	SCS
	0900	10.4	52.0	4.0	982	65	22	VSCS

	1200	10.4	51.5	4.5	976	75	26	VSCS
		Crossed Somalia Coast near lat 10.45 ⁰ N and long 51.1 ⁰ E between 1400 and 1500 UTC of 22 nd Nov. with a maximum sustained wind speed 75 kts gusting to 85 kts						
	1500	10.4	51.0	-	976	75	26	VSCS
	1800	10.4	50.5	-	982	65	22	VSCS
	2100	10.4	50.1	-	986	60	18	SCS
23/11/2020	0000	10.5	50.0	-	994	45	10	CS
	0300	10.7	49.7	-	997	35	07	CS
	0600	10.9	49.2	-	998	30	06	DD
		Emerged into Gulf of Aden as a Deep Depression around 1200 UTC of 23 rd Nov.						
	1200	11.3	48.5	2.0	999	30	05	DD
	1800	11.7	47.5	2.0	1000	30	05	DD
24/11/2020	0000	11.6	47.0	1.5	1001	25	04	D
	0300	11.6	46.8	1.5	1002	20	03	D
	0600	Weakened into a well-marked low-pressure area over the same region at 0600UTC of 24 th Nov.						

2.8.3. Brief life history

2.8.3.1. Genesis

A low-pressure area formed over central parts of south Arabian Sea (AS) at 0300 UTC of 19th November. It lay as a well-marked low pressure area over southwest AS & neighborhood at 0000 UTC of 21st. It concentrated into a depression over the same region at 1800 UTC of 21st.

During 18th – 20th November, the convectively active regime of Madden Julian Oscillation (MJO), represented mathematically by the MJO index, lay in Phase 2 (western Indian Ocean) with amplitude more than 1. It shifted eastwards into Phase 3 (eastern Indian Ocean) with amplitude close to 1, on 21st November, the day of formation of the Depression. Thus, the MJO had favored the genesis of the system.

The Sea Surface Temperature (SST) was around 29-30°C over most parts of south and east-central Arabian Sea (AS). It was slightly less (26-28°C) over west-central & north AS.

High Tropical Cyclone Heat Potential (TCHP), (100-120 KJ/cm²) prevailed over Comorin area and adjoining southwest BOB off south Sri Lanka coast and Kerala coast. TCHP was around 60-80 KJ/cm² over major parts of south AS except off north Somalia coast. It was less than 50KJ/cm² to the west of 68°E and north 11°N over the central & north AS and 60 – 80 KJ/cm² over remaining parts of east-central & northeast AS.

On 18th November, Positive relative vorticity ($25-50 \times 10^{-6} \text{s}^{-1}$) prevailed over southeast and adjoining southwest & west-central AS with vertical extension upto 200 hPa level. Area of positive divergence ($20-30 \times 10^{-5} \text{s}^{-1}$) prevailed over southeast AS to the southwest of the potential genesis area. Area of positive convergence zone ($05-10 \times 10^{-5} \text{s}^{-1}$) prevailed over southeast AS to the southeast of this zone. The vertical wind shear (VWS) has been moderate (10-15 KTS) over southeast and adjoining southwest & west-central AS. The upper tropospheric ridge at 200 hPa ran along 15°N over the AS.

On 19th November, Positive relative vorticity ($25-50 \times 10^{-6} \text{s}^{-1}$) prevailed over southeast and adjoining southwest & west-central AS with vertical extension upto 200 hPa level. Area of positive divergence ($30 \times 10^{-5} \text{s}^{-1}$) prevailed over southwest AS. Area of positive convergence zone ($05-10 \times 10^{-5} \text{s}^{-1}$) prevailed over central parts of south AS. The vertical wind shear (VWS) was low to moderate (5-20 kts) over central parts of AS and adjoining south AS. The upper tropospheric ridge at 200 hPa ran along 15°N over the AS.

On 20th November, Positive relative vorticity ($25-50 \times 10^{-6} \text{s}^{-1}$) prevailed over central parts of south AS and adjoining west-central AS with vertical extension upto 200 hPa level. Area of positive divergence ($5-20 \times 10^{-5} \text{s}^{-1}$) prevailed over west-central AS to the northwest of the potential genesis area. Area of positive convergence zone ($05-10 \times 10^{-5} \text{s}^{-1}$) prevailed over central parts of south AS and adjoining central AS. The vertical wind shear (VWS) was low to moderate (5-20 kts) over central parts of AS and adjoining south AS. The upper tropospheric ridge at 200 hPa ran along 15°N over the AS.

On 21st November, two fragmented positive relative vorticity zones ($25-50 \times 10^{-6} \text{s}^{-1}$) prevailed over southwest AS and another ($20-30 \times 10^{-6} \text{s}^{-1}$) prevailed over southwest & adjoining southeast AS with vertical extension upto 500 hPa level. Two areas of positive divergence ($10 \times 10^{-5} \text{s}^{-1}$ & $20 \times 10^{-5} \text{s}^{-1}$) prevailed over southwest AS. Another divergence zone of $30 \times 10^{-5} \text{s}^{-1}$ prevailed over southwest AS. Area of positive convergence zone ($20 \times 10^{-5} \text{s}^{-1}$) prevailed over southwest AS. The vertical wind shear (VWS) was low to moderate (5-20 kts) over central parts of AS and adjoining south AS. The upper tropospheric ridge at 200 hPa ran along 15°N over the AS.

Thus, it may be concluded that, under the large scale convective environment, other favourable dynamic & thermodynamic features like, a marginally high TCHP, Low VWS and a vertically coupled low level convergence & upper level divergence zones led to a steady build up of cyclonic vorticity over southwest Arabian Sea leading to the formation of the Depression on 21st Night.

2.8.3.2 Intensification and movement

The intensification of VSCS GATI was explosive in nature, as the Depression, while moving west-southwestwards, intensified into a deep depression by 0000 UTC of 22nd, further into the cyclonic storm “**GATI**” by 0300 UTC, into a severe cyclonic storm by 0600 UTC and into very severe cyclonic storm by 0900 UTC over southwest AS, all on 22nd November. It reached its peak intensity of 75 knots in the same evening (1200 UTC) over southwest AS. Continuing to move westwards, it crossed Somalia coast between 1400 and 1500 UTC of 22nd as a very severe cyclonic storm. Continuing to move nearly westwards, it weakened into a severe cyclonic storm by 2100 UTC of 22nd, into a cyclonic storm by 0000 UTC of 23rd and into a deep depression by 0600 UTC over north Somalia. Thereafter, it moved west-northwestwards and emerged into Gulf of Aden by 1200 UTC of 23rd. Continuing to move west-northwestwards, it weakened into a depression by 0000 UTC of 24th over Gulf of Aden and adjoining north Somalia and into a well marked low pressure area by 0600 UTC of 24th over the same region.

The environmental features which supported this type of rapid intensification and movement are described below:

All through the life cycle, the MJO index lay in phase 3 with amplitude close to 1, favouring convective environment over the Arabian Sea. Also the SST was around 29-

30°C over most parts of south and east-central Arabian Sea (AS). TCHP was around 60-80 KJ/cm² over major parts of south AS except off north Somalia coast.

At 1800 UTC of 21st November, Relative vorticity zone ($100 \times 10^{-6} \text{s}^{-1}$) prevailed over south Arabian Sea to the southwest of the system. An area of positive upper level divergence $20 \times 10^{-5} \text{s}^{-1}$ and an area of positive low level convergence zone ($10 \times 10^{-5} \text{s}^{-1}$) prevailed to the southwest of the system. The vertical wind shear (VWS) was low to moderate (10-15 kts) over and to the west of the system. The upper tropospheric ridge at 200 hPa ran along 15°N.

At 0000 UTC of 22nd November, Relative vorticity zone ($100 \times 10^{-6} \text{s}^{-1}$) prevailed around the system. An area of positive divergence $20 \times 10^{-5} \text{s}^{-1}$ and an area of positive convergence zone ($10 \times 10^{-5} \text{s}^{-1}$) prevailed over and to the southwest of the system. The vertical wind shear (VWS) was low to moderate (10-15 kts) over and to the west of the system. The upper tropospheric ridge at 200 hPa ran along 15°N.

At 0300 UTC of 22nd November, Relative vorticity zone ($100 \times 10^{-6} \text{s}^{-1}$) prevailed around the system. An area of positive divergence $20 \times 10^{-5} \text{s}^{-1}$ and area of positive convergence zone ($20 \times 10^{-5} \text{s}^{-1}$) prevailed around the system. The vertical wind shear (VWS) was low to moderate (15-20 kts) over and to the west of the system. The upper tropospheric ridge at 200 hPa ran along 15°N.

At 0600 UTC of 22nd November, Relative vorticity zone ($100 \times 10^{-6} \text{s}^{-1}$) prevailed around the system. An area of positive divergence $30 \times 10^{-5} \text{s}^{-1}$ and area of positive convergence zone ($40 \times 10^{-5} \text{s}^{-1}$) prevailed around the system. The vertical wind shear (VWS) was low to moderate (15-20 kts) over and to the west of the system. The upper tropospheric ridge at 200 hPa ran along 15°N.

At 0900 UTC of 22nd November, Relative vorticity zone ($100 \times 10^{-6} \text{s}^{-1}$) prevailed around the system. An area of positive divergence $30 \times 10^{-5} \text{s}^{-1}$ and area of positive convergence zone ($40 \times 10^{-5} \text{s}^{-1}$) prevailed around the system. The vertical wind shear (VWS) was low to moderate (15-20 kts) over and to the west of the system. The upper tropospheric ridge at 200 hPa ran along 15°N.

The very severe cyclonic storm "GATI" crossed Somalia coast around 1500 UTC of 22nd November. At 2100 UTC of 22nd November, Relative vorticity zone ($50 \times 10^{-6} \text{s}^{-1}$) prevailed around the system. An area of positive divergence ($10 \times 10^{-5} \text{s}^{-1}$) and another area of divergence zone ($05 \times 10^{-5} \text{s}^{-1}$) prevailed around the system. The vertical wind shear (VWS) was low to moderate (15-20 kts) over and to the west of the system. The upper tropospheric ridge at 200 hPa ran along 15°N.

At 0000 UTC of 23rd November, Relative vorticity zone ($50 \times 10^{-6} \text{s}^{-1}$) prevailed around the system. An area of positive convergence ($10 \times 10^{-5} \text{s}^{-1}$) and area of divergence zone ($05 \times 10^{-5} \text{s}^{-1}$) prevailed around the system. The vertical wind shear (VWS) was low to moderate (15-20 kts) over and to the west of the system. The upper tropospheric ridge at 200 hPa ran along 15°N.

At 0600 UTC of 23rd November, Relative vorticity zone ($50 \times 10^{-6} \text{s}^{-1}$) prevailed around the system. An area of positive convergence ($10 \times 10^{-5} \text{s}^{-1}$) and area of divergence zone ($20 \times 10^{-5} \text{s}^{-1}$) prevailed around the system. The vertical wind shear (VWS) was low to moderate (15-20 kts) over and to the west of the system. The upper tropospheric ridge at 200 hPa ran along 16°N. By this time, the system had weakened into a well marked low pressure area over Gulf of Aden and adjoining north Somalia.

Apart from the large scale convective environment provided by the favourable phase of MJO, sufficiently warm SST & TCHP, low level convergence associated with the easterly wave regime, low VWS & enhanced upper level divergence could have aided the anomalously rapid intensification. Its near westward movement was facilitated by the easterly winds to the south of the sub-tropical Ridge axis.

The Total Precipitable Water vapour (TPW) imageries during 21-24 Nov. 2020 are presented in **Fig.2.8.2**. These imageries indicate continuous warm and moist air advection from the near equatorial belt of Inter Tropical convergence Zone across the southeast sector of the system into its core till the night of 22nd November, during the period of its rapid intensification. However, as the system approached coast, there was land interaction and moisture supply also reduced relatively as evident from TPW imageries on 23rd and 24th Nov. The TPW image also indicates relatively cold air advection from Somalia on 23rd and 24th Nov. helping in weakening of the system.

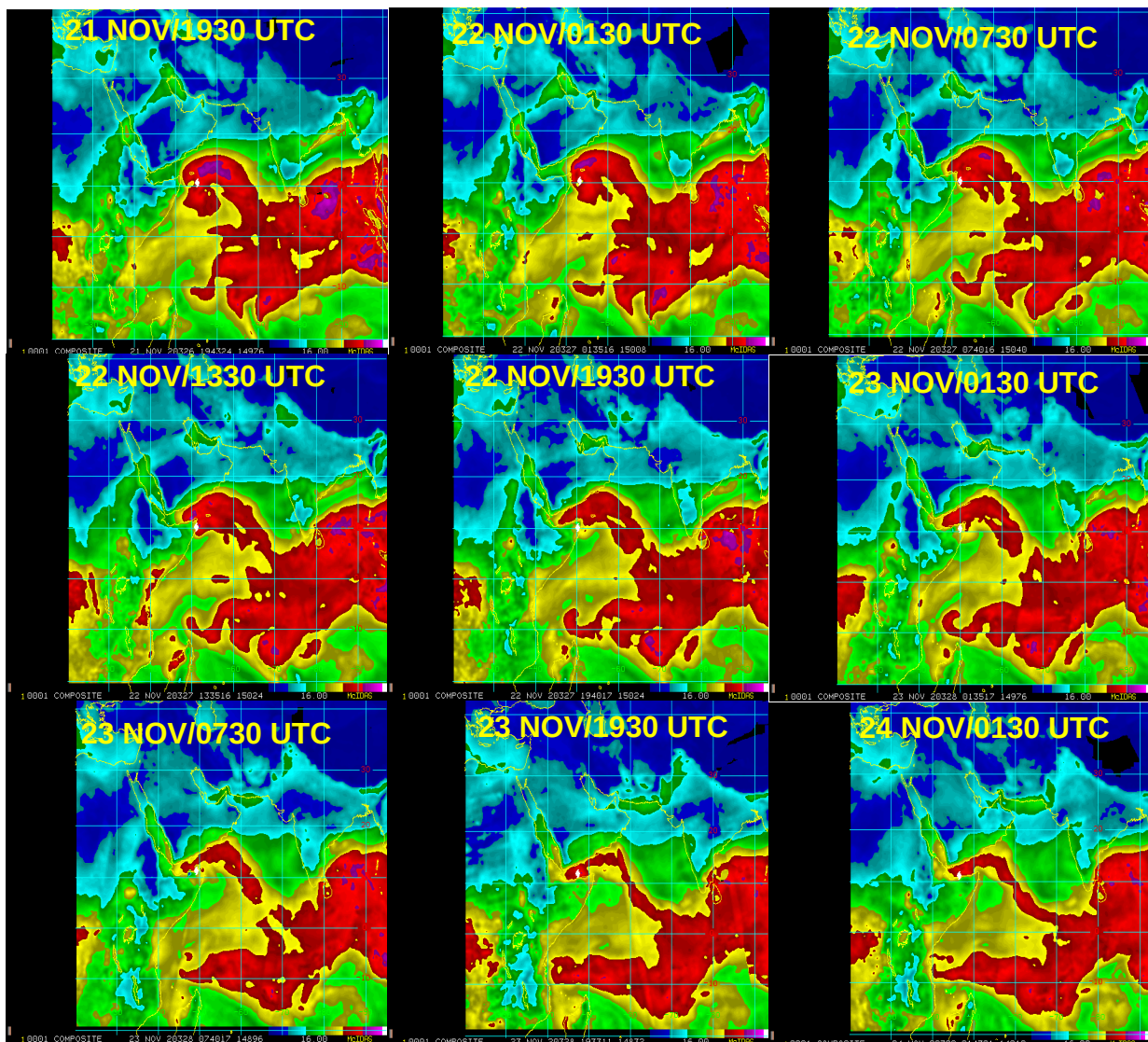


Fig. 2.8.2: Total Precipitable Water vapour (TPW) imageries of VSCS GATI during 21-24 November, 2020

The wind speed in middle and deep layer around the system centre is presented in **Fig.2.8.3**. low to moderate easterly shear (around 15 knots) prevailed during the genesis & mature phase of the system which gradually increased and became High westerly shear during the dissipation stage.

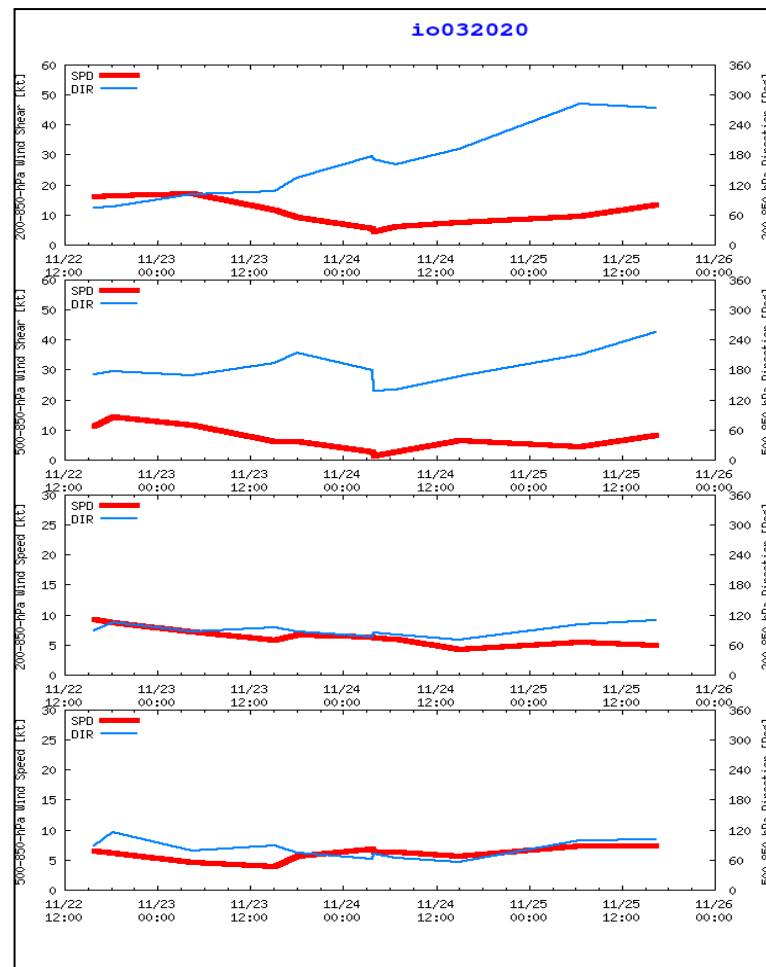


Fig.2.8.3 Wind shear and wind speed in the middle and deep layer around the system VSCS GATI during 21-24 November, 2020

Fig.2.8.3, also indicates that from the genesis stage, the mean deep layer winds between 200-850 hPa levels steered the system initially westwards till 15 UTC of 22nd Nov. and west-northwestwards subsequently.

2.8.3.3 Maximum Sustained Surface Wind speed and estimated central pressure

The lowest estimated central pressure and the maximum sustained wind speed are presented in Fig.2.8.4a. There was rapid fall in pressure during the period 1800 UTC of 21st to 1200 UTC of 22nd. The lowest estimated central pressure had been 976 hPa during at 1200 UTC of 22nd November. The estimated maximum sustained surface wind speed (MSW) was 75 at 1200 UTC of 22nd with pressure drop of 26 hPa. The pressure rapidly increased during 1200 UTC of 22nd to 0000 UTC of 23rd. At the time of landfall, the ECP was 976 hPa and MSW was 75 knots (very severe cyclonic storm) gusting to 85 kts.

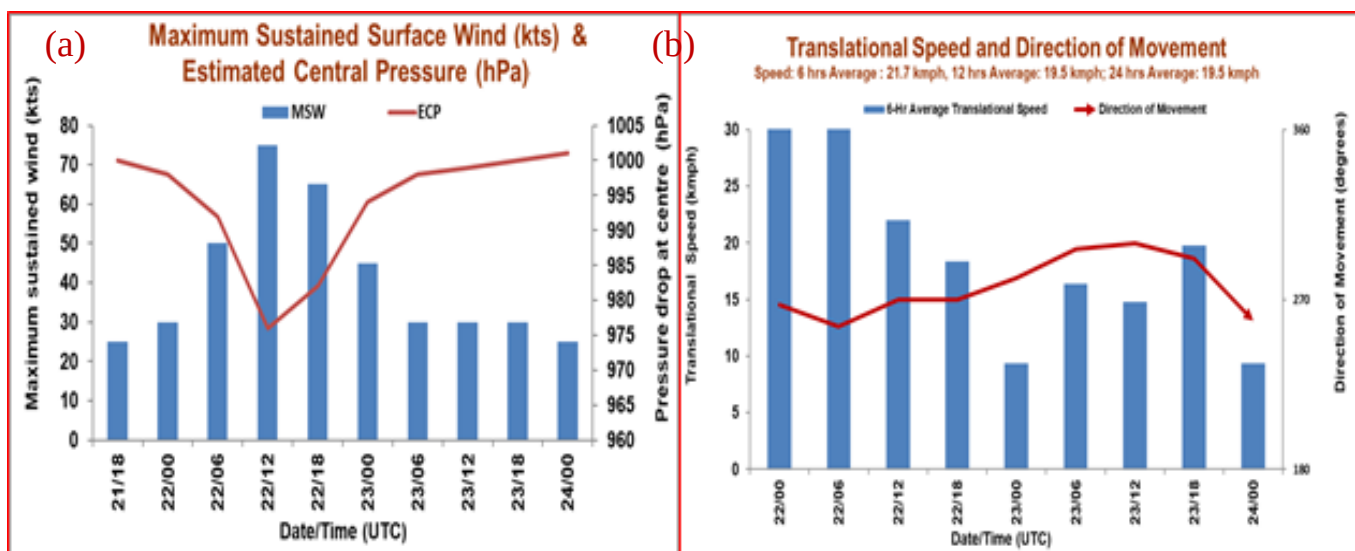


Fig.2.8.4. (a) Maximum sustained surface winds (kts) & (b) Estimated Central Pressure and (b) Mean Translational Speed during life cycle of VSCS GATI

2.8.3.3 Translational speed & direction of movement

The twelve hourly movement of VSCS GATI is presented in **Fig.2.8.4b**. The 12 hour average translational speed of the cyclone was about 19.5 kmph against the normal speed of 19.3 kmph for VSCS category over AS during post monsoon season. During initial stages of it's development from 1800 UTC of 21st to 0600 UTC of 22nd, it moved very fast with an average speed of 35-45 kmph. The east-northeasterly winds in the upper level contributed to this faster movement of the system. The mean wind speed and direction in the deep layer between 850-200 hPa level and the middle layer between 850-500 hPa level is presented in Fig. 2.8.3.

2.8.4 Monitoring of VSCS, 'GATI'

India Meteorological Department (IMD) maintained round the clock watch over the north Indian Ocean and the cyclone was monitored since 12th November, about 10 days prior to the formation of depression over southwest AS on 22nd. The cyclone was mainly monitored with the help of available satellite observations from INSAT 3D and 3DR, SCAT SAT, polar orbiting satellites and available ships & buoy observations in the region. Various numerical weather prediction models run by Ministry of Earth Sciences (MoES) institutions (IMD, IITM, NCMRWF, INCOIS), global models and dynamical-statistical models were utilized to predict the genesis, track, landfall and intensity of the cyclone. A digitized forecasting system of IMD was utilized for analysis and comparison of various models' guidance, decision making process and warning products' generation.

2.8.4.1 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.2.8.5**. The system showed curved band pattern during genesis and growth stage upto the intensity of CS. It had central dense overcast (CDO) pattern during SCS stage. It showed sheared pattern after landfall.

At 0000 UTC of 22.11.2020 as per satellite imagery, the intensity of the system was T 2.0. Broken low and medium clouds with embedded intense to very intense convection lay over southwest & adjoining west-central Arabian Sea between latitude 7.5°N & 12.5°N and longitude 50.5°E & 57.5°E in association with the system. The minimum cloud top temperature has been (Minus) 93°C .

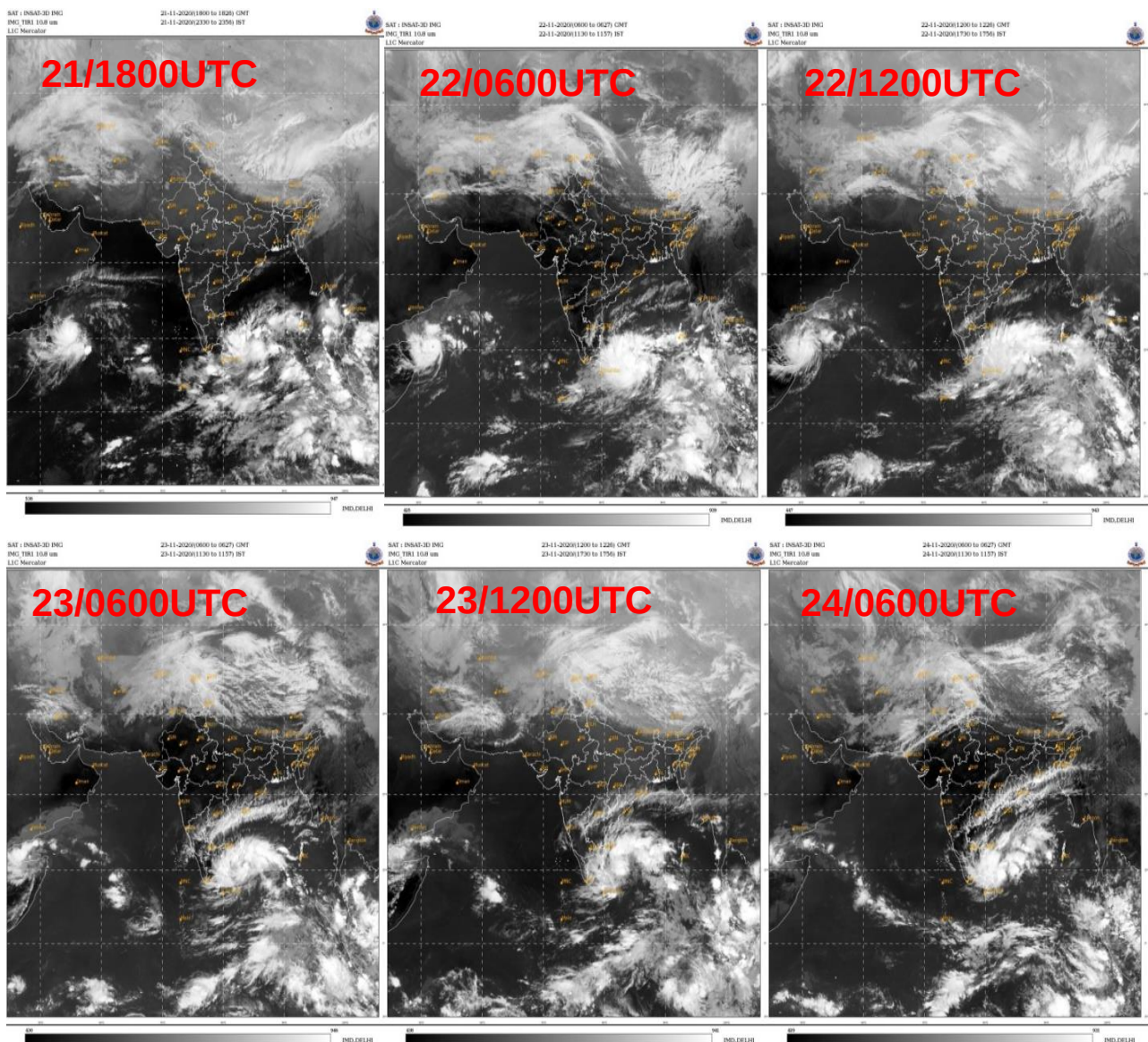


Fig. 2.8.5(a): INSAT-3D IR1 imageries during life cycle of VSCS GATI (21 NOV-24 NOV, 2020)

At 0300 UTC of 22.11.2020 as per satellite imagery, the intensity of the system was T 2.5. It showed curved band pattern with spiral banding of 0.6. Maximum convection lay in the southern sector of vortex. Broken low and medium clouds with

embedded intense to very intense convection lay over southwest & adjoining west-central Arabian Sea between latitude 8°N & 12°N and longitude 49.5°E & 55.5°E in association with the system. The minimum cloud top temperature has been (Minus) 93°C .

At 0600 UTC of 22.11.2020 as per satellite imagery, the intensity of the system was T 3.0. It showed curved band pattern with spiral banding of 0.75. Satellite imagery indicated rapid organization. Maximum convection lay in the southern sector of vortex. Broken low and medium clouds with embedded intense to very intense convection lay over southwest & adjoining west-central Arabian Sea between latitude 8°N & 12°N and longitude 49.5°E & 55.5°E in association with the system. The minimum cloud top temperature has been (Minus) 93°C .

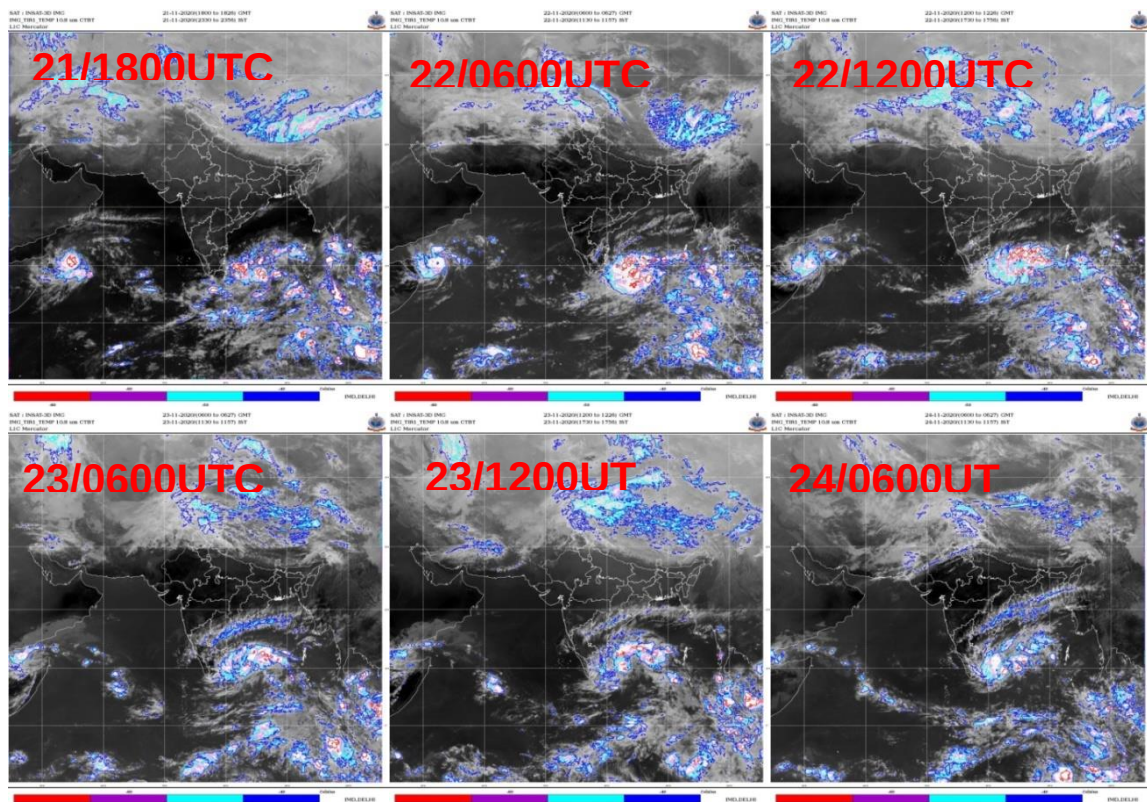


Fig. 2.8.5(b): INSAT-3D CTBT imageries during life cycle of VSCS GATI (21 NOV-24 NOV, 2020)

At 0900 UTC of 22.11.2020. as per satellite imagery, the intensity of the system was T 4.0. It showed eye pattern with irregular eye. Spiral band had entered into the land indicating interaction of the system with land surface. Maximum convection lay in the southern sector of vortex. Broken low and medium clouds with embedded intense to very intense convection lay over southwest & adjoining west-central Arabian Sea between latitude 8°N & 12°N and longitude 49.5°E & 55.5°E in association with the system. The minimum cloud top temperature was -93°C

At 1200 UTC of 22.11.2020 as per satellite imagery, the intensity of the system was T 4.5. It showed eye pattern with rugged eye and eye temperature was -37.0°C . Spiral band had entered into the land indicating interaction of the system with land surface. Maximum convection lay in the southern sector of the vortex. Broken low and medium clouds with embedded intense to very intense convection lay over southwest & adjoining

west-central Arabian Sea between latitude 8.0° N & 12.0° N and longitude 49.5°E & 55.5°E in association with the system.

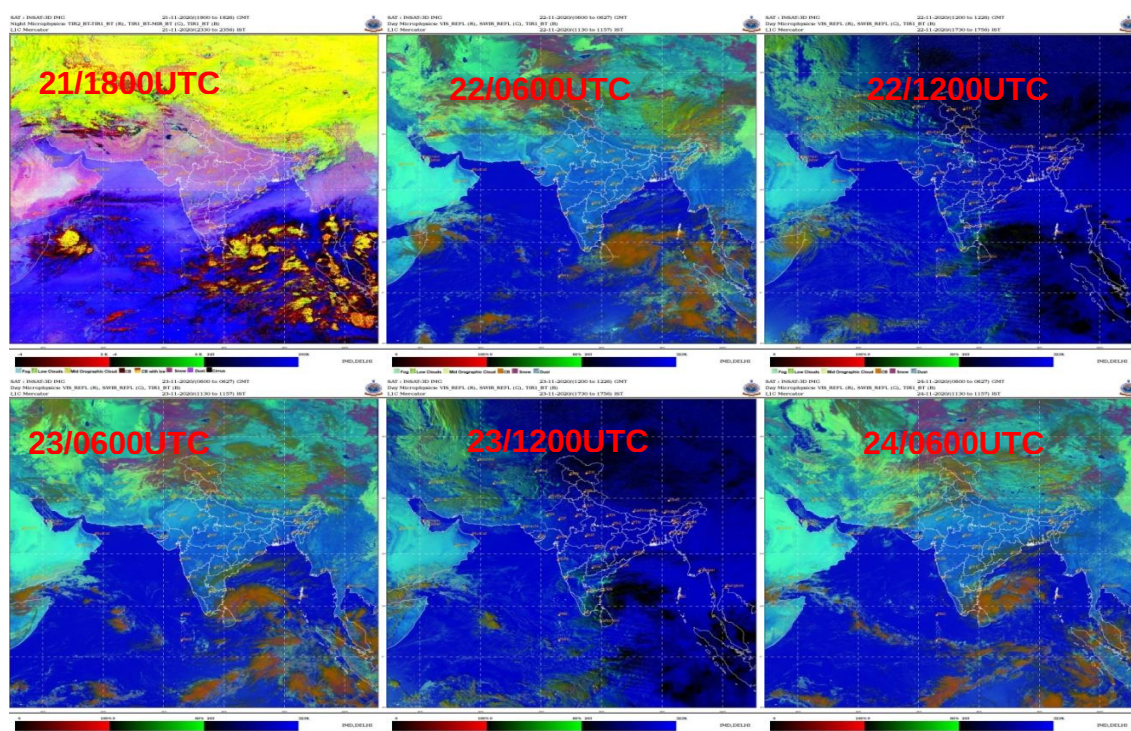


Fig. 2.8.5(c) : INSAT-3D MER_MP imageries during life cycle of VSCS GATI (21 NOV-24 NOV, 2020)

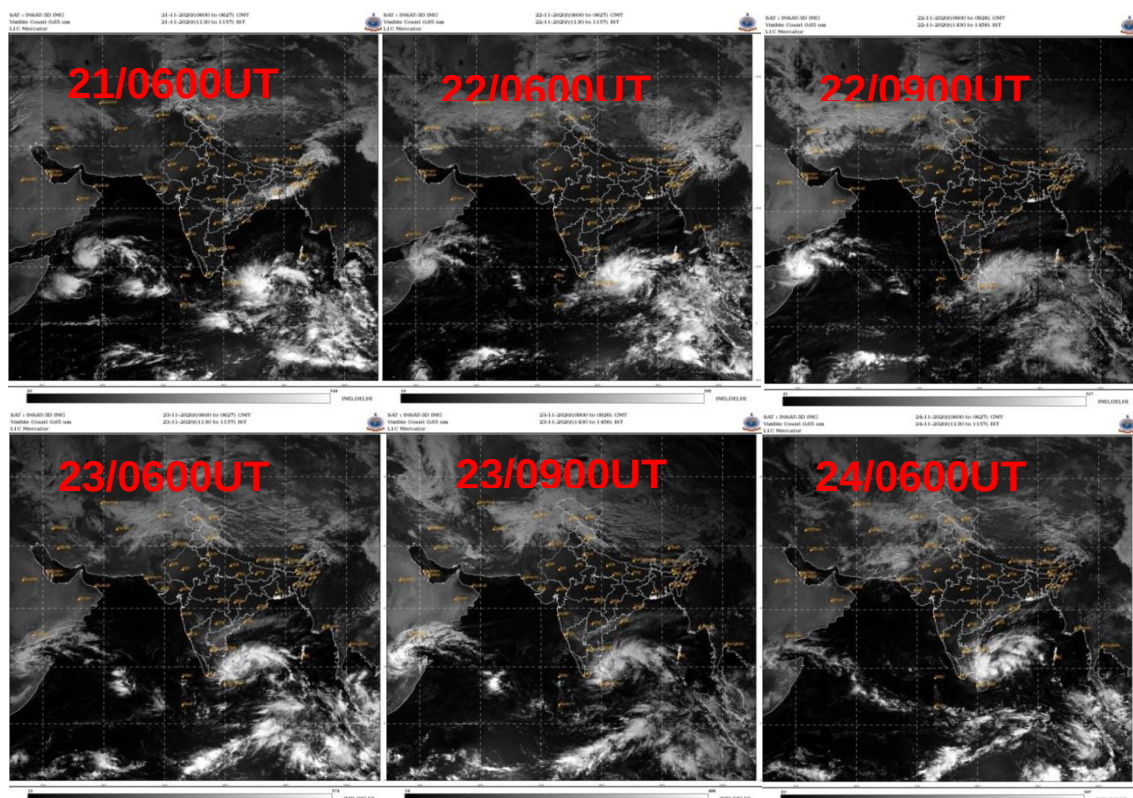


Fig. 2.8.5(d): INSAT-3D Visible imageries during life cycle of VSCS GATI (21 NOV-24 NOV, 2020)

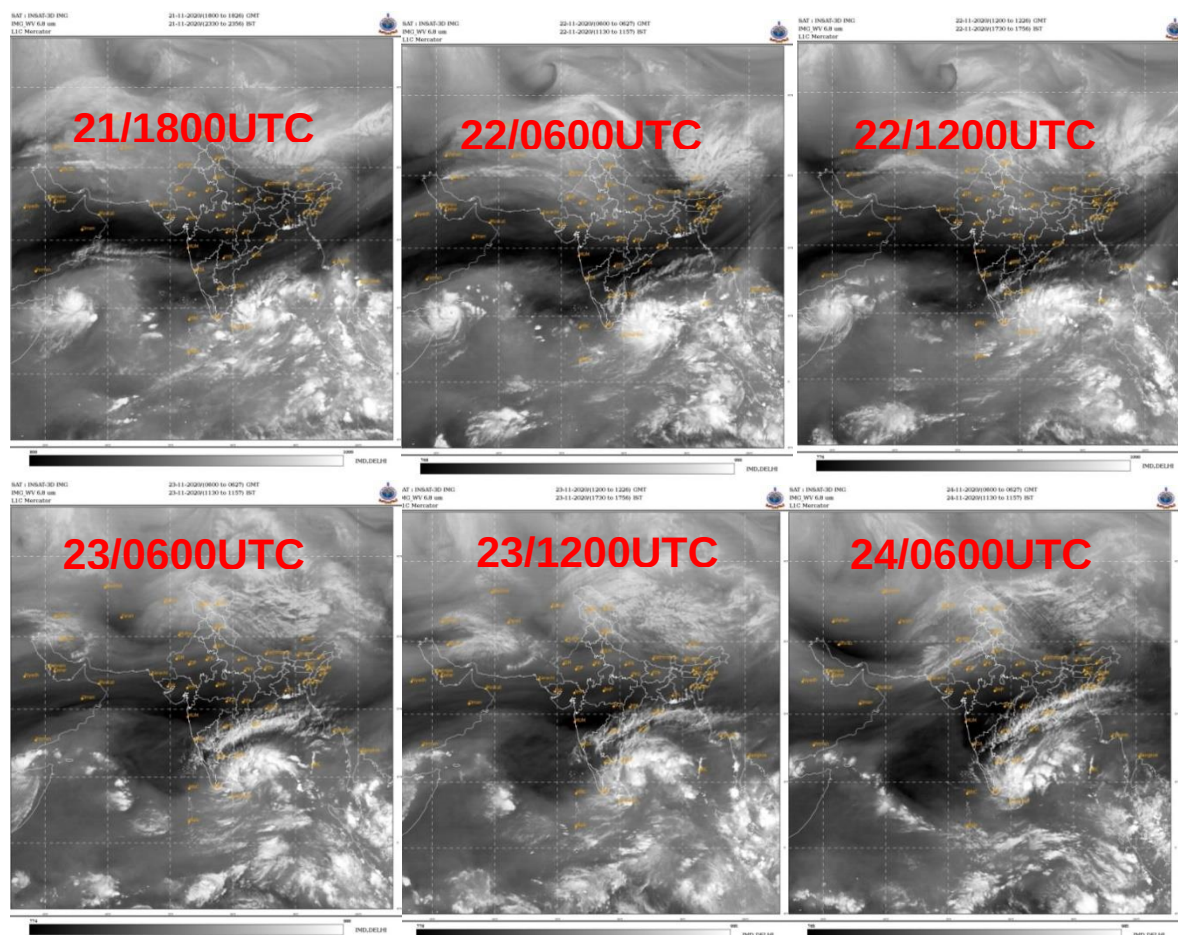


Fig. 2.8.5(e): INSAT-3D Water Vapour imageries during life cycle of VSCS GATI (21-24 NOV, 2020)

At 2100 UTC of 22.11.2020, as per satellite imagery, associated broken low and medium clouds with embedded moderate to intense convection lay over north Somalia and southwest Arabian Sea between latitude 8.5°N & 12.5°N and longitude 40.0°E & 50.5°E in association with the system. Minimum cloud top temperature is -62.0°C

At 0000 UTC of 23.11.2020 as per satellite imagery, associated broken low and medium clouds with embedded moderate to intense convection lay over north Somalia and southwest Arabian Sea between latitude 8.5°N & 12.5°N and longitude 44.0°E & 50.5°E in association with the system. Minimum cloud top temperature was -62.0°C

At 0600 UTC of 23.11.2020, as per satellite imagery, associated broken low and medium clouds with embedded moderate to intense convection lay over north Somalia coast and adjoining Gulf of Aden. Minimum cloud top temperature was -80.0°C .

At 0000 UTC of 24.11.2020 as per satellite imagery, intensity was T1.5. Convective clouds had sheared away to the north-west of the system. Associated scattered low and medium clouds with embedded intense to very intense convection lay over north Somalia and adjoining Gulf of Aden and neighbourhood. Minimum cloud top temperature was -75.0°C .

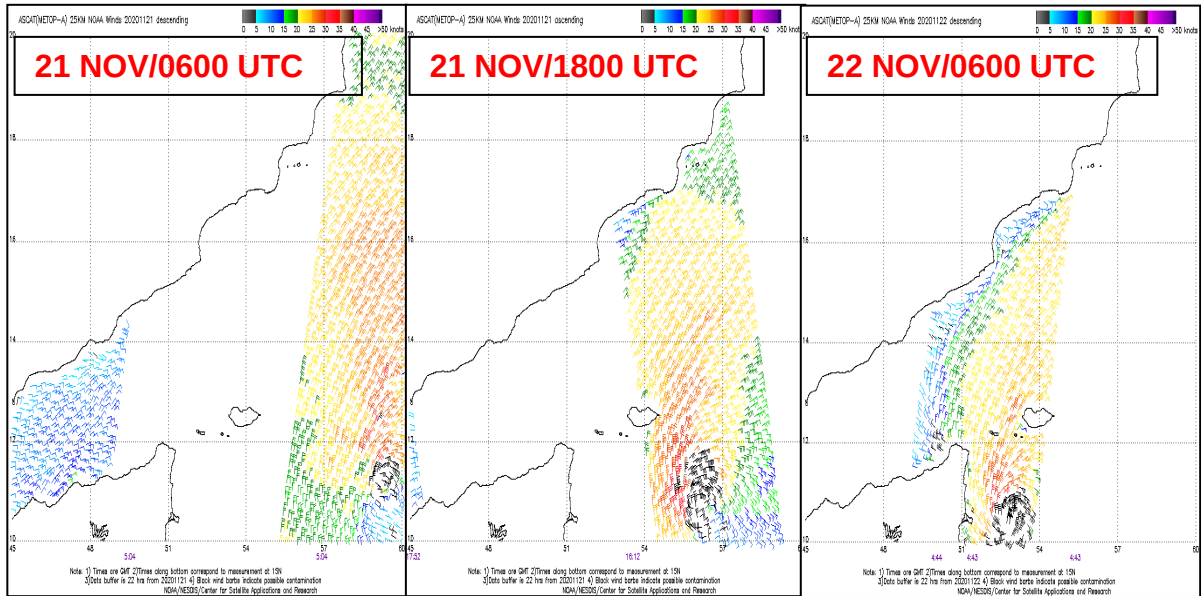


Fig. 2.8.5(f): ASCAT imageries during life cycle of VSCS GATI (21-24 NOV, 2020)

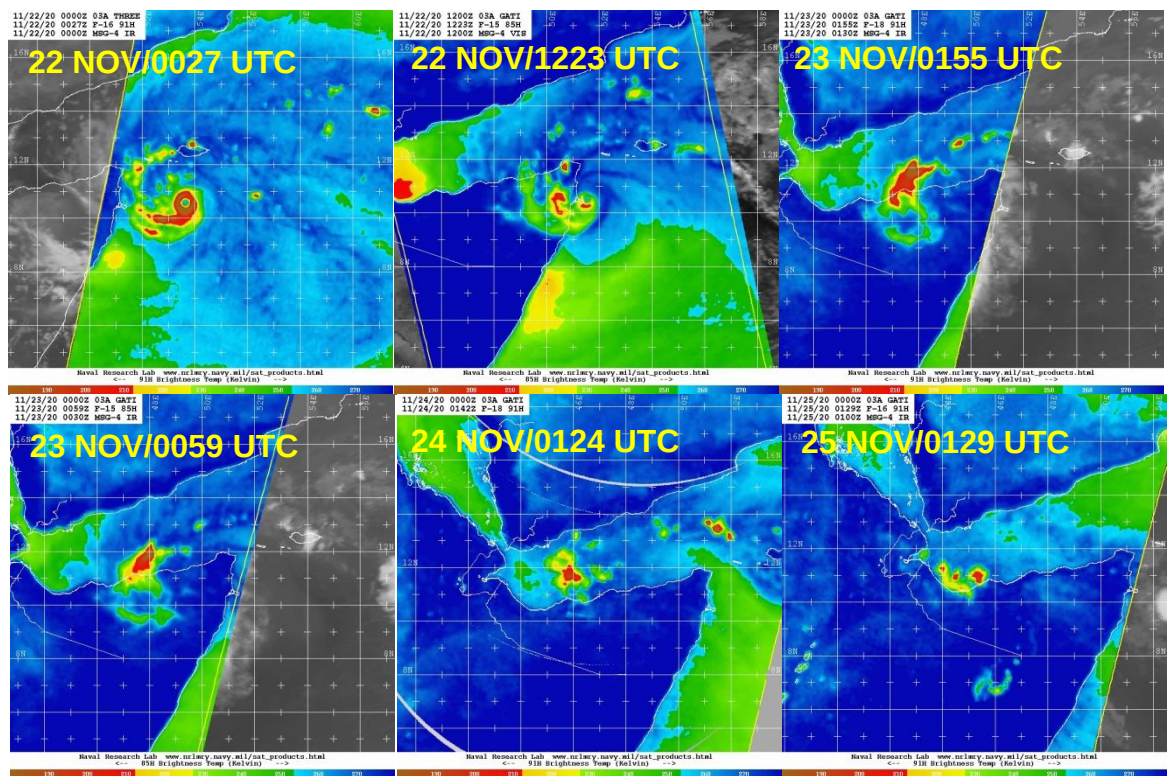


Fig. 2.8.5(g): Microwave imageries during life cycle of VSCS GATI (21-24 NOV, 2020)

2.8.5 Dynamical features

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels during 21st -24th November are presented in **Fig.2.8.6**. (The forecast fields are not shown). The analysis of IMD-GFS T-1534 model forecasts based on 0000 UTC of 21st November, 2020 indicated presence of a Well Marked Low (WML) over south AS on 21st. Forecasts were indicating its slight westward movement and weakening in to a Low Pressure Area (LPA) over southwest AS on 23rd, persistence as LPA over southwest AS off Somalia coast on 24th and weakening on 25th.

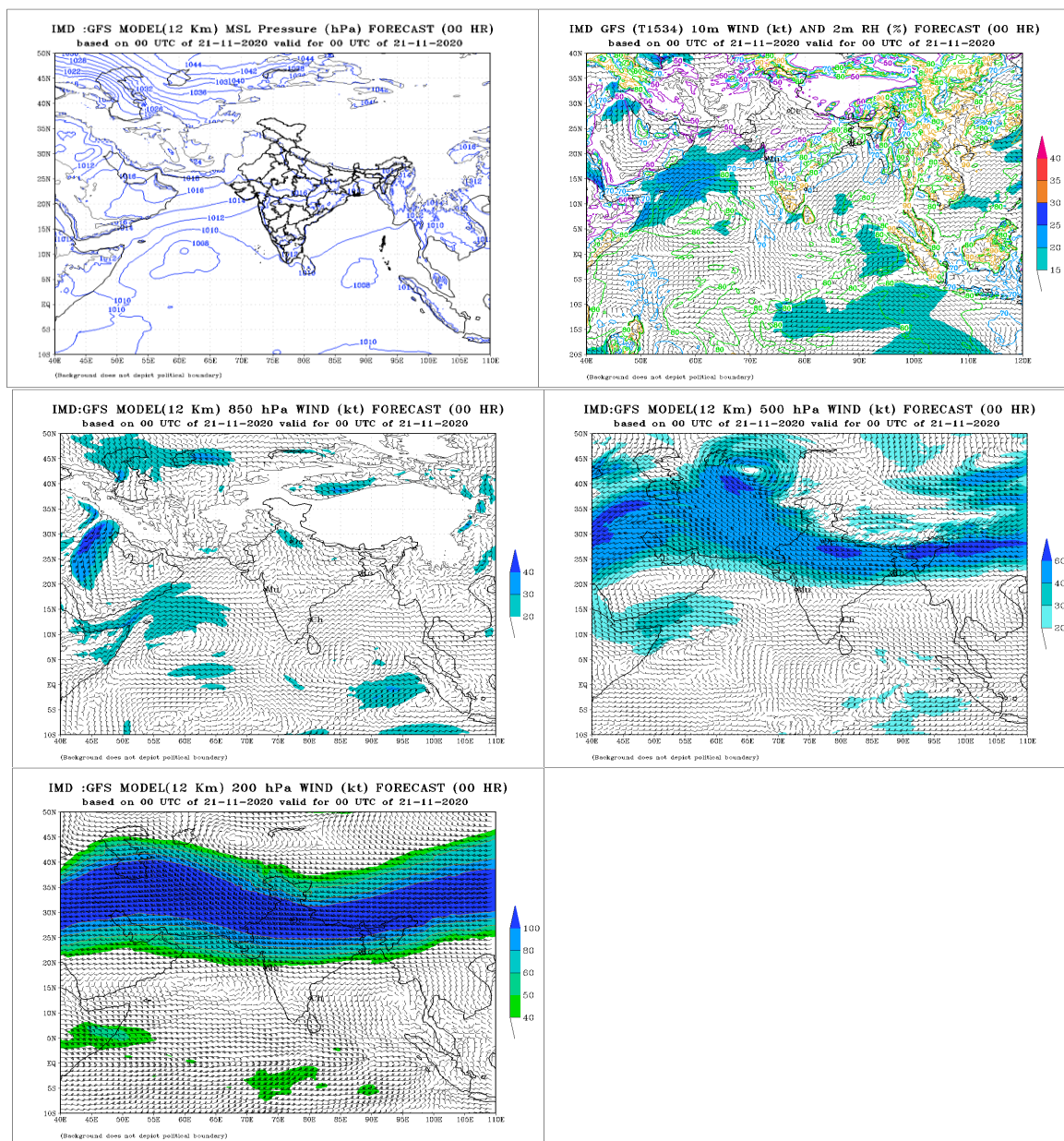


Fig. 2.8.6(a): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 21st November 2020

The analysis of IMD-GFS T-1534 model based on 0000 UTC of 22nd November, 2020 indicated presence of a CS over southwest AS on 22nd. The forecast fields indicated its slight westward movement and weakening into a D over southwest AS off north Somalia coast on 23rd and weakening on 24th.

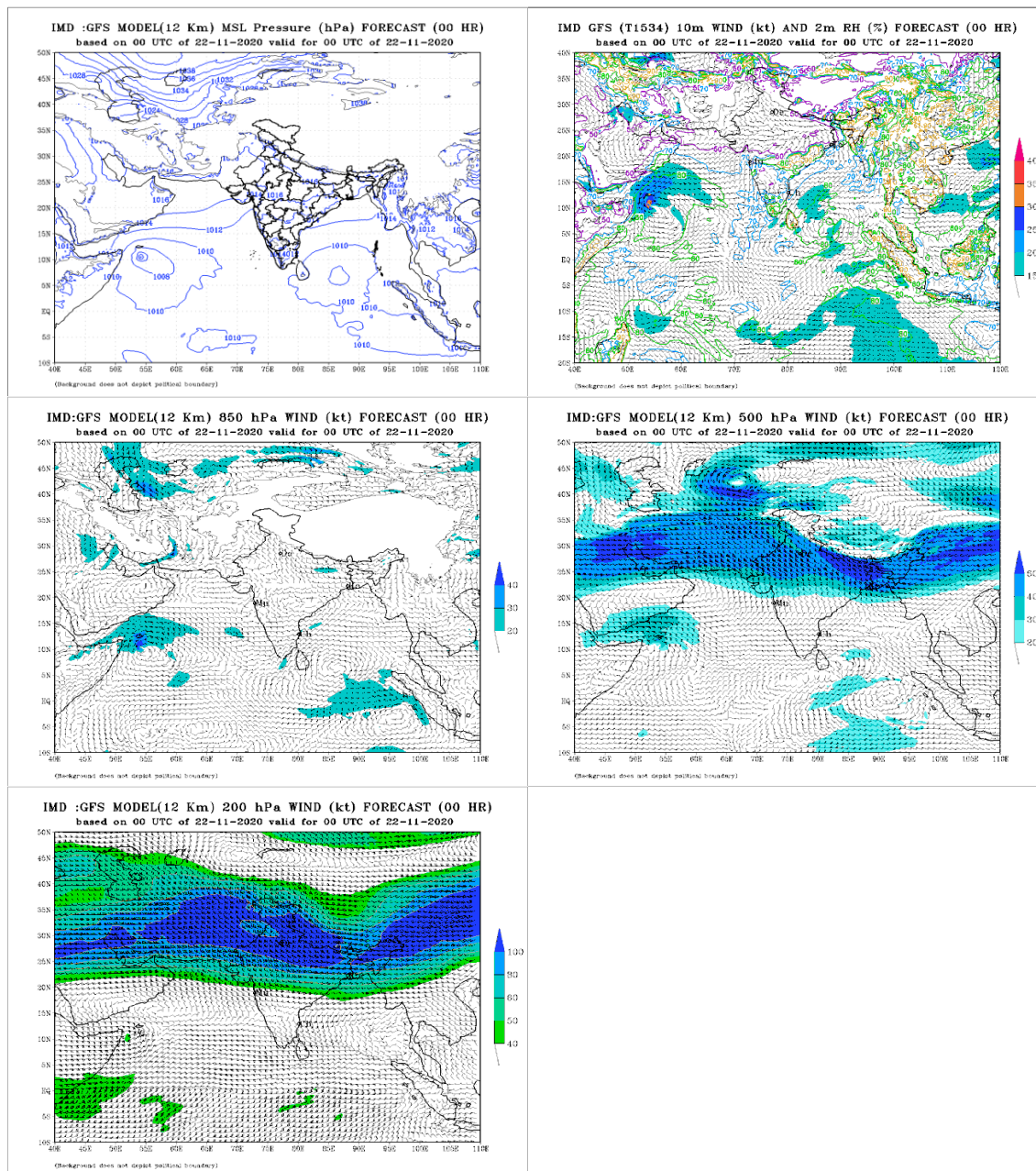


Fig. 2.8.6(b): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 22nd November 2020

The analysis of IMD-GFS T-1534 model forecasts based on 0000 UTC of 23rd November, 2020 indicated an LPA over north Somalia, though the system lay as a CS over north Somalia.

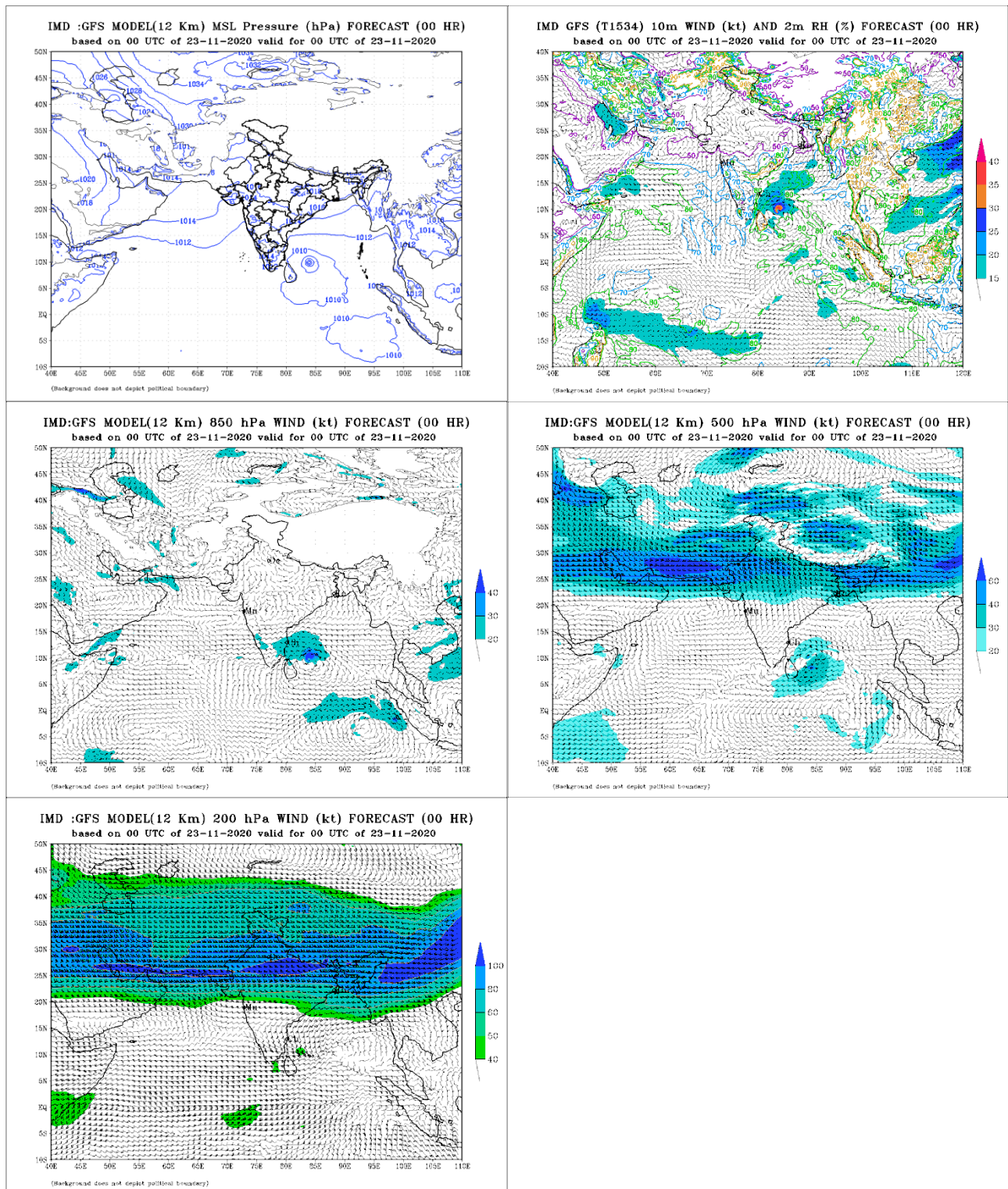


Fig. 2.8.6(c): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 23rd November 2020

The analysis of IMD-GFS T-1534 model forecasts based on 0000 UTC of 24th November, 2020 indicated a feeble LPA over Gulf of Aden. At that time, the system lay as a depression over Gulf of Aden.

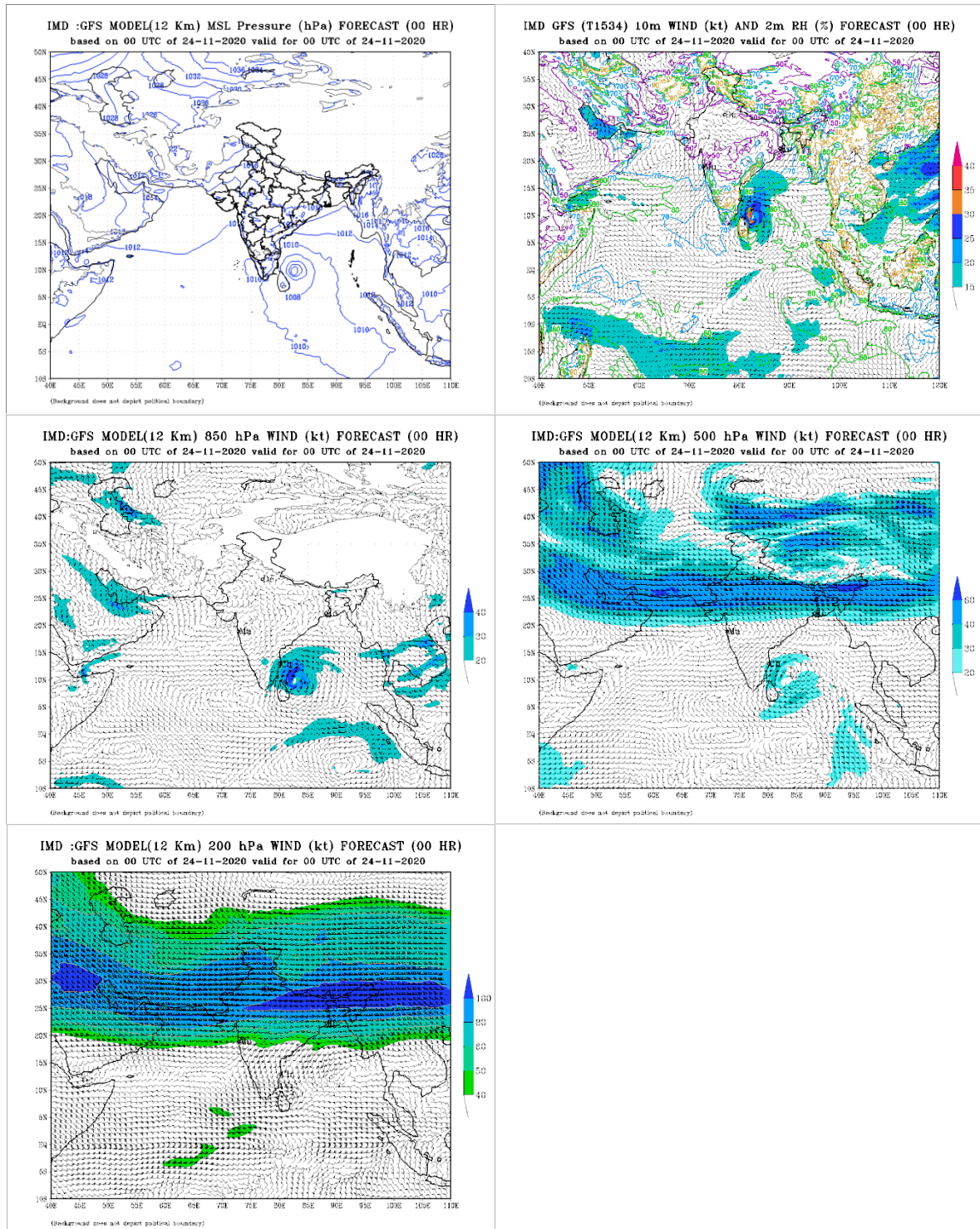


Fig.2.8.6 (d): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 24th November 2020

Thus, IMS GFS couldn't capture the intensity of system correctly. Movement was correctly picked by the model.

2.8.6.1 Realized Weather:

Rainfall associated with VSCS GATI based on IMD-NCMRWF GPM merged gauge rainfall data is depicted in **Fig2.8.7**. It indicates heavy rainfall (7-12 cm) over Socotra Islands on 22nd, heavy to very heavy rainfall (7-19 cm) at many places over northeast Somalia with extremely heavy falls (≥ 20 cm) at a few places on 23rd November, extremely heavy rainfall over Gulf of Aden and adjoining north Somalia on 24th November.

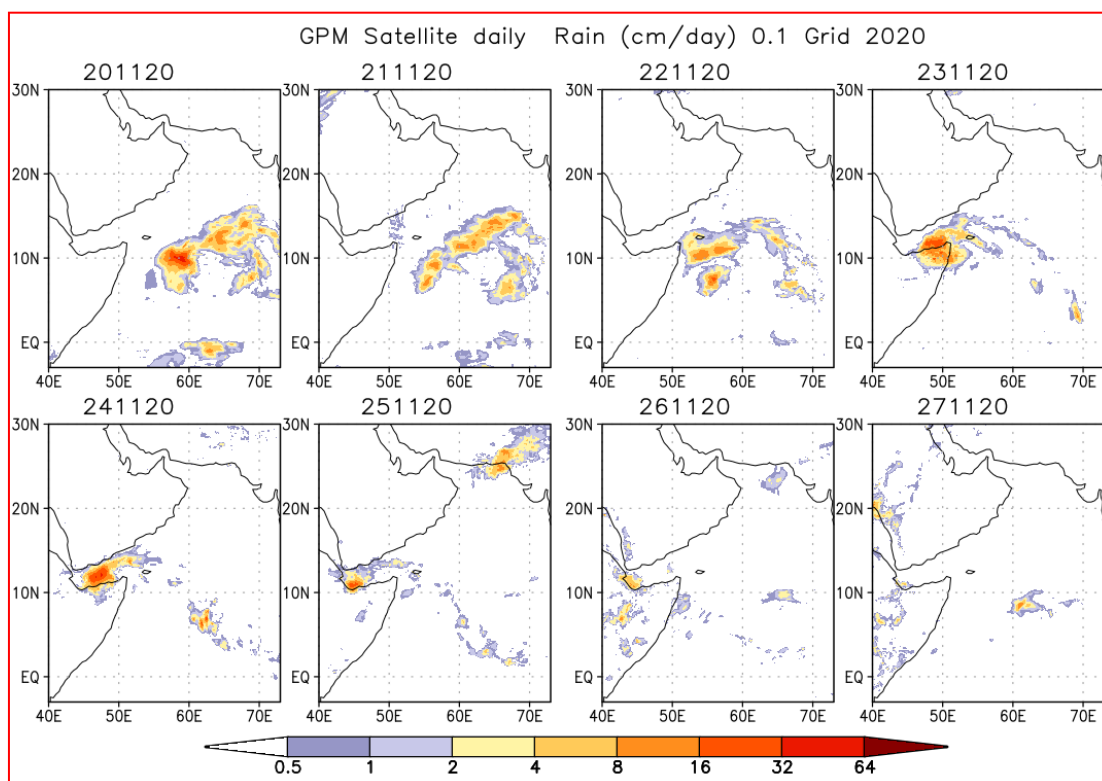


Fig.2.8.7: IMD-NCMRWF GPM merged gauge rainfall during 20th Nov- 27th Nov and 7 days average rainfall (cm/day)

2.8.6.2. Wind

The system crossed north Somalia coast with a maximum sustained wind speed 75 kts gusting to 85 kts.

2.8.6.3 Realized storm surge:

No records are available.

2.8.6 Damage due to VSCS GATI

Very Severe Cyclonic Storm GATI was the strongest tropical cyclone on record to make landfall in Somalia, and one of few tropical cyclones to do so in the country. GATI caused heavy rainfall over Somalia, peaking at 128 mm in Bosaso. An estimated 10,000 animals were killed by Gati in Ufeyn. The storm killed at least 9 people and displaced approximately 42,000 others in the country and caused millions of dollars in damages. Minor impacts were also observed on the Yemeni island of Socotra and the Ethiopian Highlands. A UN report said, "according to estimates compiled by Puntland authorities,

the cyclone has affected about 180,000 people including fishermen, pastoralists, farmers, traders and other vulnerable groups, such as refugees and IDPs (internally displaced persons).”



Fig. 2.8.8(a) A house damaged by Cyclone Gati in Xaafuun district. (source: OCHA report dated 25 Nov.).(b) Damaged houses (source: <https://www.aa.com.tr>, dated 25 Nov.). (c) Fallen electric pole (source: from a twitter user) . (d) Flood in Puntland’s Bari region in Somalia (source : <https://newscentral.africa> ,dated 25 Nov.) . (e) Gati battered Puntland coastal areas (source: <https://guquddetv.com/> dated 23 Nov.) .(f) Flood havoc in the coastal town of Bosaso in northern Somalia (source: <https://www.myanmaritv.com/> dated 24 Nov.)

2.9. Very Severe Cyclonic Storm “NIVAR” over the Bay of Bengal (22nd -27th November 2020)

2.9.1: Introduction

- A Low Pressure Area (LPA) formed over Equatorial Indian Ocean (EIO) and adjoining central parts of south Bay of Bengal (BoB) on 21st November.
- It lay as a Well Marked Low Pressure Area (WML) over southwest & adjoining southeast Bay of Bengal on 22nd November.
- It concentrated into a depression over the same region in the early hours (0230 hrs IST / 2100 UTC of 22nd) of 23rd November.
- Moving west-northwestwards, it intensified into a deep depression in the evening of 23rd and further into the cyclonic storm “**NIVAR**” in the early morning (0530 hrs IST / 0000 UTC) of 24th over southwest BoB.
- Continuing to move west-northwestwards, it further intensified into a severe cyclonic storm in the midnight (2330 hrs IST / 1800 UTC) of 24th and into a very severe cyclonic storm in the afternoon (1430 hrs IST / 0900 UTC) of 25th.
- Moving further northwestwards, it crossed Tamilnadu & Puducherry coasts near Puducherry (near lat. 12.1°N and long. 79.9°E) during 2330 IST of 25th to 0230 IST of 26th as a very severe cyclonic storm with estimated wind speed of 120 kmph gusting to 135 kmph.
- Continuing to move northwestwards, it weakened into a severe cyclonic storm in the early morning hours (0230 hrs IST) of 26th.
- Thereafter, it moved north-northwestwards and weakened into a cyclonic storm in the morning (0830 hrs IST / 0300 UTC) of 26th November, 2020 over north coastal Tamilnadu.
- Thereafter, it started re-curving north-northeastwards and weakened into a deep depression in the afternoon (1430 hrs IST) of 26th over south Rayalaseema, into a depression in the same midnight (2330 hrs IST) over south coastal Andhra Pradesh.
- Thereafter, it weakened into a well marked low pressure area over south coastal Andhra Pradesh and adjoining westcentral BoB in the early morning (0000 UTC) of 27th November.
- Under the influence of this system, intense rainfall activity occurred over north Tamil Nadu & Puducherry, Rayalaseema and south coastal Andhra Pradesh. Heavy to very heavy rainfall occurred at a few places and isolated extremely heavy rainfall (≥ 20 cm) occurred over north Tamilnadu, Puducherry on 24th, 25th & 26th and over Rayalaseema & south coastal AP on 25th and 26th.
- The observed track of the system during 22nd to 27th November is presented in Fig. 2.9.1.

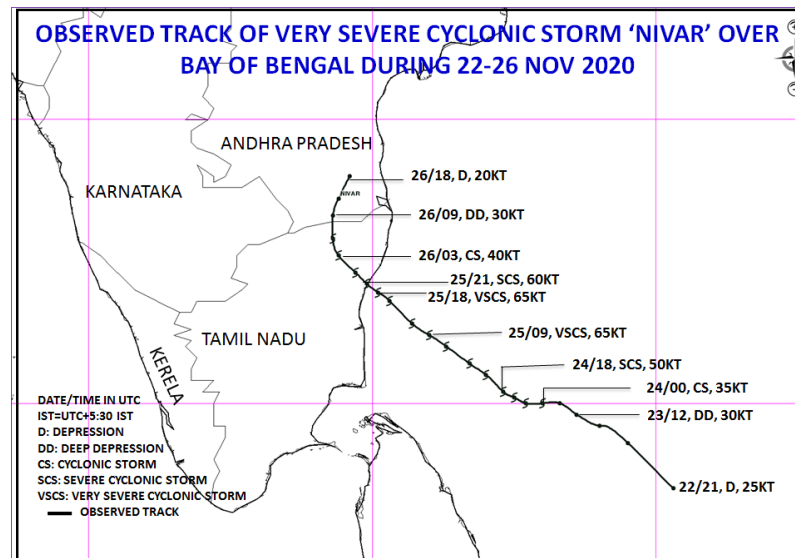


Fig.2.9.1: Observed track of very severe cyclonic storm "NIVAR" over Bay of Bengal

2.9.2. Monitoring of "NIVAR"

India Meteorological Department (IMD) maintained round the clock watch over the north Indian Ocean and the cyclone was monitored since 5th November, about 16 days prior to the formation of low pressure area over equatorial Indian Ocean and adjoining central parts of south BoB on 21st November and 18 days prior to the formation of depression over central parts of south BoB on 23rd. The cyclone was monitored with the help of available satellite observations from INSAT 3D and 3DR, SCAT SAT, polar orbiting satellites and available ships & buoy observations in the region. The system was also monitored by Doppler Weather RADARs (DWR) Chennai, Karaikal and Sriharikota. Various numerical weather prediction models run by Ministry of Earth Sciences (MoES) institutions (IMD, IITM, NCMRWF, INCOIS), global models and dynamical-statistical models were utilized to predict the genesis, track, landfall and intensity of the cyclone. A digitized forecasting system of IMD was utilized for analysis and comparison of various models' guidance, decision making process and warning products generation. Typical satellite and radar imageries are presented in Fig. 2.9.2.

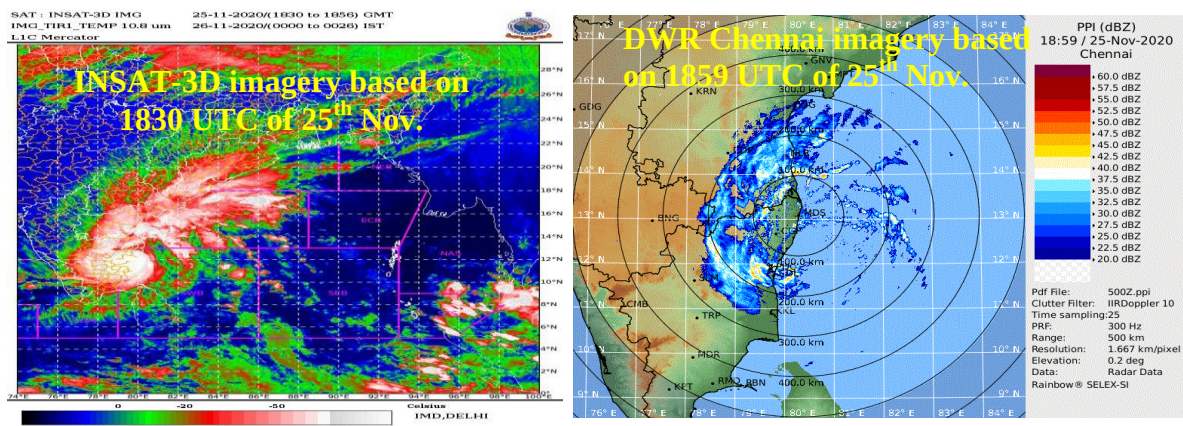


Fig.2.9.2: Typical satellite and radar imageries from DWR Chennai of VSCS "NIVAR"

Table 2.9.1: Best track positions and other parameters of the Very Super Cyclonic Storm, 'NIVAR' over the Arabian Sea during 22 Nov- 26 Nov, 2020

Date	Time (UTC)	Centre lat. ^o N/ long. ^o E		C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
22/11/2020	2100	8.5	85.3	1.5	1002	25	3	D
23/11/2020	0000	9.3	84.5	1.5	1002	25	3	D
	0300	9.5	84.2	1.5	1002	25	3	D
	0600	9.6	84.0	1.5	1001	25	4	D
	1200	9.8	83.6	2.0	999	30	5	DD
	1800	10.0	83.3	2.0	998	30	6	DD
24/11/2020	0000	10.0	83.0	2.5	997	35	7	CS
	0300	10.0	83.0	2.5	997	35	7	CS
	0600	10.0	82.7	2.5	994	40	8	CS
	0900	10.0	82.6	3.0	994	45	10	CS
	1200	10.1	82.5	3.0	994	45	10	CS
	1500	10.1	82.4	3.0	994	45	10	CS
	1800	10.2	82.3	3.5	992	50	12	SCS
	2100	10.3	82.2	3.5	988	55	16	SCS
25/11/2020	0000	10.5	82.0	3.5	986	60	18	SCS
	0300	10.7	81.7	3.5	986	60	18	SCS
	0600	11.0	81.3	3.5	986	60	18	SCS
	0900	11.2	81.0	4.0	982	65	22	VSCS
	1200	11.4	80.7	4.0	982	65	22	VSCS
	1500	11.7	80.4	4.0	982	65	22	VSCS
	1800	12.0	80.1	4.0	982	65	22	VSCS
		Crossed Tamilnadu and Puducherry coasts near Puducherry (near Lat 12.1 ^o N and Log 79.9 ^o E) during 1800 – 2100 UTC of 25 th .						
	2100	12.1	79.9	-	986	60	18	SCS
26/11/2020	0000	12.3	79.7	-	992	50	12	SCS
	0300	12.6	79.4	-	996	40	8	CS
	0600	12.9	79.3	-	998	30	6	CS
	0900	13.3	79.3	-	999	30	5	DD
	1200	13.6	79.4	-	1000	30	5	DD
	1800	14.0	79.6	-	1002	20	3	D
27/11/2020	0000	Weakened into a Well-Marked Low Pressure Area over south coastal Andhra Pradesh and adjoining westcentral Bay of Bengal.						

2.9.3. Brief life history

2.9.3.1. Genesis, intensification and movement

A Low Pressure Area (LPA) formed over Equatorial Indian Ocean (EIO) and adjoining central parts of south Bay of Bengal (BoB) on 21st November. On 21st, the Madden Julian Oscillation (MJO) index lay in phase 3 with amplitude equal to 1. SST was around 29-30°C over most parts of Bay of Bengal (BOB). High tropical cyclone heat potential (TCHP) (120-140 KJ/cm²) prevailed in the near equatorial belt of and adjoining south BOB & Sumatra coast. Higher TCHP (120-140 KJ/cm²) also prevailed off Myanmar

coast and north Andhra Pradesh coast (India). TCHP was 60-80 KJ/cm² over remaining parts of BOB and Andaman Sea. Considering the environmental conditions over BOB, positive relative vorticity ($20-50 \times 10^{-6} \text{s}^{-1}$) prevailed over equatorial Indian Ocean & adjoining central parts of south BOB with vertical extension upto 500 hPa level. Area of positive divergence ($30 \times 10^{-5} \text{s}^{-1}$) prevailed over equatorial Indian Ocean & adjoining central parts of south BOB. Area of positive convergence zone ($05-10 \times 10^{-5} \text{s}^{-1}$) prevailed over the same region. The vertical wind shear (VWS) was moderate (10-20 kts) over south and adjoining central BOB. The upper tropospheric ridge at 200 hPa ran along 11.5°N over the BOB.

It lay as a Well Marked Low Pressure Area (WML) over southwest & adjoining southeast Bay of Bengal on 22nd November. At 0300 UTC of 22nd November, similar Sea conditions prevailed. Considering the environmental conditions over BOB, positive relative vorticity ($25-50 \times 10^{-6} \text{s}^{-1}$) prevailed over the system area over central parts of south BOB with vertical extension upto 500 hPa level. Area of positive upper level divergence ($40 \times 10^{-5} \text{s}^{-1}$) prevailed to the southwest of the system area over central parts of south BOB. Area of positive low level convergence zone ($10-20 \times 10^{-5} \text{s}^{-1}$) prevailed over the same area. The vertical wind shear (VWS) was low (05-10 kts) over south and adjoining central BOB. The upper tropospheric ridge at 200 hPa ran along 11.5°N over the BOB.

At 2100 UTC of 22nd November, the system intensified into a depression. Similar Sea conditions prevailed. Positive relative vorticity ($150 \times 10^{-6} \text{s}^{-1}$) prevailed to the south of the system area over central parts of south BOB with vertical extension upto 500 hPa level. Area of positive divergence ($40 \times 10^{-5} \text{s}^{-1}$) prevailed over the system area over southwest BOB. Area of positive convergence zone ($30 \times 10^{-5} \text{s}^{-1}$) prevailed over the same area. The vertical wind shear (VWS) was low (05-10 kts) over south and adjoining central BOB. The upper tropospheric ridge at 200 hPa ran along 11.5°N over the BOB.

At 1200 UTC of 23rd November, it further intensified into a deep depression. Similar Sea conditions prevailed. Positive relative vorticity ($150 \times 10^{-6} \text{s}^{-1}$) prevailed over the south of the system area over central parts of south BOB with vertical extension upto 300 hPa level. Area of positive divergence ($30 \times 10^{-5} \text{s}^{-1}$) prevailed over the system area over southwest BOB. Area of positive convergence zone ($20 \times 10^{-5} \text{s}^{-1}$) prevailed over the same area. The vertical wind shear (VWS) was low (05-15 kts) over south and adjoining central BOB. The upper tropospheric ridge at 200 hPa ran along 13.5°N over the BOB.

At 0000 UTC of 24th November, it intensified into the cyclonic storm "NIVAR". Similar Sea and MJO conditions prevailed. Lower level positive relative vorticity ($200 \times 10^{-6} \text{s}^{-1}$) prevailed around system centre. Upper level positive divergence of $40 \times 10^{-5} \text{s}^{-1}$ prevailed around the system centre. The lower level positive convergence was $30 \times 10^{-5} \text{s}^{-1}$ around system centre. The vertical wind shear (VWS) was low (05-15 kts) over the region. The sub-tropospheric ridge at upper and middle tropospheric levels ran along 13.0°N over the BOB with an anti-cyclonic circulation to the northeast of system centre. The system lay in the southern periphery of the above ridge. As a result, it was moving west northwestwards. It was expected to be steered by the above ridge resulting in west-northwestward movement for next 12 hrs followed by northwestward movement. The above environmental conditions were favouring further intensification of the system during next 24 hrs into a severe cyclonic storm.

At 1800 UTC of 24th November, the system intensified into a severe cyclonic storm. SST was around 29-30°C over southwest Bay of Bengal (BOB). The tropical cyclone heat potential was about 80-100 KJ/cm² over southwest BOB. Lower level positive relative vorticity ($200 \times 10^{-6} \text{s}^{-1}$) prevailed to the southwest of system centre. Upper level positive divergence of $40 \times 10^{-5} \text{s}^{-1}$ prevailed to the southwest of the system centre. The lower level positive convergence was $20 \times 10^{-5} \text{s}^{-1}$ around southwest sector of the system. The vertical wind shear (VWS) was low (05-15 kts) over the region. The upper tropospheric ridge at upper and middle tropospheric levels ran along 13.0°N over the BOB with an anti-cyclonic circulation to the northeast of system centre. The system lay in the southern periphery of the above ridge. As a result, the system was moving initially west northwestwards. It was expected to be steered by the above ridge resulting in northwestward movement thereafter. The above environmental conditions were favourable for further intensification of the system into a very severe cyclonic storm during the subsequent 12 hours.

At 0900 UTC of 25th November, the system intensified into a very severe cyclonic storm. SST was around 29-30°C over southwest Bay of Bengal (BOB). The tropical cyclone heat potential was about 80-100 KJ/cm² over southwest BOB. Lower level positive relative vorticity ($250 \times 10^{-6} \text{s}^{-1}$) prevailed around the system centre. Upper level positive divergence of $40 \times 10^{-5} \text{s}^{-1}$ prevailed to the northwest of the system centre. The lower level positive convergence was $20 \times 10^{-5} \text{s}^{-1}$ to the south of the system center. The vertical wind shear (VWS) was low (10-15 kts) over the region. The upper tropospheric ridge at upper and middle tropospheric levels shifted north and ran along 14.0°N over the BOB with an anti-cyclonic circulation to the northeast of system centre. The system lay in the southern periphery of the above ridge. As a result, the system was moving northwestward towards Tamilnadu coast. The above environmental conditions were favourable for the system to remain as a very severe cyclonic storm during subsequent 12 hours.

The system crossed Tamilnadu & Puducherry coasts near Puducherry (near lat. 12.1°N and long. 79.9°E) during 2330 IST of 25th to 0230 IST of 26th as a very severe cyclonic storm with estimated wind speed of 120 kmph gusting to 135 kmph.

At 2100 UTC of 25th November, it weakened into a severe cyclonic storm. Lower level positive relative vorticity ($250 \times 10^{-6} \text{s}^{-1}$) prevailed around the system centre. Upper level positive divergence of $40 \times 10^{-5} \text{s}^{-1}$ prevailed to the north of the system centre. The lower level positive convergence was $40 \times 10^{-5} \text{s}^{-1}$ to the south of system center. The vertical wind shear (VWS) was low (10-15 kts) over the region.

At 0300 UTC of 26th November, it further weakened into a cyclonic storm. Lower level positive relative vorticity decreased and was about $200 \times 10^{-6} \text{s}^{-1}$ to the southeast of the system centre. Upper level positive divergence of $40 \times 10^{-5} \text{s}^{-1}$ prevailed to the northeast of the system centre. The lower level positive convergence $40 \times 10^{-5} \text{s}^{-1}$ prevailed to the northeast of system center. The vertical wind shear (VWS) was low (10-15 kts) over the southern peninsular region and along the expected track.

At 0900 UTC of 26th November, it weakened into a deep depression. Lower level positive relative vorticity decreased and was about $200 \times 10^{-6} \text{s}^{-1}$ to the southeast of the system centre. Upper level positive divergence of $40 \times 10^{-5} \text{s}^{-1}$ prevailed to the northeast of the system centre. The lower level positive convergence $40 \times 10^{-5} \text{s}^{-1}$ prevailed to the

northeast of system center. The vertical wind shear (VWS) was low (10-15 kts) over the southern peninsular region and along the expected track.

Similar unfavourable environment continued and the system weakened into a depression at 1800 UTC of 26th and into a well marked low pressure area at 0000 UTC of 27th November. Typical total precipitable water vapour imagery during life cycle of NIVAR are presented in Fig.2.9.3. Un-hindered convergence of warm & moist air from the near equatorial belt may be noticed until the night of 25th November.

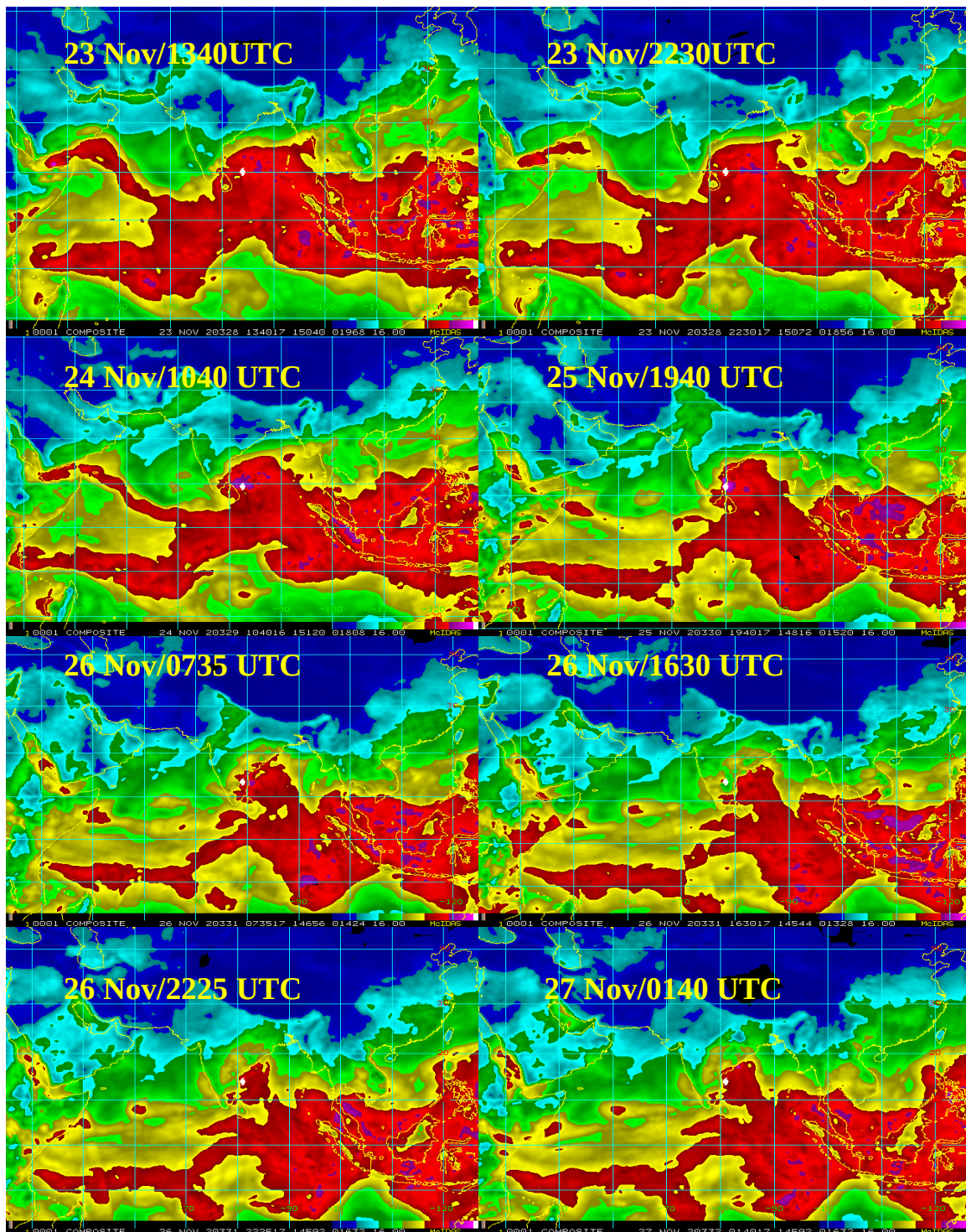


Fig. 2.9.3: Total Precipitable Water (TPW) imageries during VSCS NIVAR during 22nd -27th November 2020

The wind speed in middle and deep layer around the system centre is presented in Fig.2.9.4. The wind shear around the system between 200 & 850 hPa levels remained low till 26th November and thereafter, it became moderate. The mean wind speed in the deep layer was low (05 kts) till 26th and thereafter, it increased becoming 10 kts.

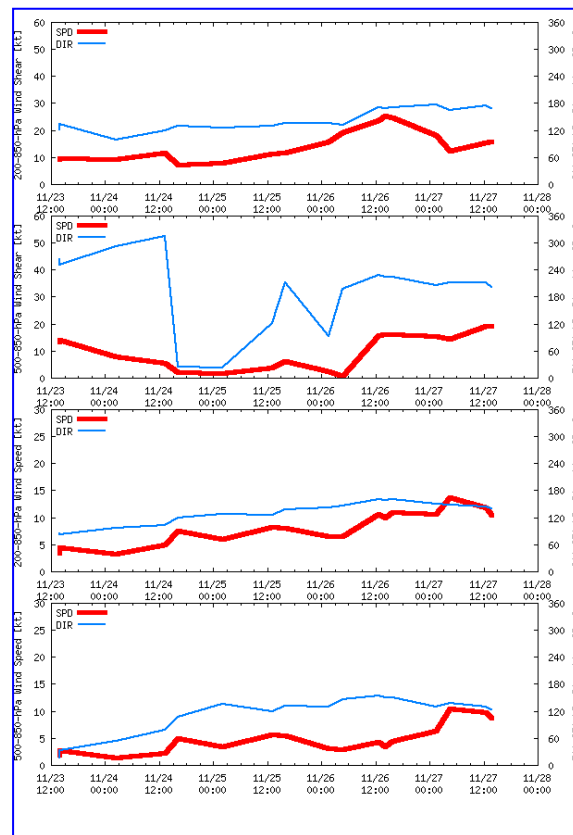


Fig.2.9.4: Mean wind speed and shear in deep (850-200 hPa) and middle (500-850 hPa) layers

2.9.3.2. Maximum Sustained Surface Wind speed and estimated central pressure

There was gradual increase in intensity during the period 0000 UTC of 23rd November to 1200 UTC of 25th November. The system reached it's peak intensity of 65 knots at 1200 UTC of till 1800 UTC of 25th November. Thereafter, it weakened rapidly. The minimum estimated central pressure of 982 hPa was observed during 1200 UTC to 1800 UTC of 25th November. The lowest estimated central pressure and the maximum sustained wind speed are presented in Fig.2.9.5 a.

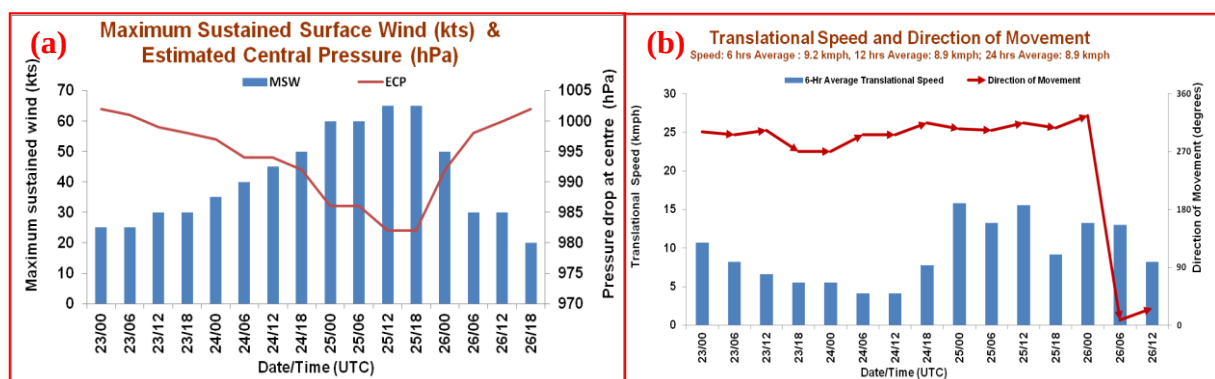


Fig.2.9.5. (a) Maximum sustained surface winds (kts) & Estimated Central Pressure and (b) Translational speed & direction of movement

2.9.3.2. Translational speed & direction of movement

The six hourly movement of VSCS NIVAR is presented in Fig.2.9.5 b. The 12 hourly average translational speed of VSCS NIVAR was about 8.9 kmph against the normal speed of 15.0 kmph for VSCS category over BoB during post monsoon season. The system moved nearly northwestwards till 0000 UTC of 26th November. Thereafter, it recurved north-northeastwards. The mean wind speed and direction in the deep layer between 850-200 hPa level and the middle layer between 850-500 hPa level is presented in Fig. 2.9.4.

2.9.4. Features observed through satellite and Radar

2.9.4.1. 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, Metops were also considered. Typical INSAT-3D visible/IR imageries, enhanced colored imageries and cloud top brightness temperature imageries are presented in Fig.2.9.6.

At 2100 UTC of 22nd November, the vortex associated with this system lay over central parts of south Bay of Bengal centered 8.6°N/85.2°E. And intensity is increase T1.5/1.5. Broken low and medium clouds with embedded intense to very intense convection lay over south Bay of Bengal, between latitude 8.0°N & 12.0°N and longitude 82.0°E & 89.0°E in association with the system. Minimum cloud top temperature is -93.0°C.

At 1200 UTC of 23rd November, the vortex associated with this system lay over central parts of south Bay of Bengal centered 9.7°N/83.7°E. And intensity was T2.0/2.0. Shear pattern. Broken low and medium clouds with embedded intense to very intense convection lay over south Bay of Bengal, between latitude 9.0°N & 12.5°N and longitude 80.0°E & 84.0°E in association with the system. Minimum cloud top temperature is -80.0°C.

At 0000 UTC of 24th November, the intensity was T2.5. Associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over south and adjoining central Bay of Bengal, between latitude 8.0°N & 14.0°N and longitude 79.0°E & 84.0°E in association with the system. Minimum cloud top temperature is -93.0°C.

At 1800 UTC of 24th November, the intensity was T3.5 associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over south west and adjoining west central Bay of Bengal, between latitude 8.5°N & 14.0°N and longitude 80.0°E & 86.0°E in association with the system. Minimum cloud top temperature is -93.0°C.

At 0900 UTC of 25th November the intensity was T4.0 with CDO pattern. Associated broken low and medium clouds with embedded intense to very intense convection lay over southwest and adjoining westcentral Bay of Bengal, between latitude 9.0°N & 15.0°N and longitude 80.0°E & 85.0°E in association with the system. Minimum cloud top temperature is -93.0°C.

At 2100 UTC of 25th November the intensity was T4.0 with CDO pattern. Associated broken low and medium clouds with embedded intense to very intense convection lay over southwest and adjoining westcentral Bay of Bengal, between latitude 11.0°N & 13.0°N and longitude 79.0°E & 80.5°E in association with the system. Minimum cloud top temperature is -93.0°C.

At 0300 UTC of 26th November broken low and medium clouds with embedded intense to very intense convection lay over Tamilnadu, south coastal Andhra Pradesh, Rayalaseema, south interior Karnataka and over westcentral southwest Bay of Bengal between latitude 10.0°N & 16.0°N and longitude 80.0°E & 82.5°E in association with the system. Minimum cloud top temperature is -87.0°C.

At 0900 UTC of 26th November broken low and medium clouds with embedded intense to very intense convection lay over north Tamilnadu, south coastal Andhra Pradesh, Rayalaseema, south interior Karnataka and over westcentral southwest Bay of Bengal between latitude 11.0°N & 16.0°N and longitude 80.0°E & 83.0°E in association with the system. Minimum cloud top temperature is -87.0°C.

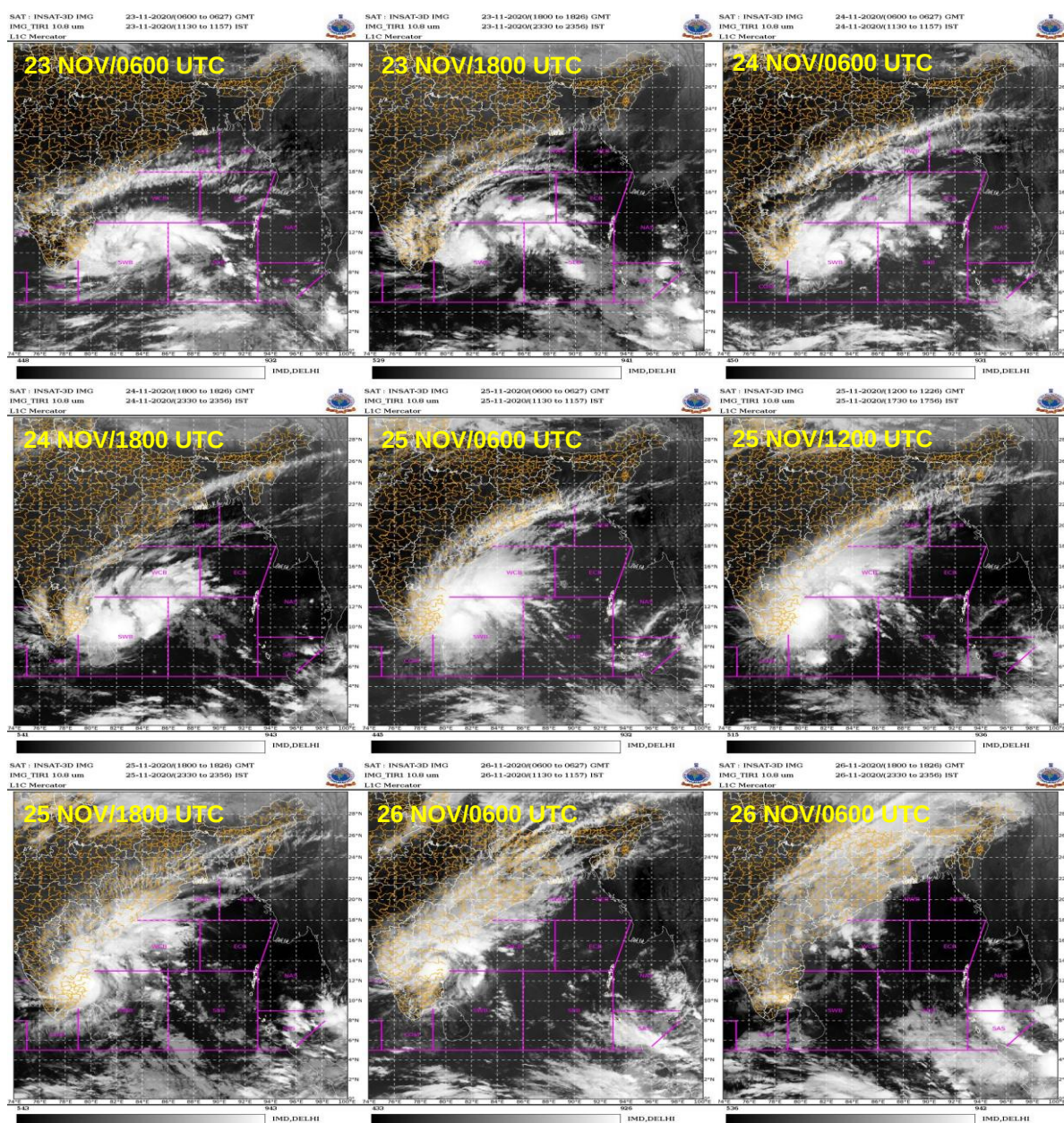


Fig. 2.9.6 (a): INSAT-3D IR imageries during life cycle of VSCS NIVAR (22 Nov-27 Nov), 2020

At 1800 UTC of 26th November broken low and medium clouds with embedded intense to very intense convection lay over north Tamilnadu, south coastal Andhra

Pradesh, Rayalseema, south interior Karnataka and over westcentral southwest Bay of Bengal. Minimum cloud top temperature is -59.0°C .

At 0000 UTC of 27th November, the system was over south castal Andhra Pradesh and neighbourhood centered within half a degree of 14.0N/80.0E. Center not clearly defined in IR imagery. Broken low and medium clouds with embedded weak to moderate convection lay over north-east Tamilnadu, south coastal Andhra Pradesh, Rayalseema, and over westcentral southwest Bay of Bengal.

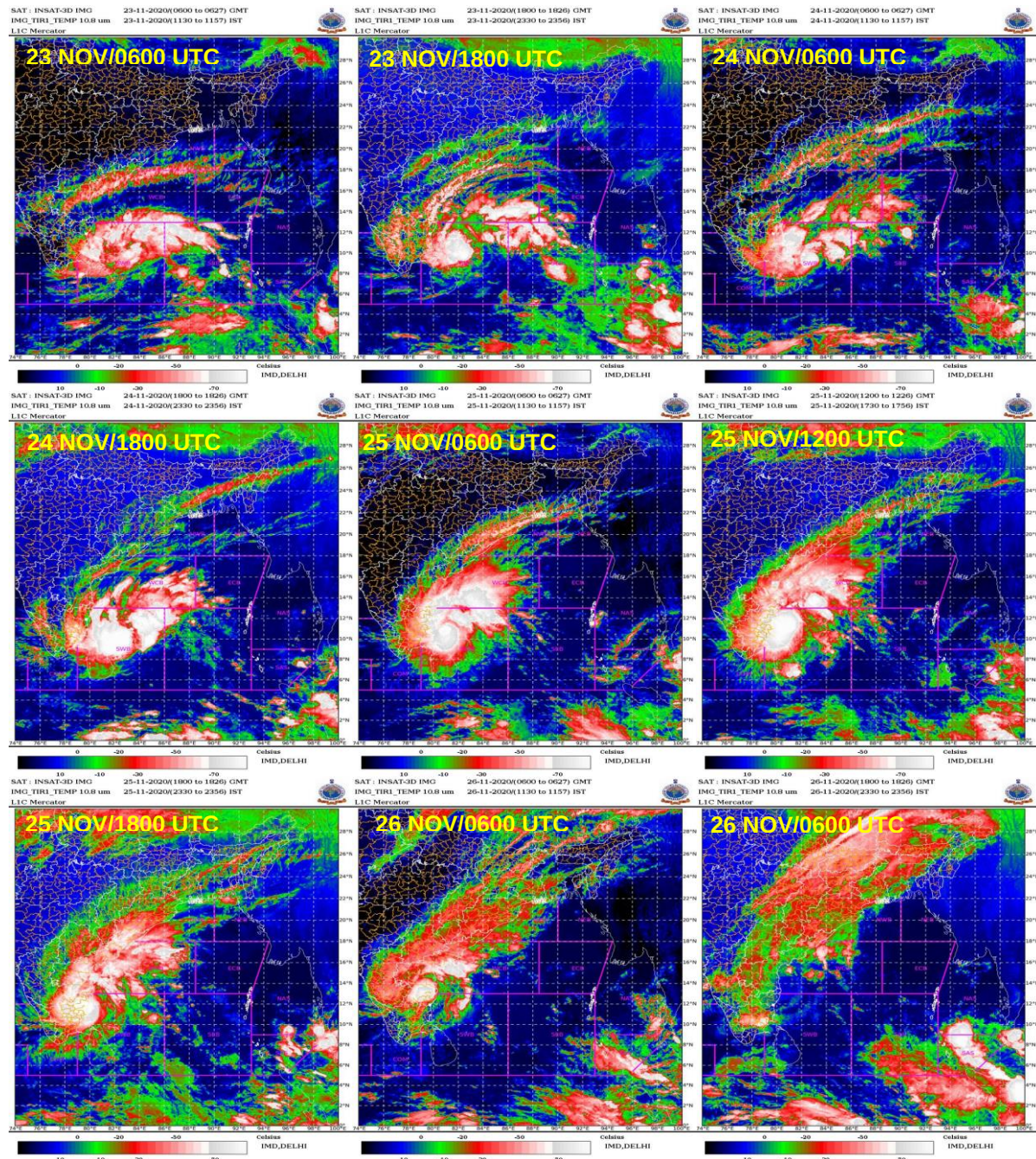


Fig. 2.9.6.(b): INSAT-3D enhanced colored imageries during life cycle VSCS NIVAR (22 Nov-27 Nov), 2020

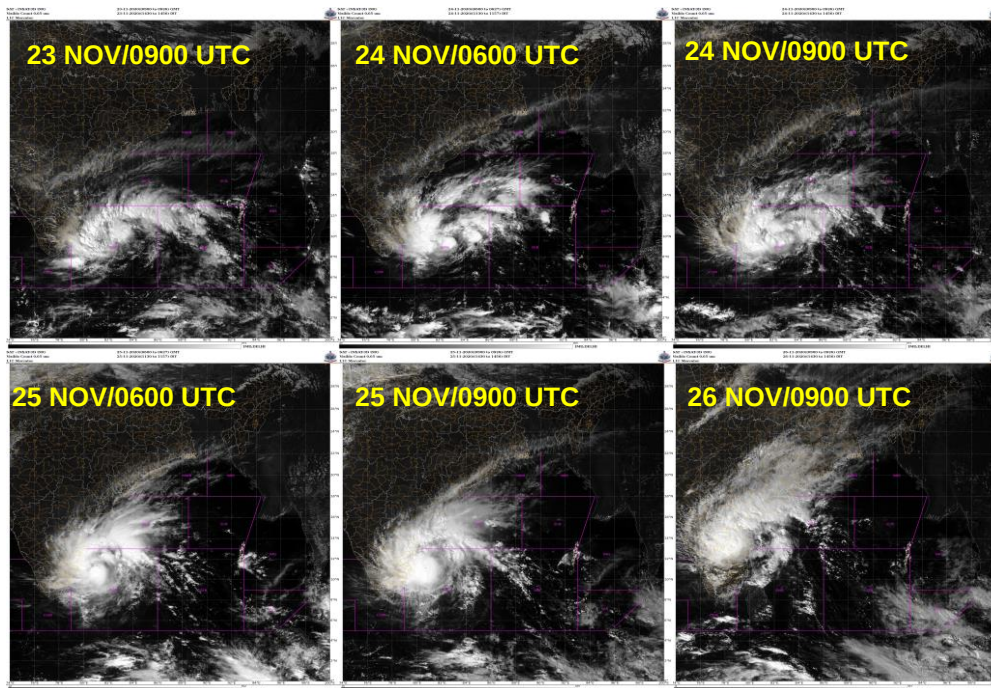


Fig. 2.9.6.(c): INSAT-3D Visible imageries during life cycle of VSCS NIVAR (22 Nov-27 Nov), 2020

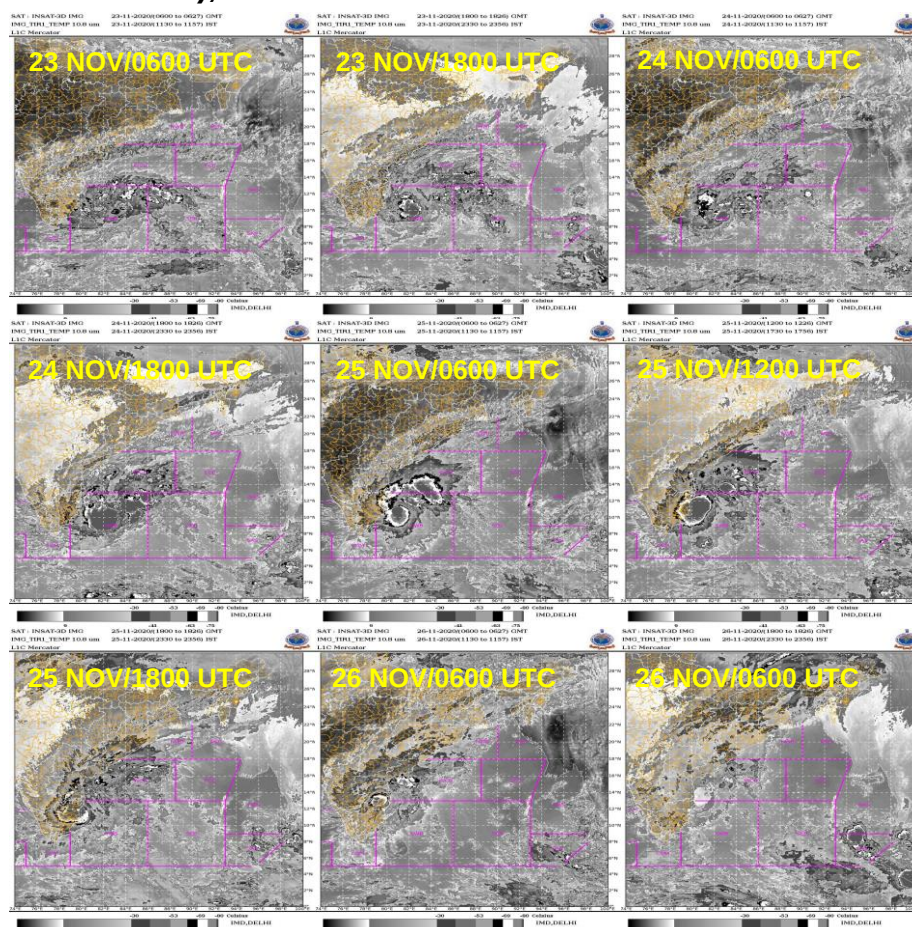


Fig. 2.9.6.(d): INSAT-3D Water Vapor imageries during life cycle of VSCS NIVAR (22 Nov-27 Nov), 2020

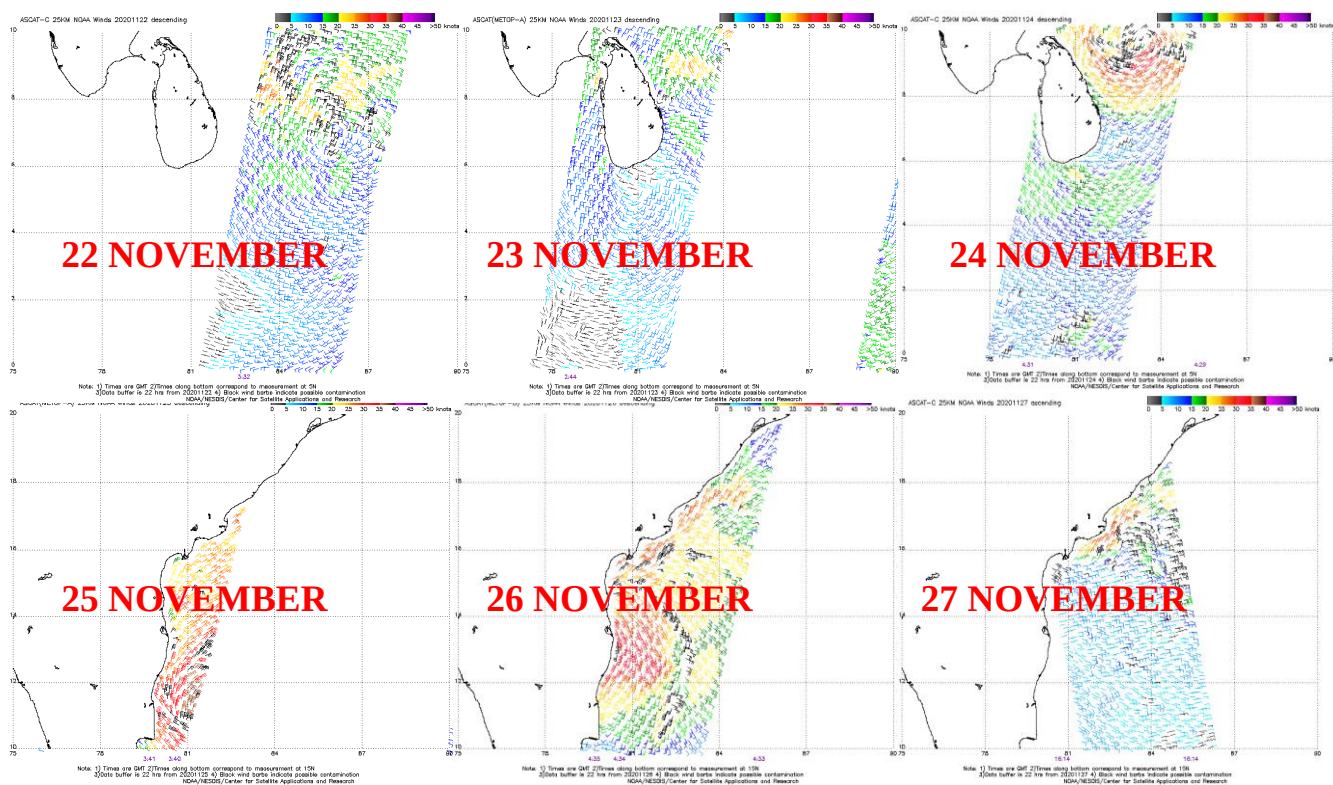


Fig. 2.9.6.(e): ASCAT imageries during life cycle of VSCS NIVAR (22-27 November, 2020)

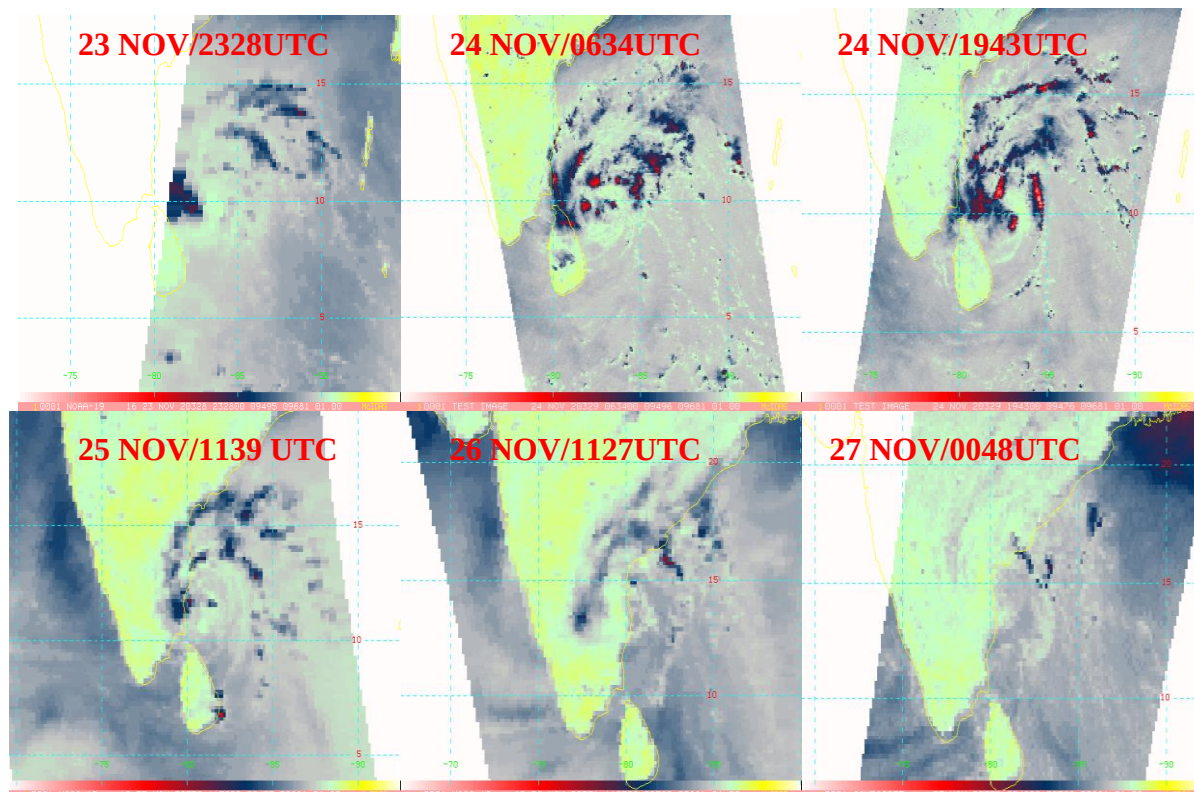


Fig. 2.9.6.(f): Microwave imageries during life cycle of VSCS NIVAR (23-27 Nov), 2020

2.9.4.2. Features observed through Radar

The VSCS NIVAR was tracked by DWRs Shriharikota, Karaikal, Chennai. Typical DWR imageries from these radars are presented in Fig. 2.9.7.

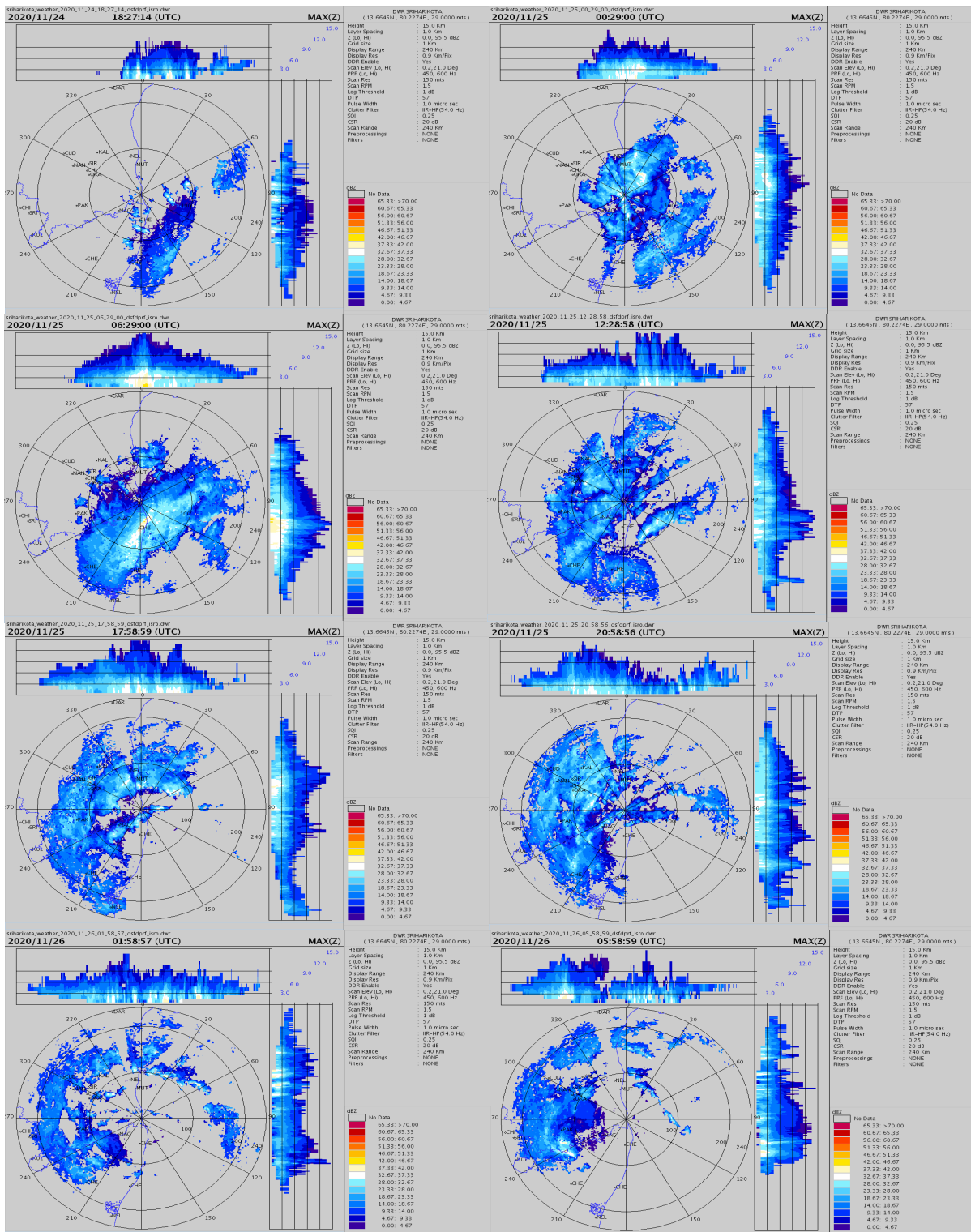


Fig.2.9.7. (a): Typical Radar imagery MAX-Z from DWR Shriharikota during 24-26 November

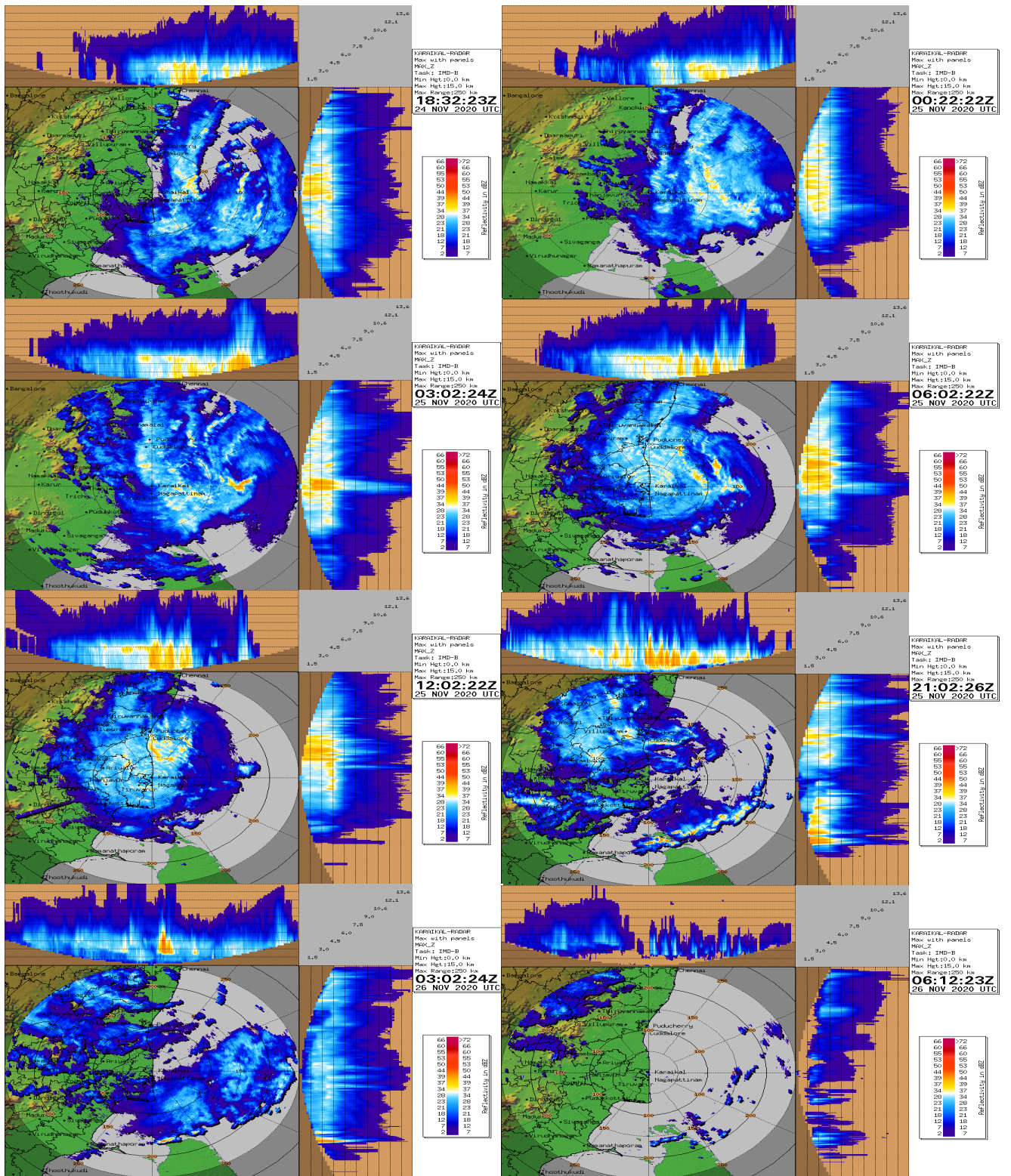


Fig.2.9.7.(b): Typical Radar imagery MAX-Z from DWR Karaikal during 24-26 November

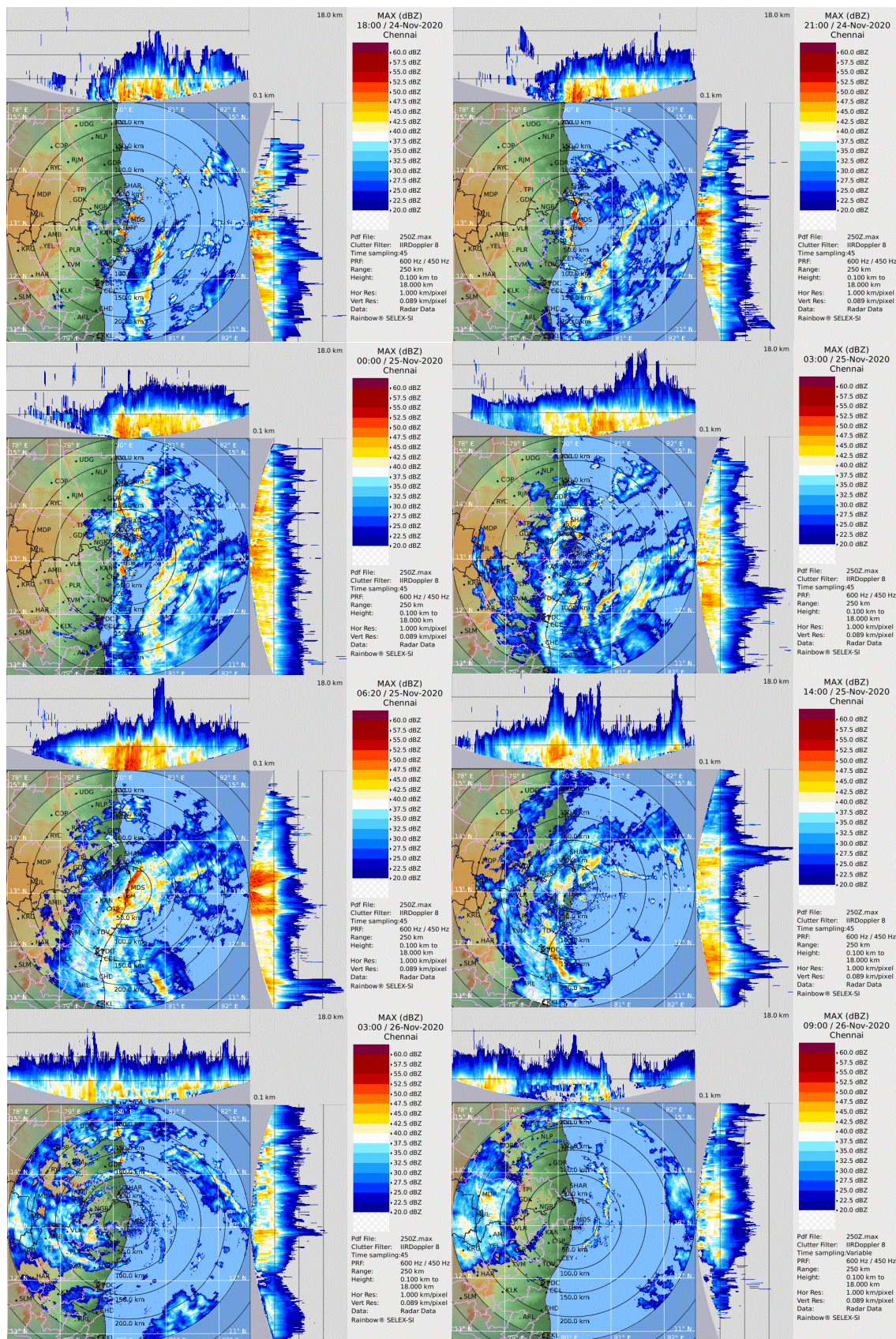


Fig.2.9.7(c):Typical Radar imagery MAX-Z from DWR Chennai during 24-26 November

2.9.5. Dynamical features

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels during 22nd - 27th November are presented in **Fig. 2.9.8**. The analysis of IMD-GFS T-1534 model based on 0000 UTC of 22nd, is indicating presence of an LPA over central parts of south BoB on 22nd with vertical extension upto 500 hPa level.

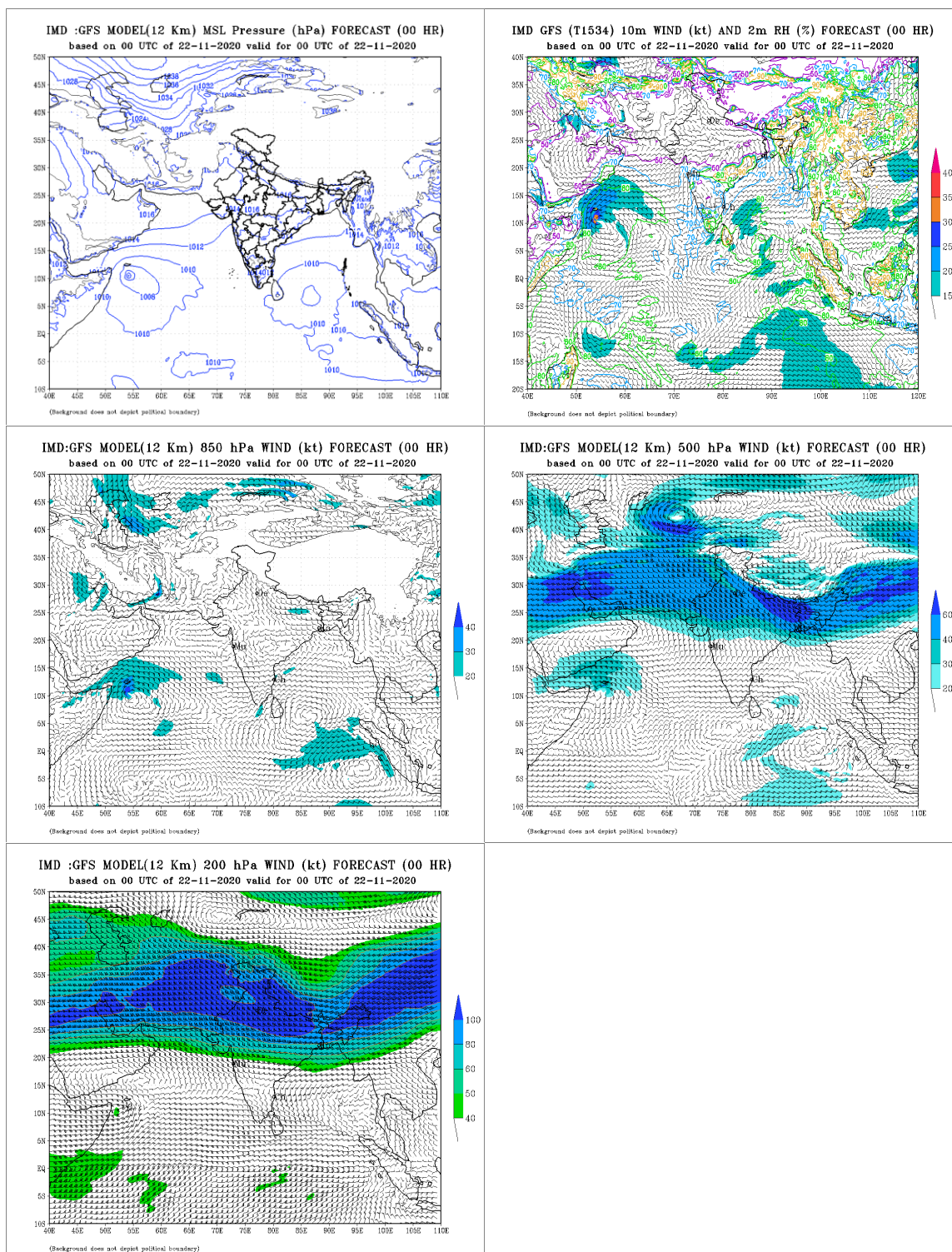


Fig. 2.9.8 (a): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 22nd November 2020

The analysis of IMD-GFS T-1534 model based on 0000 UTC of 23rd, IMD GFS was indicating presence of a cyclonic storm over southwest BoB with vertical extension upto 500 hPa level. At this time, the model over estimated the intensity of the system.

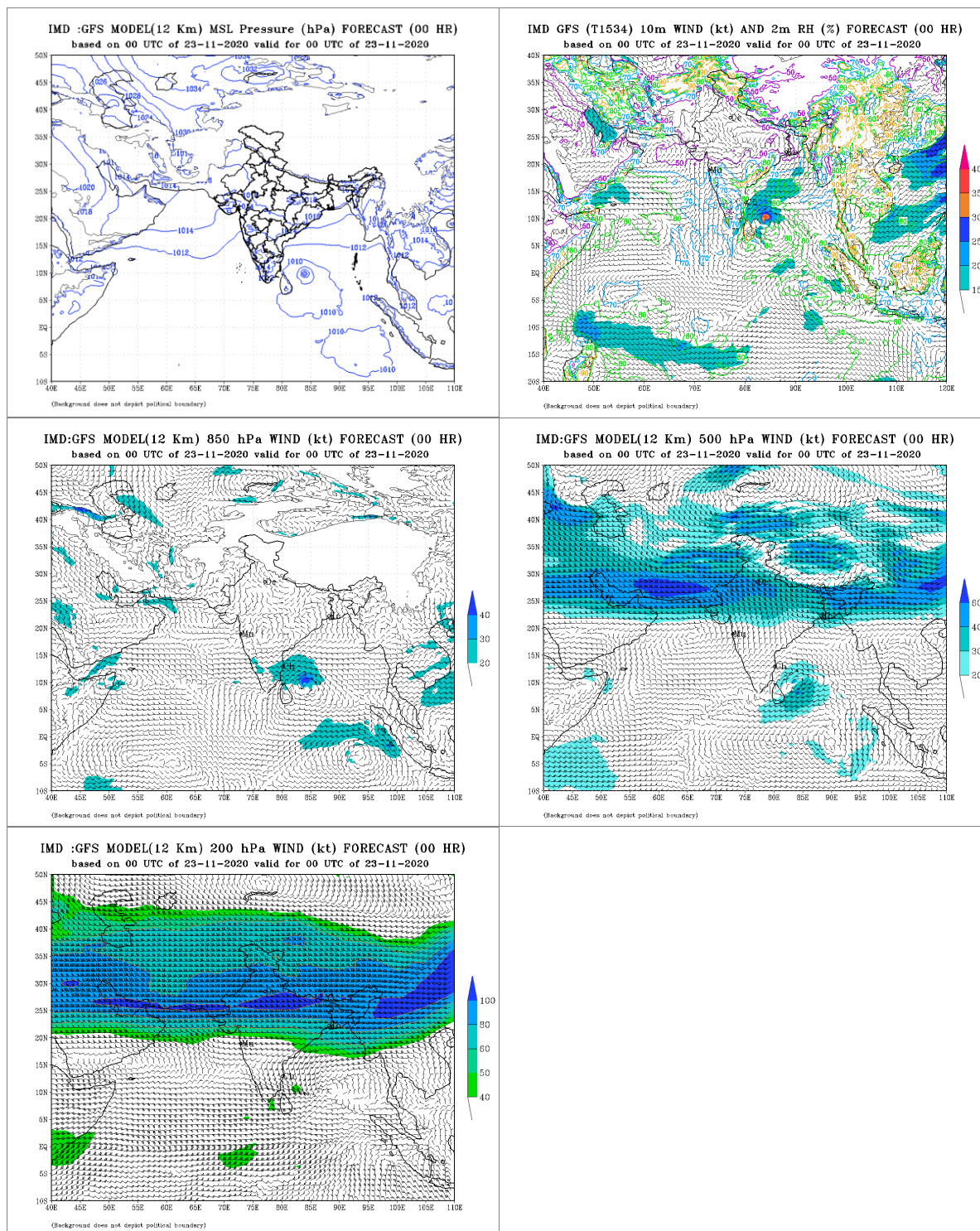


Fig. 2.9.8.(b): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 23rd November 2020

The analysis of IMD-GFS T-1534 model based on 0000 UTC of 24th, IMD GFS was indicating presence of a cyclonic storm over southwest BoB with west-northwestwards movement towards Tamil Nadu coast with vertical extension upto 500 hPa level.

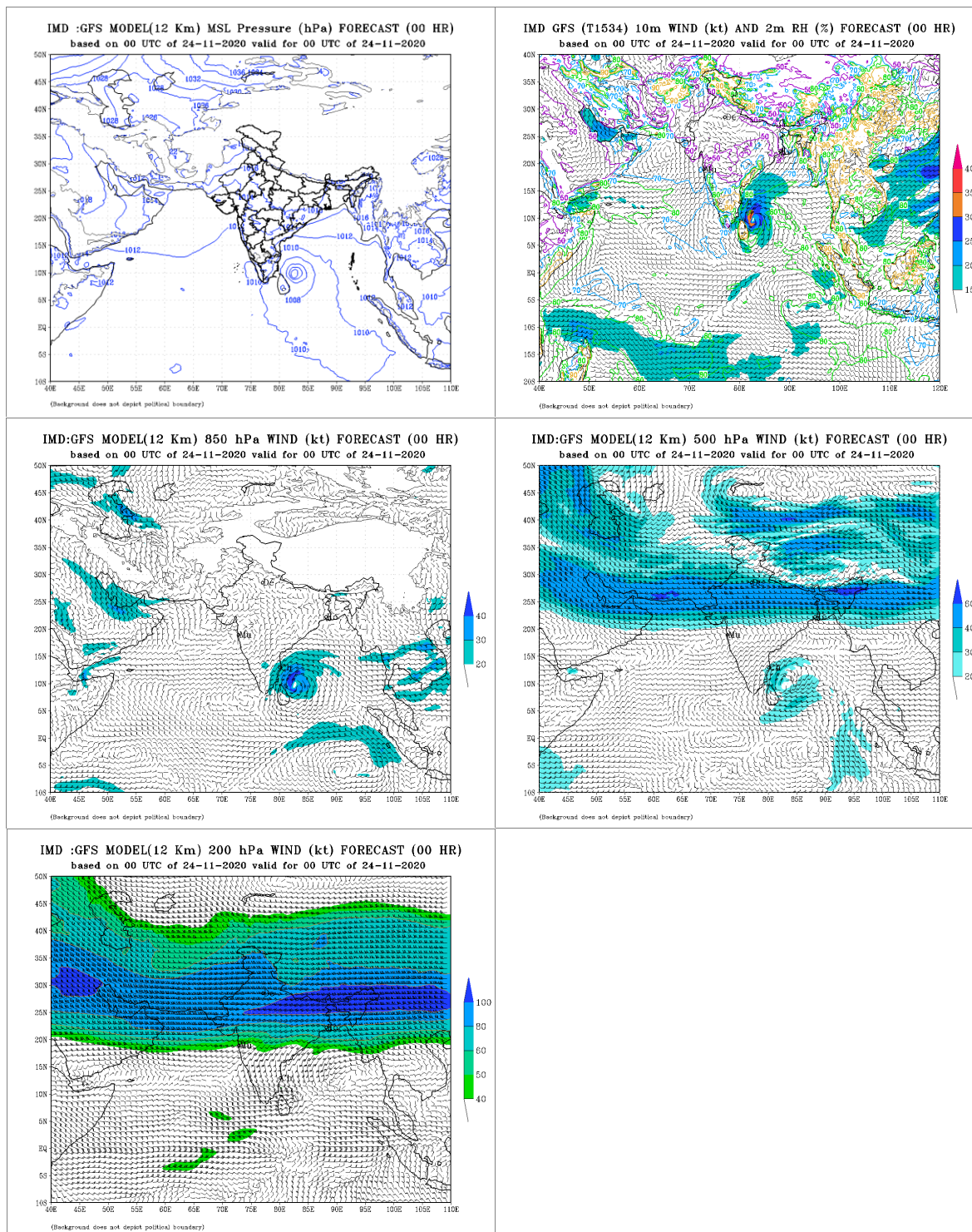


Fig. 2.9.8. (c): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 24th November 2020

The analysis of IMD-GFS T-1534 model based on 0000 UTC of 25th, IMD GFS was indicating presence of an Extremely Severe Cyclonic Storm (ESCS) over southwest BoB off Tamil Nadu coast on 25th with vertical extension upto 200 hPa level.

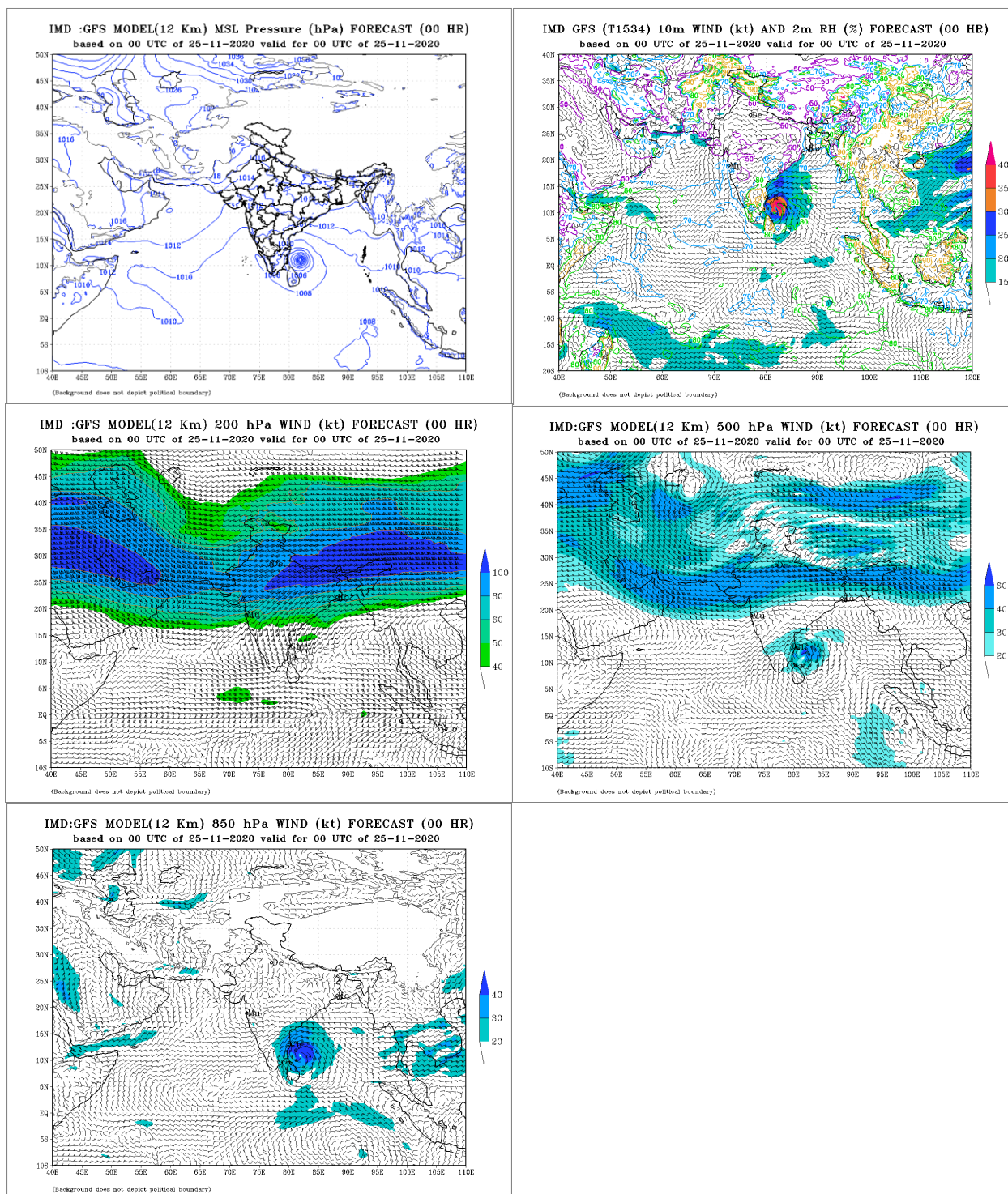


Fig. 2.9.8. (d): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 25th November 2020

The analysis of IMD-GFS T-1534 model forecasts based on 0000 UTC of 26th November, 2020 indicated presence of a Very Severe Cyclonic Storm (VSCS) over north coastal Tamil Nadu on 26th with vertical extension upto 200 hPa level.

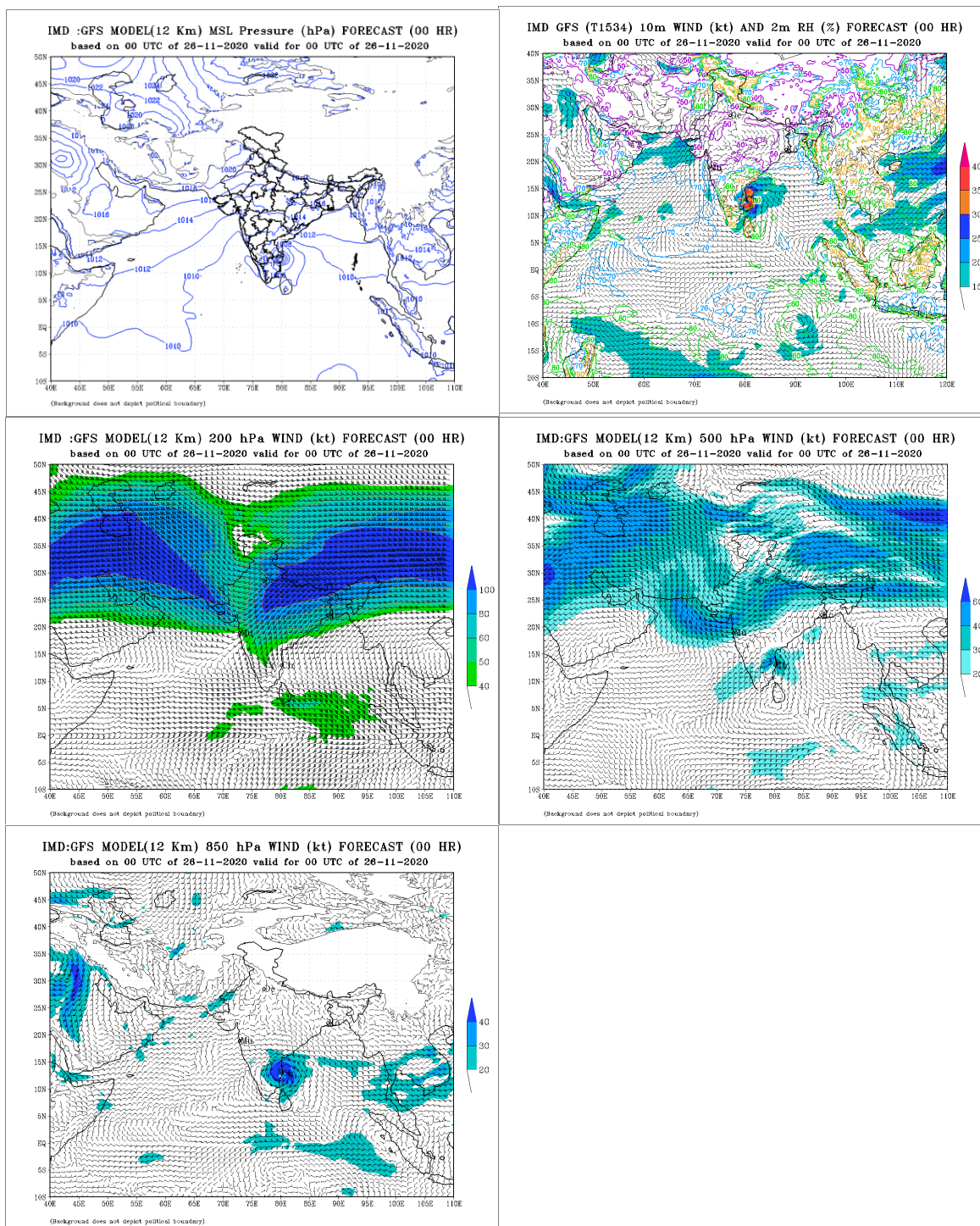


Fig. 2.9.8. (e): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 26th November 2020

The analysis of IMD-GFS T-1534 model forecasts based on 0000 UTC of 27th November, 2020 indicated presence of the remnant of the Very Severe Cyclonic Storm (VSCS - NIVAR) as a Depression (D) over south coastal Andhra Pradesh on 27th. The model over estimated the intensity of the system at 0000 UTC of 27th.

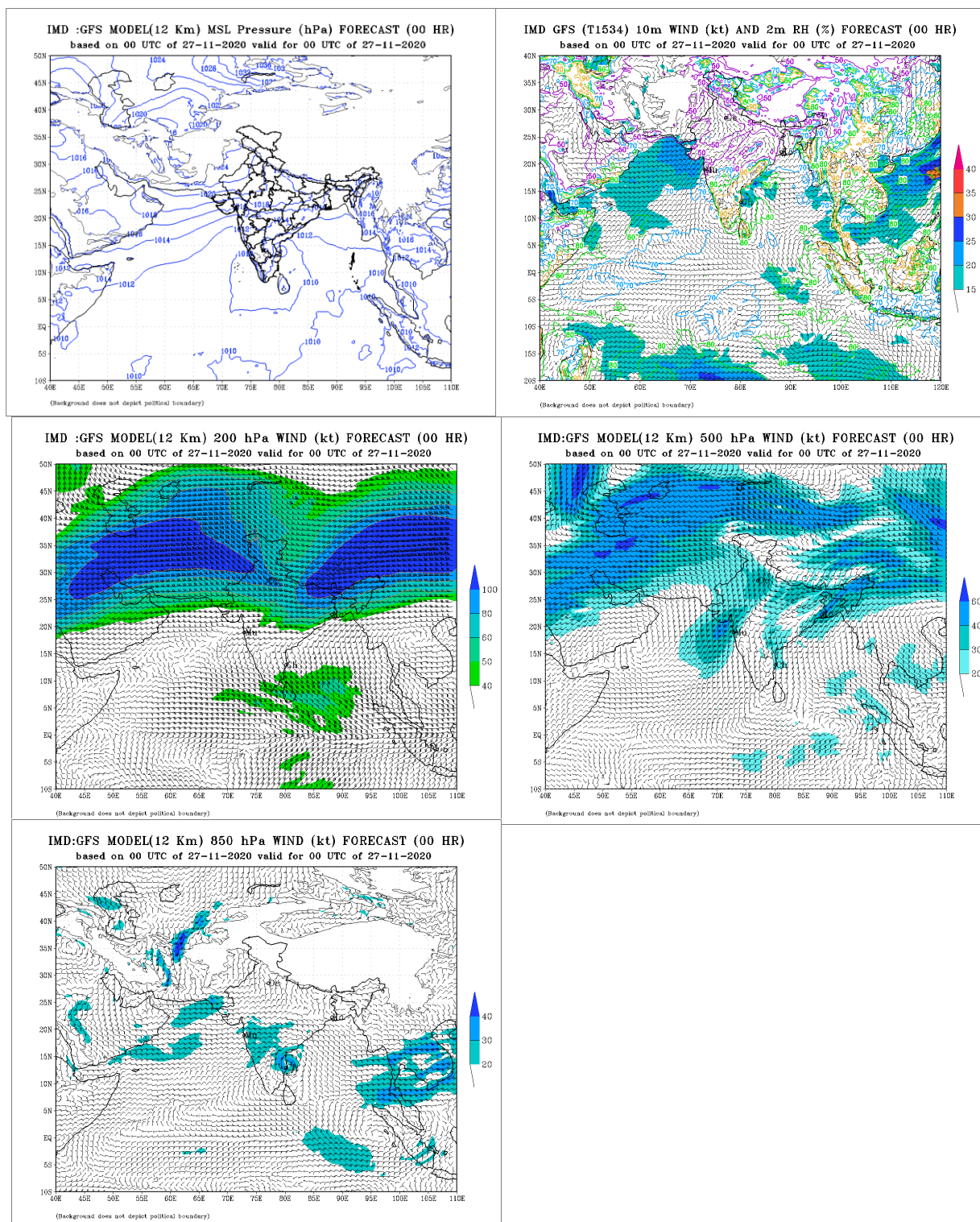


Fig. 2.9.8. (f): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 27th November 2020

2.9.6. . Realized Weather

2.9.6.1 Realised rainfall

Rainfall associated with VSCS NIVAR based on IMD-NCMRWF GPM merged gauge rainfall data is depicted in Fig 2.9.9. It indicates heavy rainfall (7-12 cm) over coastal Tamilnadu on 24th, heavy to very rainfall at few places over coastal Tamilnadu on 25th, heavy to very heavy rainfall at many places over coastal Tamilnadu and south Andhra Pradesh on 26th and 27th with extremely heavy falls at isolated places.

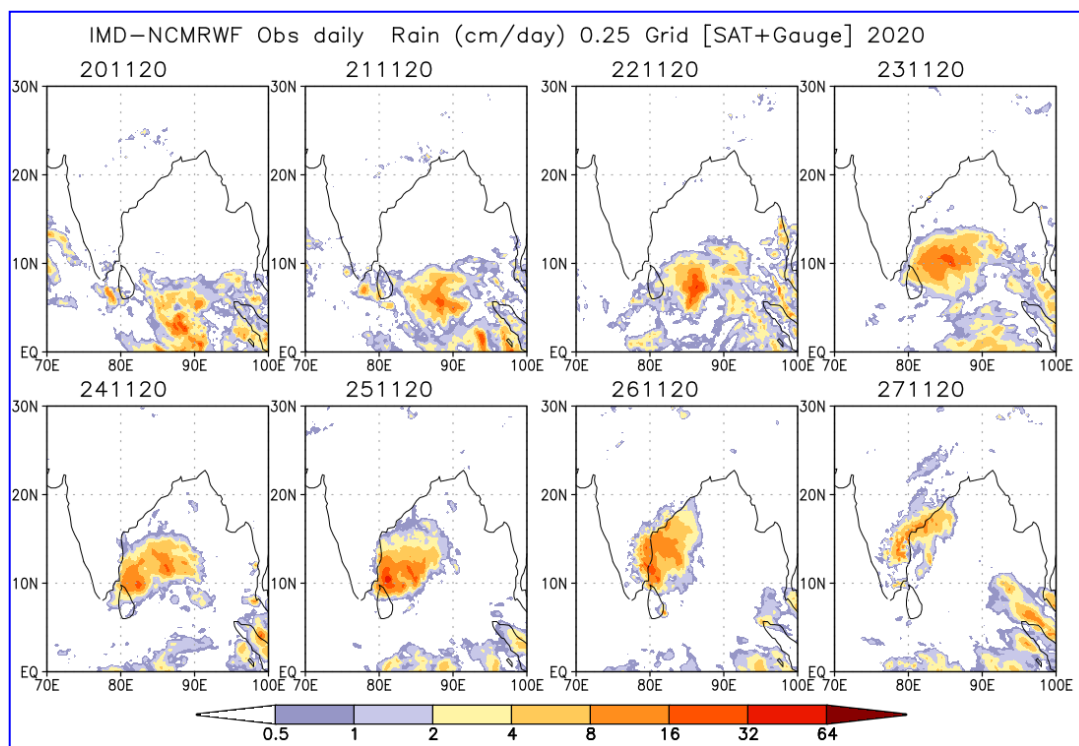


Fig.2.9.9: IMD-NCMRWF GPM merged gauge rainfall during 20th -27th Nov and 7 days average rainfall (cm/day)

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

24 November 2020

Tamilnadu, Puducherry & Karaikal: Tambaram-9, MGR Nagar, Chennai-8 each, Alandur-7.

25 November 2020

Tamilnadu, Puducherry & Karaikal: Chennai (Nungambakkam)-16, Anna University, Chennai (Meenambakkam), Sholinganallur-15 each, Taramani, Anna University, DGP Office, MGR Nagar-14 each, Mahabalipuram, Alandur, Hindusthan University, Puzhal, Chembarambakkam-12 each, Tambaram, Ambathur-11 each, Perambur, Red Hills, Kolapakkam, Poonamallee-10 each, Ennore, Thirupporur, Cholavaram- 9 each, Maduranthagam, Kelambakkam-8 each, Sriperumbudur-7.

26 November 2020

Andhra Pradesh: Kodur-25, Venkatagiri-24, Gudur-19, Rapur-16, Atmakur, Sullurpeta-15 each, Nellore, Kavali, Satyavedu, Sambepalle-14 each, Nagari, Rajampet, Tirupati-13 each, Thottambedu, Puttur-12 each, Palamaner, Srikalahasti, Tada-11 each, Penagaluru, Kalakada-10 each, Palasamudram, Royachoti, Amalapuram-9 each, Vinjamur, Udayagiri, Pullampeta, Pakala-8 each, Chittoor, Chinnamandem, Cuddapah, Madanapalle-7 each.

Tamilnadu, Puducherry & Karaikal: Tambaram-31, Puducherry-30, Vilupuram-28, Cuddalore-27, DGP Office, Chennai-26, Sholinganallur-22, Thamaraipakkam-19, Parangipettai-18, Pallipattu-17, Cholavaram-16, Gingee, Poonamallee, Ambathur, Tiruvallur, Mahabalipuram, Gummidipoondi-15 each, Tindivanam, Maduranthagam, Chembarabakkam, Anna University, Vanur, Kollidam, Bhuvanagiri-14 each, MGR Nagar, Kancheepuram, Kurinjipadi, Alandur, Chidambaram, Red Hills, Marakkanam, Chengalpattu, Tiruttani, Chidambaram-13 each, Ulundurpet, Poondi, Keelpennathur, Vadapudupattu, Koratur, Sirkali-12 each, Chennai Airport, Vandavasi, Sethiyathope, Vembakkam, Poonamalle-11, Arakonam, Thirukalukundram, Sriperumbudur, Panruti-11 each, Ponneri, Arcot, Taramani, Perambur, Uthiramerur, Sholingur, Cheyyur-10 each, Anna University, Chembarambakkam, Thiruvalangadu, Tirukoilur, Polur, Mayiladuthurai, Thirupporur, Kelambakkam, Karaikal, Manalmedu, Puzhal-9 each, Arani, Chennai (Nungambakkam), Vridhachalam, Vepur, Hindusthan University, Ammundi, Vellore, R.K.Pet, Kodavasal, Manjalaru-8 each, Uthukottai, Ambur, Kaveripakkam, Agaram Seegoor, Tiruttani, Tozhudur, Tarangambadi, Pelandurai, Tiruvannamalai, Srimushnam, Ennore, Needamangalam, Sendurai, Katpadi, Cheyyar, Aduthurai-7 each.

27 November 2020

Andhra Pradesh: Kavali-27, Nambulipulikunta-25, Gurramkonda-21, Sambepalle-20, Royachoti, Madanapalle, Chinnamandem, Kalakada-18 each, Punganur, Udayagiri, Vinjamur- 17 each, Atmakur, Pullampeta, Thambalapalle, Palamaner-16 each, Chapad, Chittoor, Proddutur, Arogyavaram, Avanigada, Ongole, Amalapuram-15 each, Yanam, Marripudi, Podili, Veligandla, Kandukur, Utukuru(A), Vempalle, Kamalapuram-14 each, Atlur-13, Kakinada, Palakoderu, Cuddapah -12 each, Bheemavaram, Bapatla, Vijayawada Airport, Gudivada, Narsapuram, Chimakurthi, Duvvur-11, Raju Palem, Pakala, Palasamudram-11 each, Vallur, Kodur, Rajampet, Karamchedu, Repalle, Seetharamapuram, Tanuku-10 each, Mundlamuru, Addanki, Mangalagiri, Tadepalligudem, Masulipatnam, Peddapuram, Kaikalur, Jammalamadugu, Badvel, Porumamilla, Puttur-9 each, Pulivendla, Muddanur, Lakkireddipalle, Konakanamitla, Cumbum, Bestavaripeta, Markapur, Nellore, Darsi-8 each, Vijayawada, Tuni, Anakapalle, Rapur, Santhamaguluru, Guntur, Bhimadole, Racherla, Prathipadu, Visakhapatnam, Eluru, Penagaluru, Kadiri, Tanakal, Venkatagiri Kota-7 each.

Tamilnadu, Puducherry & Karaikal: Sholingur-23, Vadapudupattu-16, Vellore, Ponnai Dam, Ammundi-14 each, Ambur, R.K.Pet-13 each, Alangayam, Katpadi-12 each, Vaniyambadi, Tirupuvanam, Kaveripakkam-9 each, Wallajah, Gudiyatham, Virinjipuram-8 each, Devakottai, Vembakkam, Melalathur-7 each.

2.9.6.2. Realised wind

The system crossed Tamil nadu and Puducherry coasts as a very severe cyclonic storm with an estimated wind speed of 120 kmph gusting to 135 kmph.

2.9.6.3. Realised storm surge:

No significant storm surge was reported.

2.9.7. Damage due to VSCS NIVAR

The Cyclone brought heavy to very heavy rains over North coastal Tamilnadu starting 23rd November 2020. Chennai received continuous downpours on 23,24,25 November 2020 with IMD Chennai recording 163mm ending 25th November 8:30 AM IST. Chennai and other parts of North TN saw gusty winds touching 60-70kmph on 24th, 25th November. Several roads were closed in the area of the Greater Chennai Corporation were closed due to water logging. Due to intense rainfall, Chembarambakkam lake have released water for the first time after five years. Many

areas including Madipakkam, Velachery, Adambakkam and suburbs around Tambaram and low lying regions along the river Adyar were flooded. Rainwater entering houses was also seen in some places in the western suburbs. The Greater Chennai Corporation removed uprooted trees from 223 roads. The estimates of Chennai civic officials reported that flood water entered around 40,000 homes within the borders of the Corporation. Five people were reported dead in Tamil Nadu.

In Puducherry, trees were uprooted, electric poles were damaged and several areas were flooded as of November 26. The Chief Minister of Puducherry V. Narayanasamy reported that the initial loss in agriculture and other sectors was estimated at ₹4 billion.

Eight people were reported dead in Andhra Pradesh. The rainfalls made significant impact on the districts of Chittoor, Prakasam, Kadapa and Nellore, 112000 people were affected, 2,294 houses/huts were damaged, 6,133 homes were left stranded, 2,618 small animals, 88 large animals and 8,130 poultry birds were reported dead based on a preliminary evaluation. In Nellore district, Paddy seedlings in 2500 hectares drowned and in Prakasam district, standing crops in 34,000 hectares were damaged. Loss of APSPDCL amounted to be ₹50.7 million.



Fig.2.9.10.(a): Damaged houses Bommayarpalayam on the East Coast Road (source:thehindu.com), (b) A man pushes his bicycle through a water-logged neighbourhood after Cyclone Nivar's landfall, in Chennai (source: science.thewire.in), (c) Severe cyclonic storm Nivar lashed Puducherry and TN on Thursday, uprooting trees, damaging electric poles (source: <https://www.newindianexpress.com/>) and (d) Flooded railway station in Puducherry (source: <https://www.newindianexpress.com/>)

2.10. Cyclonic Storm “BUREVI” over the Bay of Bengal (30th November - 05th December 2020)

2.10.1. Introduction

The cyclonic storm, ‘Burevi’ originated as a Low Pressure area in the equatorial easterly wave over South Andaman Sea and adjoining areas of Southeast Bay of Bengal & Equatorial Indian Ocean on 28th November 2020, which became a Well Marked Low pressure area over Southeast Bay of Bengal & adjoining areas of South Andaman Sea and Equatorial Indian Ocean on 29th. Under favourable environmental conditions, it concentrated into a Depression in the early morning (0530 hrs IST / 0000 UTC) of 30th November 2020 over Southeast Bay of Bengal. Moving nearly westwards, it intensified into a Deep Depression in the early morning of 01st December 2020 over Southwest and adjoining Southeast Bay of Bengal. Subsequently it moved west-northwestwards and intensified into Cyclonic Storm ‘Burevi’ over Southwest Bay of Bengal in the evening (1730 hrs IST / 1200 UTC) of 01st December 2020. Continuing the west-northwestward movement, it crossed Sri Lanka coast close to north of Trincomalee near Lat. 8.85°N and Long. 81.0°E between 2230 and 2330 hrs IST (1700 & 1800 UTC) of 2nd December 2020 as a Cyclonic Storm with a maximum sustained wind speed of 80-90 kmph gusting to 100 kmph. Moving across northern parts of Sri Lanka, it emerged into Gulf of Mannar in the morning and lay centred close to Pamban around noon (1130 hrs IST / 0600 UTC) of 03rd December. It crossed Pamban area around 0800 UTC of 3rd. Continuing to move west-northwestwards, it weakened into a Deep Depression over the same region in the evening (1200 UTC) of 03rd December. Thereafter the movement slowed down significantly and it remained practically stationary over Gulf of Mannar close to Ramanathapuram district coast for nearly 18 hours and further weakened into a Depression in the evening of 04th December over the same region. Further remaining stationary at the same place for subsequent 18 hours, it gradually weakened into a well marked Low pressure area around noon (1130 hrs IST / 0600 UTC) of 05th December. This system during its initial stage as a Low pressure area had caused fairly widespread rainfall with isolated very heavy falls over Andaman & Nicobar Islands on 29th November. Under the influence of this system, widespread rainfall with heavy to very heavy falls at a few places & extremely heavy (≥ 20 cm) falls at isolated places occurred over Tamil Nadu during 02nd – 04th December.

The observed track of the system during 30th November to 05th December is presented in Fig. 2.10.1.

2.10.2. Salient Features:

- Burevi, after weakening, remained practically stationary for nearly 36 hours over Gulf of Mannar close to Ramanathapuram district. It is mainly due to the fact that it came under the regime of very light steering winds in the middle & upper tropospheric levels over this region, sandwiched between two upper level

anticyclonic circulations to its northeast and northwest. In meteorological parlance, such a region is known as a 'col' region.

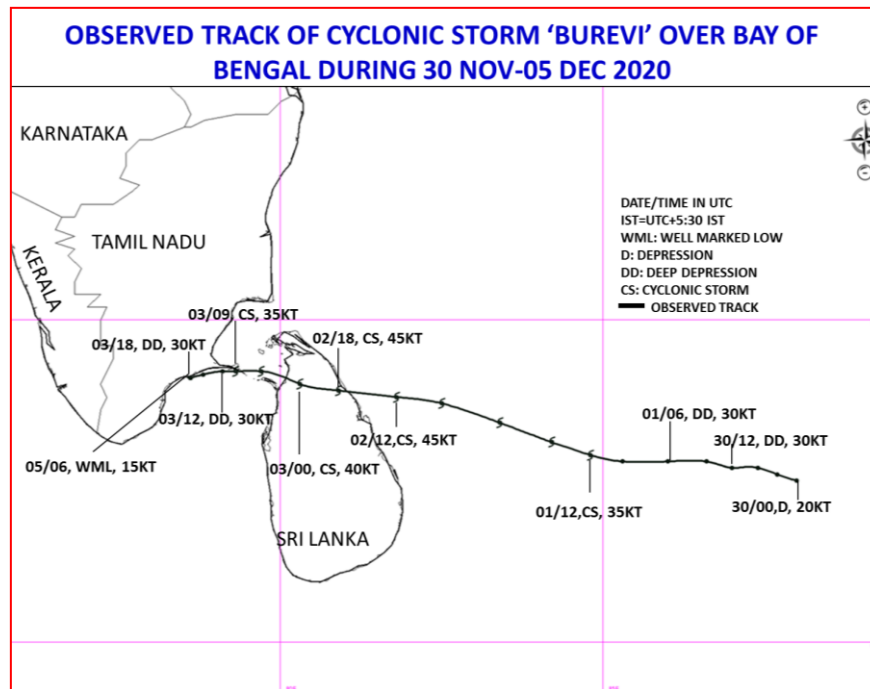


Fig. 2.10.1: Observed track of cyclonic storm "BUREVI" over Bay of Bengal

- It could intensify only upto cyclonic storm stage, due to following reasons
 - Its predecessor very severe cyclonic storm "NIVAR" caused upwelling over the Sea region in which Burevi matured. As a result there was relative cooling of Sea surface and thus couldn't get enough energy from the Sea for further intensification.
 - Also the cyclone Burevi had originated in the near equatorial region experiencing lower Coriolis force. Higher Coriolis force which is directly proportional to the latitude of occurrence of the cyclone favours intensification.
 - The interaction with the land surface as it lay close to Sri Lanka and south Tamil Nadu coasts also limited its intensification.
 - The vertical wind shear remained moderate to high as it approached towards the coast. The high wind shear is unfavourable for intensification.
- Climatologically, during the recorded history (1891-2019), out of a total of 58 cyclonic storms & above intensity storms developing over the Bay of Bengal in the grid (5°N - 10°N & 75°E - 80°E) during October-December, total 11 (about 19%) reached the state of Kerala. Out of these 11, 3 crossed Kerala after emerging from Sri Lanka and remaining 8 reached Kerala after crossing Tamil Nadu (Fig. 2.10.2 a).

- Also, during the period 1891-2019, there have been 13 cyclonic storms and above intensity storms that crossed the east coast of Sri Lanka (Fig. 2.10.2 b). Out of these, 10 emerged into Gulf of Mannar-Comorin area & crossed Tamil Nadu coast (7 near Pamban, 3 near Kanniyakumari) and 2 weakened over Sri Lanka with 1 moving west-southwestwards towards southeast Arabian Sea. Considering season-wise distribution, out of 13 cyclonic storms and above intensity storms that crossed east coast of Sri Lanka, 11 crossed the east Sri Lanka coast during post monsoon season (October to December) (Fig. 2.10.2 c) and remaining 2 crossed east Sri Lanka during January, 1906 and March, 1907 (Fig. 2.10.2d).

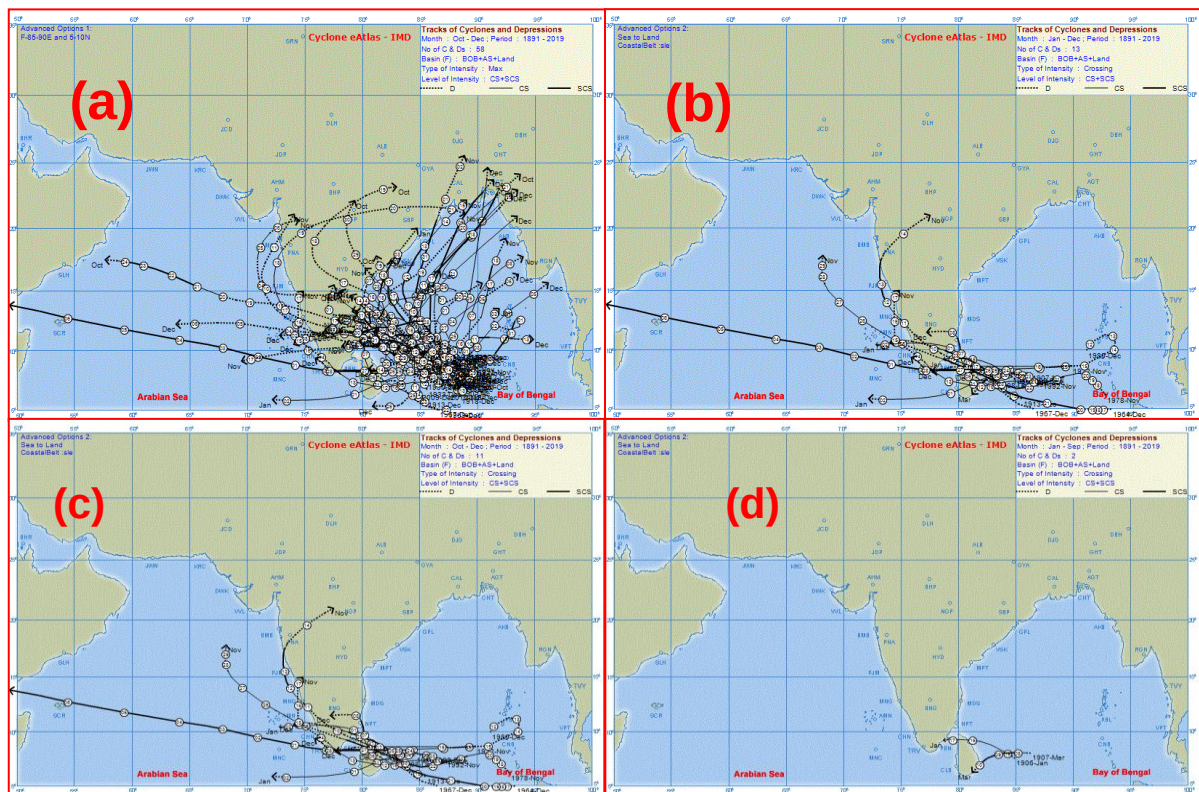


Fig. 2.10.2 Number of cyclonic storms and above intensity storms during 1891-2019 (a) developing in the grid (5°N - 10°N & 75°E - 80°E), (b) developing over Bay of Bengal & crossing East Sri Lanka coast, (c) cyclones developing over Bay of Bengal and crossing East Sri Lanka coast during October-December and (d) cyclones developing over Bay of Bengal and crossing East Sri Lanka coast during January-September

- Track of the Cyclonic Storms which crossed south Tamil Nadu coast are given in **Fig. 2.10.3**. It may be noted that, the monthly frequency of Cyclonic storms crossing south Tamil Nadu coast during 1891 – 2019 has been 01 in January and 4 each during November & December. Rest of the months (viz., February to October) has not witnessed any cyclone crossing south Tamil Nadu. This also implies that no cyclone so far has crossed south Tamil Nadu coast during the pre-monsoon months. Thus Sri Lanka and south Tamil Nadu coasts are more

prone to cyclonic activity during post-monsoon season, especially during November and December.

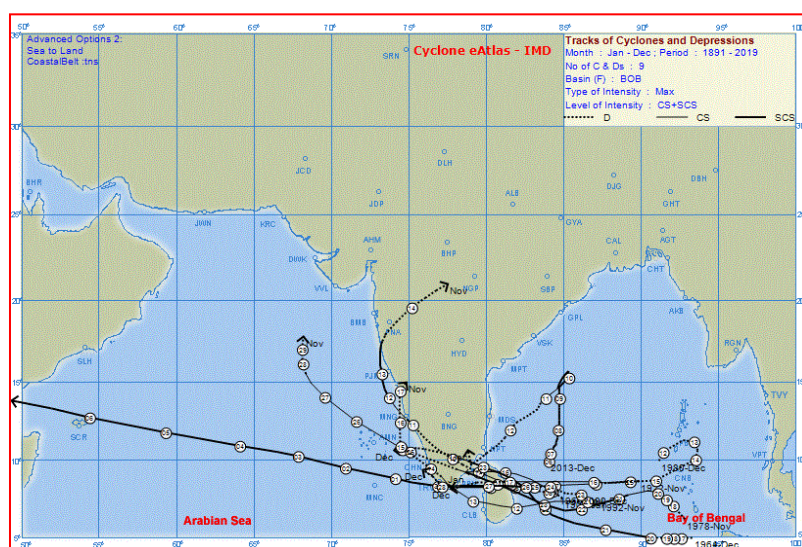


Fig. 2.10.3: Track of Cyclonic Storms & Severe Cyclonic Storms which crossed south Tamil Nadu coast during 1891- 2019

- During 1891 – 2019, a total of 09 Cyclonic Storms crossed south Tamil Nadu coast & 58 crossed north Tamil Nadu coast.
- There were 5 years in which 2 or more number of systems crossed Tamil Nadu coast viz., 1906, 1964, 1966, 1978 & 2000. But none of these events were within a span of a week's time as occurred during this year when the Very Severe Cyclonic Storm 'NIVAR' (22nd – 27th November 2020) crossed Tamil Nadu coast, near Puducherry on 25th November and the Cyclonic Storm 'BUREVI' (30th November – 05th December) after moving across Sri Lanka, crossed Pamban area of south Tamil Nadu coast on 03rd December. Salient features of the past systems, when 2 or more Cyclonic Storms crossed Tamil Nadu coast is enlisted in the Table 2.10.1.

Table 2.10.1. Salient features of the past systems, when 2 or more Cyclonic Storms crossed Tamil Nadu coast

Sl. No	Year	Period	Characteristics
1	1906	15-17 Jan	Crossed Sri Lanka coast, emerged into Gulf of Mannar & weakened
		26-27 Dec	Crossed north Tamil Nadu coast & weakened
2	1964	4-8 Nov	Crossed north Tamil Nadu coast as Cyclonic Storm
		17-24 Dec	Crossed north of Pamban, weakened into a Depression and re-emerged into southeast Arabian

			Sea off Kerala coast
3	1966	28April – 4 May	Formed over southeast BoB, crossed north Tamil Nadu coast, moved across Karnataka as a Depression, re-curved over to Madhya Maharashtra and weakened.
		01 – 11 Nov.	Formed over Andaman Sea, crossed north Tamil Nadu coast, weakened into a Depression, moved west-southwestwards, moved across Kerala, emerged into southeast Arabian Sea, moved westwards, re-intensified into a Severe Cyclonic Storm over south Arabian Sea, moved west-northwestwards and crossed south Oman coast as an SCS on 11th Nov.
		08- 14 Nov	Formed over southwest BoB, crossed as a CS over northeast coast of Sri Lanka, emerged close to Pamban as a Depression, moved across Karnataka coast close to Mangaluru, re-intensified into an SCS over east-central Arabian Sea, re-curved northeastwards, crossed south Maharashtra coast, weakened into a Depression and dissipated over Marathwada.
		25 Nov – 4 Dec	Formed over Andaman Sea, crossed north Tamil Nadu coast close to Chennai as a Severe Cyclonic Storm, moved inland, weakened into a Cyclonic Storm, moved across Karnataka as a Depression & weakened over Goa.
4	1978	03-13 Nov	Formed over southwest BoB, crossed north Tamil Nadu coast as a Depression, intensified into Severe Cyclonic Storm only after re-emerging into the Arabian Sea across north Kerala. After re-intensification, re-curved & crossed north Gujarat coast.
		18-29 Nov	Formed over southeast BoB, crossed northeast coast of Sri Lanka as an SCS, re-emerged & crossed south Tamil Nadu coast close to Pamban as SCS, weakened into a Depression, moved across Kerala coast, close to Kochi, re-emerged into the Arabian Sea, re-intensified into a Cyclonic Storm, moved north-westwards and weakened over east-central Arabian Sea.
5	2000	26-30 Nov	Formed over south Andaman Sea, crossed north Tamil Nadu coast as SCs, moved inland and weakened.

		23-28 Dec	Formed over southeast BoB, crossed north Sri Lanka as SCS, emerged into Gulf of Mannar, moved across Kanniyakumari, weakened into a Depression and moved along south Kerala coast.
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- A system analogous to that of CS 'BUREVI' occurred during 15-17 January 1906 which crossed the east coast of Sri Lanka, close to north of Trincomali and moved across Pamban area and weakened near Ramanathapuram district coast. After 113 years, this is the first Cyclonic Storm following a similar track & intensity characteristic. However, unlike the previous one, it remained practically stationary for about 36 hrs near the coast.
- Considering the extraordinarily long stationary period of cyclone Burevi, during past 30 years (1990-2020), last such stationary behaviour was witnessed during 1999, Odisha Super Cyclone which remained stationary over land for 30 hours. However, cyclonic storm Burevi crossed that record and remained stationary over Gulf of Mannar close to Ramanathapuram for 36 hours.
- Plausible reasons for this stagnation probably could be attributed to the weakened dynamics of the system and the light steering environment as stated above. A few of the physical & dynamical features experienced by the system are re-produced below.

(a) Shallow vertical extention & small horizontal scale.

Cyclonic Storm (BUREVI) emerged into Gulf of Mannar, after crossing north Sri Lanka. The topography of Sri Lanka is re-produced in the map (**Fig. 2.10.4**). It may be noted that though the stretch of land across which the system moved is narrow, subsequent to the re-emergence, the system underwent land interaction, causing the system to loose momentum.

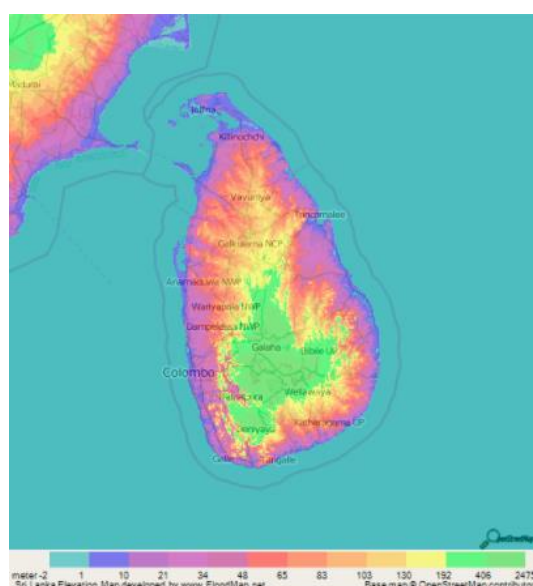


Fig. 2.10.4 Topographic features surrounding Gulf of Mannar.

Thus the vertical extension & horizontal scale of the system, reduced significantly after re-emerging into Gulf of Mannar. Vertically the cyclonic circulation extended roughly upto 7.6 km above mean sea level (400 hPa) and it had a rapidly expanding radius of maximum winds, implying weakening. (Figures not given).

(b) Less Ocean Thermal Energy

Tropical Cyclone Heat Potential (TCHP) is a measure of the integrated vertical temperature from the Sea surface to the depth of 26°C isotherm. It is a measure of the Potential energy associated with the heat content available to any tropical cyclonic disturbance for resulting in intensity changes.

The slowing down of the cyclonic disturbances over the tropical Oceans cause an increase in momentum exchange from the cyclonic system to the Sea surface. This would lead to deeper vertical mixing and enhanced Sea surface cooling. As a consequence, the heat flux would decrease from the Ocean to the cyclonic disturbance, thereby inhibiting its further intensification. (Liu et al 2007, Lin et al 2009, Mei et al 2012, Horman et al 2014, Kim et al 2020). Fig. 2.10.5 shows the average Tropical Cyclone Heat Potential (TCHP) analysis (30th November – 10th December) from INCOIS analysis.

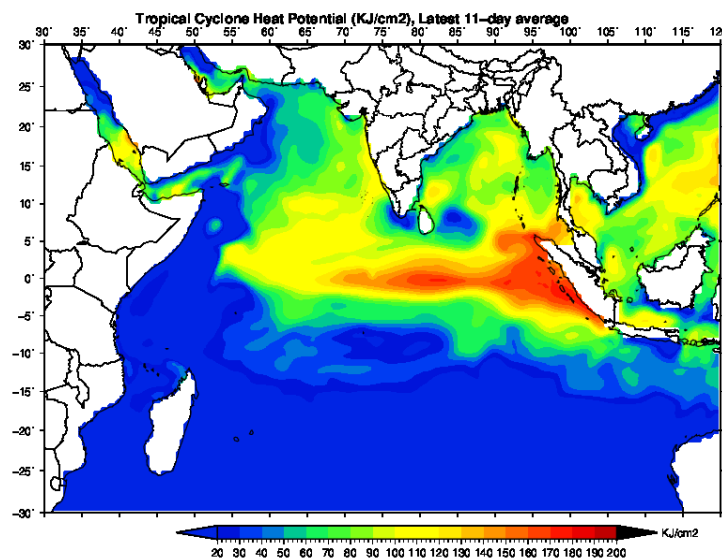


Fig. 2.10.5: TCHP pattern (Latest 11 day average ending on 10th December 2020) by INCOIS

(c) Vertical wind shear

The vertical wind shear (both directional as well as speed) during the life cycle of the system is given in **Fig. 2.10.6**. It may be noted that the system originated in the equatorial easterly wave regime and had remained under the mid & upper level easterly steering influence and hence under low vertical wind shear field upto the early morning of 04th December.

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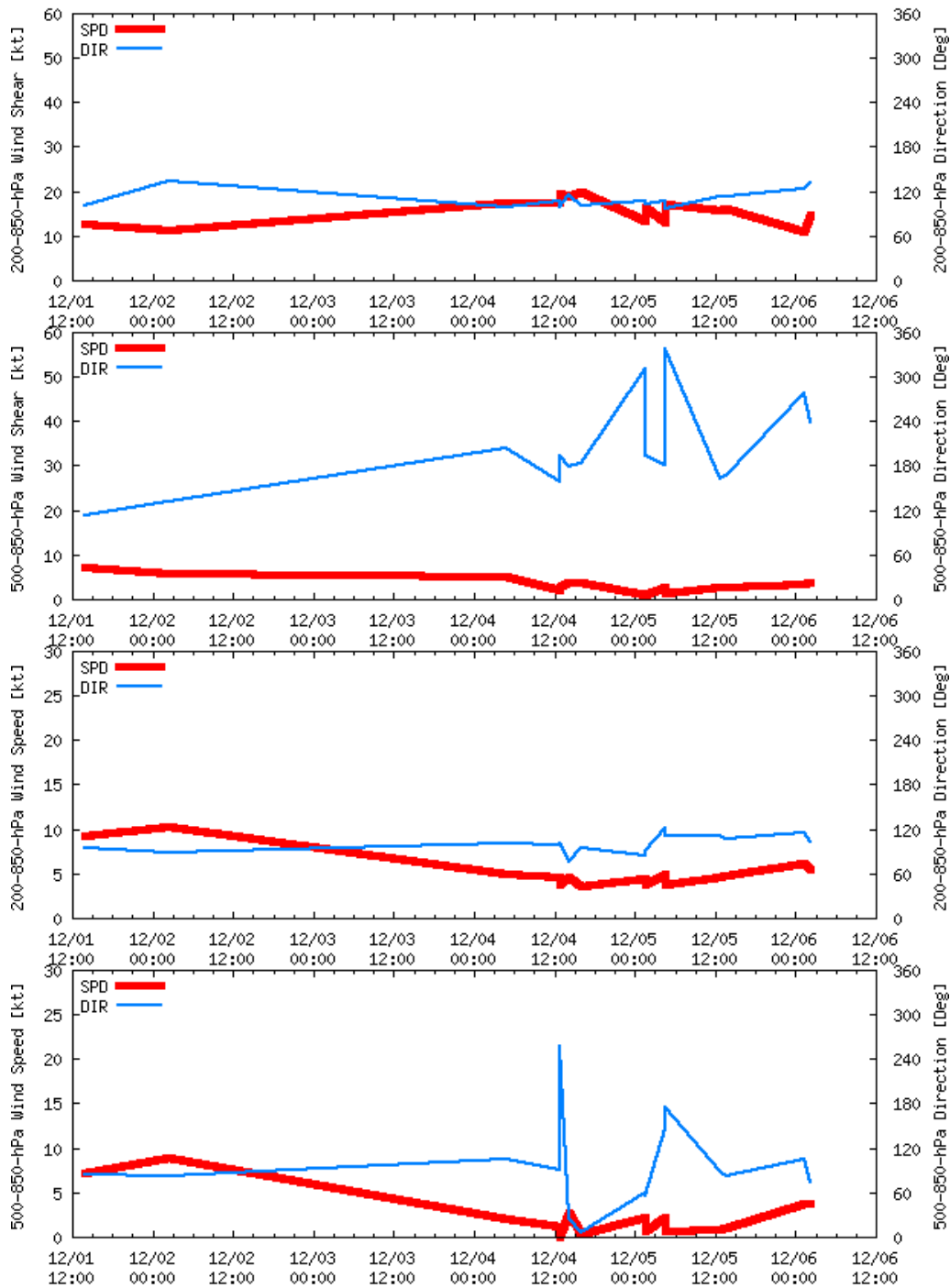


Fig. 2.10.6: Vertical wind shear associated with Cyclonic Storm BUREVI (courtesy: Cooperative Institute for Research in the Atmosphere website)

(a) Latent heat release due to the intense convection & heavy rainfall to the northeast of the system over coastal Tamil Nadu

Role of the mid-level warming as is evidenced in Fig.2.10.7, owing to the Latent heat of condensation associated with the meso-scale convective complex generated to the north of the system (resulting in extremely heavy

rainfall) prior to & during the stagantion period needs to be further addressed.

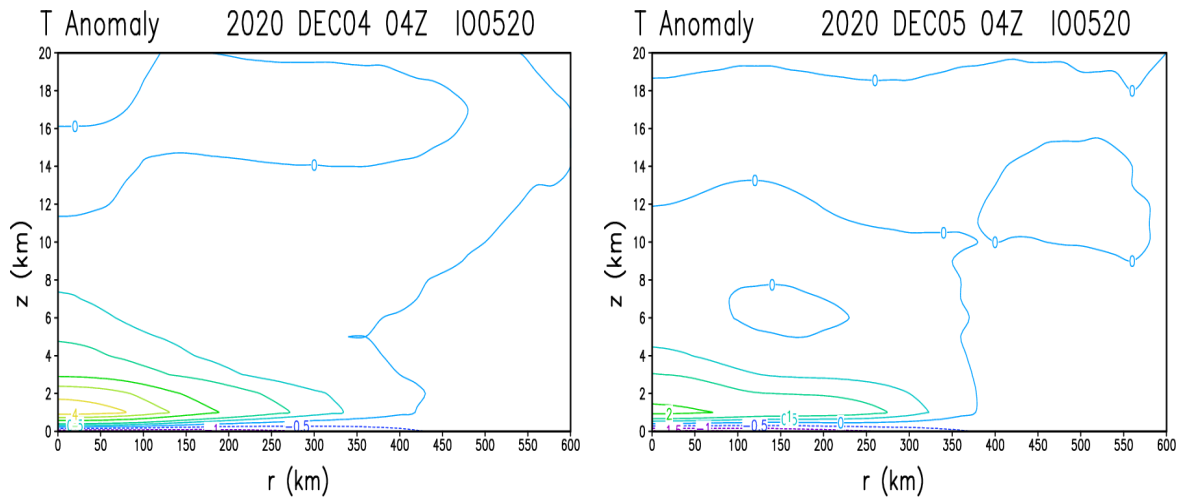


Fig. 2.10.7: Vertical thermal structure associated with Cyclonic Storm BUREVI (courtesy: Cooperative Institute for Research in the Atmosphere website)

All the above preliminary analyses indicate that due to the prevailing middle to upper tropospheric environment with a COL region due to two anticyclones on either side to northeast and northwest of the cyclone over Gulf of Mannar, the system remained practically stationary for about 36 hrs. Further persistence over this land-locked region of Gulf of Mannar led to cooling of Gulf of Mannar through continuous rainfall and upwelling over the region and hence cooling of the Sea region. Further the increased wind shear and interaction of land surface favoured the weakening. However this persistence of the system over Gulf of Mannar for such a long period led to extremely heavy rainfall over Tamil Nadu & Puducherry for a longer period and the rainfall was confined to Tamil Nadu and Puducherry only.

2.10.3. Monitoring of "BUREVI":

India Meteorological Department (IMD) maintained round the clock watch over the north Indian Ocean and the cyclone was monitored since 26th November, about 03 days prior to the formation of low pressure area over Southeast Bay of Bengal & Equatorial Indian Ocean on 28th November 2020 and 05 days prior to the formation of depression over southeast BoB on 30th November. The cyclone was monitored with the help of available satellite observations from INSAT 3D and 3DR, SCATSAT, polar orbiting satellites and available ships & buoy observations in the region. The system was also monitored by Doppler Weather RADARs (DWR) Chennai, Karaikal and Thiruvananthapuram (ISRO). Various numerical weather prediction models run by Ministry of Earth Sciences (MoES) institutions (IMD, IITM, NCMRWF, INCOIS), global models and dynamical-statistical models were utilized to predict the genesis, track, landfall and intensity of the cyclone. A digitized forecasting system of IMD was utilized for analysis and comparison of various models' guidance, decision making process and warning products generation. Typical satellite and radar imageries are presented in Fig. 2.10.8.

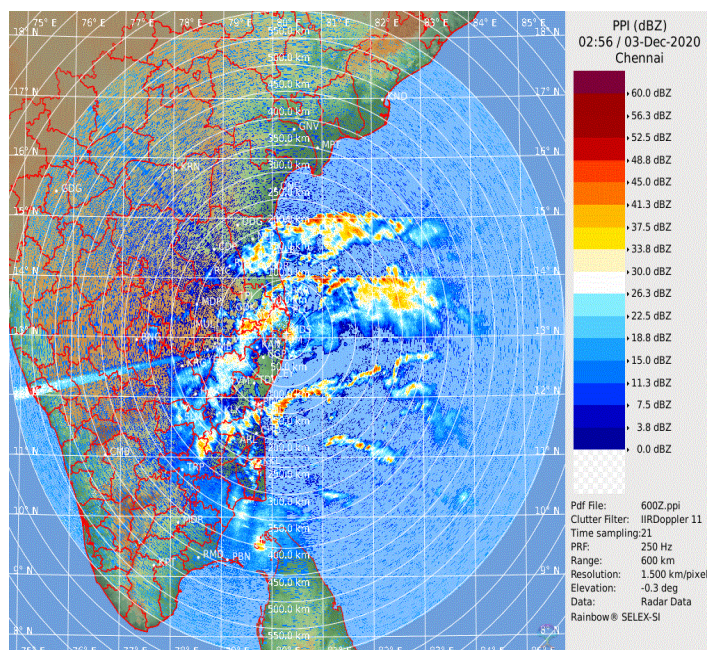
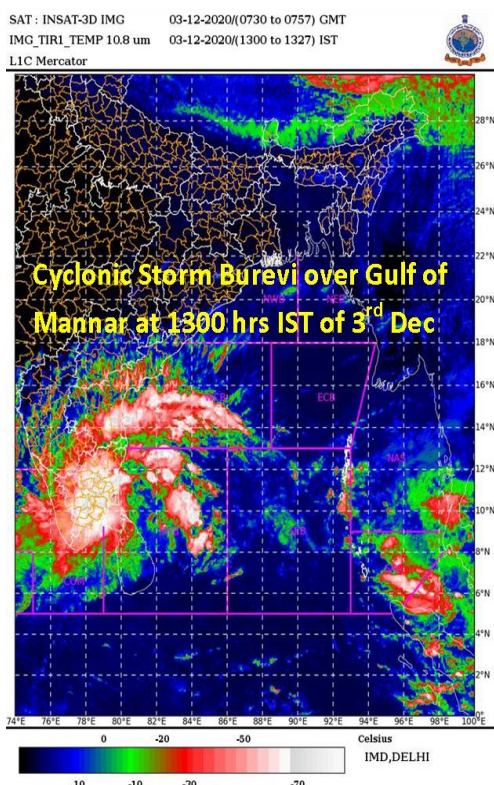


Fig.2.10.8: Typical satellite imagery of CS "BUREVI" & Doppler Weather RADAR Chennai - reflectivity image (PPZ (600KM and maximum range) product of 3rd December.

Table 2.10.2: Best track positions and other parameters of the Cyclonic Storm, 'BUREVI' over the Bay of Bengal during 30 Nov- 05 Dec., 2020

Date	Time (UTC)	Centre lat. ⁰ N/ long. ⁰ E		C.I. NO	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
30/11/2020	0000	7.5	88.0	1.5	1003	20	3	D
	0300	7.7	87.7	1.5	1002	25	4	D
	0600	7.8	87.4	1.5	1002	25	4	D
	1200	7.7	87.0	1.5	1002	25	4	D
	1800	7.8	86.6	1.5	1002	25	4	D
01/12/2020	0000	7.8	86.0	2.0	1000	30	6	DD
	0300	7.8	85.7	2.0	1000	30	6	DD
	0600	7.8	85.3	2.0	1000	30	6	DD
	1200	7.9	84.8	2.5	999	35	7	CS
	1500	7.9	84.5	2.5	999	35	7	CS
	1800	8.1	84.2	2.5	999	35	7	CS

	2100	8.4	83.4	2.5	999	35	7	CS
02/12/2020	0000	8.6	83.0	2.5	998	40	8	CS
	0300	8.7	82.5	2.5	998	40	8	CS
	0600	8.8	82.2	3.0	996	45	10	CS
	0900	8.8	81.8	3.0	996	45	10	CS
	1200	8.8	81.4	3.0	996	45	10	CS
	1500	8.8	81.4	3.0	996	45	10	CS
	Crossed Sri Lanka coast close to north of Trincomalee (near Lat 08.85°N and Long 81.0° E) during 1700 – 1800 UTC of 02 nd December 2020							
	1800	8.9	80.9	-	996	45	10	CS
	2100	9.0	80.8	-	998	40	8	CS
03/12/2020	0000	9.0	80.3	-	998	40	8	CS
	0300	9.1	80.2	-	998	40	8	CS
	0600	9.2	79.7	-	998	40	8	CS
	Crossed Pamban area (near Lat 09.2°N and Log 79.35° E) during 0800 UTC of 03 rd December 2020							
	0900	9.2	79.3	2.5	999	35	7	CS
	1200	9.2	79.1	2.0	1000	30	6	DD
	1500	9.2	78.8	2.0	1000	30	6	DD
	1800	9.1	78.6	2.0	1000	30	6	DD
	2100	9.1	78.6	2.0	1000	30	6	DD
04/12/2020	0000	9.1	78.6	2.0	1000	30	6	DD
	0300	9.1	78.6	2.0	1001	30	5	DD
	0600	9.1	78.6	2.0	1001	30	5	DD
	1200	9.1	78.6	1.5	1002	25	4	D
	1800	9.1	78.6	1.5	1003	25	4	D
05/12/2020	0000	9.1	78.6	1.5	1004	20	3	D
	0300	9.1	78.6	1.5	1006	20	3	D
	0600	Weakened into a Well-Marked Low Pressure Area over Gulf of Mannar close to Ramanathapuram district of Tamil Nadu						

2.10.4. Brief Life History

2.10.4.1. Genesis, intensification and movement

An equatorial easterly wave trough which persisted over South Andaman Sea and adjoining areas of Southeast Bay of Bengal & Equatorial Indian Ocean gradually organized into a Well Marked Low pressure area over the same region on 29th November, within a time span of 48 hours. The favourable environmental conditions, which led to its concentration into a Depression on 30th November and subsequent intensification into a Deep Depression in the early morning of 01st December & into a Cyclonic Storm in the evening of the same day are discussed in this section.

After the initial westward movement, the system followed a west-northwestward track in general and made two landfalls. The peculiarities with respect to the movement of the system have been analysed in detail under Section 2.

The convectively active phase of the Madden Julian Oscillation (MJO) represented mathematically as MJO index lay in Phase 4 (western Maritime continent) with amplitude close to 1. Hence MJO favoured the development of the system. High Sea Surface Temperatures (SST) of the order of 29-30°C and high Tropical Cyclone Heat Potential (TCHP) values of about 80-100 KJ/cm² prevailed over the region of genesis. However, as the system moved further westwards, the SST & TCHP values reduced over southwest BoB to 28°C & 70-90 KJ/cm² respectively on account of the past passage of VSCS NIVAR over the region.

At 0000 UTC of 30 November, lower level positive relative vorticity ($100 \times 10^{-6} \text{ s}^{-1}$) prevailed around system centre. Upper level positive divergence of $20 \times 10^{-5} \text{ s}^{-1}$ prevailed around the system centre. The lower level convergence was $20 \times 10^{-5} \text{ s}^{-1}$ around system centre. The vertical wind shear (VWS) was low to moderate (05-15 kts) over the region. The sub-tropical ridge at upper and middle Tropospheric levels ran along 17°N over the BoB. The system lay in the southern periphery of the above ridge. As a result, it was moving nearly westwards. The above environmental conditions remained to be favourable for Intensification of the system gradually into a cyclonic storm during the subsequent 36 Hours.

At 1200 UTC of 30 November, Lower level positive relative vorticity ($100 \times 10^{-6} \text{ s}^{-1}$) prevailed to the southeast of the system centre. Upper level divergence and lower level convergence had increased during past 12 hours while wind shear remained the same during the period. These features indicated that environmental conditions were favourable for further intensification of the system. The upper level positive divergence was around $30 \times 10^{-5} \text{ s}^{-1}$ to the northeast of the system centre. The lower level convergence was around $20 \times 10^{-5} \text{ s}^{-1}$ to the southeast of the system centre. The sub-tropical ridge at upper and middle tropospheric levels ran along 11.5°N over the BoB. The system lay in the southern periphery of the above ridge. As a result, it was moving west northwestwards. It was expected to be steered by the above ridge resulting in west-northwestward movement for next 2 days and then nearly westwards.

At 0000 UTC of 01 December, the Lower level positive relative vorticity ($100 \times 10^{-6} \text{ s}^{-1}$) prevails to the southeast of the system centre. The upper level positive divergence was around $20 \times 10^{-5} \text{ s}^{-1}$ of the system centre. The lower level convergence was around $20 \times 10^{-5} \text{ s}^{-1}$ to the northwest of the system centre. These features indicate that environmental features are favorable for further intensification of the system. The sub-tropical ridge at upper and middle tropospheric levels ran along 11.5°N over the BoB. The system lay in the southern periphery of the above ridge. As a result, it continued to move west northwestwards. Also there was another cyclonic vortex over south Indian Ocean near 10.5°S/89.0°E with estimated maximum sustained wind speed of 25 kts. These two vortices on either side of the equator (like Twin Cyclones) could have been interacting with each other.

At 1200 UTC of 01 December, the Lower level positive relative vorticity ($100 \times 10^{-6} \text{ s}^{-1}$) prevailed to the southeast of the system centre. The upper level positive divergence was around $20 \times 10^{-5} \text{ s}^{-1}$ to the northeast of the system centre. The lower level convergence was around $20 \times 10^{-5} \text{ s}^{-1}$ to the north of the system centre. These features indicate that environmental features continued to remain favourable for further intensification of the system and thus it intensified into a Cyclonic Storm. The sub-tropical ridge at upper and middle tropospheric levels ran along 12.5°N over the BoB. The system lay in the southern periphery of the above ridge. As a result, it was moving west northwestwards. By this time, the vortex over south Indian

Ocean had moved west-southwestwards and lay near $10.6^{\circ}\text{S}/87.1^{\circ}\text{E}$ with estimated maximum sustained wind speed of 25 kts.

At 0000 UTC of 02 December, the Lower level positive relative vorticity ($100\text{--}150 \times 10^{-6}\text{s}^{-1}$) prevails to the south of the system centre. The upper level positive divergence was around $30\text{--}40 \times 10^{-5}\text{s}^{-1}$ to the southwest of the system centre. The lower level convergence was around $30\text{--}40 \times 10^{-5}\text{s}^{-1}$ to the southwest of the system centre. These features indicate that environmental features were favorable for further intensification of the system. But the system did not intensify further. The sub-tropical ridge at upper and middle tropospheric levels ran along 12°N over the BoB. The system continued to lie in the southern periphery of the above ridge. The vortex over south Indian Ocean lay near $8.3^{\circ}\text{S}/83.3^{\circ}\text{E}$ with estimated maximum sustained wind speed of 20 kts.

At 1200 UTC of 02 December, the Lower level positive relative vorticity ($150 \times 10^{-6}\text{s}^{-1}$) prevails to the south of the system centre. The upper level positive divergence was around $30 \times 10^{-5}\text{s}^{-1}$ around the system centre. The lower level convergence was around $30 \times 10^{-5}\text{s}^{-1}$ to the southwest of the system centre. The sub-tropical ridge at upper and middle tropospheric levels ran along 13°N over the BoB. The system lay in the southern periphery of the above ridge. As a result, it was moving west northwestwards. The vortex over south Indian ocean lay near $8.30\text{S}/83.30\text{E}$ with estimated maximum sustained wind speed of 20 kts.

At 0000 UTC of 03 December, the Lower level positive relative vorticity ($200 \times 10^{-6}\text{s}^{-1}$) prevailed around the system centre. The upper level positive divergence was around $30 \times 10^{-5}\text{s}^{-1}$ and the lower level convergence was around $30 \times 10^{-5}\text{s}^{-1}$ over the system centre. The wind shear had increased with value 15-20 kts. The upper tropospheric ridge at upper and middle tropospheric levels run along 13°N over the BoB. The system lay in the southern periphery of the above ridge. As a result, it was moving west northwestwards. It was expected to be steered by the above ridge resulting in westward movement for next 24 hours. At 0800 UTC of 03 December, it crossed Pamban area (second landfall) and started showing signs of weakening owing to Land interaction, shallow bathymetry, increased vertical wind shear and other adverse environmental features.

At 1200 UTC of 03 December, it continued to interact with land surface as it lies very close to south Tamil Nadu coast. As a result system weakened into a deep depression at 1200 UTC. Also the high wind shear over the region was favoring further weakening of the system. The convective cloud mass was sheared to the north from the low level circulation centre in the satellite imagery. The winds were also stronger in the northern sector.

At 0000 UTC of 04 December, it remained practically stationary, sandwiched between two anti-cyclones and was weakening further under the increased windshear regime. Thus for the remaining period it remained over the same region and gradually weakened further.

The Total Precipitable Water vapour (TPW) imageries during 01-06 Dec. 2020 are presented in Fig. 2.10.9. These imageries indicate continuous warm and moist air advection from the southeast sector into the system, all through its life period. However, as the system approached Tamil Nadu coast, there was land interaction and moisture supply also reduced relatively as evident from TPW imageries on 04th and 05th Dec. However, being in the Low latitude easterly wave regime over the BoB, there was no cold air advection which could be attributed to the weakening of the system.

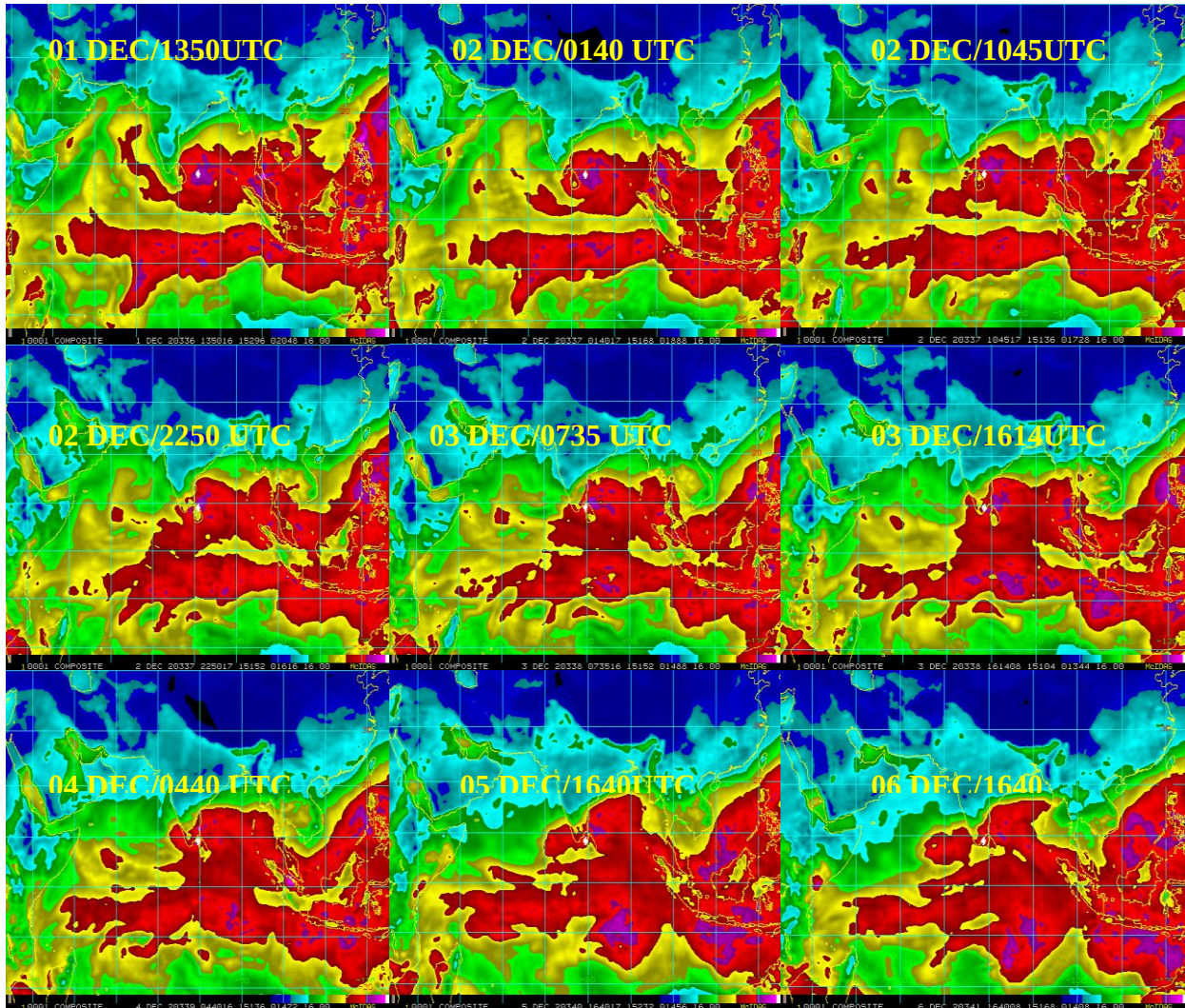


Fig. 2.10.9: Total Precipitable Water (TPW) imageries during CS BUREVI during 01-06 December, 2020

The wind speed in middle and deep layer around the system centre is presented in **Fig. 2.10.6**. The wind shear around the system between 200 & 850 hPa levels remained low to moderate (15-20 knots) initially. However, it increased gradually from the genesis stage to dissipation stage. The direction of 200-850 hPa wind shear was southeasterly during the entire period. It caused the convective cloud mass to be sheared to the northeast of the system centre.

2.10.4.2 Maximum Sustained Surface Wind speed and estimated central pressure

The lowest estimated central pressure and the maximum sustained wind speed are presented in Fig.2.10.10a. There was gradual fall in pressure during the period 0000 UTC of 30th November to 0000 UTC of 2nd December. The lowest estimated central pressure was 996 hPa during 0600 UTC to 1800 UTC of 2nd December. The estimated maximum sustained surface wind speed (MSW) was 45

knots during the period with pressure drop of 10 hPa. Thereafter, the pressure gradually increased till 1200 UTC of 3rd and thereafter, the system maintained its intensity till 0000 UTC of 5th.

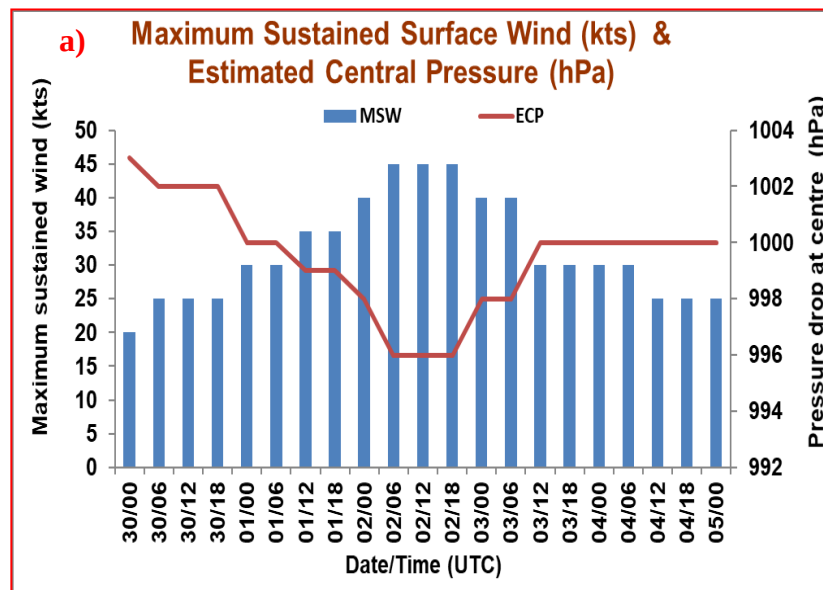


Fig. 2.10.10. (a) Maximum sustained surface winds (kts) & Estimated Central Pressure

2.10.4.3. Translational speed & direction of movement

The twelve hourly movement of CS BUREVI is presented in **Fig.2.10.10b**. The 12 hourly average translational speed of the cyclone was about 9.5 kmph against the normal speed of 12.9 kmph for CS category over the BoB during post monsoon season. The mean wind speed and direction in the deep layer between 850-200 hPa level and the middle layer between 850-500 hPa level is presented in Fig. 2.10.10a.

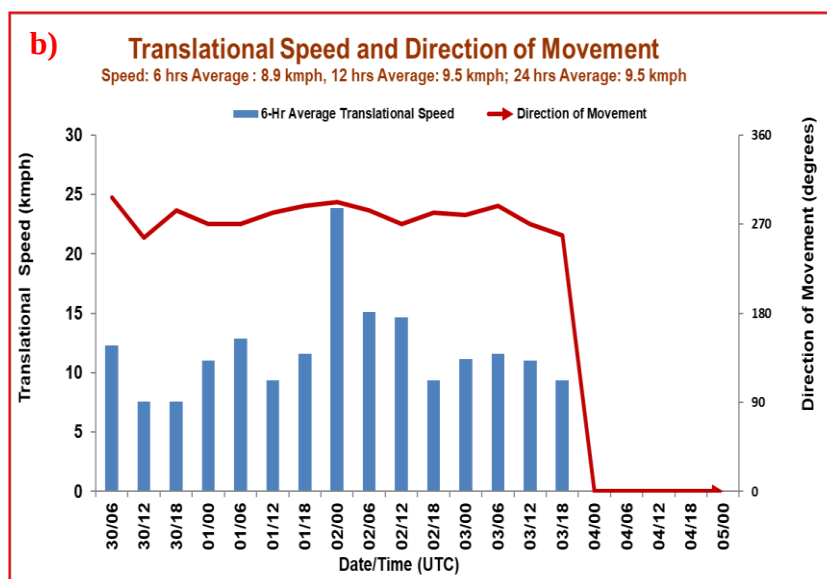


Fig.2.10.10(b) Mean Translational Speed during life cycle of CS BUREVI

2.10.5. 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, Metops were also considered. Typical INSAT-3D visible/IR imageries, enhanced colored imageries and cloud top brightness temperature imageries are presented in Fig. 2.10.11(a) -(d). The system showed curved band pattern during genesis and developing stage spiral band pattern during the mature stage. It showed sheared pattern after landfall.

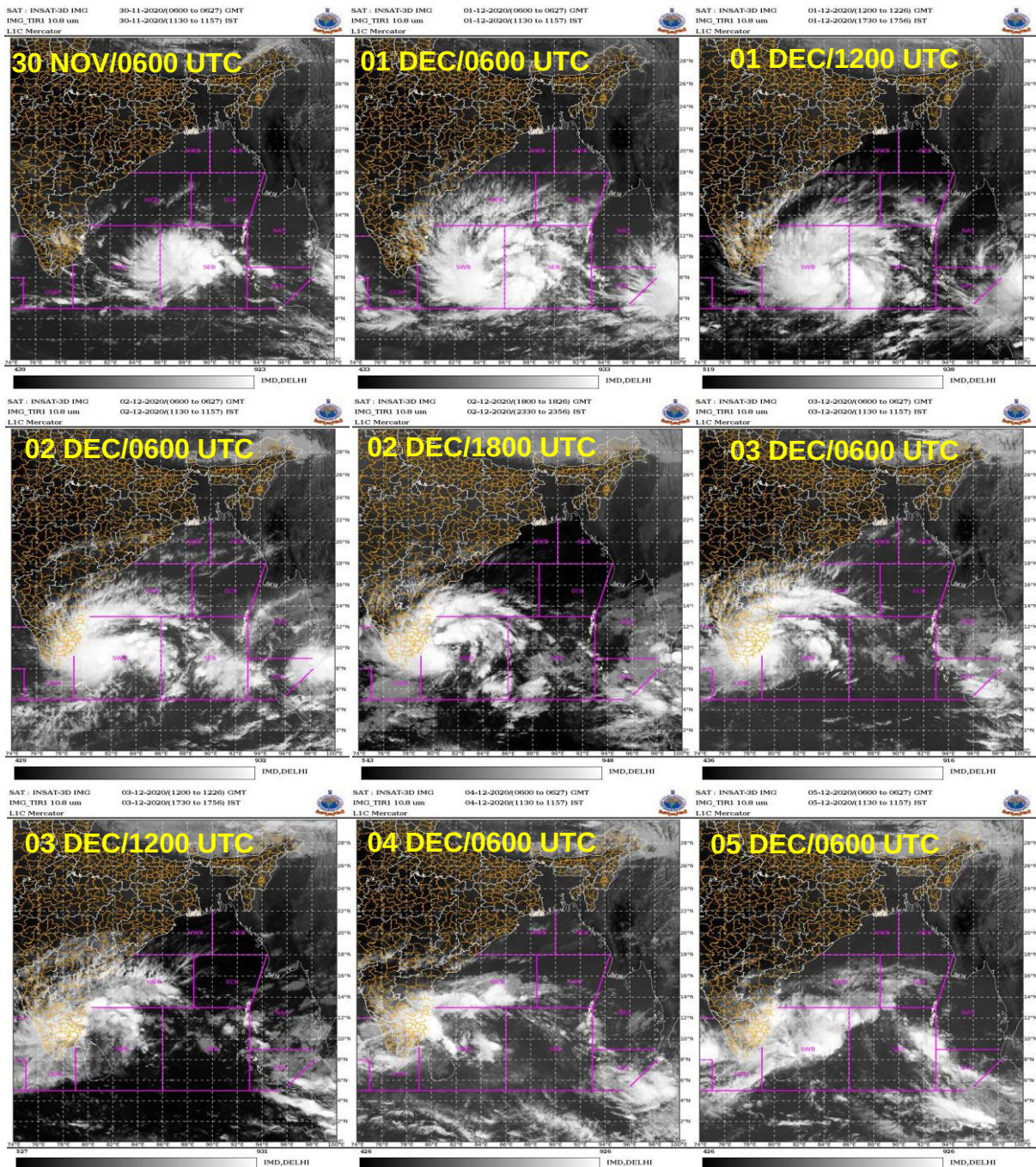


Fig. 2.10.11(a): INSAT-3D IR imageries during life cycle of CS BUREVI (30 Nov-05 DEC), 2020

At 0000 UTC of 30 November as per satellite imagery, intensity was T1.5. Broken low and medium clouds with embedded intense to very intense convection lay over south east Bay of Bengal between lat 6.0N & 10.5N and long 83.0E & 90.5E in association with the system. Minimum Cloud Top Temperature (CTT) was - 85°C.

At 1200 UTC of 30 November as per satellite imagery, the intensity of the system was T1.5. Broken low and medium clouds with embedded intense to very intense convection lay over southeast Bay of Bengal and neighbourhood between lat 5.5N & 12.5N and long 83.0E & 90.0E in association with the system. Minimum CTT was - 93°C.

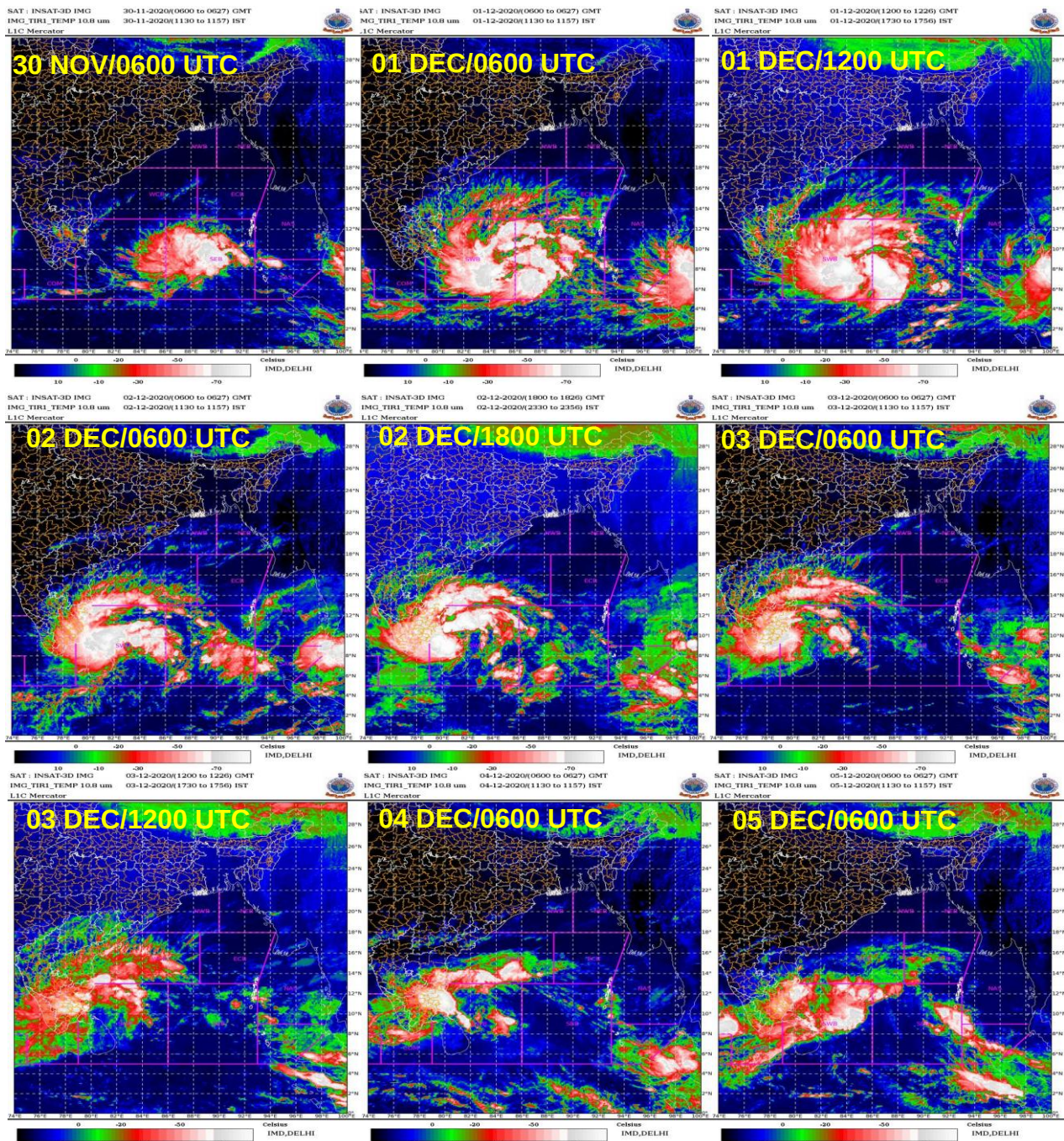


Fig. 2.10.11(b): INSAT-3D enhanced colored imageries during life cycle of CS BUREVI (30 Nov-05 DEC), 2020

At 0000 UTC of 01 December, as per satellite imagery the intensity of the system was T2.0/2.0. Centre was not clearly defined in satellite imagery. Broken low and medium clouds with embedded intense to very intense convection lay over south Bay of Bengal between lat 4.5°N & 14.5°N and long 81.5°E & 92.5°E in association with the system. Minimum CTT was -93°C .

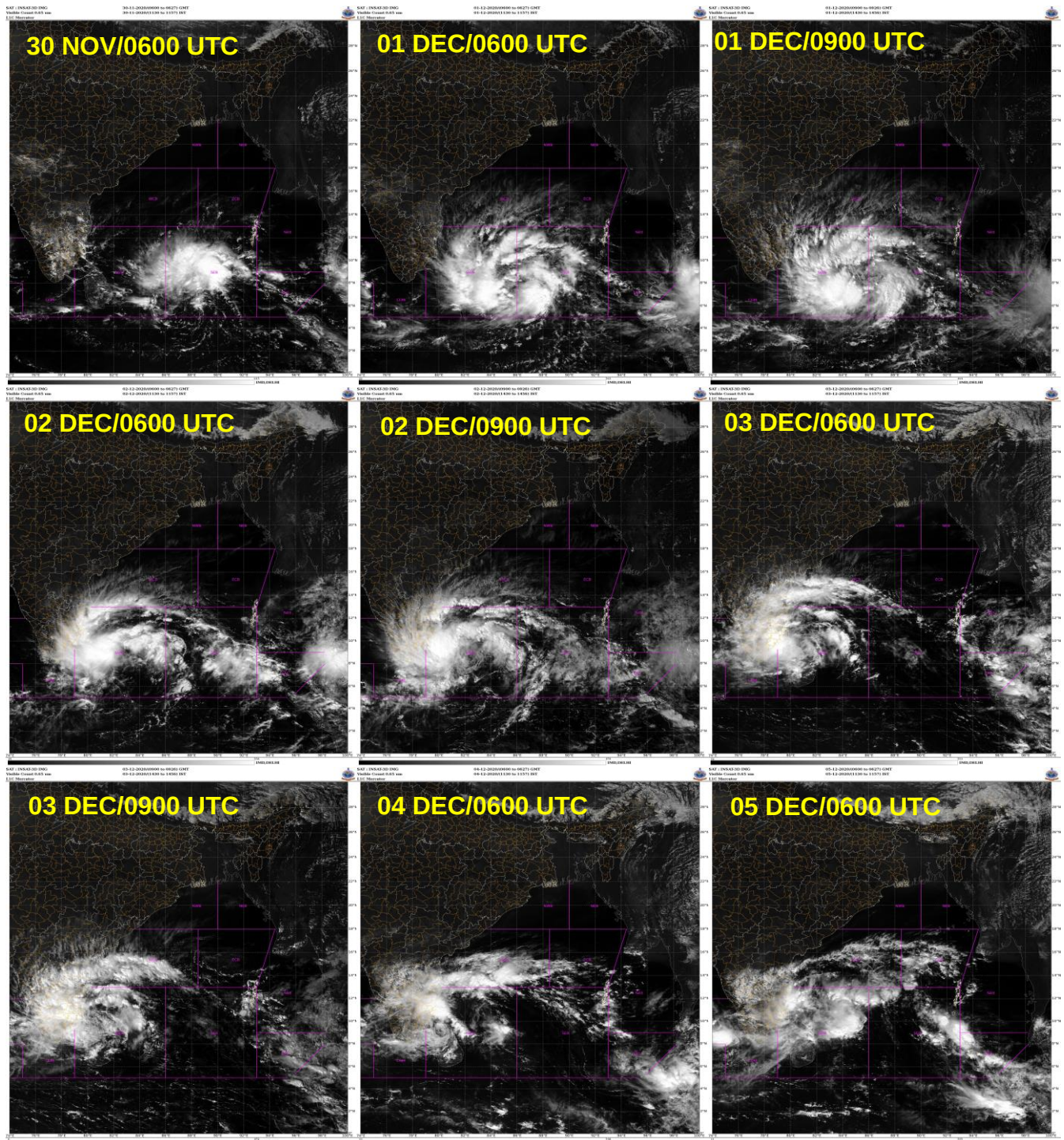


Fig. 2.10.11(c): INSAT-3D Visible imageries during life cycle of CS BUREVI (30 Nov-05 DEC), 2020

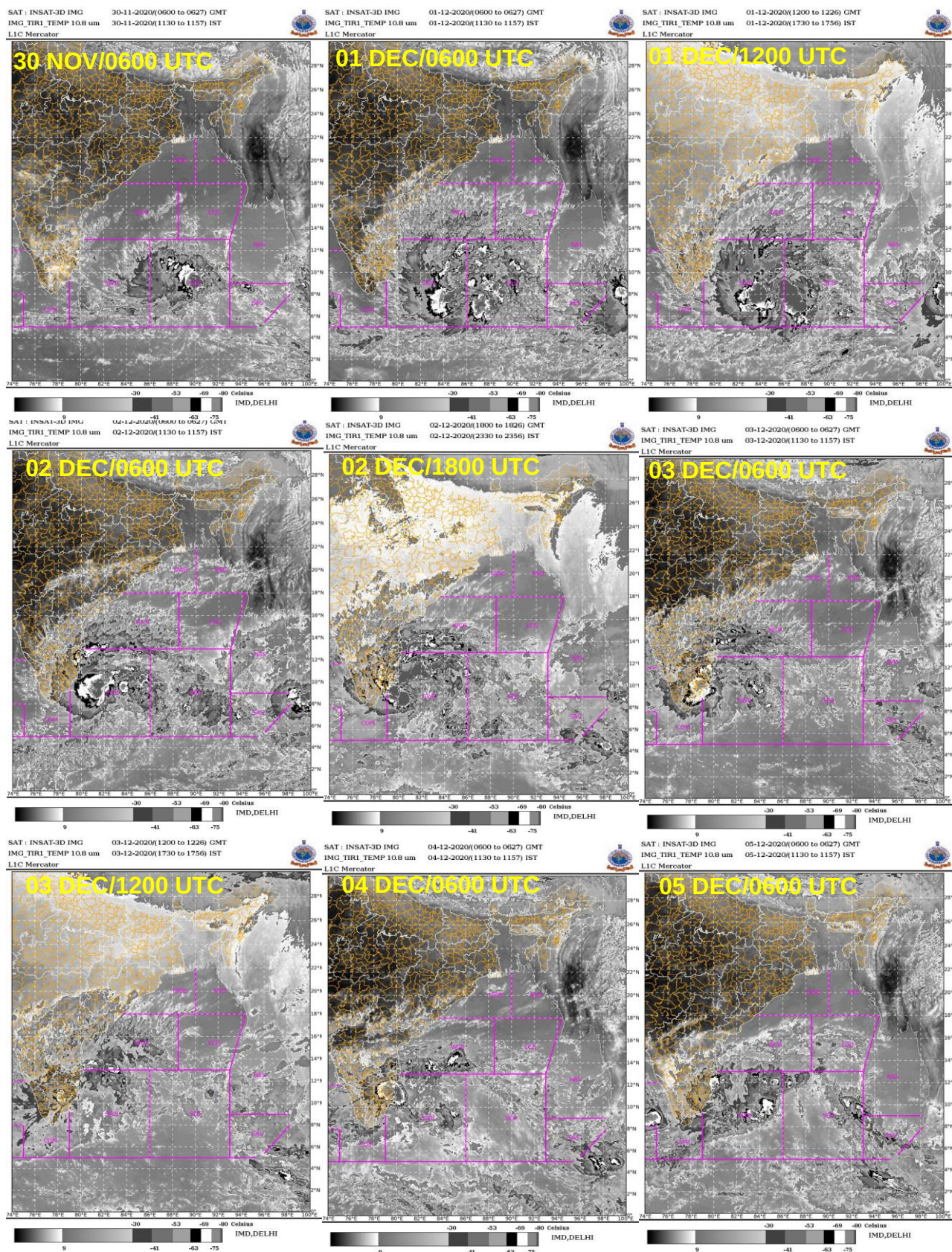


Fig. 2.10.11(d): INSAT-3D BD curve imagerys during life cycle of CS BUREVI (30 Nov-05 DEC), 2020

At 1200 UTC of 01 December, as per satellite imagery, the intensity of the system was T2.5 with shear pattern. Broken low and medium clouds with embedded intense to very intense convection lay over south Bay of Bengal between lat 5.0°N & 13.5°N and long 80.0°E & 90.0°E and also over Sri Lanka in association with the system. Minimum CTT was -93°C .

At 0000 UTC of 02 December, as per satellite imagery, the intensity of the system was T2.5. Broken low and medium clouds with embedded intense to very intense convection lay over south Bay of Bengal between lat 6.0°N & 13.5°N and long 81.5°E & 90.0°E and moderate to intense convection over Sri Lanka in association with the system. Minimum CTT was -93°C .

At 1200 UTC of 02 December, as per satellite imagery, the intensity of the system was T3.0. Broken low and medium clouds with embedded intense to very intense convection lay over south & adjoining central Bay of Bengal between lat 7.0°N & 14.0°N and long 80.0°E & 87.0°E and over east Tamil Nadu, Palk strait and Sri Lanka. Minimum CTT was -93°C . As the system was approaching coast, intense convective cloud was found over Sri Lanka and cloud band was interacting with land. Another cloud band associated with the system was also lying over coastal Tamil Nadu and Gulf of Mannar.

At 0000 UTC of 03 December, as per satellite imagery, the system was over land of Sri Lanka. The centre was not clearly defined and associated broken low / medium clouds with embedded intense to very intense convective clouds lay over southwest and adjoining west central Bay of Bengal between lat 8.0°N & 14.0°N and long 77.0°E & 84.0°E and also over Tamil Nadu and adjoining Andhra Pradesh, Gulf of Mannar & north Sri Lanka with minimum cloud top temperature -93°C .

At 1200 UTC of 03 December, as per satellite imagery, the intensity of the system was T2.0. Associated broken scattered to broken low/medium clouds with embedded intense to very intense convective clouds lay over Tamil Nadu and moderate to intense convection over Palk strait, Gulf of Mannar & Comorin area with minimum cloud top temperature -93°C .

At 0000 UTC of 04 December, as per satellite imagery, associated broken low/medium clouds with embedded intense to very intense convective clouds lay over Tamil Nadu, Gulf of Mannar and Palk strait with minimum cloud top temperature -93°C .

At 1200 UTC of 04 December, as per satellite imagery, associated broken low/medium clouds with embedded intense to very intense convective clouds lay over Tamil Nadu, Gulf of Mannar, Palk strait and Comorin with minimum cloud top temperature -93°C .

At 0600 UTC of 05 December, as per satellite imagery, associated broken low/medium clouds with embedded moderate to intense convection lay over Tamil Nadu, Gulf of Mannar, Palk strait, Comorin area and Sri Lanka.

Typical Scatterometer (ASCAT) and Microwave imageries are presented in **Fig.2.10.11(e) & 11(f)** respectively.

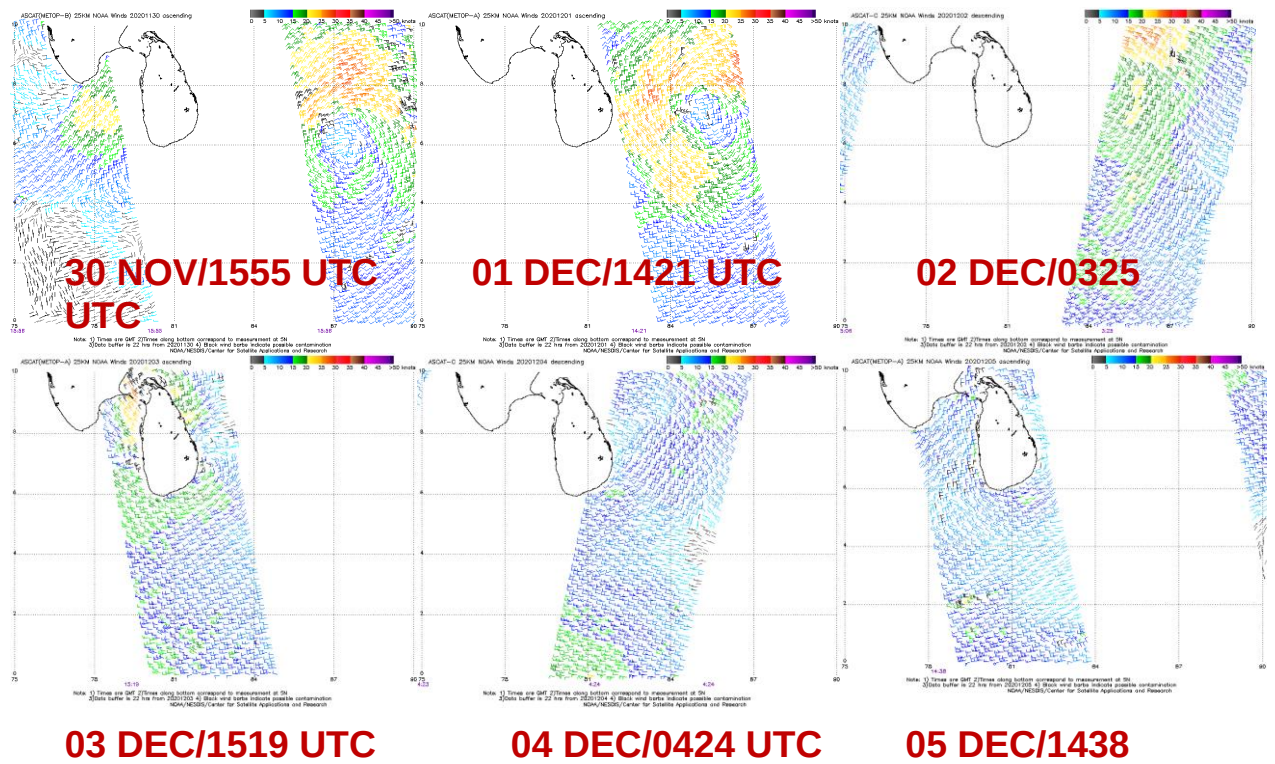


Fig. 2.10.11(e): ASCAT imagery during life cycle of CS BUREVI (30 Nov-05 Dec, 2020)

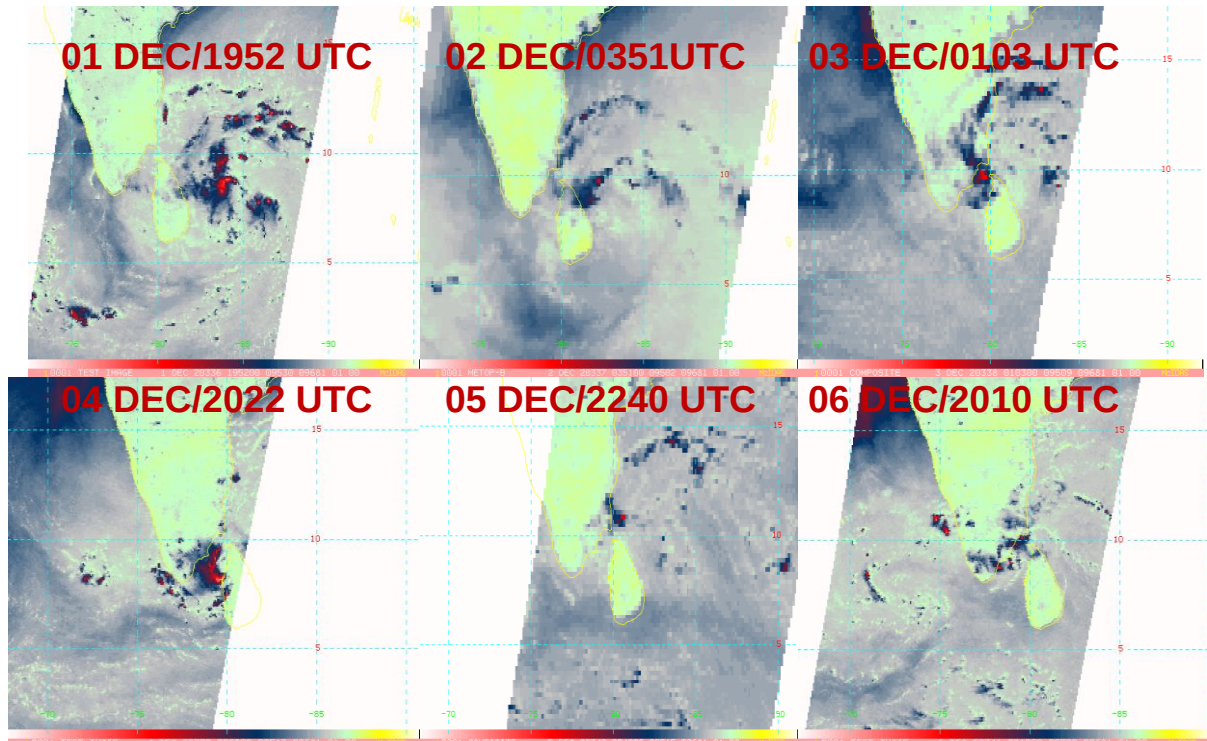


Fig. 2.10.11(f): Microwave imagery during life cycle of CS BUREVI (30 Nov-05 Dec, 2020)

2.10.5. Dynamical features

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels during 30th November - 05th December are presented in **Fig. 2.10.12(a) – (f)**. Forecast fields are not presented. The analysis of IMD-GFS T-1534 model forecasts based on 0000 UTC of 30th November, 2020 indicated presence of a Depression (D) over southeast BoB on 30th November, its rapid intensification into a Very Severe Cyclonic Storm (VSCS) over southeast & adjoining southwest BoB on 01st December, as VSCS over eastern coast of Sri Lanka on 02nd, after moving across north Sri Lanka, as a D over extreme south coastal Tamil Nadu on 03rd, weakening as a trough of Low over Lakshadweep – Maldives area on 04th, westward movement as a Well Marked Low Pressure Area (WML) over to southeast Arabian Sea (AS) and adjoining Lakshadweep area on 05th and further westward movement and weakening over southeast AS on 08th December.

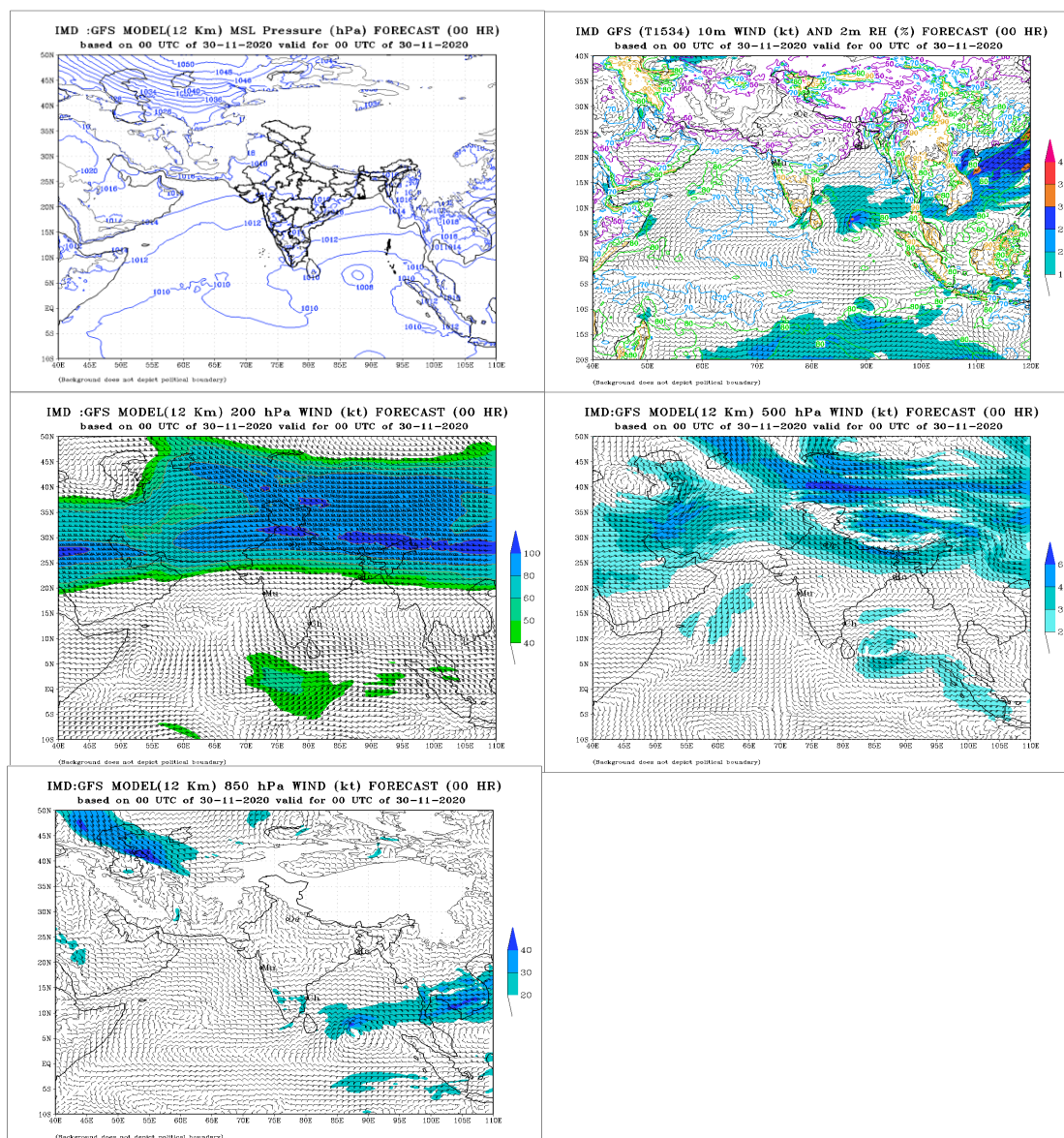


Fig. 2.10.12(a): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 30th November 2020

The analysis of IMD-GFS T-1534 model forecasts based on 0000 UTC of 01st December, 2020 indicates presence of a Deep Depression (DD) over southeast & adjoining southwest BoB on 01st December, its intensification into a Cyclonic Storm (CS) over southwest BoB off Sri Lanka coast on 02nd December, after crossing Sri Lanka coast, rapid intensification into a Very Severe Cyclonic Storm (VSCS) over Comorin area, very close to south Tamil Nadu coast on 03rd, crossing south Tamil Nadu coast & emerging as a Low Pressure Area (LPA) over southeast Arabian Sea (AS) off south Kerala coast on 04th, moving westwards and re-intensifying into a Depression (D) over southeast AS and adjoining Lakshadweep area on 05th, into a CS over southeast & adjoining east-central AS on 06th, CS over central & adjoining south AS on 07th, rapid weakening into an LPA over southwest AS on 08th and LPA over southwest AS off Somalia coast on 09th and weakening on 10th December.

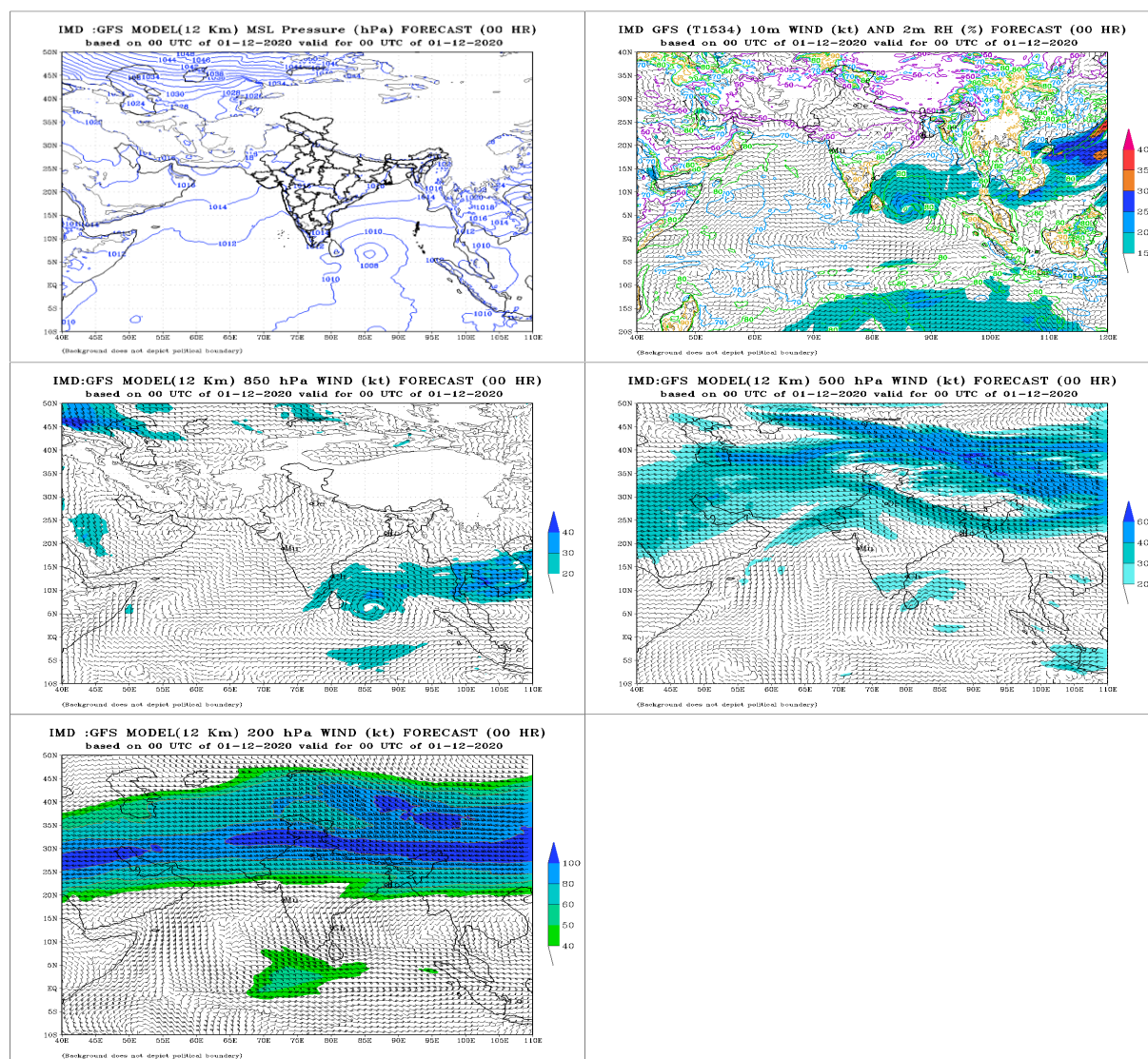


Fig. 2.10.12(b): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 1st December 2020

The analysis of IMD-GFS T-1534 model forecasts based on 0000 UTC of 02nd December, 2020 indicates presence of a Super Cyclonic Storm (SuCS) southwest

BoB off Sri Lanka coast on 02nd December, after crossing Sri Lanka, as an Extremely Severe Cyclonic Storm (ESCS) over Gulf of Mannar, close to south Tamil Nadu coast on 03rd, as a Depression over south coastal Tamil Nadu on 04th, re-emerging and re-intensification into a Cyclonic Storm (CS) over Lakshadweep area on 05th, westward movement & further intensification into an ESCS over southeast Arabian Sea (AS) on 06th, as an SuCS over southeast & adjoining east-central AS on 07th, over central parts of AS on 08th, further west-southwestward movement & gradual weakening into an ESCS over west-central AS on 09th, Very Severe Cyclonic Storm (VSCS) over southwest AS on 10th, as D over southwest AS off Somalia coast on 11th and rapid weakening on 12th.

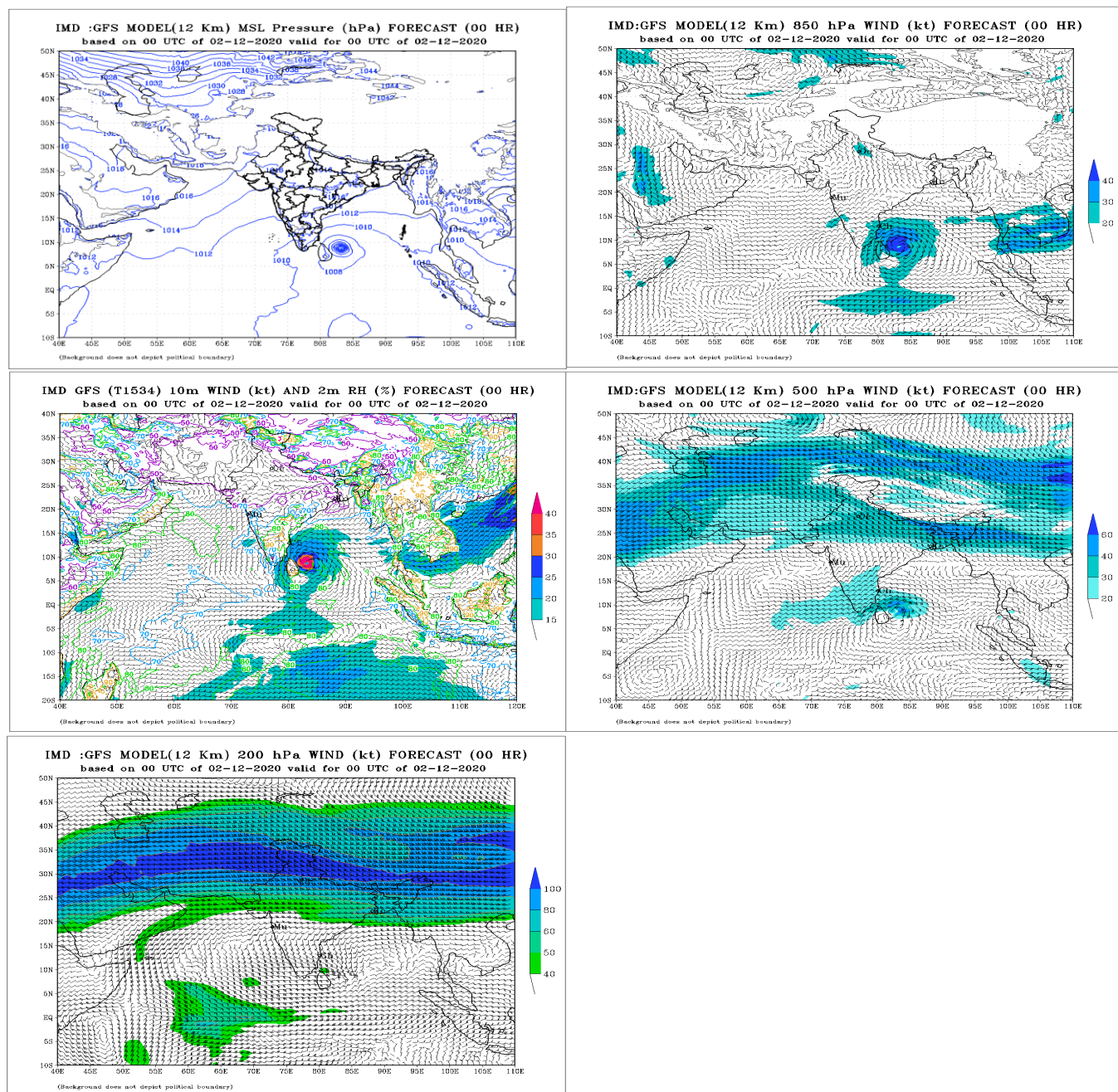


Fig.2.10.12 (c): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 2nd December 2020

The analysis of IMD-GFS T-1534 model forecasts based on 0000 UTC of 03rd December, 2020 indicates presence of a Very Severe Cyclonic Storm (VSCS) over north Sri Lanka coast on 03rd December, a Depression over south Tamil Nadu coast on 04th, emerging as a Low pressure Area (LPA) over southeast Arabian Sea (AS) and adjoining Lakshadweep area on 05th, westward movement & slight re-organisation over southeast Arabian Sea (AS) on 06th, further westward movement without any significant intensification over to southwest AS during 07th – 10th December and weakening over the same region on 11th & 12th December. So unlike the forecasts based on 02nd December, the forecasts based on 3rd December initial conditions were found to be ruling out the chance of re-intensification over the AS.

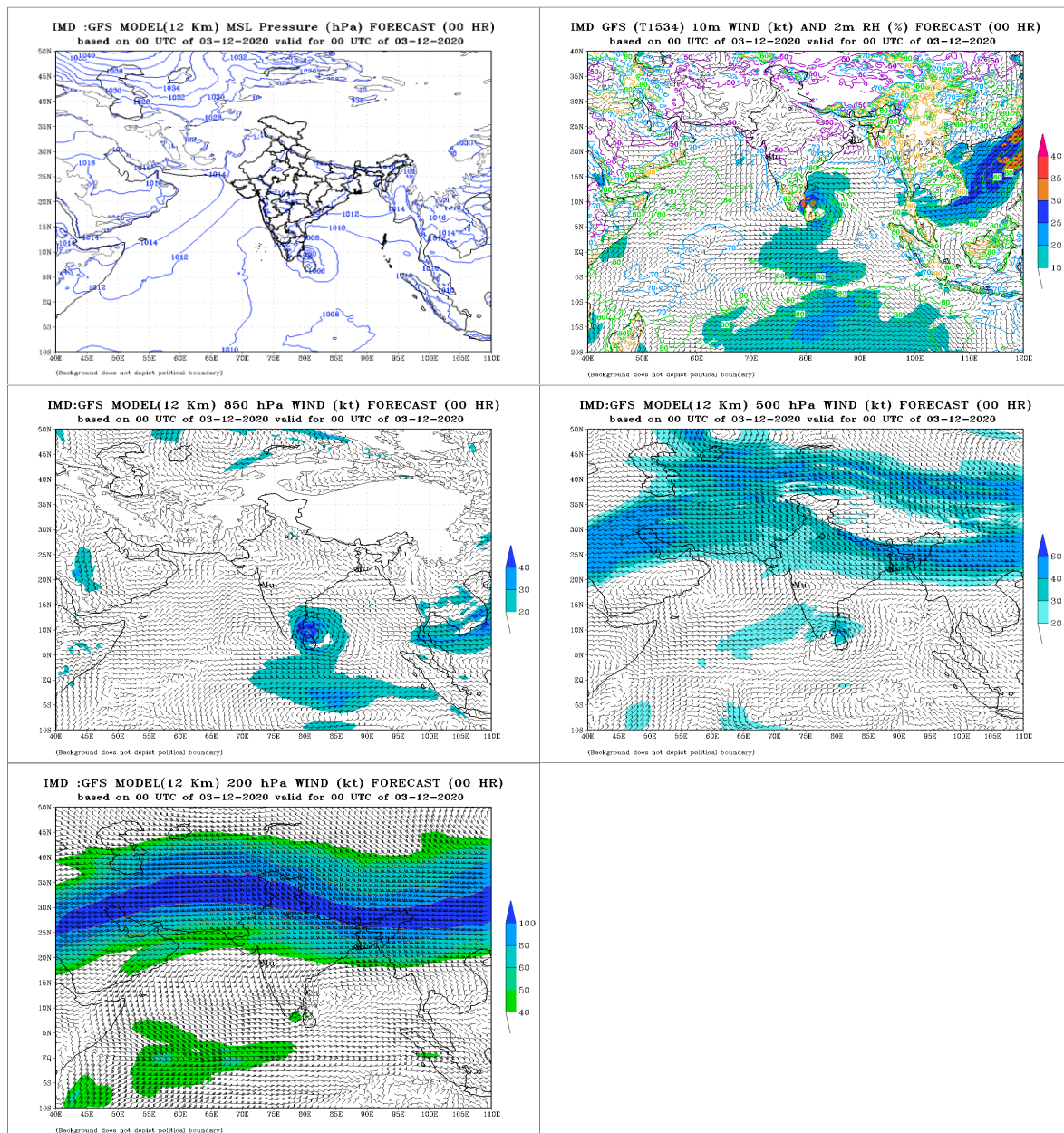


Fig.2.10.12 (d): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 3rd December 2020

The analysis of IMD-GFS T-1534 model forecasts based on 0000 UTC of 04th December, 2020 indicates presence of a Depression (D) over Gulf of Mannar on 04th, emerging as a Low pressure Area (LPA) over southeast Arabian Sea (AS) off Kerala coast on 05th, persistence on 06th, as an extended Low over southeast BoB on 07th, again as an LPA over southeast & adjoining southwest AS on 08th and its gradual westward movement without any significant intensification over to southwest AS during 09th – 11th December and weakening over southwest AS off Somalia coast by 13th December.

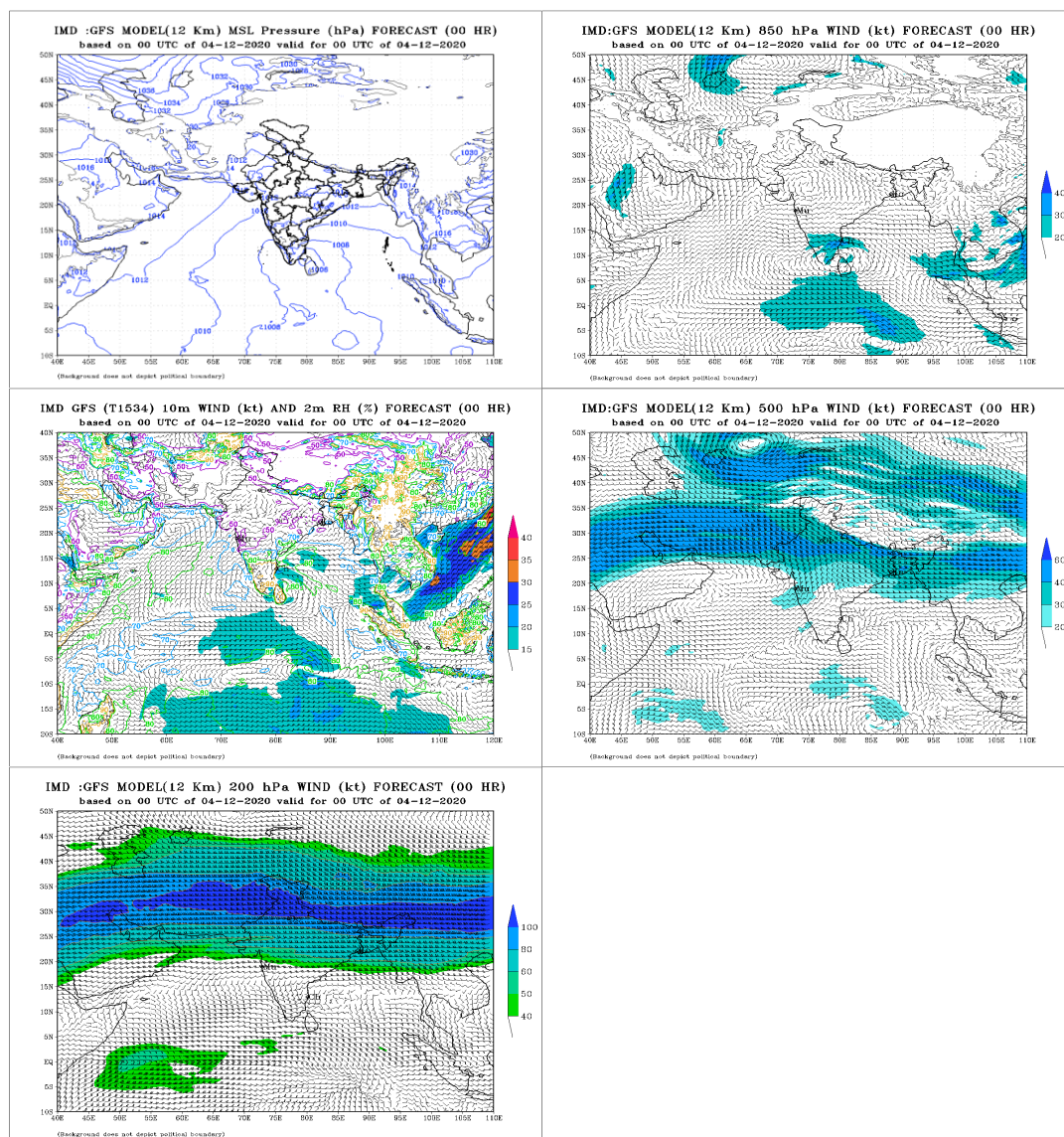


Fig. 2.10.12(e): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 4th December 2020

The analysis of IMD-GFS T-1534 model forecasts based on 0000 UTC of 05th December, 2020 indicates presence of a Depression (D) over Gulf of Mannar on 05th, its weakening into a Low Pressure Area (LPA) over the same region on 06th, emerging as an extended over southeast Arabian Sea (AS) on 07th, again as an LPA over southeast AS on 08th and its gradual westward movement without any

significant intensification over to southwest AS during 09th – 13th December and weakening over southwest AS on 14th December.

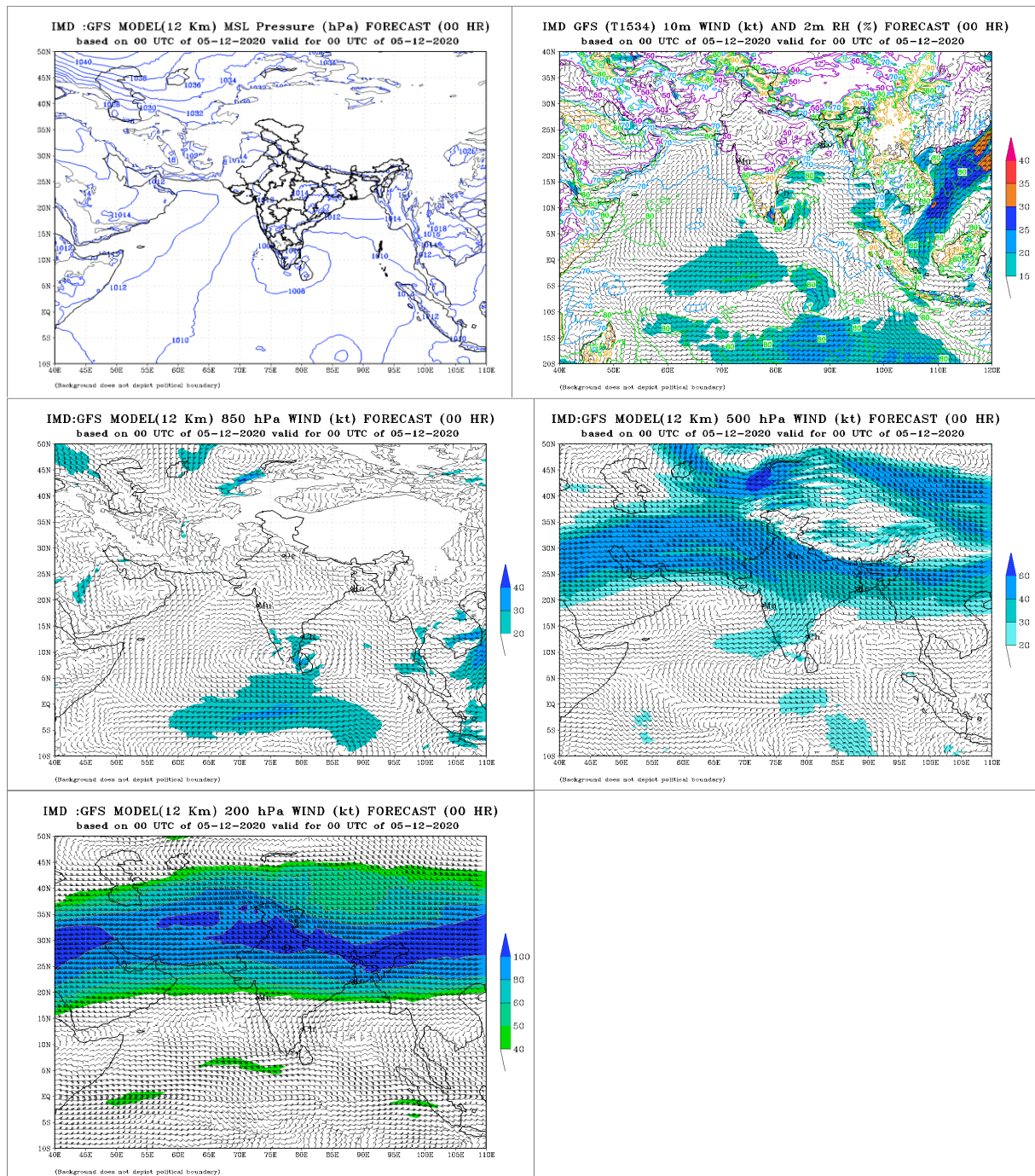


Fig. 2.10.12(f): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 5th December 2020

2.10.7. Realized Weather

2.10.7.1 Rainfall

Rainfall associated with CS BUREVI based on IMD-NCMRWF GPM merged gauge rainfall data is depicted in **Fig 2.10.13**. It indicates heavy rainfall (7-12 cm) over southwest BoB during 30th November to 02nd December and heavy to very

heavy rainfall (7-19 cm) at many places over coastal Tamil Nadu with extremely heavy falls (≥ 20 cm) at a few places during 02nd – 05th December.

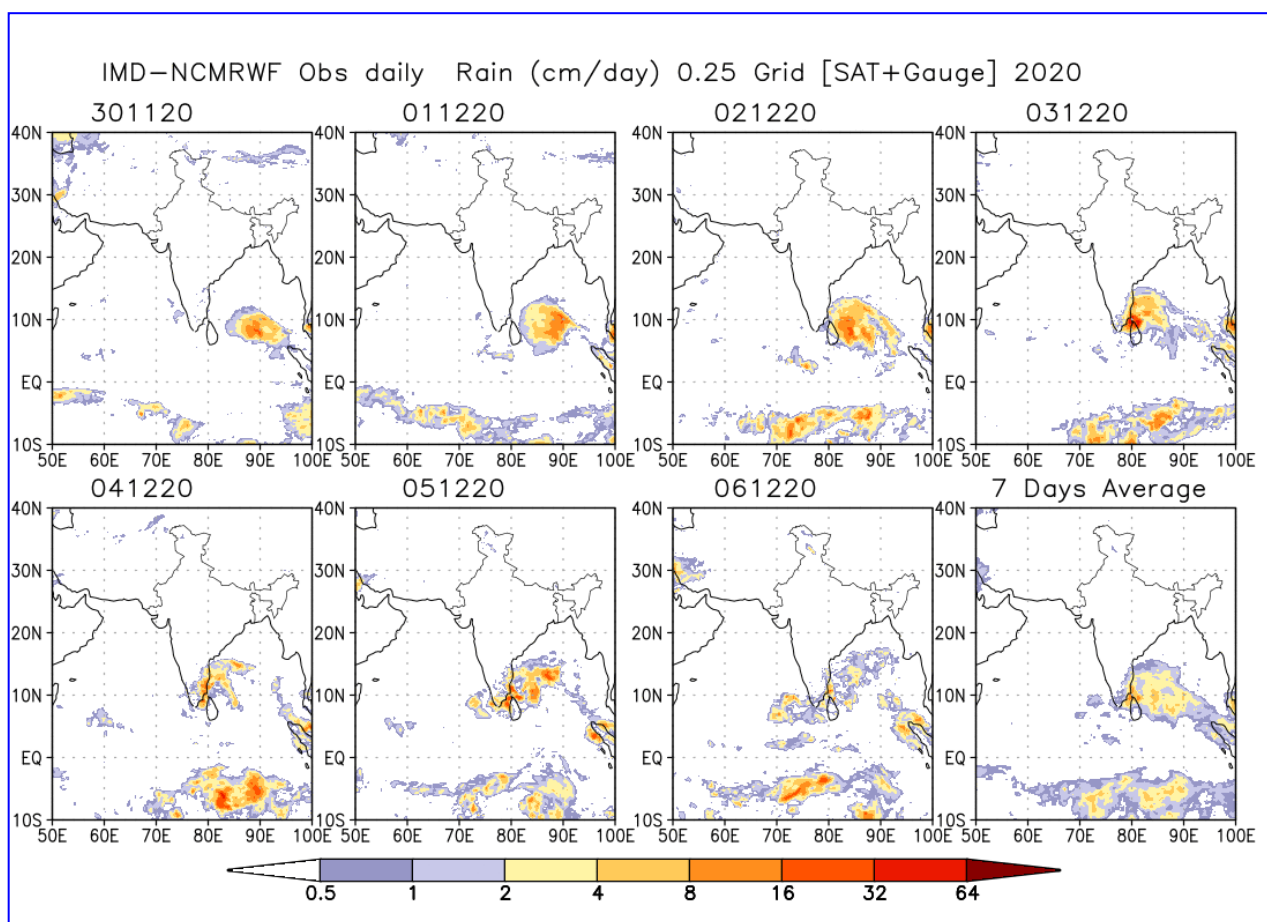


Fig.2.10.13: IMD-NCMRWF GPM merged gauge rainfall during 30th Nov- 01st Dec and 7 days average rainfall (cm/day)

Realized 24 hrs accumulated rainfall (≥ 7 cm) over Tamil Nadu, Puducherry & Karaikal during the life cycle of the system is presented below:

2nd December:

Vedaranyam (dist Nagapattinam) - 20, Karaikal (dist Karaikal)- 16, Thalaignayer (dist Nagapattinam) & Tirupoondi (dist Nagapattinam) -15 each, Nagapattinam (dist Nagapattinam)- 14, Thiruthuraipoondi (dist Tiruvarur) -13, Mayiladuthurai (dist Nagapattinam) , Rameswaram (dist Ramanathapuram)- 12 each, Mudukulatur (dist Ramanathapuram) - 11, Sirkali (dist Nagapattinam), Kodavasal (dist Tiruvarur) , Adirampatnam (dist Thanjavur) , Manjalaru (dist Thanjavur) - 10 each, Tiruvarur (dist Tiruvarur) ,Aduthurai (dist Thanjavur) , Tambaram (dist Chengalpattu) , Pattukottai (dist Thanjavur) - 9 each, Nannilam (dist Tiruvarur), Marakkanam (dist Villupuram), Pamban (dist Ramanathapuram), Thiruvidaimaruthur (dist Thanjavur), Thirukalukundram (dist Chengalpattu), Puducherry (dist Puducherry), Valangaiman (dist Tiruvarur) -8 each, Manalmedu (dist Nagapattinam), Kollidam (dist Nagapattinam), Kelambakkam (dist Chengalpattu), K.M.koil (dist Cuddalore), Vanur (dist Villupuram), Mannargudi (dist Tiruvarur), Taramani (dist Chennai), Madukkur

(dist Thanjavur), Parangipettai (dist Cuddalore), Ayyampettai (dist Thanjavur), ThanjaiPapanasam (dist Thanjavur), Cuddalore (dist Cuddalore), Needamangalam (dist Tiruvarur) -7 each

3rd December:

Kollidam (dist Nagapattinam) - 36, Chidambaram (dist Cuddalore) - 34, Parangipettai (dist Cuddalore) - 26, Manalmedu (dist Nagapattinam), Kurinjipadi (dist Cuddalore) - 25 each, Thiruthuraipoondi (dist Tiruvarur) - 22, Sirkali (dist Nagapattinam) , Kodavasal (dist Tiruvarur) - 21 each, Rameswaram (dist Ramanathapuram) - 20, Peravurani (dist Thanjavur), Manjalaru (dist Thanjavur), Bhuvanagiri (dist Cuddalore), Mayiladuthurai (dist Nagapattinam)- 19 each, Karambakudi (dist Pudukkottai), Pattukottai (dist Thanjavur)-17 each, Madukkur (dist Thanjavur)-16, Srimushnam (dist Cuddalore)-15, Tindivanam (dist Villupuram), Nannilam (dist Tiruvarur), Thiruvidadaimaruthur (dist Thanjavur)-14 each, Kumbakonam (dist Thanjavur), Ayyampettai (dist Thanjavur), Valangaiman (dist Tiruvarur), Panruti (dist Cuddalore), Ulundurpet (dist Villupuram)-13 each, Aduthurai (dist Thanjavur), Alangudi (dist Pudukkottai), Pandavaiyar Head (dist Tiruvarur) 12 each, Tiruvarur (dist Tiruvarur), Budalur (dist Thanjavur), Mahabalipuram (dist Chengalpattu), Mannargudi (dist Tiruvarur)-11 each, Vallam (dist Thanjavur), Perambalur (dist Perambalur), Thanjavur (dist Thanjavur), Thirumanur (dist Ariyalur) , Needamangalam (dist Tiruvarur)-10 each, Sendurai (dist Ariyalur) , Tirukattupalli (dist Thanjavur) , Vilupuram (dist Villupuram) , Mylam Aws (dist Villupuram) , Cholavaram (dist Tiruvallur) , Vanur (dist Villupuram) , Gandarvakottai (dist Pudukkottai) , Marakkanam (dist Villupuram) , Chengalpattu (dist Chengalpattu) , Gingee (dist Villupuram) - 9 each, Keeranur (dist Pudukkottai) , Thalaigaiyur (dist Nagapattinam) , Agaram Seegoor (dist Perambalur) , Eraiyur (dist Perambalur) , Gummidipoondi (dist Tiruvallur) , Adirampatnam (dist Thanjavur) , Manamelkudi (dist Pudukkottai) , Pullambadi (dist Trichy) , Annavasal (dist Pudukkottai) , Samayapuram (dist Trichy) , Pamban (dist Ramanathapuram) , Perungalur (dist Pudukkottai) , Tarangambadi (dist Nagapattinam) - 8 each , Labbaikudikadu (dist Perambalur) , Tozhudur (dist Cuddalore) , Tirukoilur (dist Villupuram) , Thuvakudi Imti (dist Trichy) , Uthukottai (dist Tiruvallur) , Ariyalur (dist Ariyalur) , Anna UTY (dist Chennai) , Uthiramerur (dist Chengalpattu) , Tirupoondi (dist Nagapattinam) , Tirumayam (dist Pudukkottai) , Tondi (dist Ramanathapuram) , TRP Town (dist Trichy) - 7 each

4th December:

Nagapattinam (Nagapattinam) and Karaikal (Karaikal)-16 each, Kodavasal (Tiruvarur) and Bhuvanagiri (Cuddalore)- 15 each, Sethiyathope (Cuddalore)-14, Tarangambadi (Nagapattinam)-13, Sirkali (Nagapattinam), DGP Office (Chennai), Vembakkam (Tiruvannamalai) and Srimushnam (Cuddalore)- 12 each, Rameswaram (Ramanathapuram), Anna University (Chennai), Tirupoondi (Nagapattinam) and Kayalpattinam (Toothukudi)-11 each, Sriperumbudur (Kancheepuram), Kollidam (Nagapattinam), Mgr Nagar (Chennai) and Pelandurai (Cuddalore)-10 each, Uthukottai (Tiruvallur), Chembarambakkam (Tiruvallur), Tuticorin (Toothukudi), Thalaigaiyur (Nagapattinam)-9 each

5th December:

Muthupet (dist Tiruvarur)-10, Mahabalipuram (dist Chengalpattu)-7 each, Kodavasal (dist Tiruvarur), Nannilam (dist Tiruvarur) & Thalaigaiyur (dist Nagapattinam)-6 each and Thiruthuraipoondi (dist Tiruvarur), Cheyyur (dist Chengalpattu), Kollidam

(dist Nagapattinam), Cholvaram (dist Tiruvallur), Tirupoondi (dist Nagapattinam) and Chidambaram (dist Cuddalore) 5 each.

6th December:

Maniyachi (dist Toothukudi) -16, Vaippar (dist Toothukudi) -12, Kadambur (dist Toothukudi) -11, Kayathar (dist Toothukudi), Sirkali (dist Nagapattinam), Karaikal (dist Karaikal), Chittar—(dist Kanyakumari) - 9 each, Thalaigayyer (dist Nagapattinam), Mayiladuthurai (dist Nagapattinam), Valinokam (dist Ramanathapuram), Needamangalam (dist Tiruvarur) - 8 each, Kodavasal (dist Tiruvarur) , Manalmedu (dist Nagapattinam), Palayamkottai (dist Tirunelveli), Vilathikulam (dist Toothukudi) - 7 each

2.10.8. Damage due to CS BUREVI

In Sri Lanka, 57 houses were destroyed with 2,753 others being damaged. According to the European Civil Protection and Humanitarian Aid Operations, 10,336 people were displaced. Burevi left 11 people dead and 5 others missing as on 6th December, 2020.

The Wellington Dam's water level reached above the highest flood stage, flooding isolated many villages from the capital city of Chennai. The Chidambaram Nataraja Temple in the district of Cuddalore was flooded after receiving 340 mm of precipitation. In Barathampattam, agricultural land was flooded, causing crop damage.



Fig.2.10.14(a): Paddy crop and sugarcane crop have suffered severe damage (source: <https://www.newsclick.in/>) **(b)** Flood in Tamil Nadu (source: <https://www.thenewsminute.com/>) **(c)** Uprooted trees in Chennai (source: <http://www.uniindia.com>) **(d)** A scene in Jaffna (source: [tamilguardian.com](http://www.tamilguardian.com))

In Puducherry, precipitation amounts of 138 mm were recorded on December 4, 2020. The power supply of the city was briefly cut off on December 3. In the area, damage to trees, crops and huts was reported.

CHAPTER- III

3.1. NWP Models in operational use during the year 2020

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 four times in a day (00, 06, 12 and 18 UTC). 00 & 12 UTC runs are available for next 10 days forecast period. 06 & 18 UTC runs are available for 3 days forecast period. 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>).

IMD operationally runs three regional models WRFDA-WRFARW (v3.6), and HWRF for short-range prediction during cyclone condition.

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. 23°S to 46°N long 40°E to 120°E 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.

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°x80°, 24°x24° and 7°x7° 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 are being provided since FANI cyclone over Bay of Bengal.

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.

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.

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.

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.

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

when the total number of indices satisfied increases from zero to eight. The forecasts are made available in real time since 2013.

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.

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) in 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.

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. GEFS model is run twice a day based on 00 & 12 UTC initial conditions.

The NCUM-G (Rajagopal et al., 2012; George et al., 2016) uses a seamless modeling approach. It has a horizontal grid resolution of ~12 km and 70 vertical levels (reaching 80 km height), is being used for the 240 hrs numerical weather forecast since 2018 (Kumar et al., 2018). These model and assimilation systems have been updated periodically to adapt to various scientific and technical developments. Advanced ENDGame dynamical core is used in the model, which provides improved accuracy of the solution of primitive model equations and reduced damping. ENDGame also increases variability in the tropics, which leads to an improved representation of TCs and other tropical phenomena (Walters et al., 2017). An advanced data assimilation method Hybrid 4D-Var is used for the creation of

NCUM global atmospheric analysis. Ensemble Transform Kalman Filter (ETKF) based on the NCUM ensemble prediction system (NEPS) provides flow-dependent background errors to this Hybrid 4D-Var system. Utmost importance has been given to the assimilation of Indian satellite observations in this data assimilation system. INSAT-3D Atmospheric Motion Vector (AMV), MeghaTropiques (MT)-SAPHIR radiance, Scatsat Ocean Surface Winds are being assimilated in the operational NCUM global data assimilation system, in addition to other global observations. A list of observations assimilated in the latest NCUM global data assimilation system is given in Table-2. Salient Features of NCUM Assimilation–Forecast System is shown in Table-3

NCUM global data assimilation system produces analyses at 00, 06, 12, and 18 UTC. In each 6 hourly data assimilation cycle, the available observations distributed over the 6 hour assimilation window (center of the analysis cycle ± 3 hr) are combined with the model background to produce the NCUM-G analysis. Table 1 summarizes the model configurations operational at NCMRWF. Details on the model parameterizations schemes, data assimilation, etc., can be found in Kumar et al. (2018).

NCUM-R has a horizontal grid resolution of ~ 4 km and 80 vertical levels, with the model top at 38.5 km and 14 model levels below 1 km. The model has a time step of 1 minute. The model domain covers India and the adjacent oceanic regions and is operationally producing 72hrs forecasts. In this convection-permitting model configuration, sub-grid scale deep convection is not parameterized. The prognostic cloud fraction and prognostic condensate (PC2) scheme used in this model is based on Wilson (2008 a & b). The sub-grid turbulence scheme used is a blended scheme (Boutle et al., 2014), which dynamically combines the one-dimensional (1D) boundary-layer scheme of Lock et al. (2000) with a 3D Smagorinsky scheme using a mixing factor of 0.5. The model employs NASA Shuttle Radar Topographic Mission (SRTM) 90 m digital elevation map orography.

NCUM-R uses the high resolution analysis prepared by the 4D-Var data assimilation (DA) system. In addition to most of the observations used in the NCUM global data assimilation system (even though data thinning strategies are different), Indian Doppler Weather Radar observations of radial wind are also used in the regional DA system with a time window of ± 3 hours. The vortex initialization scheme is also employed in the NCUM-R. The model domain covers the South Asian region, covering BOB and part of the Arabian Sea (6°S - 41°N and 62° - 106°E). The details of NCUM-R model configuration can be found in Dutta et al. 2019, Jayakumar et al. 2019 and Bush et al. 2020.

NCMRWF Ensemble Prediction System (NEPS-G) 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 operational NCMRWF Ensemble Prediction System (NEPS) has 22 ensemble members. The horizontal resolution of NEPS is $\sim 12\text{km}$. The NCUM model analysis is used as the initial condition for the control model forecast. The perturbations are generated by

Ensemble Transform Kalman Filter (ETKF) method which is added to the global deterministic analysis to create 22 perturbed initial conditions. These are used for generating ensemble member forecasts. One control and 11 perturbed ensemble members run from initial condition of 00UTC of current day and 11 more perturbed members run from 12 UTC of previous day to give 23 members (11 + 11 + 1 control) ensemble forecasts up to 10 days lead time. More details about NEPS-G are available in Mamgain et al. (2018). The new 12-km NEPS-G is the highest resolution for Ensemble forecasting.

3.2 Super Cyclonic Storm, 'AMPHAN' over Southeast Bay of Bengal (16 May – 21 May 2020)

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

Fig. 3.2.1(a-f) indicates that the GPP could predict the potential zone for cyclogenesis on 11th over southeast BoB about 120 hours 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. Average GPP ≥ 8.0 is the threshold value for system likely to develop into a cyclonic storm and average GPP < 8.0 indicates a non-developing system: The area average analysis of GPP based on 0000 & 1200 UTC during 13th – 16th May is presented in Fig. 3.2.2. The area average analysis was predicting the system to develop into a cyclonic storm since 13th May onwards.

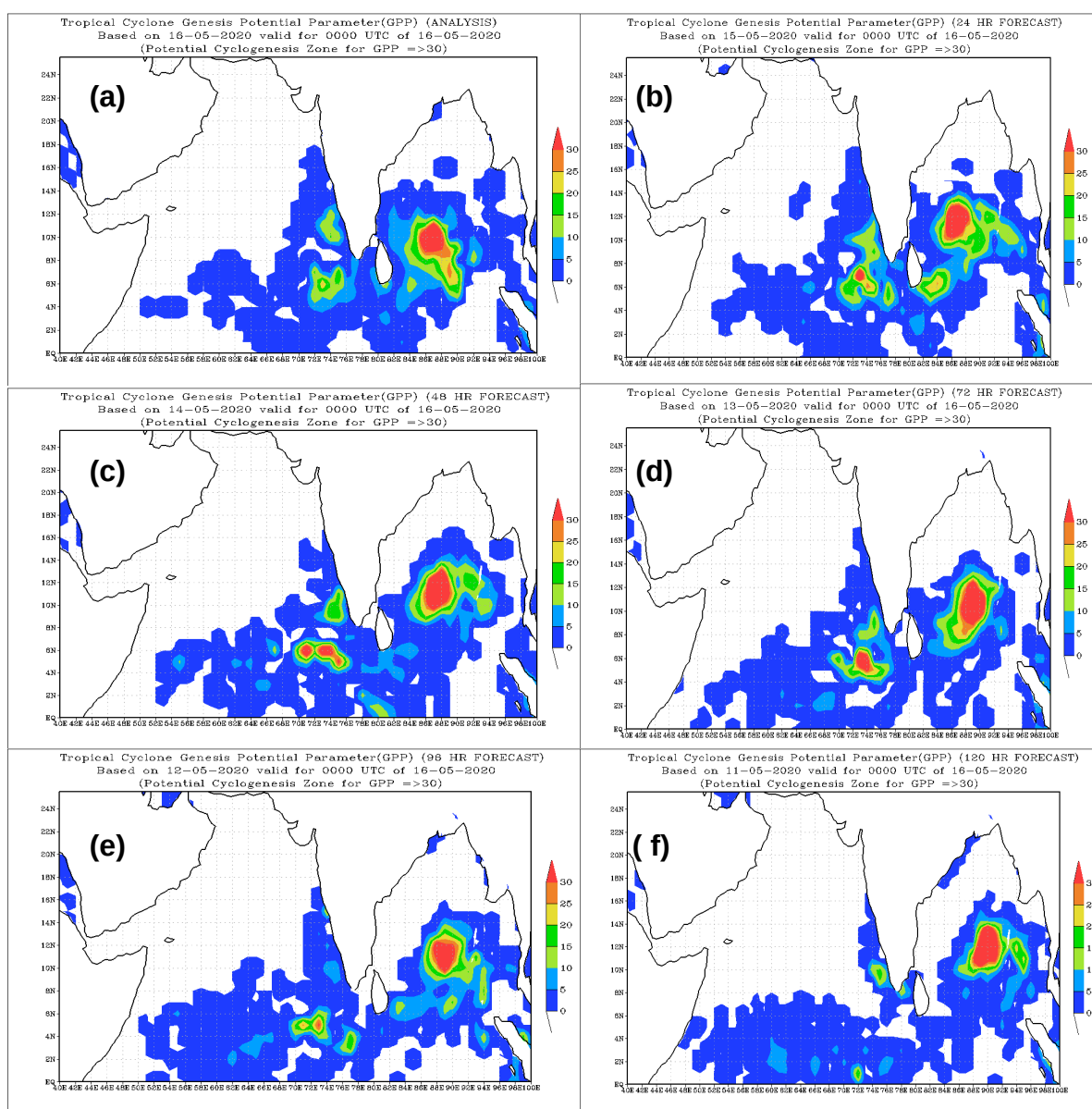


Fig.3.2.1(a-f): Predicted zone of cyclogenesis for 0000 UTC of 16th May based on 0000 UTC of 11th-16th May 2020

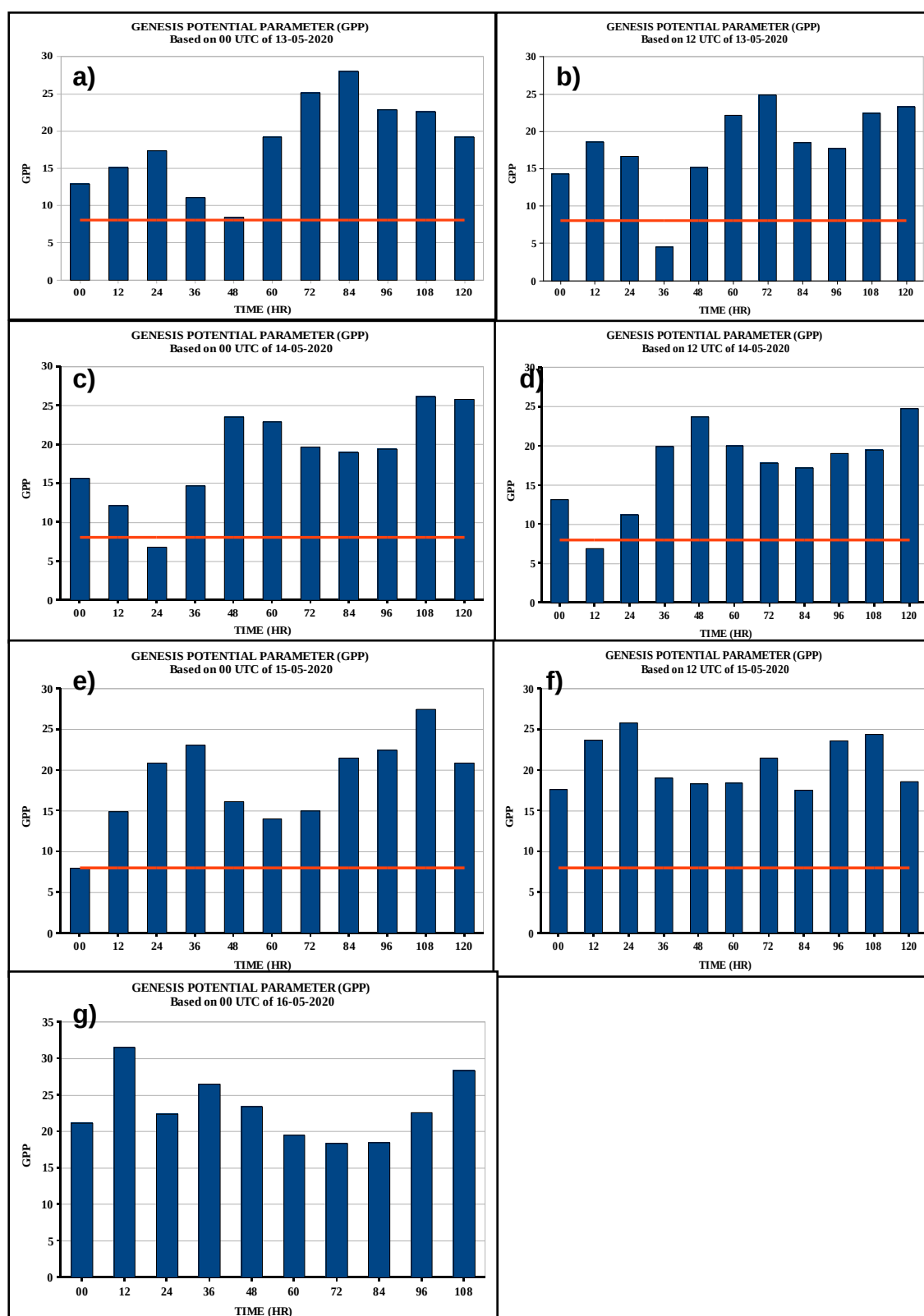
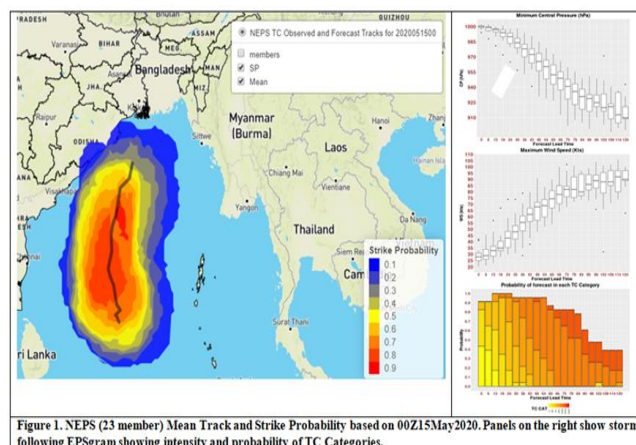
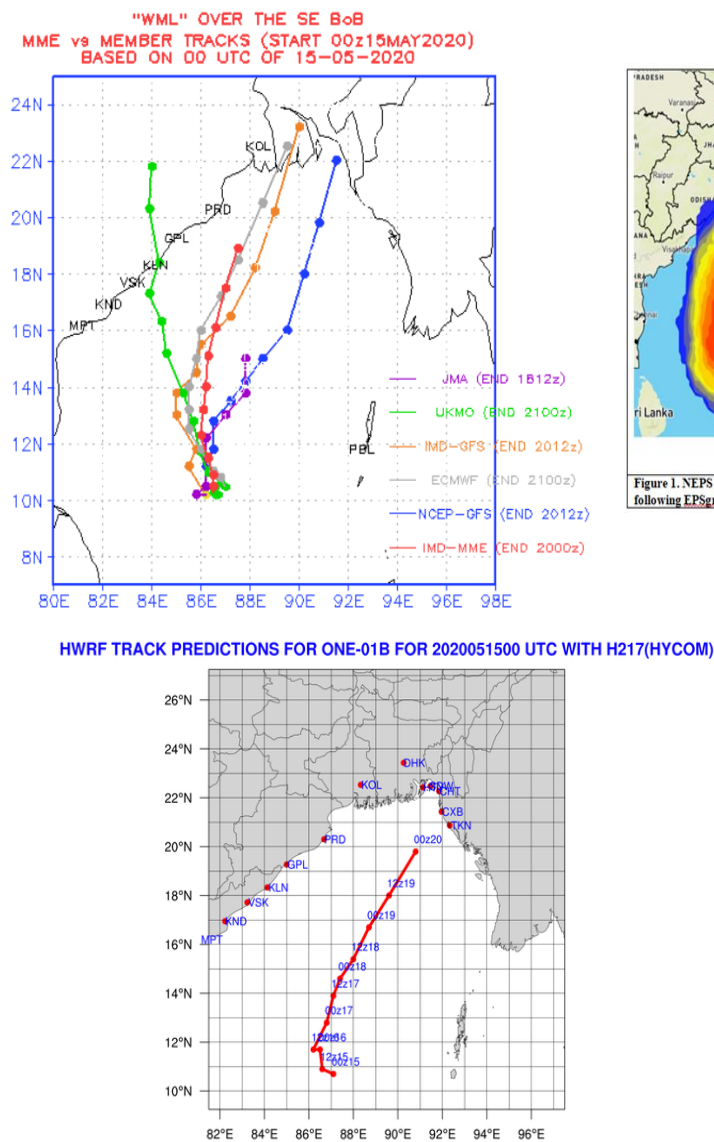


Fig. 3.2.2: Area average analysis and forecasts of GPP based on (a) 0000 of 13th, (b) 1200 UTC of 13th, (c) 0000 UTC of 14th and (d) 1200 UTC of 14th (e) 0000 UTC of 15th (f) 1200 UTC of 15th (g) 0000 UTC of 16th, May 2020

3.2.2 Track prediction by NWP models

Tracks predicted by various NWP models including IMD GFS, IMD MME, IMD HWRF, NCMRWF Unified Model (NCUM), NCEP GFS, ECMWF, UKMO and JMA during 15th May to 21st May are presented in **Fig.3.2.3**. Based on initial conditions of 0000 UTC of 15th May, there was large divergence among various models w.r.t. track. IMD GFS and ECMWF were predicting landfall over Bangladesh. MME, JMA & NCEP GFS, HWRF and NEPS were indicating weakening over sea. UKMO was predicting weakening over south Andhra Pradesh. HWRF was indicating the system to intensify upto Super cyclonic storm stage.



DI/Hr.	Lat.	Lon.	MSLP	Vmax
00z15	10.7	87.10	1003.	23.
12z15	10.9	86.60	1003.	28.
00z16	11.7	86.50	995.0	35.
12z16	11.7	86.20	988.0	44.
00z17	12.8	86.80	978.0	57.
12z17	13.9	87.10	969.0	54.
00z18	14.6	87.40	959.0	75.
12z18	15.4	88.00	941.0	92.
00z19	16.7	88.70	921.0	121.
12z19	18.0	89.60	910.0	128.
00z20	19.8	90.80	910.0	126.

Fig. 3.2.3 (a): NWP model track forecast based on 0000 UTC of 15th May, 2020

Based on initial conditions of 0000 UTC of 16th May, there was still large divergence among various models w.r.t. track. All models except JMA were now indicating landfall over Odisha and West Bengal. JMA was predicting weakening over sea. HWRF was indicating the system to intensify upto Super cyclonic storm stage on 0000 UTC of 19th with system reaching peak intensity of 130 kts at 1200 UTC of 19th.

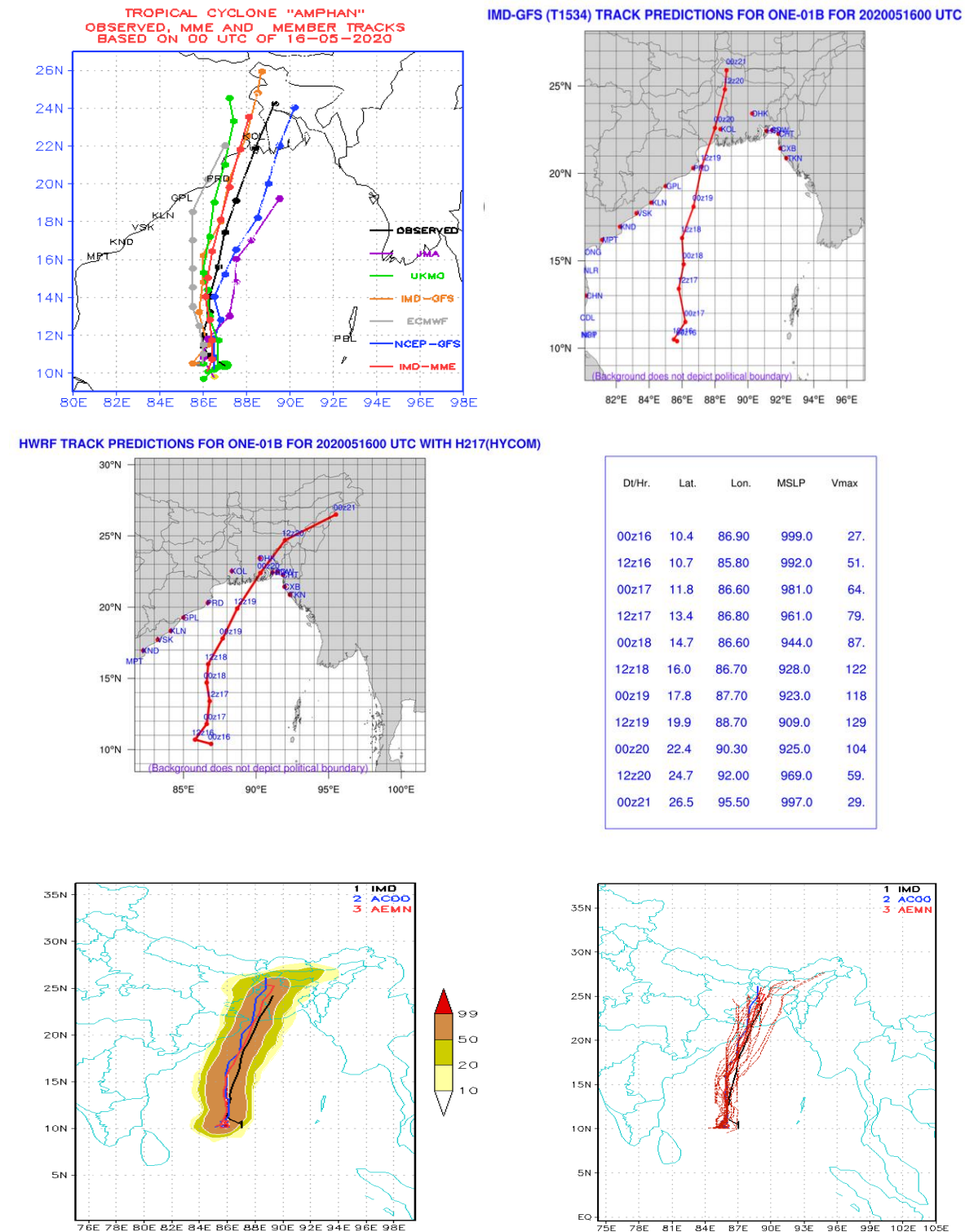


Fig. 3.2.3 (b): NWP model track forecast based on 0000 UTC of 16th May, 2020

Based on initial conditions of 0000 UTC of 17th May, there was still large divergence among various models w.r.t. track. All models were now indicating landfall over varying from south Odisha to Bangladesh. JMA and HWRF were predicting landfall over Bangladesh. MME, UKMO, NCEP GFS were predicting landfall over West Bengal. HWRF was indicating the system to intensify upto very severe cyclonic storm stage on 0000 UTC of 20th with system reaching peak intensity of 82 kts at 0000 UTC of 20th. On 17th HWRF underestimated the intensity of the system.

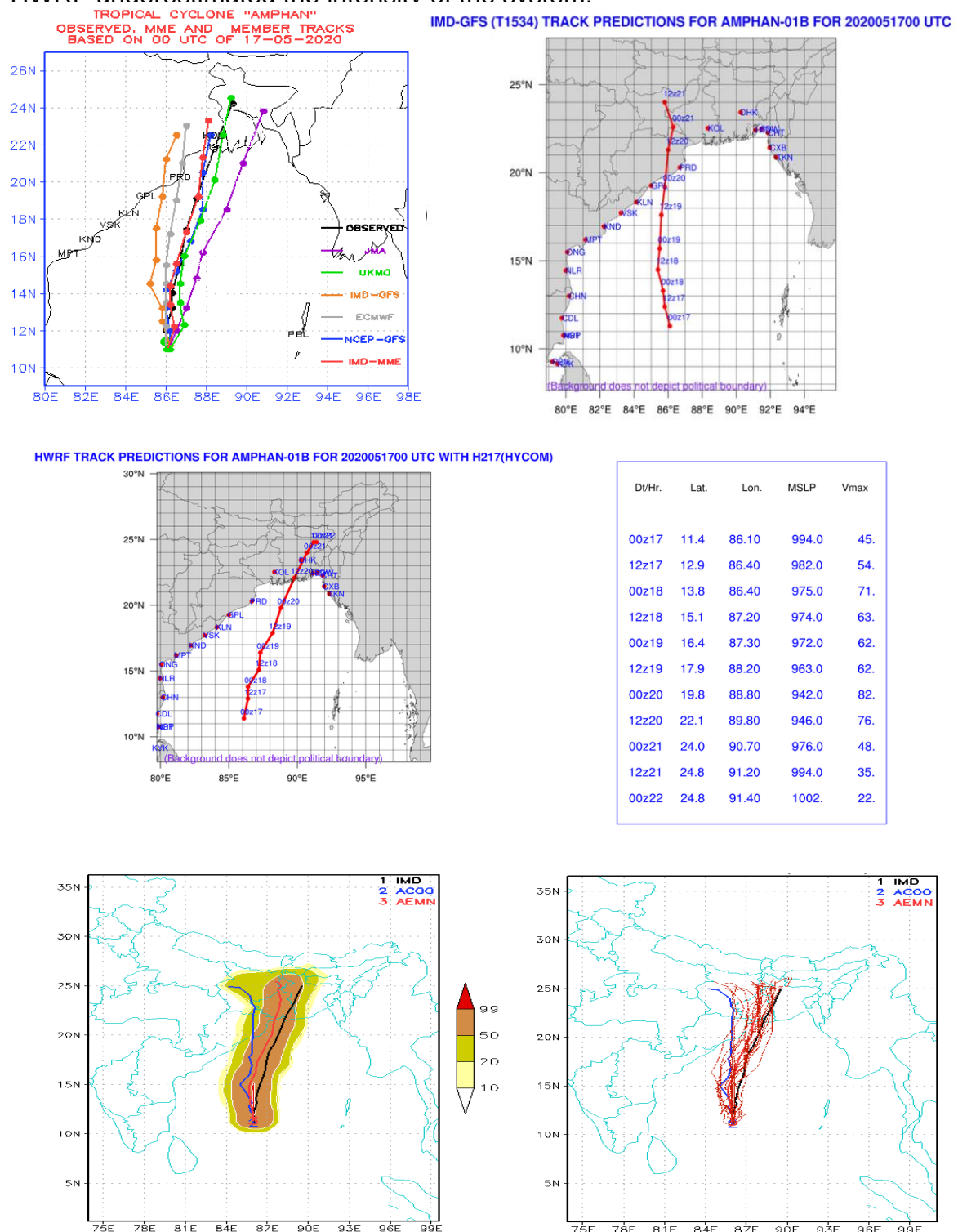


Fig. 3.2.3 (c): NWP model track forecast based on 0000 UTC of 17th May, 2020

Based on initial conditions of 0000 UTC of 18th May, all models converged and indicated landfall over West Bengal. HWRF predicted peak intensity of 120 kts at 1200 UTC of 19th. Thus, HWRF could pick up peak intensity but with a delay of about 24 hours. The system reached it's peak intensity at 0600 UTC of 18th.

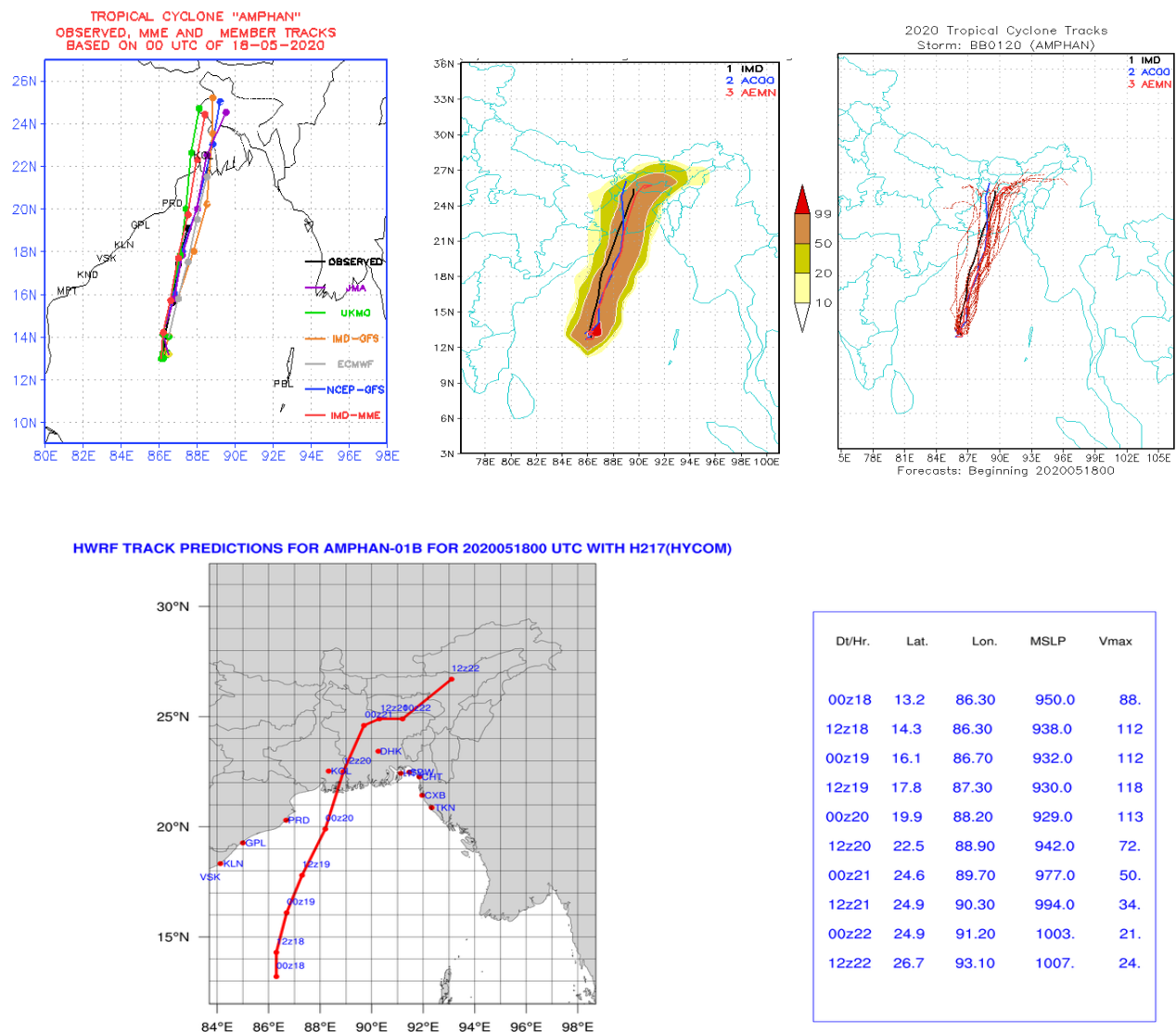
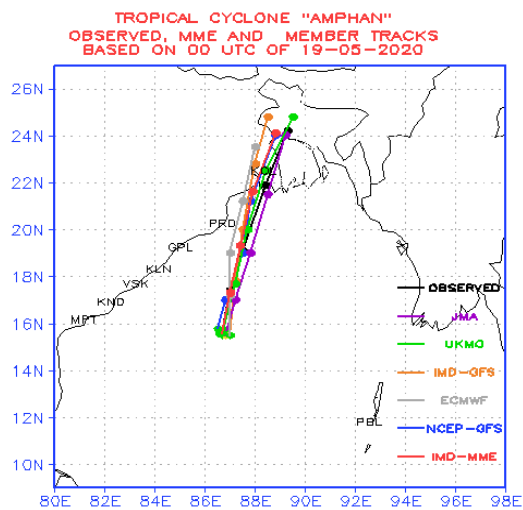
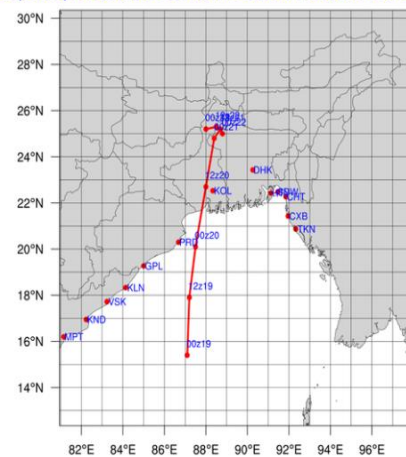


Fig. 3.2.3(d): NWP model track forecast based on 0000 UTC of 18th May, 2020

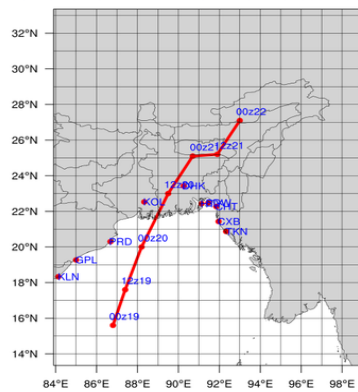
Based on initial conditions of 0000 UTC of 19th May, all models converged and indicated landfall over West Bengal. HWRF predicted landfall over Sunderbans around 1200 UTC of 20th. Thus, track and landfall point & time were correctly picked up by HWRF. However, intensity was underestimated by the system.



IMD-GFS (T1534) TRACK PREDICTIONS FOR AMPHAN-01B FOR 2020051900 UTC



HWRF TRACK PREDICTIONS FOR AMPHAN-01B FOR 2020051900 UTC WITH H217(HYCOM)



Dt/Hr.	Lat.	Lon.	MSLP	Vmax
00z19	15.6	86.80	940.0	115
12z19	17.6	87.40	937.0	111
00z20	20.0	88.20	929.0	115
12z20	23.0	89.50	945.0	71.
00z21	25.1	90.70	985.0	42.
12z21	25.2	91.90	1002.	22.
00z22	27.1	93.00	1006.	25.

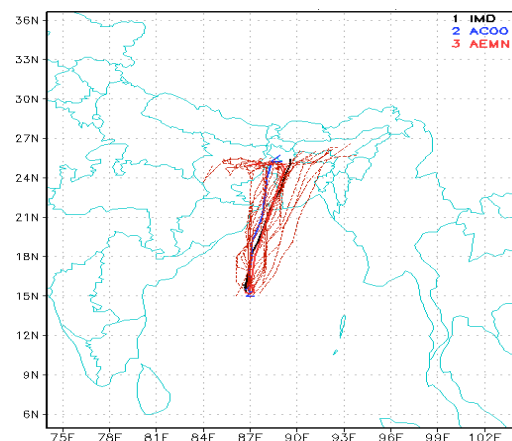
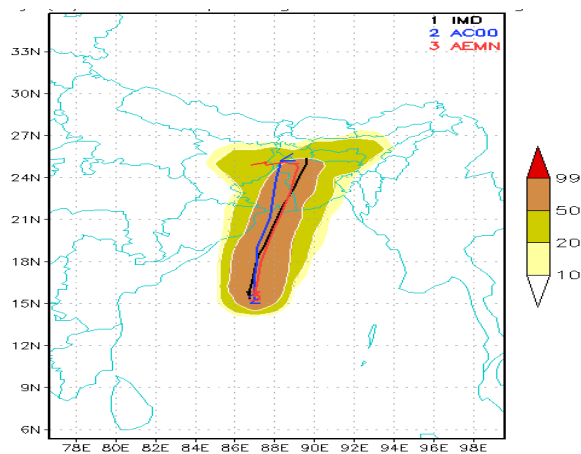


Fig. 3.2.3 (e): NWP model track forecast based on 0000 UTC of 19th May, 2020

Based on initial conditions of 0000 UTC of 20th May, all models converged and indicated landfall over West Bengal. HWRF predicted landfall over Sunderbans around 1000 UTC of 20th as a VSCS (around 80 kts). Thus, track and landfall point & time were correctly picked up by HWRF.

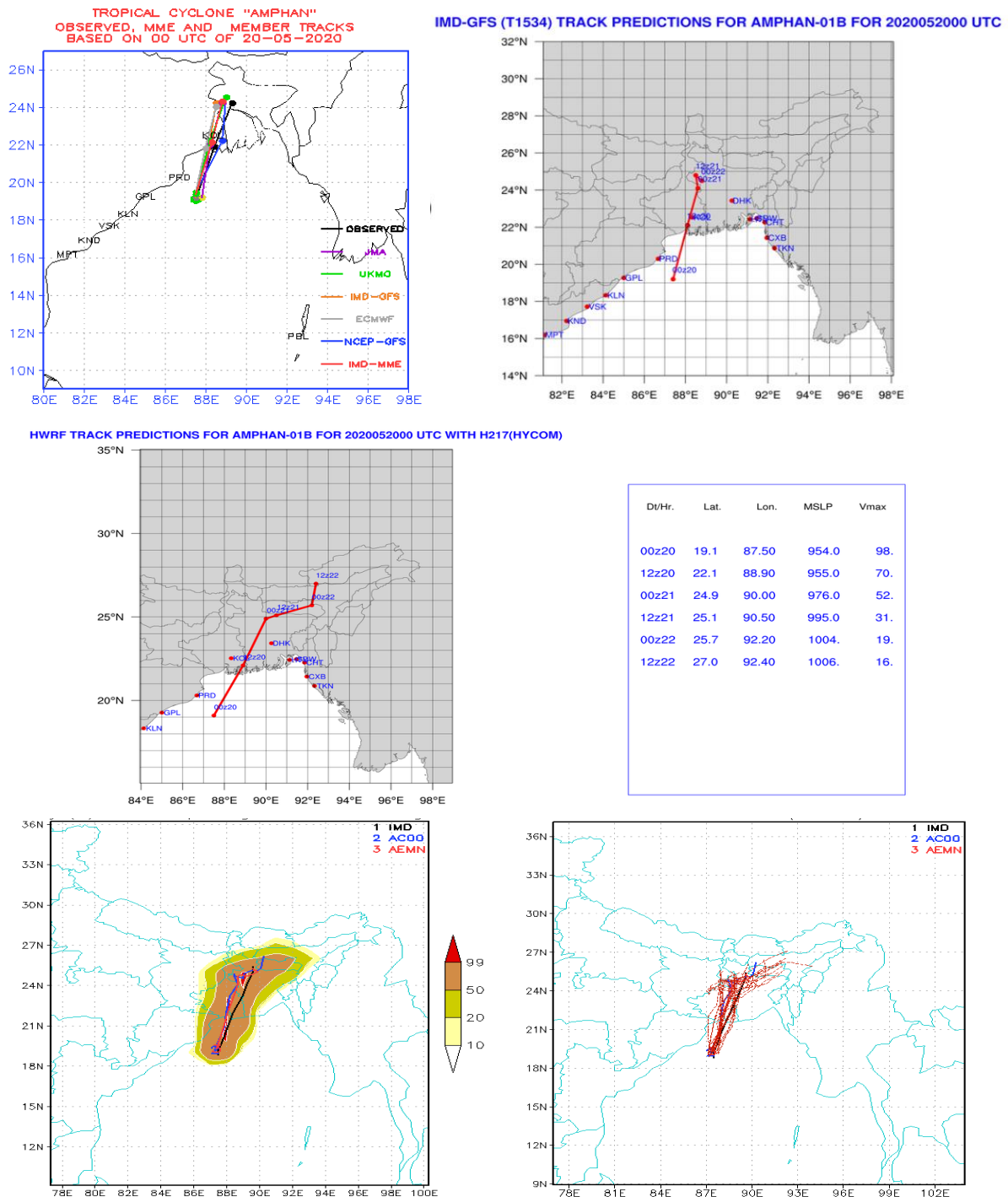


Fig. 3.2.3 (f): NWP model track forecast based on 0000 UTC of 20th May, 2020

3.2.3 Intensity Prediction :

Fig. 3.2.4 Show the intensity forecast in terms of Maximum sustained wind speed (MSW) in knots at various initial conditions. Intensity is underestimated by GEFS model.

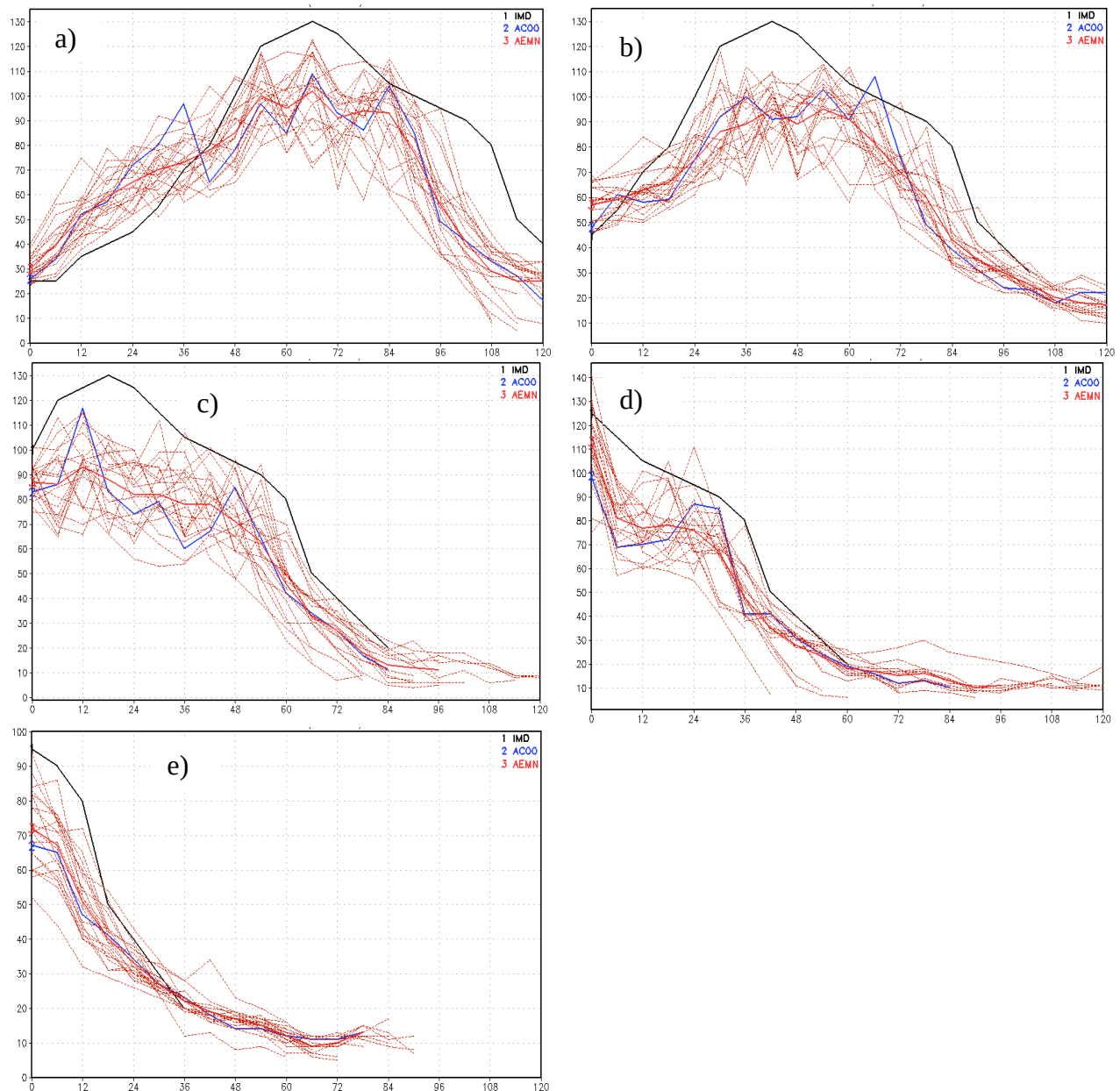


Fig. 3.2.4 Intensity in terms of Maximum Sustained Wind Speed (MSW) in knots based on a) 00UTC of 16 May 2020 b) 00UTC of 17 May 2020 c) 00UTC of 18 May 2020 d) 00UTC of 19 May 2020 e) 00UTC of 20 May 2020

3.2.4 Track forecast errors

Average track forecast errors by various NWP models are presented in Table 3.2.1a. For 24 hrs lead period track forecast error was the least i.e. MME followed by NCEP GFS, JMA, HWRF and IMD GFS. For 48 hrs lead period, the track forecast error

was the least i.r.o. MME, NCEP GFS and IMD HWRF. For 72 hours lead period, the error was the least i.r.o. MME, ECMWF, NCEP GFS and HWRF. The along track and cross track errors by different models are presented in Table 3.2.1(b & c). Along track errors were less as compared to cross track errors.

Table-3.2.1a: 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-MME*	26(9)	36(9)	55(8)	58(7)	57(6)	67(5)	71(4)	99(3)	76(2)	145(1)
ECMWF	51	73	101	118	74	101	139	209	261	339
NCEP-GFS	31	42	61	74	96	123	148	209	171	94
UKMO	50	61	79	112	140	184	216	170	198	215
JMA	40	59	93	123	170	205	280	---	---	---
HWRF	53 (18)	80 (18)	96 (17)	107 (15)	120 (13)	152 (11)	198 (9)	262 (7)	286 (5)	407 (3)
IMD-GFS	52	62	95	132	157	173	239	312	221	198
NCUM	58	62	98	124	187	237	294	326	429	--
NEPS	58	77	117	157	219	272	321	335	310	282
GEFS(CNTL)	61(9)	64(9)	103(9)	135(8)	139(7)	170(6)	217(5)	310(4)	306(3)	148(2)
GEFS(MEAN)	53(9)	71(9)	105(9)	114(8)	125(7)	140(6)	173(5)	220(4)	224(3)	83(2)

* The numbers within the parentheses against DP Errors for IMD-MME indicate the number of forecasts issued corresponding to the lead-time. The number of forecasts, corresponding to a particular lead-time, is the same for all the models (No forecast for JMA beyond 84h).

Table-3.2.1b. Average along-track forecast errors (ATE) in km
(Number of forecasts verified is given in the parentheses)

Lead Time	12 Hr	24 Hr	36 Hr	48 Hr	60 Hr	72 Hr	84 Hr	96 Hr	108 Hr	120 Hr
HWRF	24 (18)	28 (18)	35 (17)	38 (15)	57 (13)	81 (11)	119 (9)	148 (7)	216 (5)	336 (3)

Table-3.2.1c Average cross-track forecast errors (CTE) in km
(Number of forecasts verified is given in the parentheses)

Lead Time	12 Hr	24 Hr	36 Hr	48 Hr	60 Hr	72 Hr	84 Hr	96 Hr	108 Hr	120 Hr
HWRF	116 (18)	154 (18)	173 (17)	178 (15)	170 (13)	168 (11)	191 (9)	268 (7)	260 (5)	299 (3)
IMD-GFS	77	66	123	150	167	203	232	381	--	--
IMD-GEFS	53	71	105	114	125	140	173	220	--	--

3.2.5 Landfall forecast errors

Average model errors in landfall point and time are presented in Table 3.2.2(a & b). The tables indicate that landfall point errors upto 72 hrs lead period were the least by MME followed by HWRF. Landfall time errors by MME were the least for all lead period.

Table-3.2.2a. Landfall point forecast errors (km) of NWP Models at different lead time (hour)

Lead Time	12 Hr	24 Hr	36 Hr	48 Hr	60 Hr	72 Hr	84 Hr	96 Hr	108 Hr
HWRF	33	18	56	33	25	40	165	211	211
MME	11	11	22	--	44	33	44	55	66
GEFS(CNTL)	48	--	74	--	33	--	336	--	55
GEFS(MEAN)	46	--	9	--	119	--	4	--	51

Table-3.2.2b. Landfall time forecast errors (hour) at different lead time (hr) ((forecast time – Observed time) [-ve early +ve delay])

Lead Time	12 Hr	24 Hr	36 Hr	48 Hr	60 Hr	72 Hr	84 Hr	96 Hr	108 Hr
HWRF	0	0	-3	0	+3	0	+3	0	-9
MME	0	1	2	-1	-1	0	2	1	1
GEFS(CNTL)	-1	--	-4	--	-7	--	-3	--	-16
GEFS(MEAN)	-1	--	-4	--	-4	--	-4	--	-10

3.2.6. Intensity forecast errors by various NWP Models

The intensity forecasts errors of various models are presented in Table 3.2.3. It is seen that errors were the least by MME followed by IMD GFS, HWRF & GEFS.

Table-3.2.3. Average absolute errors (AAE) and Root Mean Square (RMSE) errors in knots of various models (Number of forecasts verified is given in the parentheses)

Lead Time	12 Hr	24 Hr	36 Hr	48 Hr	60 Hr	72 Hr	84 Hr	96 Hr	108 Hr	120 Hr
HWRF (AAE)	12.9 (18)	17.7 (18)	19.6 (17)	21.0 (15)	16.0 (13)	19.5 (11)	23.0 (9)	13.4 (7)	14.8 (5)	9.7 (3)
IMD-GFS (AAE)	12.2	15	12.2	7.5	14.3	8.7	15.3	24.5	19.8	11.5
IMD-SCIP (AAE)	6.1	13	19.3	21.3	20.2	9	9.3	23	19	--
GEFS(CNTL) (AAE)	20(9)	22(9)	23(9)	17(8)	23(7)	22(6)	16(5)	26(4)	20(3)	12(2)
GEFS(MEAN) (AAE)	24(9)	23(9)	22(9)	21(8)	21(7)	21(6)	19(5)	24(4)	24(3)	11(2)
HWRF (RMSE)	15.6 (18)	20.2 (18)	24.5 (17)	28.1 (15)	22.4 (13)	22.7 (11)	24.6 (9)	14.8 (7)	14.5 (5)	10.8 (3)
IMD-GFS (RMSE)	14.5	19.4	15.5	8	17.6	10.2	22.7	27.5	26.5	15
IMD-SCIP (RMSE)	8.1	15.5	21.3	23.4	23.3	9.7	9.7	23	19	--
GEFS(CNTL) (RMSE)	23(9)	27(9)	31(9)	20(8)	28(7)	25(6)	21(5)	31(4)	28(3)	16(2)
GEFS(MEAN) (RMSE)	27(9)	26(9)	26(9)	23(8)	24(7)	23(6)	23(5)	30(4)	32(3)	11(2)

Table 3.2.4 Average Intensity Forecast Errors in knots (Number of forecasts verified is given in the parentheses). Negative sign indicates underestimation of intensity and vice versa

Lead Time	12H	24H	36H	48H	60H	72H	84H	96H	108H	120H	132H
GEFS(CNTL)	-14 (9)	-16 (9)	-16(9)	-17(8)	-23 (7)	-22 (6)	-16 (5)	-23(4)	-20(3)	-12(2)	-6(1)
GEFS(MEAN)	-18 (9)	-19 (9)	-21 (9)	-21 (8)	-21 (7)	-21 (6)	-19 (5)	-24(4)	-24(3)	-11(2)	-1(1)

Intensity forecast by IMD Statistical Cyclone Intensity Prediction (SCIP) model is presented in Fig.3.2.6(a). It is seen that upto 72 hrs lead period, IMD SCIP underestimated the intensity of the system and beyond that it over estimated the intensity of the system. However, HWRF underestimated the intensity upto 60 hours lead period. But for longer lead period, intensity was correctly captured.

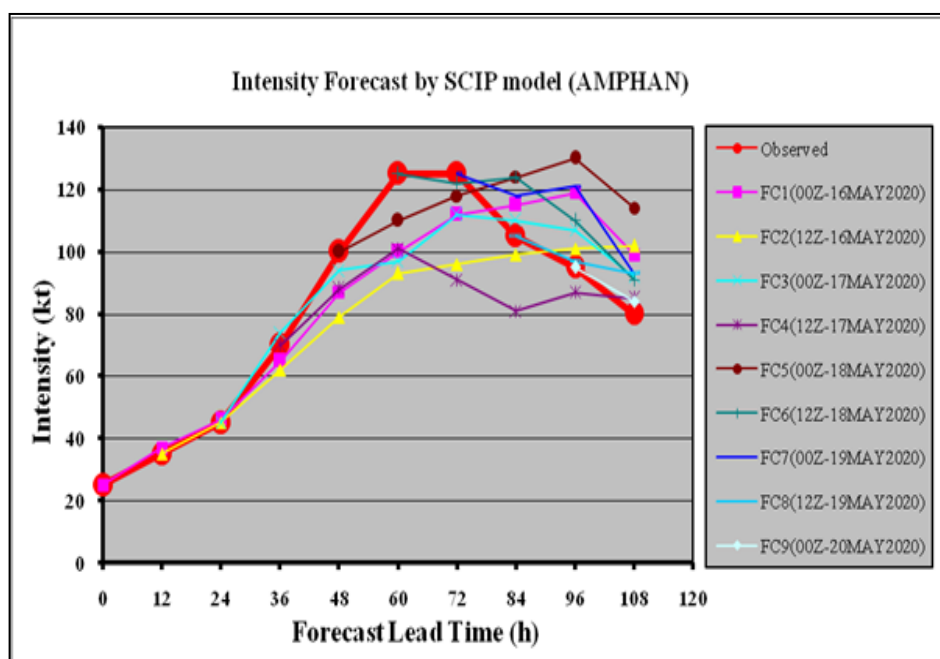


Fig.3.2.5 (a): Intensity forecast based on 0000 and 1200 UTC during 16th May to 20st May and (b) Landfall intensity prediction by SCIP Model

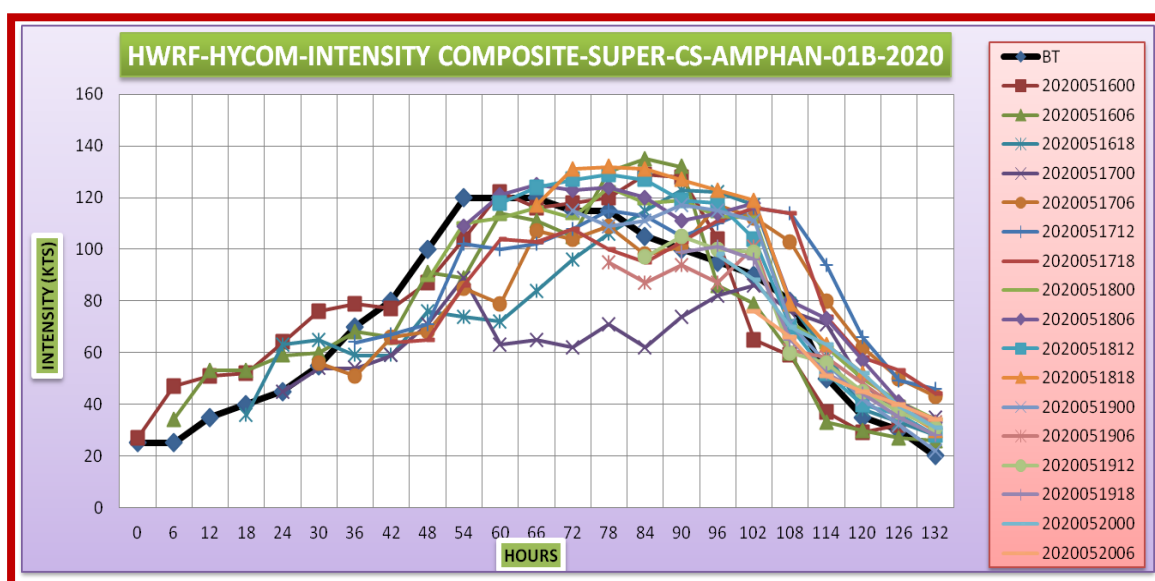


Fig. 3.2.5 (b): HWRf intensity forecast for various lead periods i.r.o. "SUPER-CS-AMPHAN-01B-2020"

3.3 Performance of operational NWP models during SCS Nisarga

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

Grid point analysis and forecast of GPP is used to identify potential zone of cyclogenesis. Fig. 3.3.1 (a-h) shows the predicted zone of cyclogenesis. Grid point analysis and forecasts of GPP predicted the cyclogenesis zone over the Bay of Bengal since 26th May (120 hrs before actual genesis).

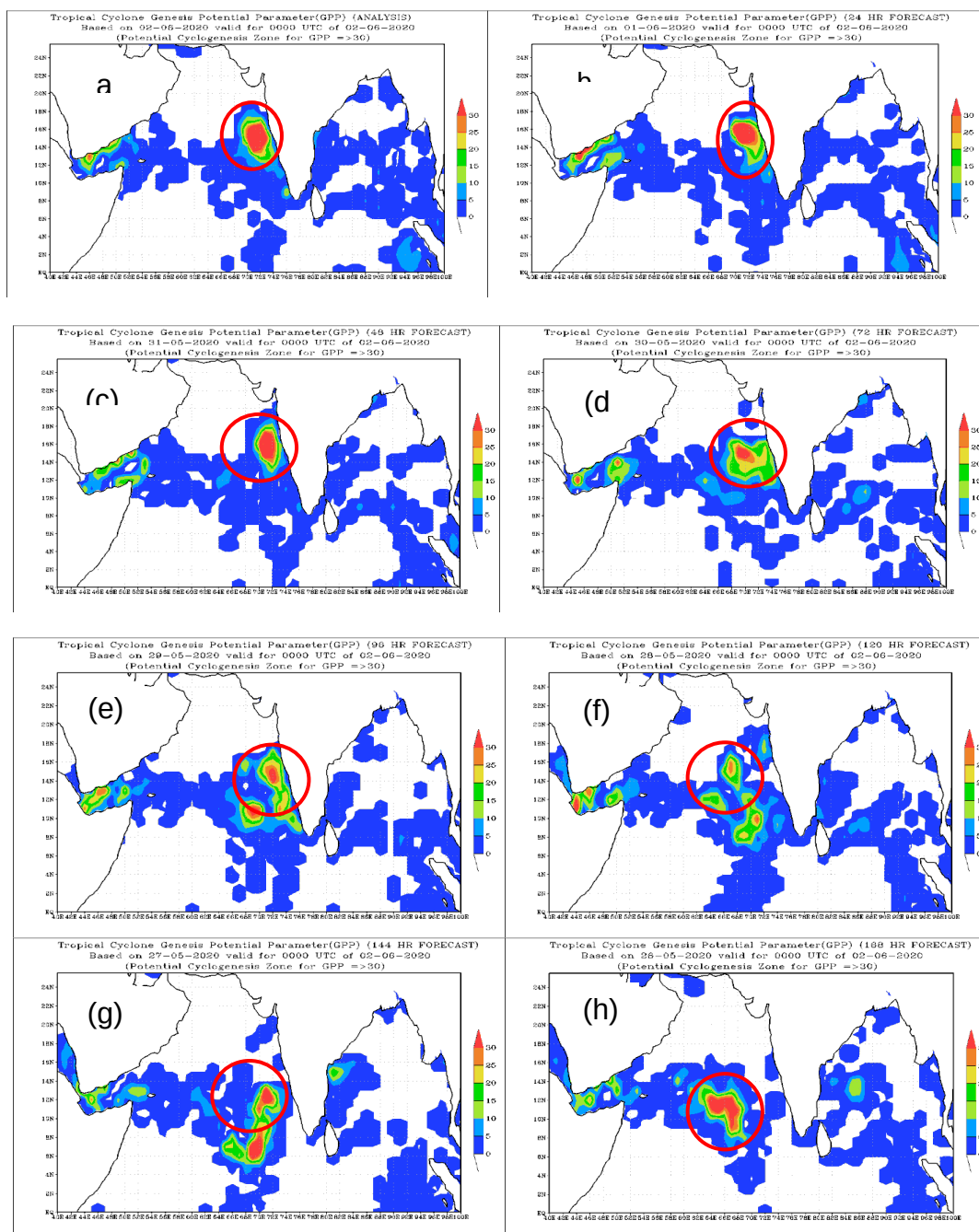


Fig.3.3.1 (a-h): Predicted zone of cyclogenesis for 0000 UTC of 2nd June based on 0000 UTC of 26th May -2nd June 2020

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 . Since 31st May, the model had predicted that the system over Arabian Sea to intensify into a cyclonic storm. Area area average analysis is presented in Fig. 3.3.2.

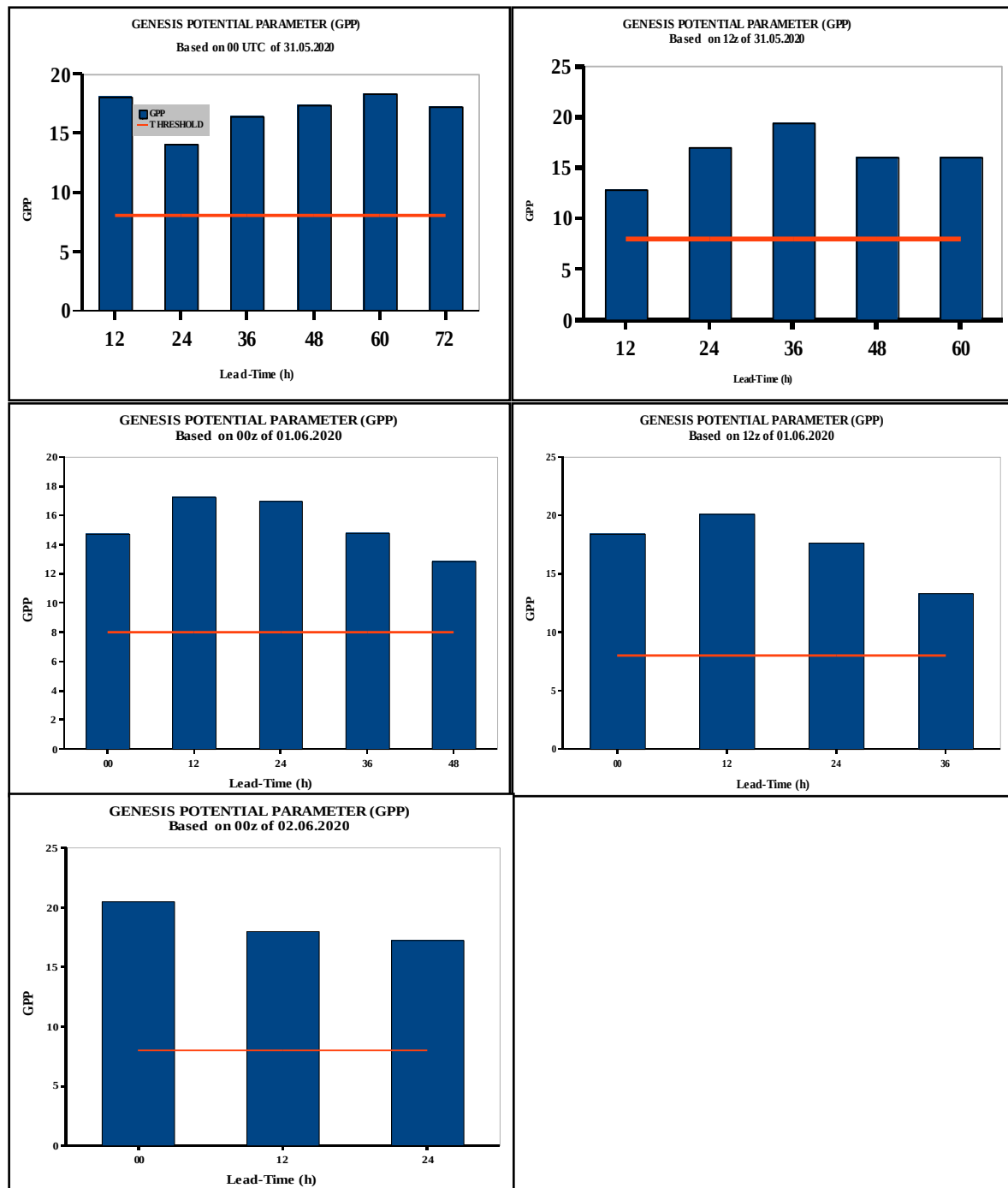


Fig. 3.3.2: (i) Area average analysis and forecasts of GPP based on 0000 UTC of 31.05.2020 (ii) 1200 UTC of 31.05.2020 (iii) 0000 UTC of 01.06.2020 (iv) 1200 UTC of 01.06.2020 and (v) 0000 UTC of 02.06.2020

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 0000 UTC of 1st June, most of the models indicated initial northwards movement followed by north-northeastwards re-curvature and crossing near 18°N. However, the landfall time varied largely. HWRF predicted intensification upto very severe cyclonic storm stage and MME indicated upto cyclonic storm stage. Figure 3.3.3 show strike probability of storm passing through 65nm as well as ensemble tracks along with GFS(control i.e. AC00), ensemble mean (AEMN) and IMD tracks ecm based on different initial conditions.

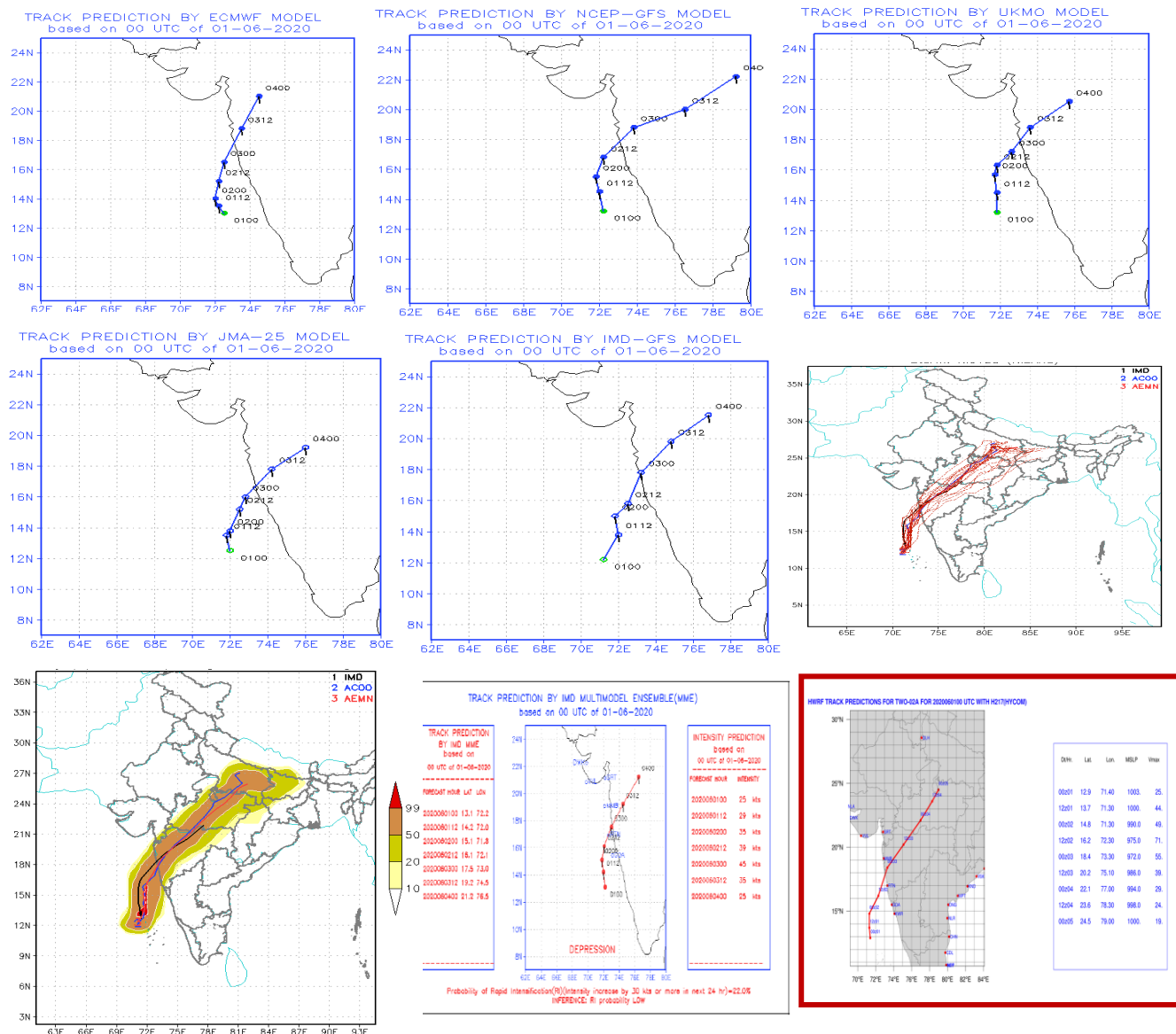


Fig. 3.3.3 (a): NWP model track forecast based on 0000 UTC of 01.06.2020

Based on initial conditions of 0000 UTC of 2nd June, most of the models indicated initial northwards movement followed by north-northeastwards re-curvature and crossing near 18°N. Both HWRF and MME correctly picked up the intensity at the time of landfall.

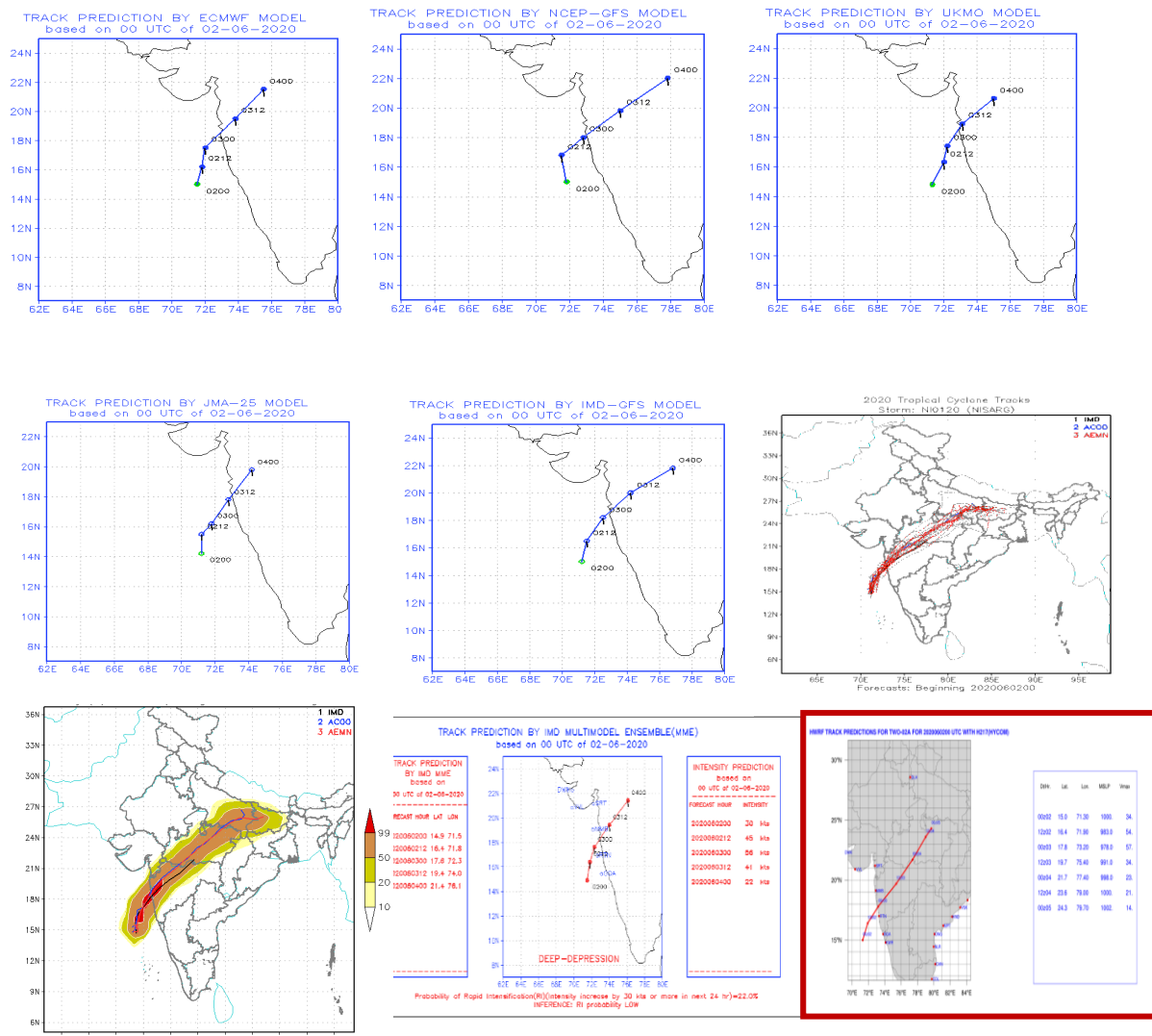


Fig. 3.3.3 (b): NWP model track forecast based on 0000 UTC of 02.06.2020

Based on initial conditions of 0000 UTC of 4th June, most of the models indicated crossing near 18.5°N. Both HWRF and MME underestimated the intensity at the time of landfall.

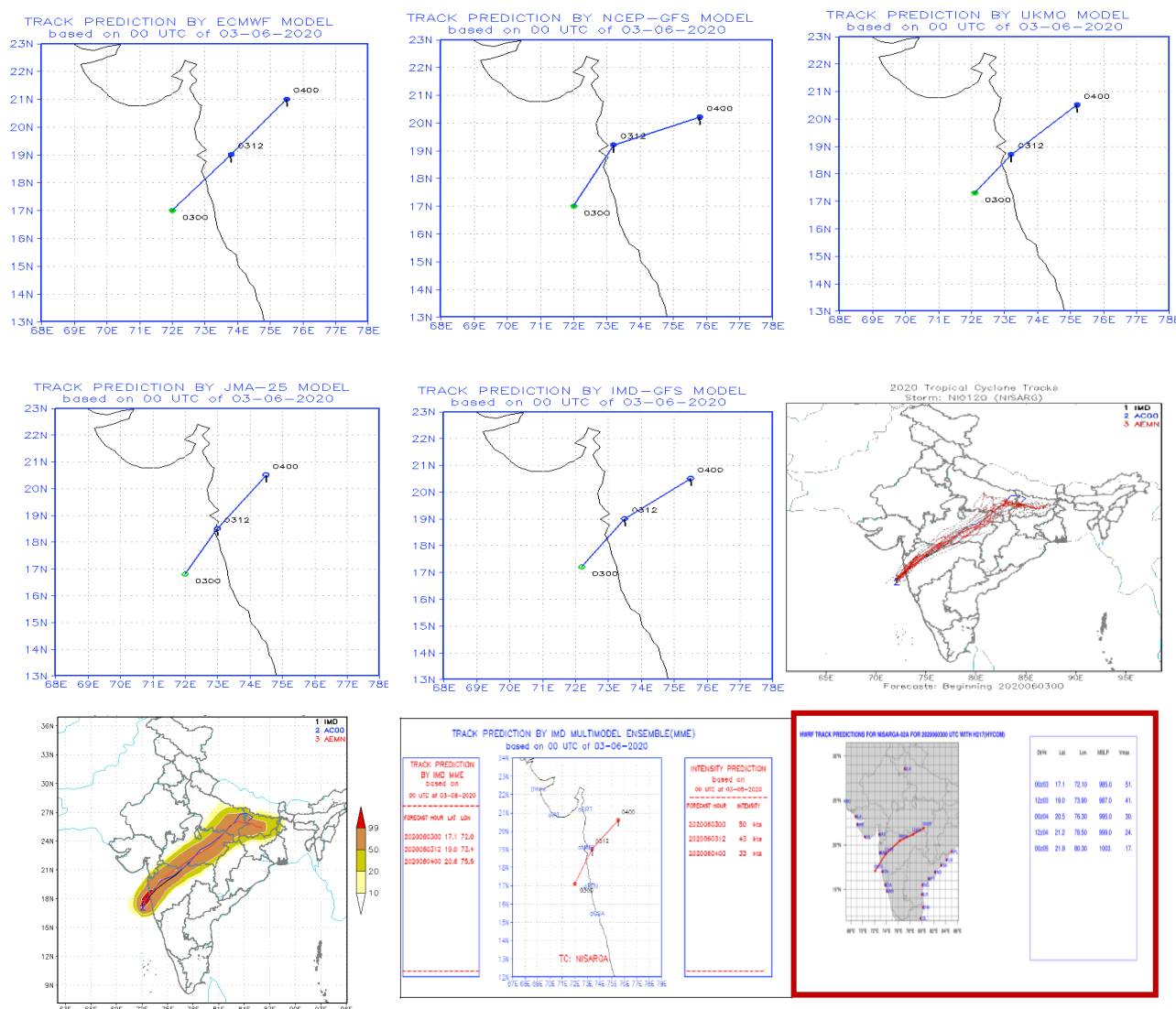


Fig 3.3.3 (c): NWP model track forecast based on 0000 UTC of 03.06.2020

3.3.3 Errors by various NWP Models

3.3.3.1 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 3.3.1**. From the verification of the forecast guidance available from various NWP models, it is found that the average track forecast errors of MME was the least followed by IMD GFS, ECMWF, IMD HWRF & UKMO model was minimum for 24 and 48 hr and 72 hours forecast.

Table-3.3.1: Average Track Forecast Error (Direct Position Error) in km of various models (Number of forecasts verified is given in the parentheses):

The average track forecast errors (Direct Position Error) in km at different lead period (hrs) for GEFS (Control (CNTL) and Ensemble mean (ENS_MEAN) models are presented in Table 3.3.1. The Track error is less in ENS_MEAN than control.

Lead time →	12h	24h	36h	48h	60h	72h
IMD-MME	52(5)	47(5)	47(4)	70(3)	80(2)	94(1)
ECMWF	58(5)	68(5)	83(4)	116(3)	123(2)	165(1)
NCEP-GFS	67(5)	72(5)	102(4)	214(3)	209(2)	381(1)
UKMO	62(5)	64(5)	50(4)	74(3)	81(2)	31(1)
JMA	95(5)	136(5)	154(4)	167(3)	148(2)	144(1)
IMD-GFS	53(5)	68(5)	101(4)	124(3)	156(2)	139(1)
HWRF	43 (10)	69 (10)	123 (8)	171 (6)	165 (4)	150 (2)
NCUM-G	64 (5)	36(5)	61(6)	91(5)	156(6)	184(5)
NEPS-G	75 (7)	66 (7)	78 (7)	101 (7)	129(6)	165(5)
NCUM-R	73(6)	103(7)	131(6)	199(7)	174(6)	249(5)
NEPS-R	78(3)	83(4)	139(3)	164(4)	137(3)	124(2)
GEFS(CNTL)	62(6)	73(5)	82(4)	141(3)	179(2)	183(1)
GEFS(MEAN)	59(6)	74(5)	94(4)	122(3)	119(2)	45(1)

3.3.4.2 Landfall forecast errors by various NWP Models

Landfall point and time forecast errors by various models run at NCMRWF are presented in Table 3.3.2.

Table 3.3.2: Error in the forecast landfall time and point by various models run at NCMRWF

(forecast time – Observed time) [-ve early +ve delay]

IC	NCUM-G		NEPS-G		NCUM-R		NEPS-R	
	Time error hh:mm	Point error (km)	Time error hh:mm	Point error (km)	Time error hh:mm	Point error (km)	Time error hh:mm	Point error (km)
12Z29052020			04:00	8				
00Z30052020	16:00	96	13:00	117				
12Z30052020	09:00	11	11:30	90				
00Z31052020	17:00	118	10:00	72				
12Z31052020	17:00	28	14:00	96				
00Z01062020	07:00	47	09:30	22			01:00	59
12Z01062020	03:30	28	03:30	28	03:30	39		
00Z02062020	-02:00	70	-02:00	70	06:00	26	02:00	29
12Z02062020	-02:00	52	-02:00	39	01:00	81		
00Z03062020	00:30	11	00:00	12	-03:00	62	00:00	12

The landfall point and time errors for different lead periods by IMD MME are presented in Table 3.3.3. The landfall point errors was 17 km for lead period of 44 hrs and 8 km for the lead period of 20 hrs. The landfall time error also varied between 1-2 hrs for various lead periods.

The landfall point and time errors by IMD HWRF are presented in Table 3.3.3.

Table 3.3.3: Landfall point (in km) and time (in hrs) errors of IMD HWRF & MME model

((forecast time – Observed time) [-ve early +ve delay])

Lead Time	12 Hr	24 Hr	36 Hr	48 Hr	60 Hr	72 Hr	96 Hr
Landfall Point-HWRF	39	49	63	79	72	-	-
Landfall Point-MME	8	8	17	17	84	-	-
Landfall Point-GEFS Mean	45	15	-	40	-	365	335
Landfall Point-GEFS Control	22	44	-	77	-	310	138
Landfall Time-HWRF	-3	-3	-9	-12	-15	-	-
Landfall Time-MME	-1	-1	-1	-2	-9	-	-
Landfall Time-GEFS Mean	-2	-5	-	-5	-	-2	-2
Landfall Time-GEFS Control	1	-5	-	-5	-	16	13

3.3.4.3 Intensity and Landfall Forecast Errors by GEFS model:

Table 3.3.4 represents intensity forecast errors in knots. The Average absolute errors (AAE) and Root Mean Square (RMSE) errors in kts from GEFS model are given in Table 3.3.5. Table 3.3.6 and Table 3.3.7 gives the landfall errors in time and km.

Table 3.3.4 Average Intensity Forecast Errors in knots (Number of forecasts verified is given in the parentheses). Negative sign indicates underestimation of intensity and vice versa

Lead Time	12H	24H	36H	48H	60H	72H
GEFS(CNTL)	4(6)	6(5)	7(4)	3(3)	6(2)	-1(1)
GEFS(MEAN)	4(6)	3(5)	3(4)	6(3)	10(2)	6(1)

Table 3.3.5 Landfall time forecast errors (hour) at different lead time (hr) ('+' indicates delay landfall, '-' indicates early landfall)

Forecast Lead Time (h)	54h 00Z01June	30h 00Z02June	6h 00Z3June
GEFS(CNTL)	-7	-7	-1
GEFS(MEAN)	-7	-7	-1

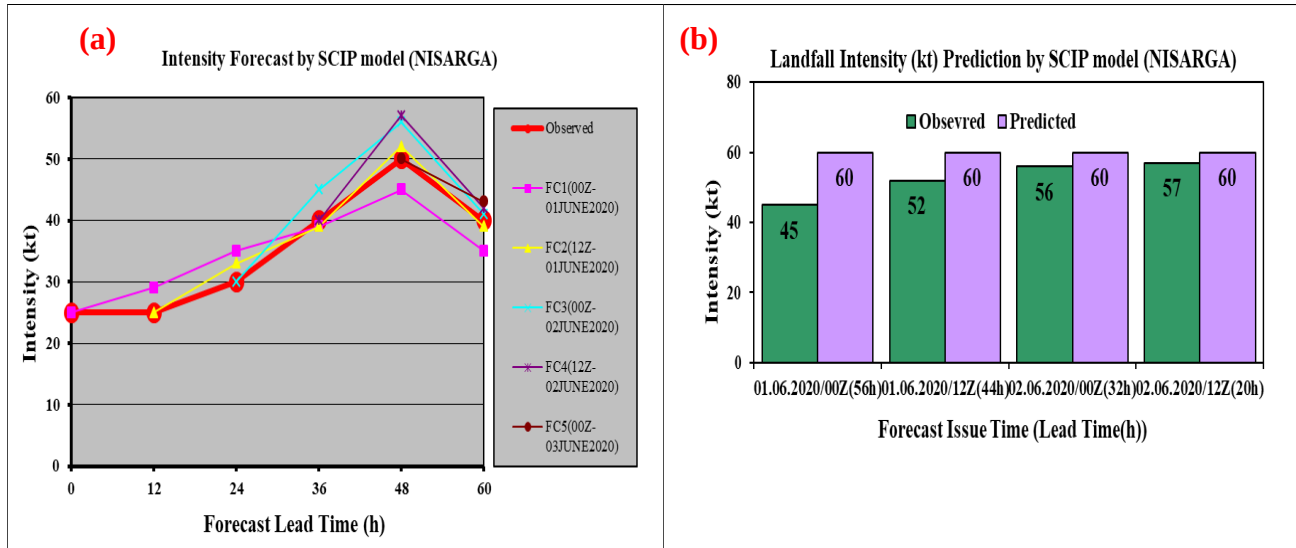
Table 3.3.6 Landfall point forecast errors (km) of NWP Models at different lead time (hour)

Forecast Lead Time (h)	54h 00Z01June	30h 00Z02June	6h 00Z3June
GEFS(CNTL)	77	44	22
GEFS(MEAN)	40	15	45

3.3.4. Intensity prediction

(a) IMD SCIP Model

The intensity forecast by IMD SCIP during life cycle and intensity at the time of landfall compared to observed intensity are presented in Fig.3.3.5(a) & (b). Based on 1200 UTC of 12th June, SCIP Model correctly picked up the intensity. Intensity at the time of landfall was underestimated by the model on 1st. However, based on 0000 & 1200 UTC conditions, model could capture intensity almost correctly.



(b) GEFS model

Figure Fig. 3.3.5(c) shows the intensity forecast in terms of Maximum sustained wind speed (MSW) in knots at various initial conditions.

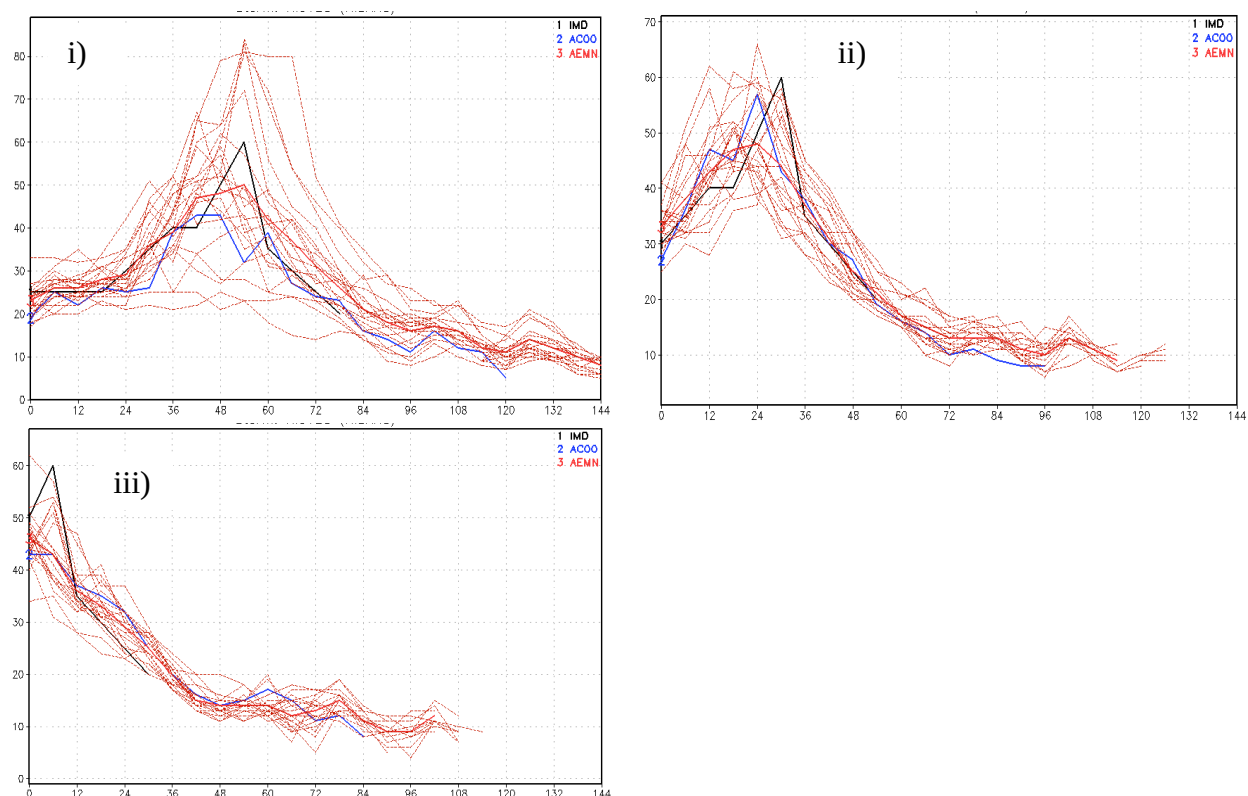


Figure Fig. 3.3.5(c): Intensity in terms of Maximum Sustained Wind Speed (MSW) in

knots based on a) 00UTC of 01 June 2020 b) 00UTC of 02 June 2020 c) 00UTC of 03 June 2020.

The intensity forecast errors are presented in Table 3.3.7. The intensity forecast errors by IMD MME were the least followed by IMD HWRF.

Table-3.3.7 Average absolute errors (AAE) and Root Mean Square (RMSE) errors in knots (Number of forecasts verified is given in the parentheses)

Lead time →	12H	24H	36H	48H	60H	72H
IMD-SCIP (AAE)	4.4(5)	3.5(4)	1.3(3)	3.0(2)	5.0(1)	
IMD-HWRF (AAE)	8.4 (10)	11.0 (10)	13.0 (8)	15.0 (6)	7.8 (4)	11.0 (2)
IMD-SCIP (RMSE)	4.6	4.1	1.4	3.6	5.0	
IMD-HWRF (RMSE)	11.4 (10)	12.9 (10)	14.8 (8)	15.7 (6)	8.8 (4)	11.2 (2)
GEFS_CNTL_AAE	5(6)	8(5)	8(4)	8(3)	6(2)	1(1)
GEFS_MEAN_AAE	4(6)	4(5)	4(4)	7(3)	10(2)	6(1)
GEFS_CNTL_RMSE	6(6)	9(5)	14(4)	10(3)	6(2)	1(1)
GEFS_MEAN_RMSE	4(6)	5(5)	5(4)	12(3)	10(2)	6(1)

3.4. Very Severe Cyclonic Storm “Gati” over the Arabian Sea (21st -24th November 2020)

3.4.1 Prediction of Cyclogenesis [Genesis Potential Parameter (GPP) for GATI]

Grid point analysis and forecast of GPP is used to identify potential zone of cyclogenesis. Fig. 3.4.1 (a-h) below shows the predicted zone of cyclogenesis.

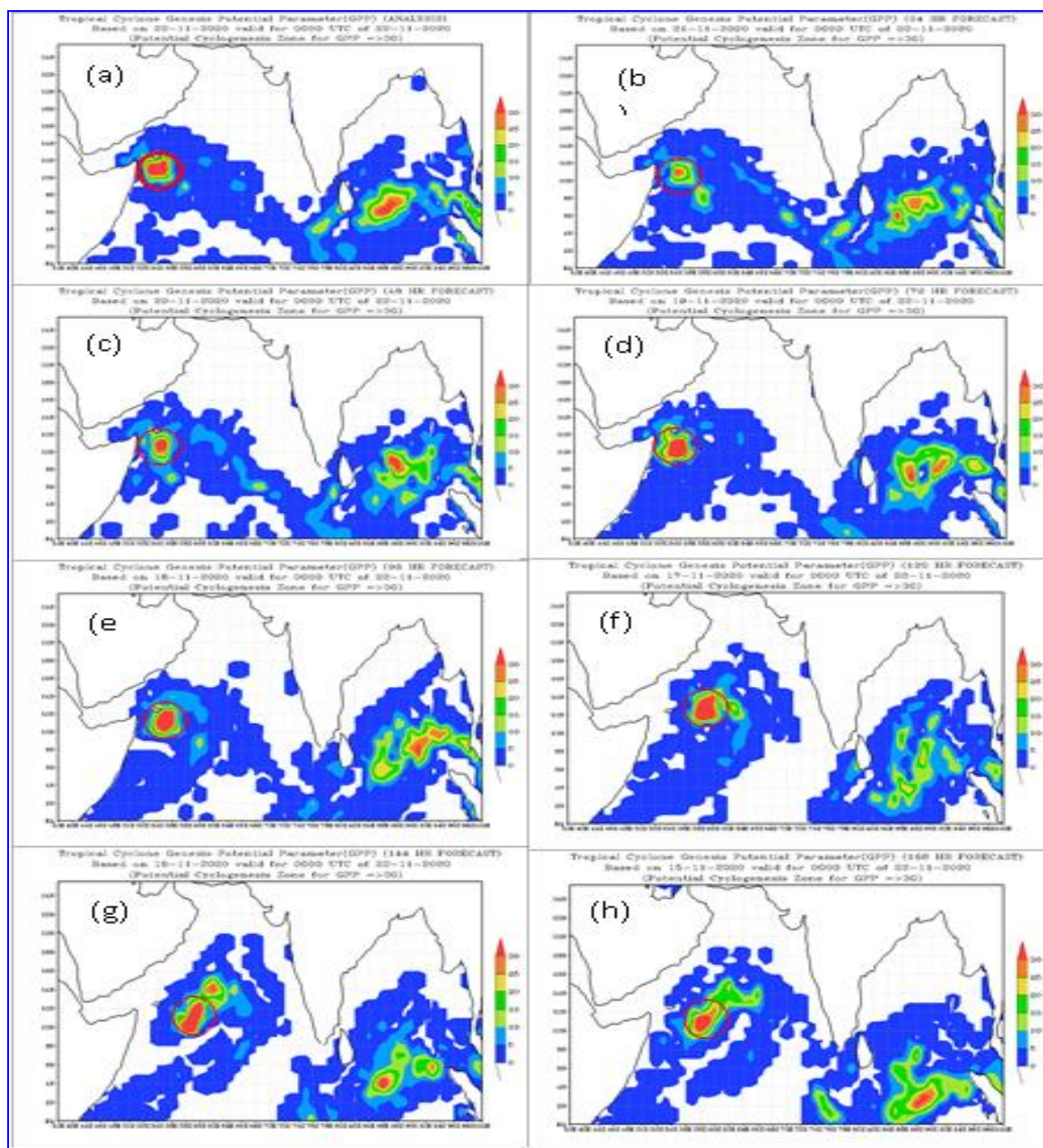


Fig.3.4.1 (a-h): Predicted zone of Cyclogenesis based on 1200 UTC from 15-22 November 2020

This GPP product predicted Cyclogenesis over the area on 22nd November, 168 hours in advance.

(Product available at http://www.rsmcnewdelhi.imd.gov.in/NWP_CYC/Analysis.htm)

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. For this purpose, an area average analysis of GPP is used. Conditions for (i) Developing system: Threshold value of average GPP ≥ 8.0 and (ii) Non-developing system: Threshold value of GPP < 8.0 . From Fig.3.4.2, it may be noted that this product also indicated potential for intensification of the system into a Cyclonic storm based on initial condition of 00 UTC of 21st November onwards.

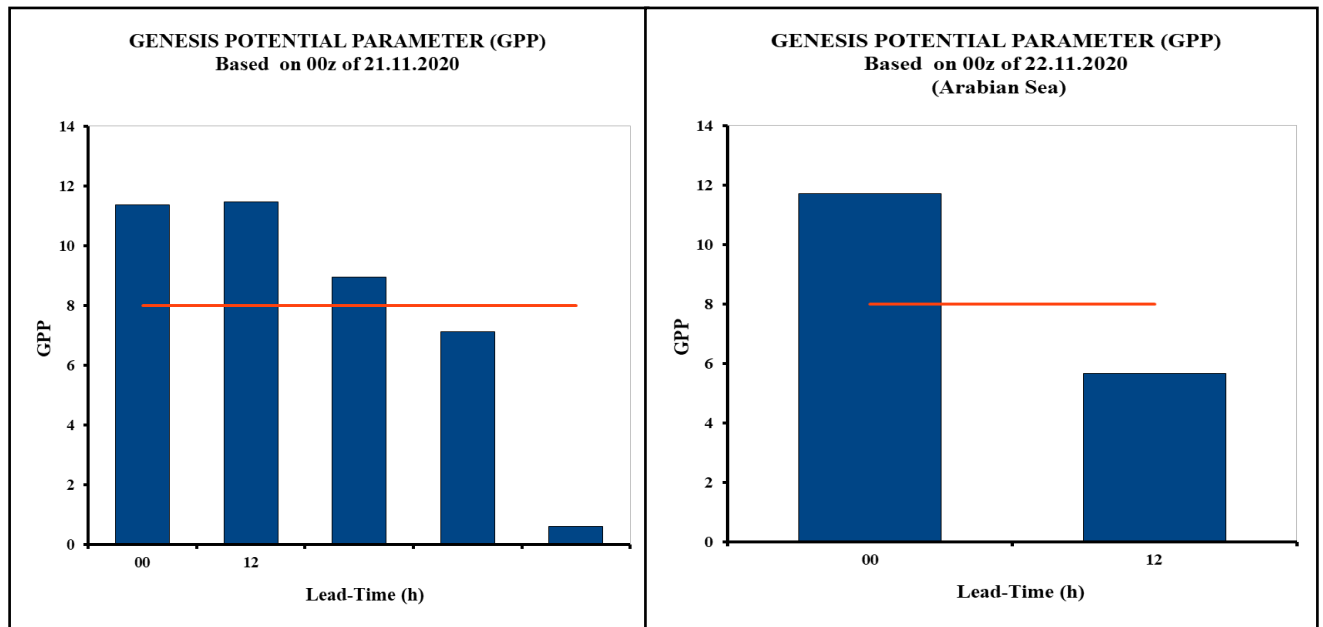


Fig. 3.4.2: Area average analysis and forecasts (a) Area average analysis and forecasts of GPP based on 0000 UTC of 21.11.2020 (b) Area average analysis and forecasts of GPP based on 0000 UTC of 22.11.2020

3.4.2 Intensity Prediction:

Figure 3.4.3 Show the intensity forecast in terms of Maximum sustained wind speed (MSW) in knots at various initial conditions. Intensity is underestimated by GEFS model.

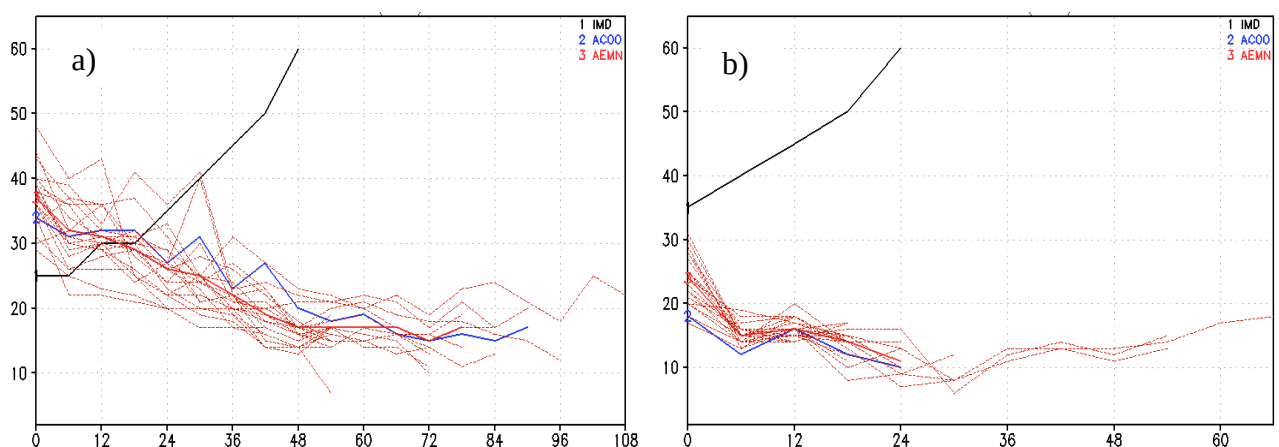


Fig. 3.4.3 Intensity in terms of MSW (knots) based on a) 00UTC of 22 November 2020 b) 00UTC of 23 November 2020.

3.4.3 Track prediction by NWP models

Track prediction by various NWP models is presented in **Fig.3.4.4**. Based on initial conditions of 0000 UTC of 22nd November, most of the models indicated initial west-northwestward movement towards north Somalia coast. However only NCEP GFS and JMA models did not indicate any landfall and HWRF indicated an initial west-southwestward movement followed by northwestward re-curvature & landfall over north Somalia coast. **Figure 3.4.4** show strike probability of storm passing through 65nm as well as ensemble tracks along with GFS (control i.e. AC00), ensemble mean (AEMN) and IMD tracks based on different initial conditions.

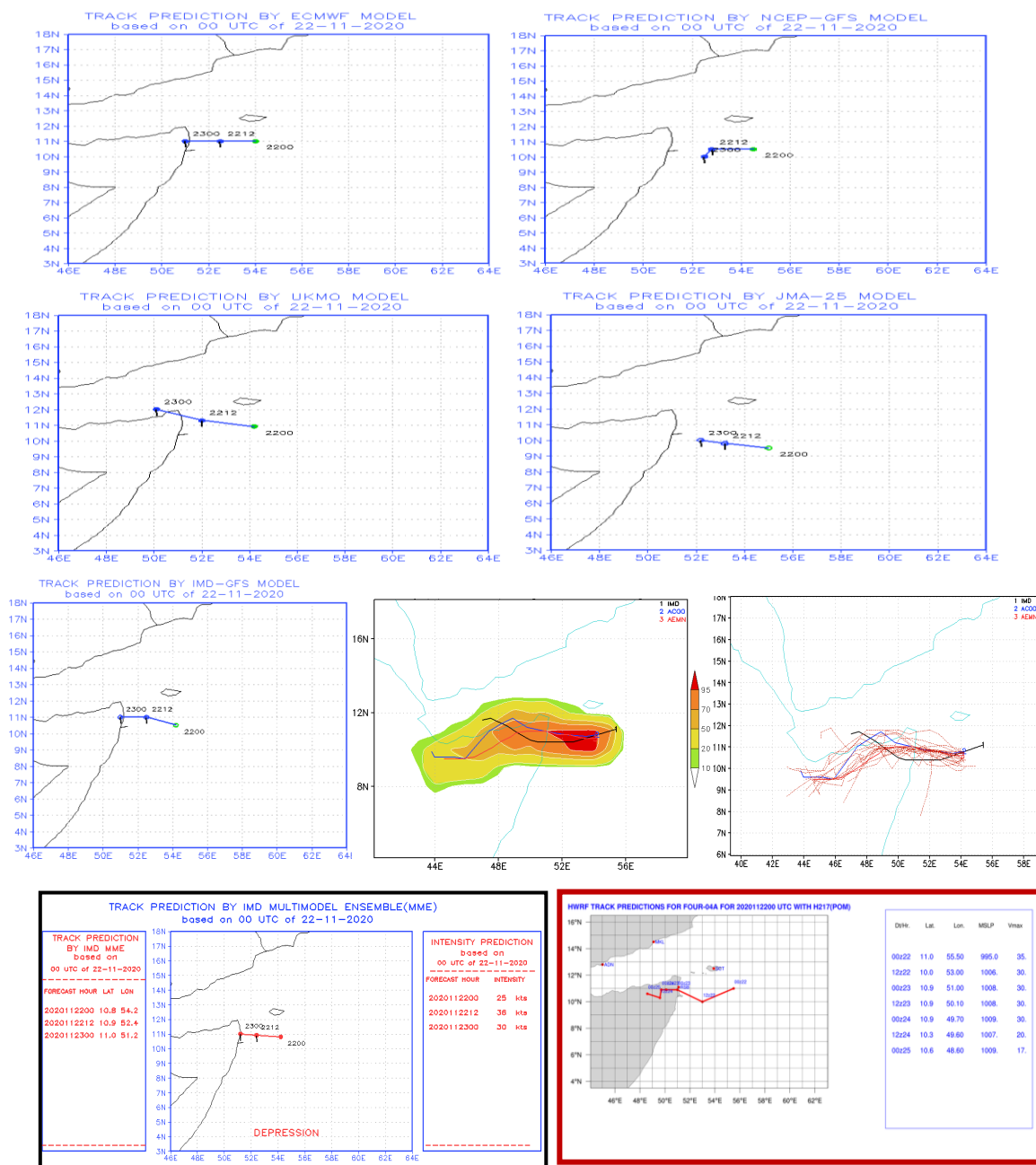


Fig. 3.4.4: NWP model track forecast based on 0000 UTC of 22.11.2020

3.4.4 Track forecast errors by various NWP Models

The average track forecast errors (Direct Position Error) in km at different lead period (hr) of various models are presented in **Table 3.4.1**. From the verification of the forecast guidance available from various NWP models, it is found that the average track forecast errors of HWRF model was minimum for 12 and 24 hours forecast followed by 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
IMD-MME	113(1)	142(1)
ECMWF	128(1)	122(1)
NCEP-GFS	142(1)	279(1)
UKMO	114(1)	167(1)
JMA	198(1)	247(1)
IMD-GFS	128(1)	122(1)
HWRF	88(5)	161(5)
GEFS	200	340

3.4.4.1 Landfall forecast error by various NWP Models

Fig.3.4.5 shows the landfall errors by the constituent models of MME along with that of MME. Other member models did not provide any landfall forecast.

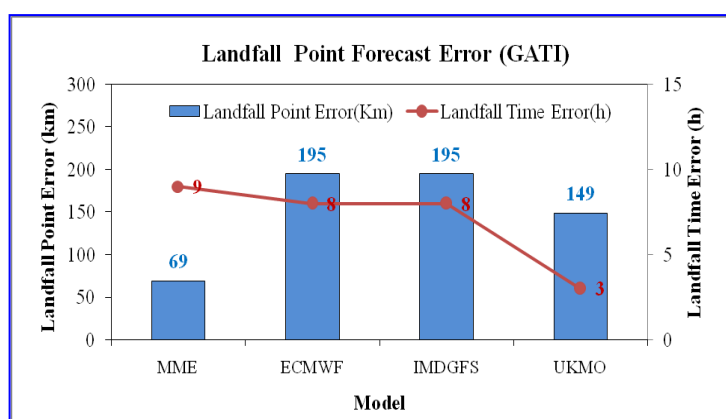


Fig. 3.4.5: MME Landfall Point and Time Forecast Error of GATI (Forecast based on 00UTC of 22.11.2020; lead time-15h)

3.4.4.2 Intensity forecast errors by HWRF Model

The intensity forecasts by HWRF model is shown in Table 3.4.2(a-b). The intensity error was high with HWRF model.

Table-3.4.2(a) Average Absolute Error (INTENSITY) of IMD-HWRF Model

(Number of forecasts verified is given in the parentheses) ::

Lead Time	12 Hr	24 Hr	36 Hr	48 Hr
<u>HWRF</u>	9.2 (5)	7.4 (5)	6.0 (3)	5.0 (1)
<u>GEFS</u>	20	21.5	24.5	-

Table-3.4.2 (b) Root Mean Square (RMSE) (INTENSITY) errors of IMD-HWRF Model

(Number of forecasts verified is given in the parentheses) ::

Lead Time	12 Hr	24 Hr	36 Hr	48 Hr
<u>HWRF</u>	10.3 (5)	9.0 (5)	8.1 (3)	5.0 (1)
<u>GEFS</u>	25.5	33.0	32.0	-

3.4.4.3 Track, Intensity and Landfall Forecast Errors by GEFS model:

The average track forecast errors (Direct Position Error) in km at different lead period (hrs) for GEFS (Control (CNTL) and Ensemble mean (ENS_MEAN) models are presented in Table 3.4.3(a). Table 3.4.3(b) represents Average absolute errors (AAE) and Root Mean Square (RMSE) errors in kts from GEFS model .

Table 3.4.3(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
GEFS(CNTL)	201(4)	280(3)	364(2)	79(1)
GEFS(MEAN)	200((4)	362(3)	407(2)	221(1)

Table 3.4.3(b) Average absolute errors (AAE) and Root Mean Square (RMSE) errors in kts of CNTL and ENS_MEAN from GEFS model (Number of forecasts verified is given in the parentheses)

Lead Time	12H	24H	36H	48H
GEFS_CNTL_AAE	22(4)	28(3)	31(2)	40(1)
GEFS_MEAN_AAE	22(4)	28(3)	33(2)	43(1)
GEFSCNTL_RMSE	26(4)	33(3)	32(2)	40(1)
GEFS_MEAN_RMSE	22(4)	28(3)	33(2)	43(1)

To summarise the performance of numerical models it may be noted that though majority of them indicated the genesis and track more or less accurately, the ‘explosive’ nature of intensification could not be predicted by any of them, due to various limiting factors. SCIP model also could not provide a hint in this case as the 24 hour forecast position predicted by MME based on the initial condition of 0000 UTC of 22nd November, lay over the land and the formula for calculating the Rapid Intensification Index would not perform under the scenario of Post Landfall Characteristics of a Cyclone. Thus the matter to be highlighted here is the limitations by the Dynamical & Statistical models depending on these outputs to correctly prognose the intensity of Cyclonic Storms very close to coast.

3.5. Very Severe Cyclonic Storm “NIVAR” over the Bay of Bengal (22nd -27th November 2020)

3.5.1. Prediction of Cyclogenesis (Genesis Potential Parameter (GPP) for NIVAR

Grid point analysis and forecast of GPP is used to identify potential zone of cyclogenesis. Fig.3.5.1. (a-g) below shows the predicted zone of cyclogenesis. Grid point analysis and forecasts of GPP predicted the cyclogenesis zone over the Bay of Bengal 120 hrs before its formation since 17th November.

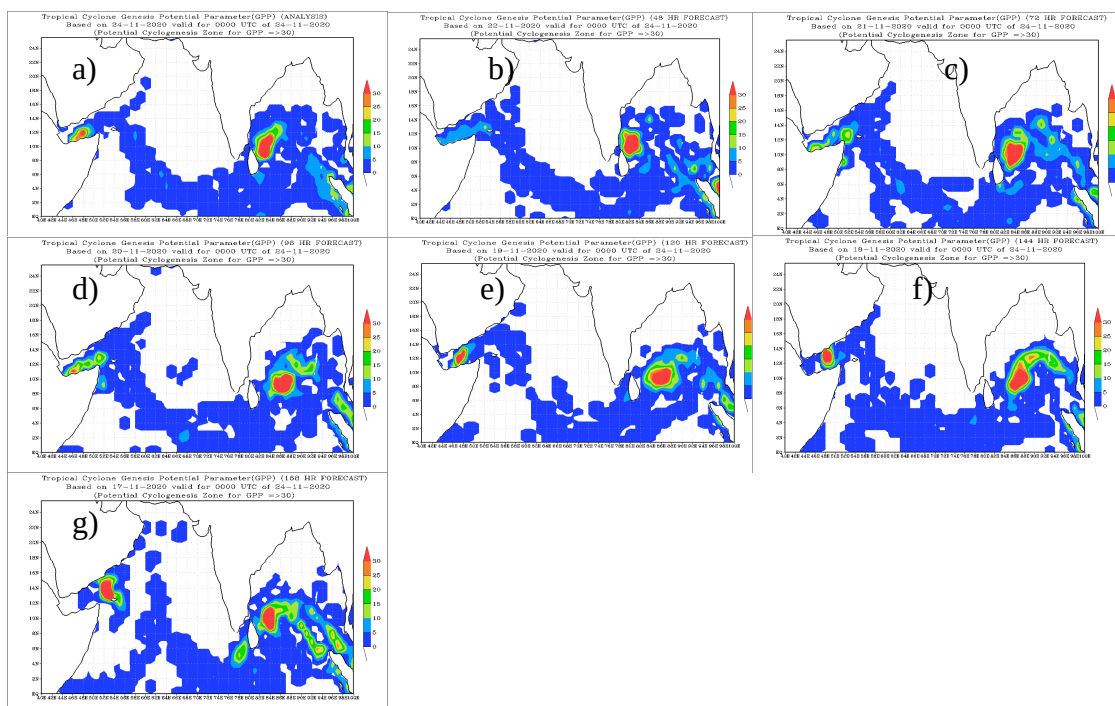


Fig.3.5.1. (a-g): Predicted zone of Cyclogenesis based on 0000 UTC from 24-27 Nov.,

The Area average analysis of GPP is presented in Fig.3.5.2. 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. For developed system, threshold value of GPP is ≥ 8.0 and for non-developed system, threshold value of GPP is < 8.0 . It is seen that since 21st/0000 UTC, the GPP area average analysis was indicating the system to intensify into a cyclonic storm. However, it was indicating the system to intensify into a cyclonic storm from 0000 UTC of 21st itself. At that time, even genesis had not occurred.

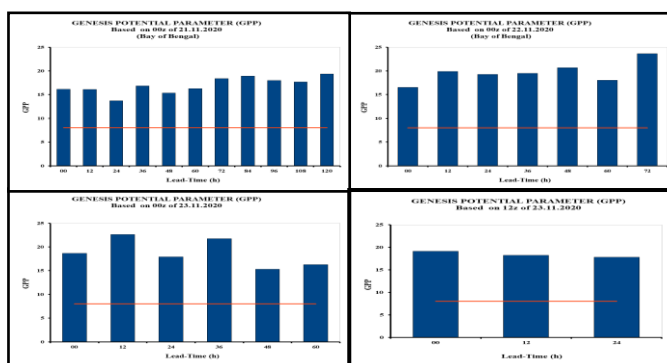


Fig.3.5.2.: Area average analysis and forecasts of GPP based on (a) 0000 UTC of 21st (b) 0000 UTC of 22nd (c) 0000 UTC of 23rd (d) 1200 UTC of 23rd

3.5.2. Track prediction by NWP models

Track prediction by various NWP models is presented in **Fig.3.5.3**. Based on initial conditions of 0000 UTC of 23rd November, most of the models indicated movement towards north Tamilnadu - south Andhra Pradesh coasts. There was large divergence among the models wrt point and time of landfall. MME predicted peak intensity of 52 kts. The landfall point and time was correctly predicted, but intensity at the time of landfall was underestimated by the MME. Figure 3.5.3. show strike probability of storm passing through 65nm as well as ensemble tracks along with GFS(control i.e. AC00), ensemble mean (AEMN) and IMD tracks based on different initial conditions.

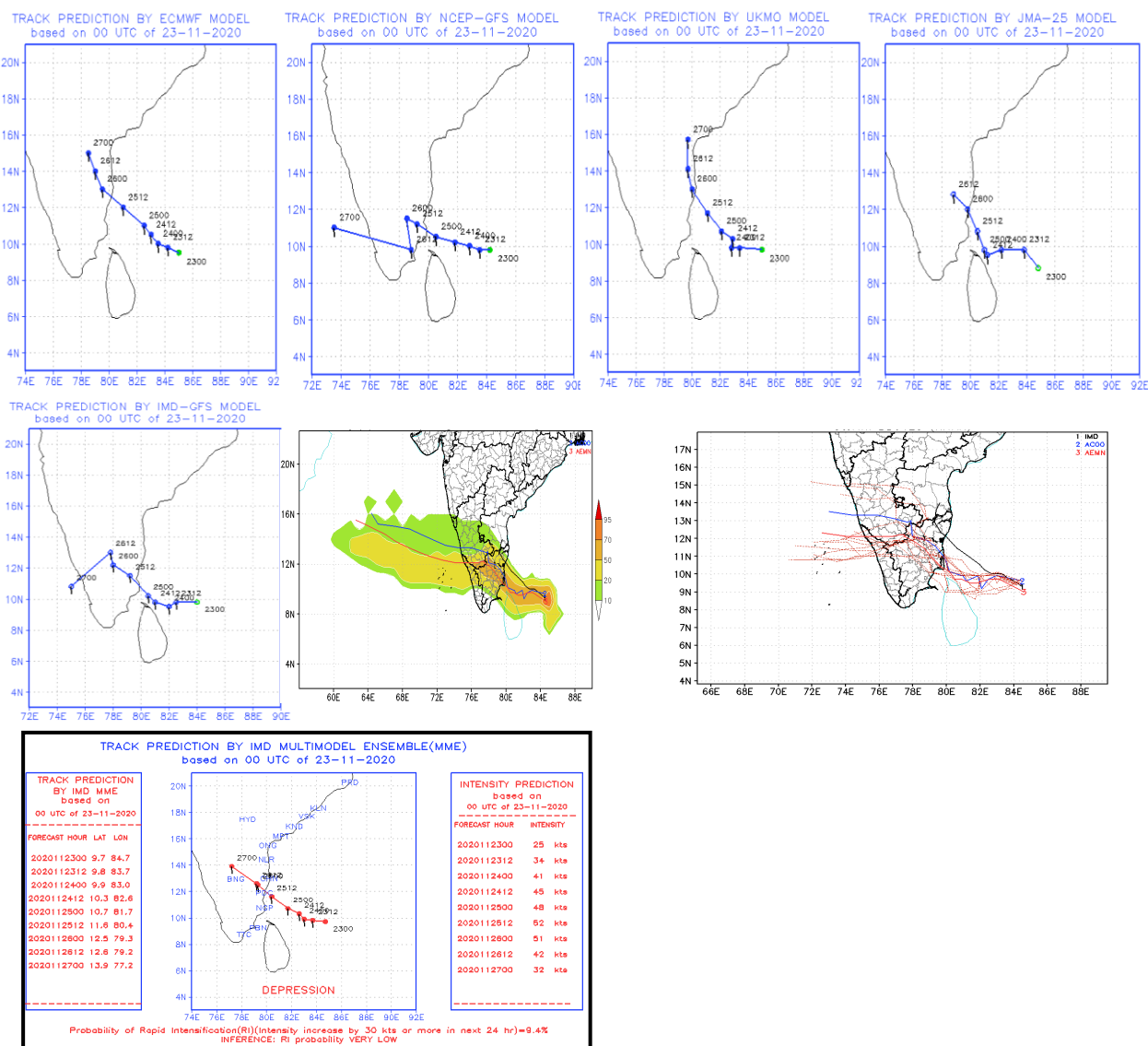


Fig. 3.5.3. (a): NWP model track forecast based on 0000 UTC of 23.11.2020

Based on initial conditions of 0000 UTC of 24th November, there was again large divergence wrt landfall point. UKMO and MME captured the northeastwards recurvature of the system. HWRF & NCEP GFS predicted it's re-emergence into Arabian Sea.

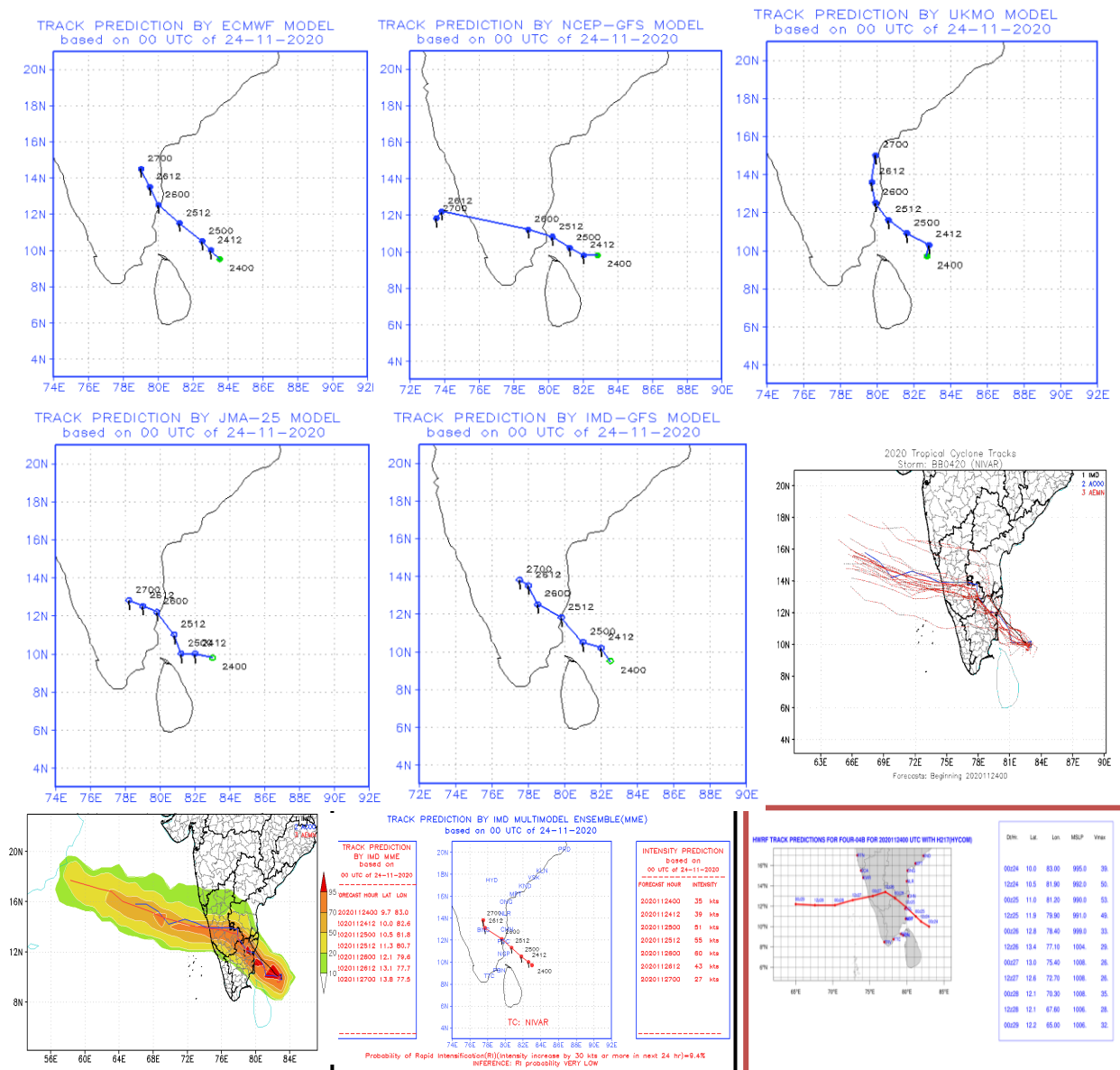


Fig. 3.5.3. (b): NWP model track forecast based on 0000 UTC of 24.11.2020

Based on initial conditions of 0000 UTC of 25th November, models were predicting landfall near 12°N. UKMO, MME, ECMWF, IMD GFS captured the northeastwards recurvature of the system. HWRF predicted it's westwards recurvature.

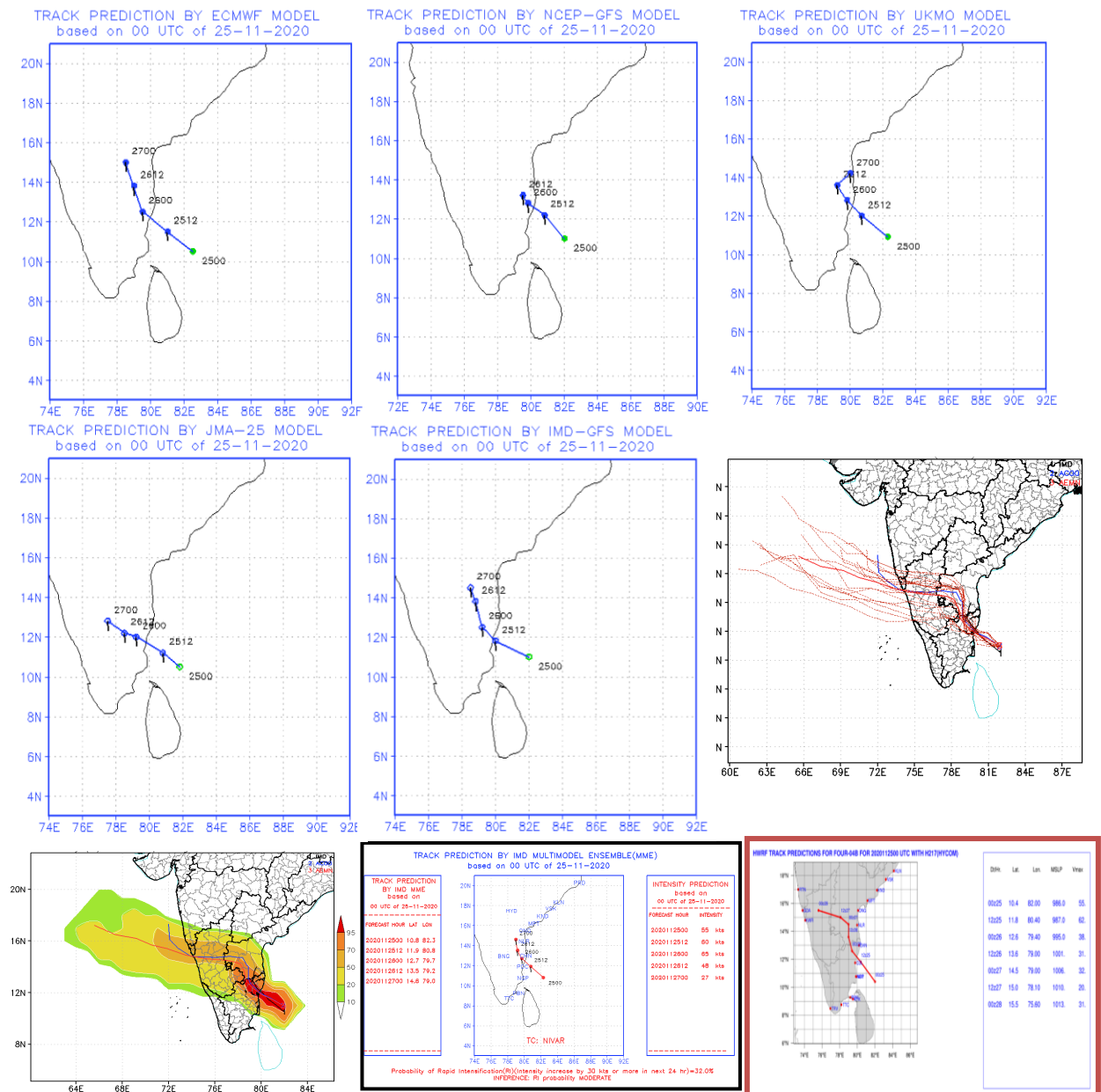


Fig. 3.5.3. (c): NWP model track forecast based on 0000 UTC of 25.11.2020

3.5.4 Errors by various NWP Models

3.5.4.1 Track forecast errors by various NWP Models

Average track forecast errors by various NWP models is presented in Table 3.5.1. For 24 hrs lead period track forecast error was the least i.r.o. MME followed by UKMO, ECMWF, NCEP GFS, JMA and HWRF. For 48 hrs lead period, the track forecast error was the least i.r.o. UKMO followed by ECMWF and MME. For 72 hours lead period, the error was the least i.r.o. ECMWF followed by UKMO and MME.

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
IMD-MME	26(5)	26(5)	29(5)	91(4)	105(3)	133(2)	113(1)
ECMWF	49(5)	61(5)	46(5)	54(4)	43(3)	52(2)	62(1)
NCEP-GFS	50(5)	67(5)	95(5)	294(4)	360(3)	401(2)	427(1)
UKMO	36(5)	46(5)	38(5)	40(4)	59(3)	67(2)	64(1)
JMA	38(5)	86(5)	126(5)	102(4)	94(3)	115(2)	110(1)
IMD-GFS	102(5)	121(5)	140(5)	184(4)	180(3)	290(2)	185(1)
HWRF	70 (11)	86 (11)	115 (9)	210 (7)	309 (5)	380 (3)	-
GEFS(CNTL)	92(6)	117(5)	145(4)	180(3)	178(3)	245(2)	178(1)
GEFS(MEAN)	74(6)	117(5)	148(4)	173(3)	182(3)	257(2)	259(1)

3.5.4. Landfall forecast errors

The landfall point and time forecast errors by IMD MME & HWRF are presented in Table 3.5.2. The landfall point error varied from 30-60 km for various lead period ranging from 18 hrs to 66 hrs. The landfall point errors varied from 15 to 75 km for various lead periods between 12 and 60 hrs. For 12 and 24 hrs lead period, the landfall time error was zero hrs.

Table-3.5.2. Landfall Point (in km) and time (in hrs) of IMD-MME & HWRF Model
((forecast time – Observed time) [-ve early +ve delay])

Lead Time	12 Hr	24 Hr	36 Hr	48 Hr	60 Hr
Landfall Point-HWRF	16	77	46	34	55
Landfall Point-MME	44	33	44	55	66
Landfall Time-HWRF	0	0	-6	-6	-12
Landfall Time-MME	2	6	3	-1	0

3.5.5. Intensity forecast errors by various NWP Models

Intensity forecast by MME for various lead periods is presented in Fig. 3.5.4 (a) and intensity prediction at the time of landfall is presented at Fig. 3.5.4 (b). MME throughout

underestimated the intensity at the time of landfall. The intensity forecasts of IMD-SCIP model and HWRF model are presented in Table 3.5.3.

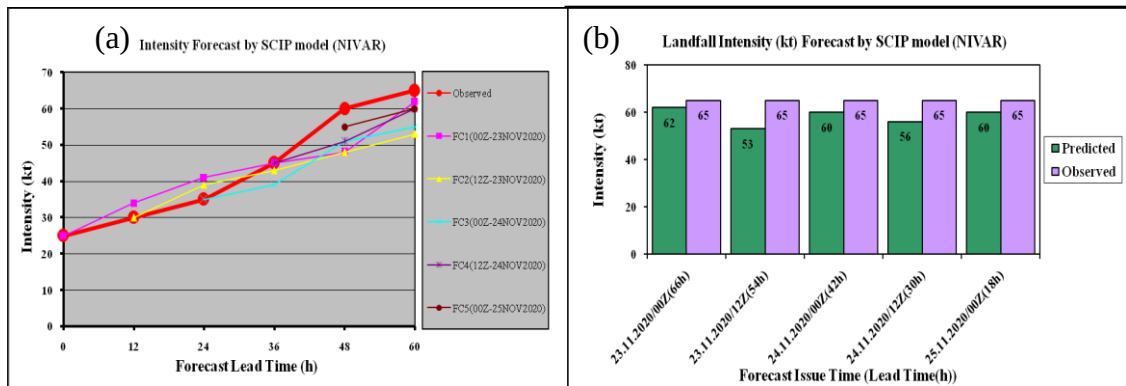


Fig. 3.5.4.: (a) SCIP Intensity Forecast Error (NIVAR) and (b) SCIP Landfall Intensity Forecast Error (NIVAR)

Figure 3.5.5 Show the intensity forecast in terms of Maximum sustained wind speed (MSW) in knots at various initial conditions.

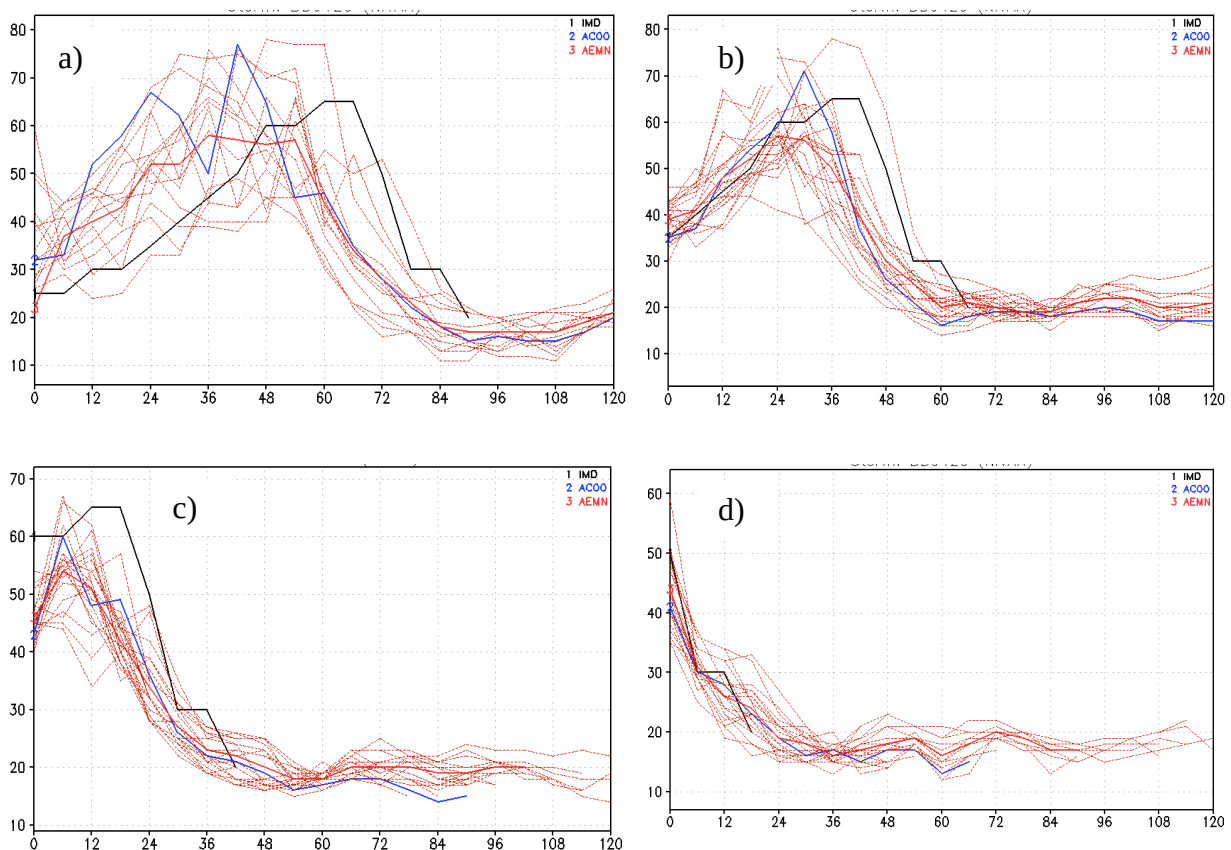


Fig. 3.5.5 Intensity in terms of MSW (knots) based on a)00UTC of 23November 2020 b) 00UTC of 24 November 2020 c)00UTC of 25November 2020 d) 00UTC of 26 November 2020.

Table-3.5.3. 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
IMD-SCIP (AAE)	5.6(5)	5.5(4)	7.3(3)	12.0(2)	3.0(1)	
IMD-HWRF (AAE)	6.6 (11)	8.4 (11)	10.8 (9)	12.1 (7)	12.6 (5)	7.7 (3)
GEFS_CNTL_AAE	5(6)	8(5)	8(4)	8(3)	6(2)	1(1)
GEFS_MEAN_AAE	4(6)	4(5)	4(4)	7(3)	10(2)	6(1)
IMD-SCIP (RMSE)	5.9	6.0	9.0	12.0	3.0	
IMD-HWRF (RMSE)	7.4 (11)	10.1(11)	13.6 (9)	16.6 (7)	18.2 (5)	8.8 (3)
GEFS_CNTL_RMSE	6(6)	9(5)	14(4)	10(3)	6(2)	1(1)
GEFS_MEAN_RMSE	4(6)	5(5)	5(4)	12(3)	10(2)	6(1)

3.6. Cyclonic Storm “Burevi” over the Bay of Bengal (30th November- 5th December 2020)

3.6.1 Prediction of Cyclogenesis [Genesis Potential Parameter (GPP) for BUREVI]

The model could predict cyclogenesis zone correctly about 144 hrs in advance (Fig. 3.6.1). 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. For a low pressure system which is having potential to develop into a CS, the Threshold value of average GPP could be ≥ 8.0 whereas for a non-developing system, the threshold value of GPP would be < 8.0 . In the present case, this product had indicated potential for intensification of the system into a Cyclonic storm based on initial condition of 00 UTC of 29th November onwards. The area average values of GPP figure are shown in Fig.3.6.2.

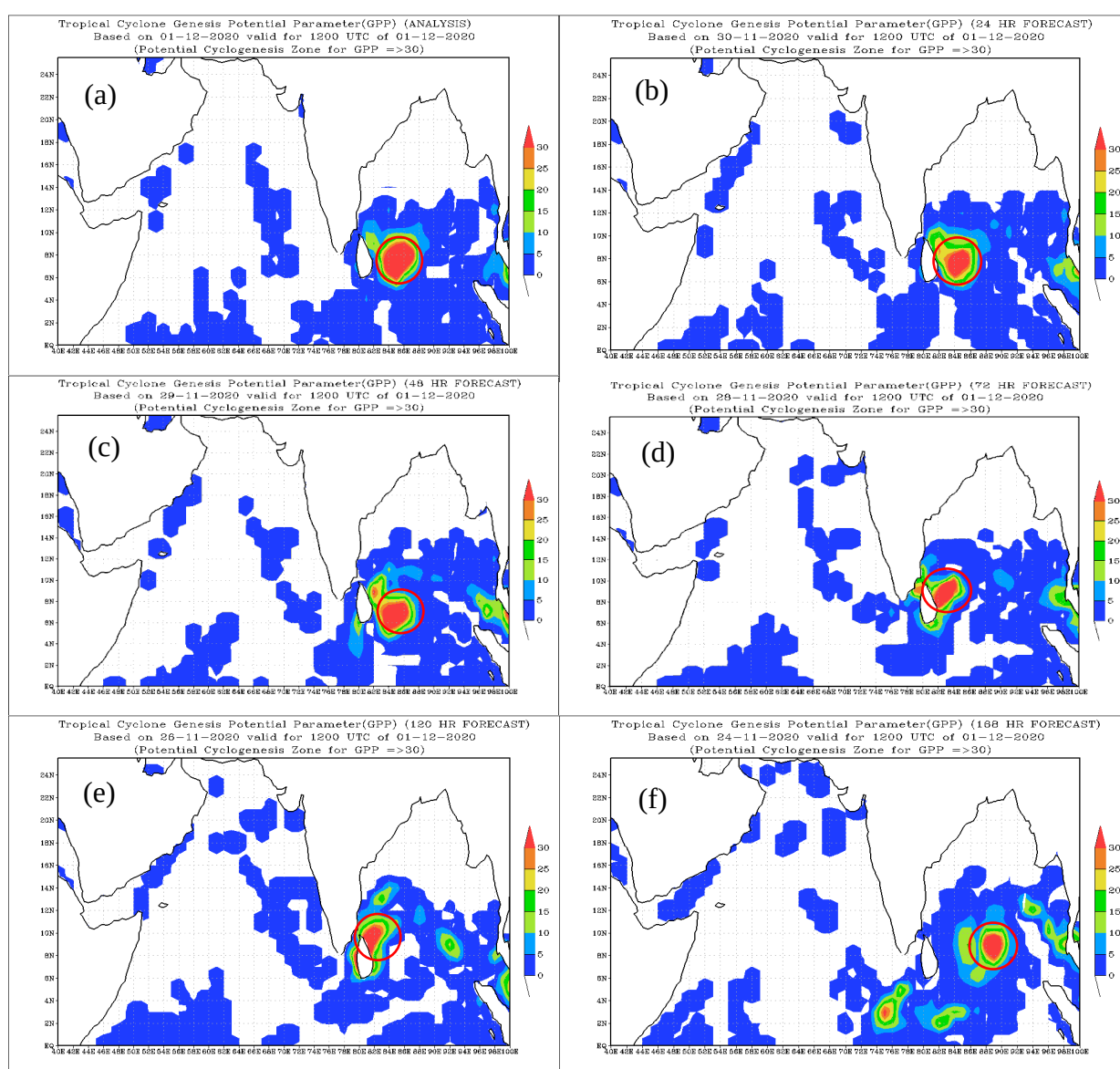


Fig.3.6.1 (a-f): Predicted zone of Cyclogenesis based on 1200 UTC from 24 November-1 December 2020

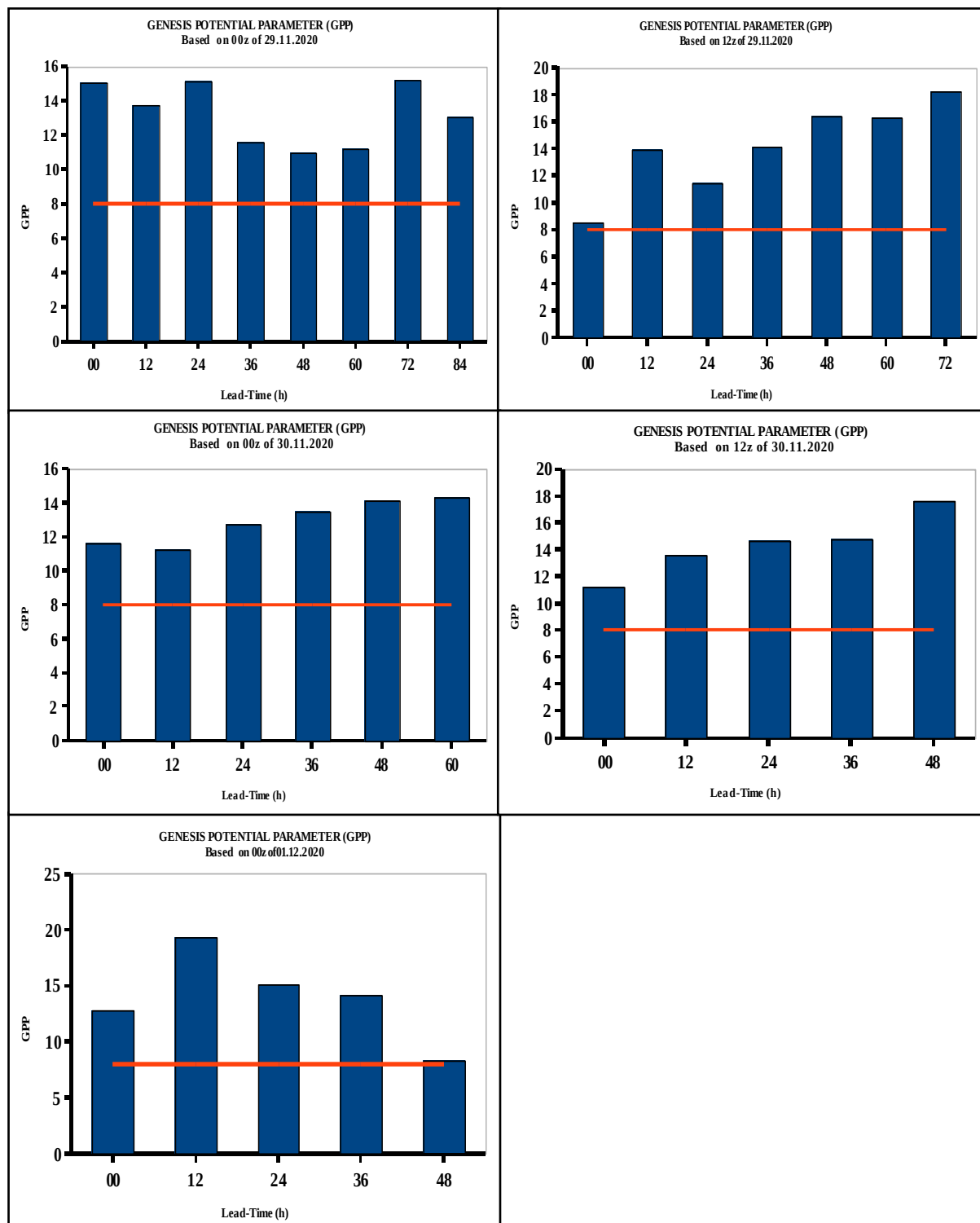


Fig. 3.6.2: Area average analysis and forecasts of GPP based on (i) 0000 UTC of 29.11.2020 (ii) 1200 UTC of 29.11.2020 (iii) 0000 UTC of 30.11.2020 (iv) 1200 UTC of 30.11.2020 (v) 0000 UTC of 01.12.2020

3.6.2 Track prediction by NWP models

Track prediction by various NWP models during 30th November to 02nd December is presented in **Fig.3.6.3**. Based on initial conditions of 0000 UTC of 30th November, most of the models indicated initial west-northwestward movement and crossing east coast of Sri Lanka over the northern part. NCEP GFS & IMD GFS models consistently indicated that after crossing Sri Lanka coast, it could re-emerge into Comorin area, maintaining the Cyclone intensity and further move westwards across south Kerala. Figure 3.6.3 show strike probability of storm passing through 65nm as well as ensemble tracks along with GFS(control i.e. AC00), ensemble mean (AEMN) and IMD tracks based on different initial conditions.

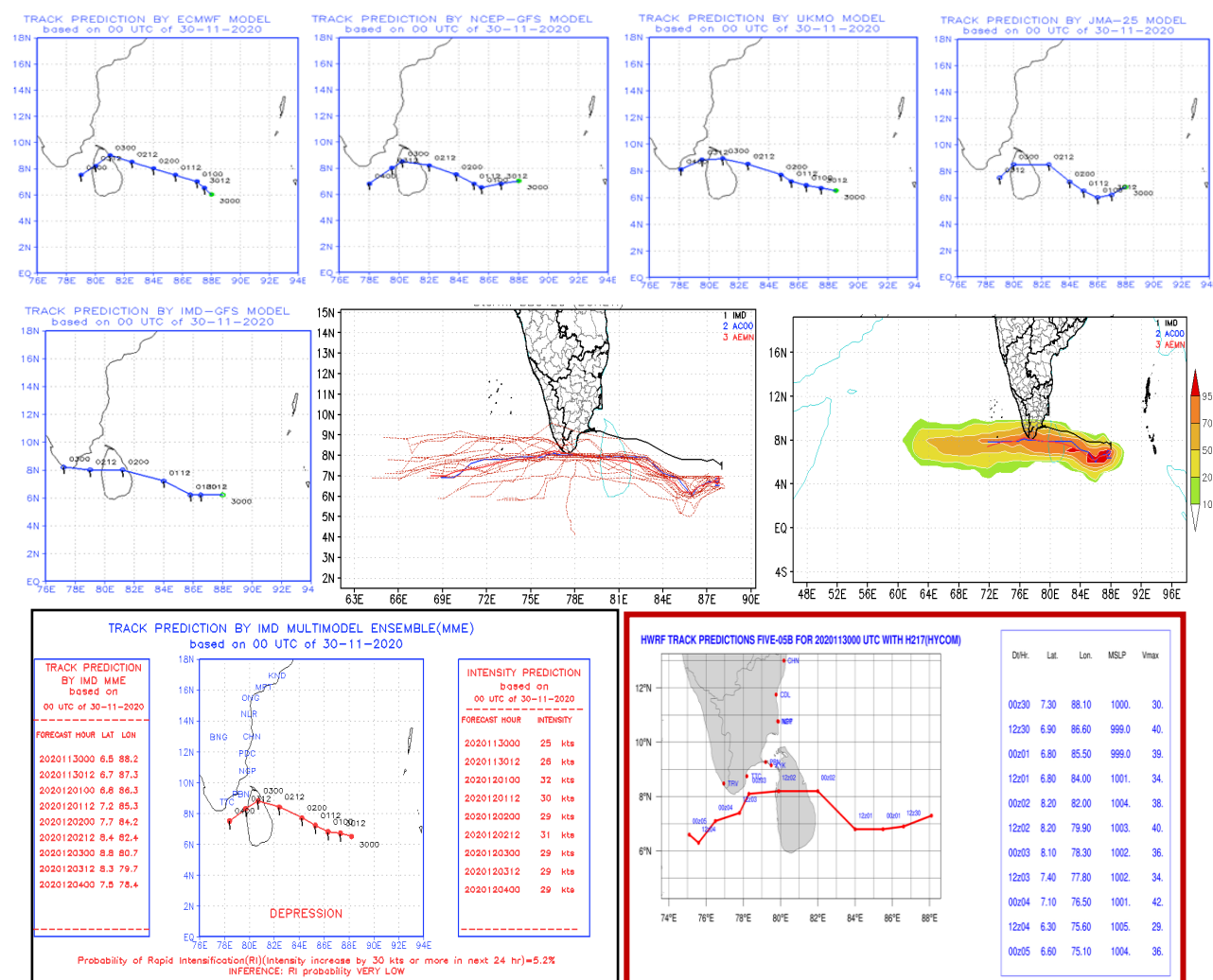


Fig. 3.6.3 (a): NWP model track forecast based on 0000 UTC of 30.11.2020

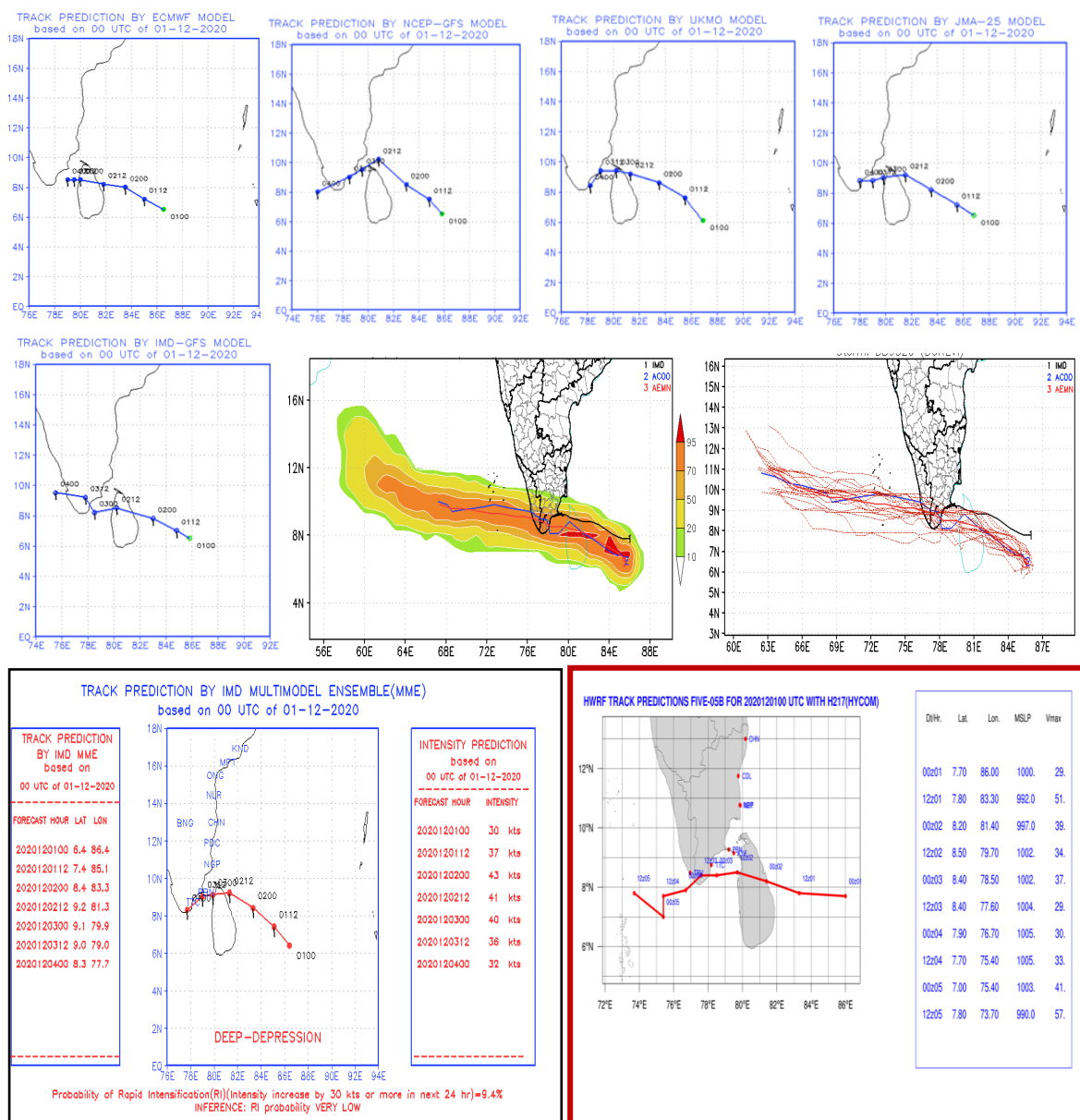


Fig. 3.6.3 (b): NWP model track forecast based on 0000 UTC of 01.12.2020

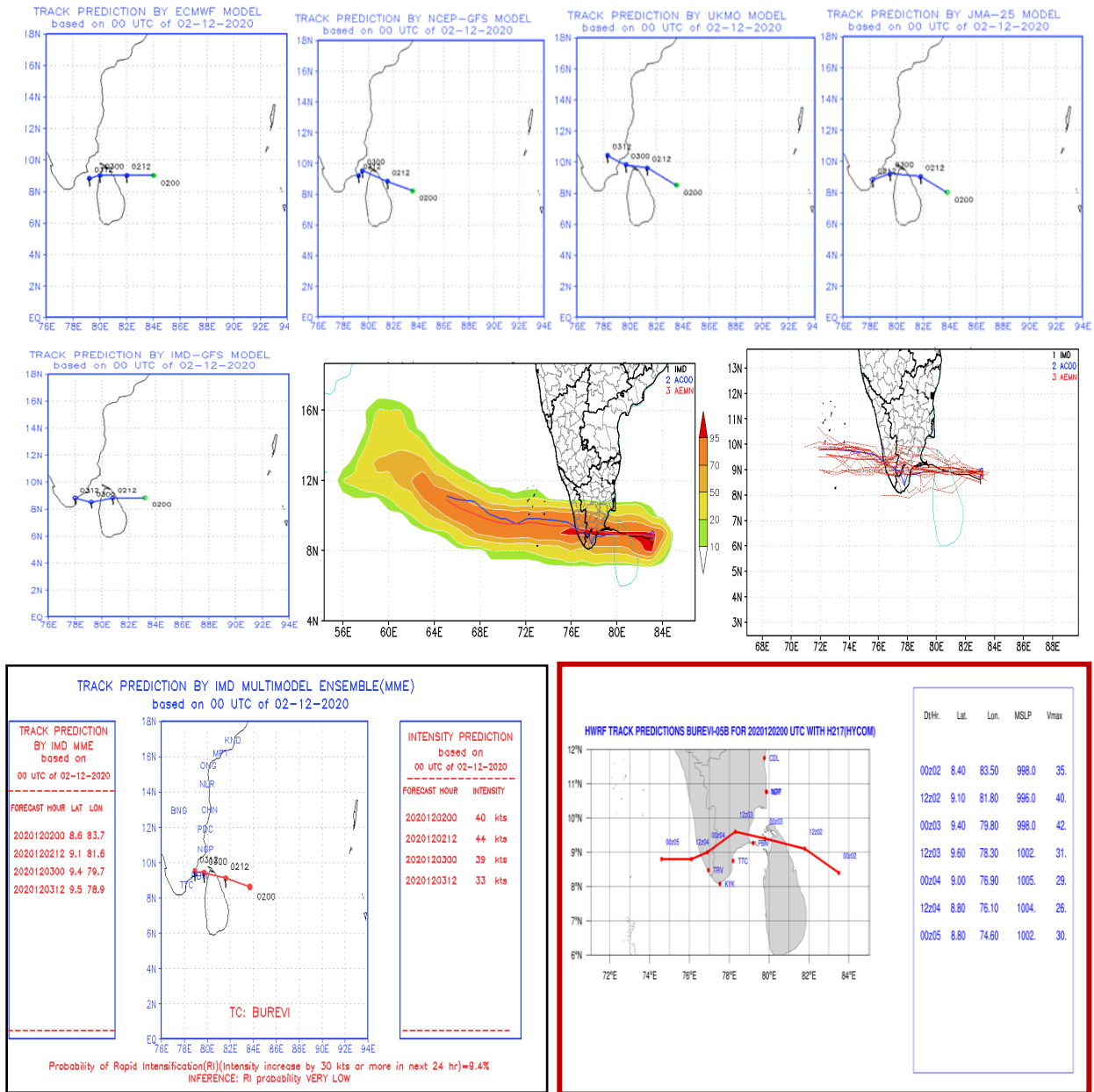


Fig. 3.6.3 (c): NWP model track forecast based on 0000 UTC of 02.12.2020

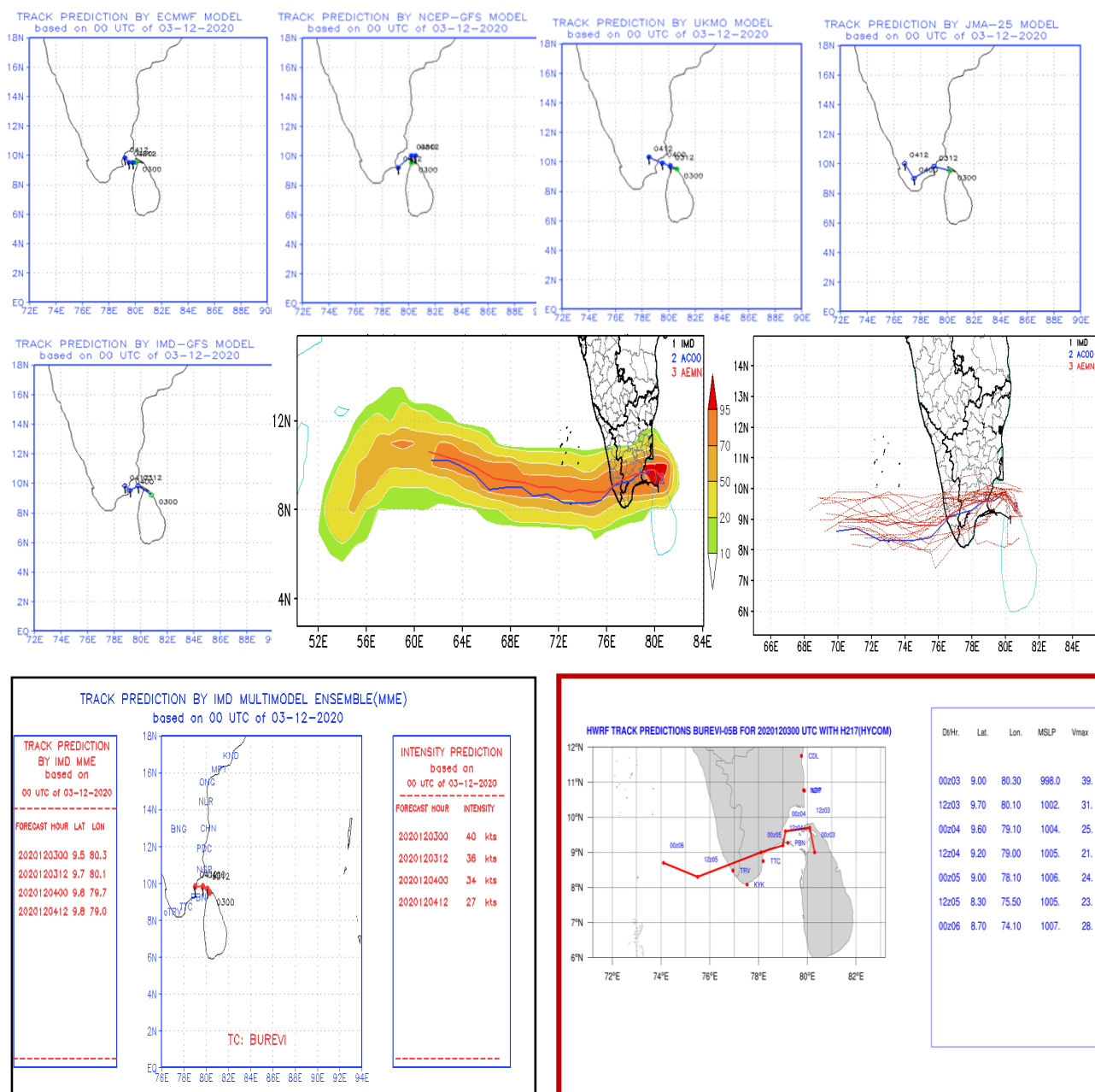


Fig. 3.6.3 (d): NWP model track forecast based on 0000 UTC of 03.12.2020

It may also be noted that HWRF was not consistent in its predictions on a day-to-day basis. Initially it predicted a west-southwestward movement across Comorin area after the first landfall and later as moving across interior Tamil Nadu & South Kerala and re-emerging over Lakshadweep area.

Thus it may be noted that the numerical models could not clearly indicate the unusually prolonged stagnation underneath the COL region in advance. Also, since the MME

solutions do not work for Islands / land locked regions as in the present case, the in-situ weakening of the system over the region also could not be predicted by MME.

3.6.3 Errors by various NWP Models

3.6.3.1 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 3.6.1**. From the verification of the forecast guidance available from various NWP models, it is found that the average track forecast errors of MME model was minimum for 24 and 48 hr and 72 hours forecast. HWRF forecasts fared well next to MME only for the 12 hour period. Performance of NEPS, NCUM (G) & ECMWF were generally better following MME for the 24, 48 & 72 hours forecast.

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	108h	120h
IMD-MME	84(7)	76(7)	71(7)	73(4)	53(3)	76(3)	120(1)	179(1)	--	--
ECMWF	96(7)	88(7)	101(7)	123(4)	116(3)	82(3)	149(1)	183(1)	--	--
NCEP-GFS	81(7)	94(7)	103(7)	79(4)	58(3)	165(3)	140(1)	264(1)	--	--
UKMO	93(7)	94(7)	101(7)	103(4)	74(3)	80(3)	62(1)	124(1)	--	--
JMA	108(7)	107(7)	146(7)	125(4)	61(3)	83(3)	189(1)	**	--	--
IMD-GFS	109(7)	101(7)	156(7)	223(4)	235(3)	327(3)	**	**	--	--
HWRF	53 (19)	87 (17)	104 (15)	105 (13)	180 (11)	229 (9)	286 (7)	321 (4)	409 (2)	423 (1)
NCUMG	107 (8)	86 (8)	91 (7)	93 (4)	133 (6)	130 (7)	177 (7)	160 (7)	213 (7)	160 (6)
NCUMR	93 (9)	86 (8)	128 (9)	159 (10)	177 (8)	190 (8)				
NEPSG	94 (10)	76 (10)	73 (10)	79 (10)	80 (10)	113 (10)	120 (10)	155 (10)	178 (9)	130 (7)
GEFS_CNTL	115 (10)	104 (9)	144 (8)	243 (7)	330 (6)	468 (5)	532 (4)	660 (3)	710 (2)	762 (1)
GEFS_MEAN	104 (10)	89 (9)	132 (8)	233 (7)	332 (6)	426 (5)	511 (4)	619 (3)	696 (2)	782 (1)

3.6.3.2 Landfall forecast errors by MME Model

Fig.3.6.4 shows the landfall forecast point & Time error by MME, with respect to the first and second landfall over east coast of Sri Lanka and south Tamil Nadu respectively.

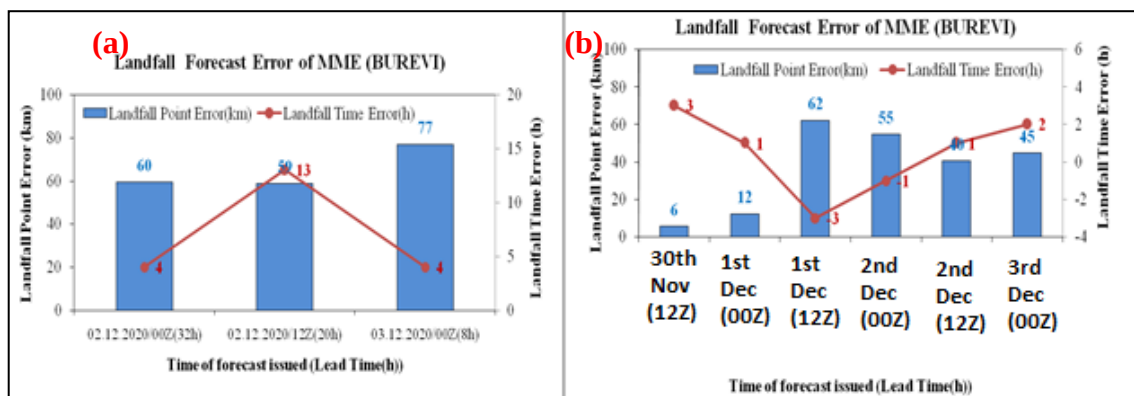


Fig. 3.6.5: MME Landfall Point and Time Forecast Error (BUREVI) (a) Sri Lanka (b) Tamil Nadu((forecast time – Observed time) [-ve early +ve delay])

3.6.3.3 Intensity forecast errors by various NWP Models

The intensity forecasts of IMD-SCIP model and HWRF model are shown in Table 3.6.2. The intensity error was very high with NCUM (R) followed by HWRF model. Performance of Intensity prediction by SCIP model is presented in **Fig. 3.6.5(a) & (b)**.

a. Intensity prediction by SCIP Model

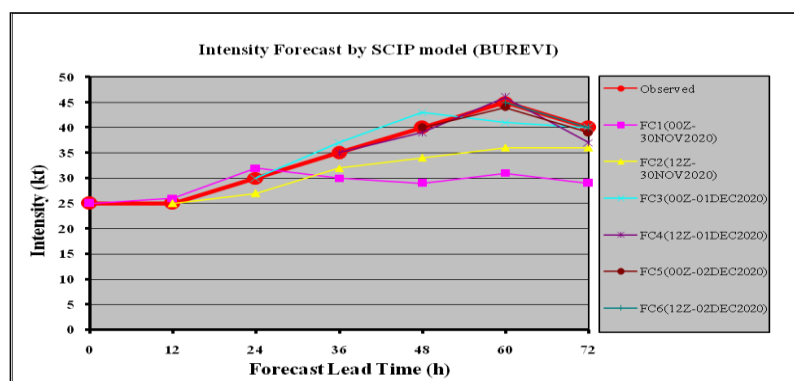


Fig. 3.6.6(a): SCIP Intensity Forecast Error (BUREVI)

b. Landfall intensity predicted by SCIP Model

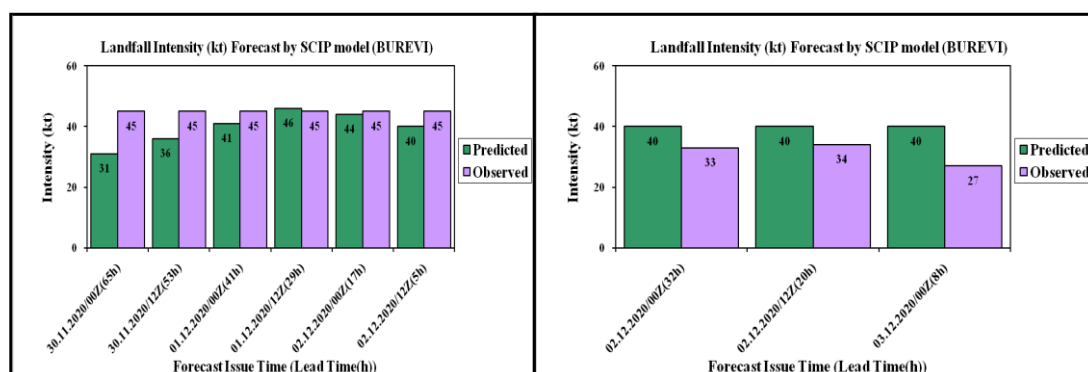


Fig. 3.6.6(b): SCIP Landfall Intensity Forecast Error (BUREVI) (i) Sri Lanka (ii) Tamil Nadu

(c) GEFS model

Figure Fig. 3.3.5: (c) Show the intensity forecast in terms of Maximum sustained wind speed (MSW) in knots at various initial conditions.

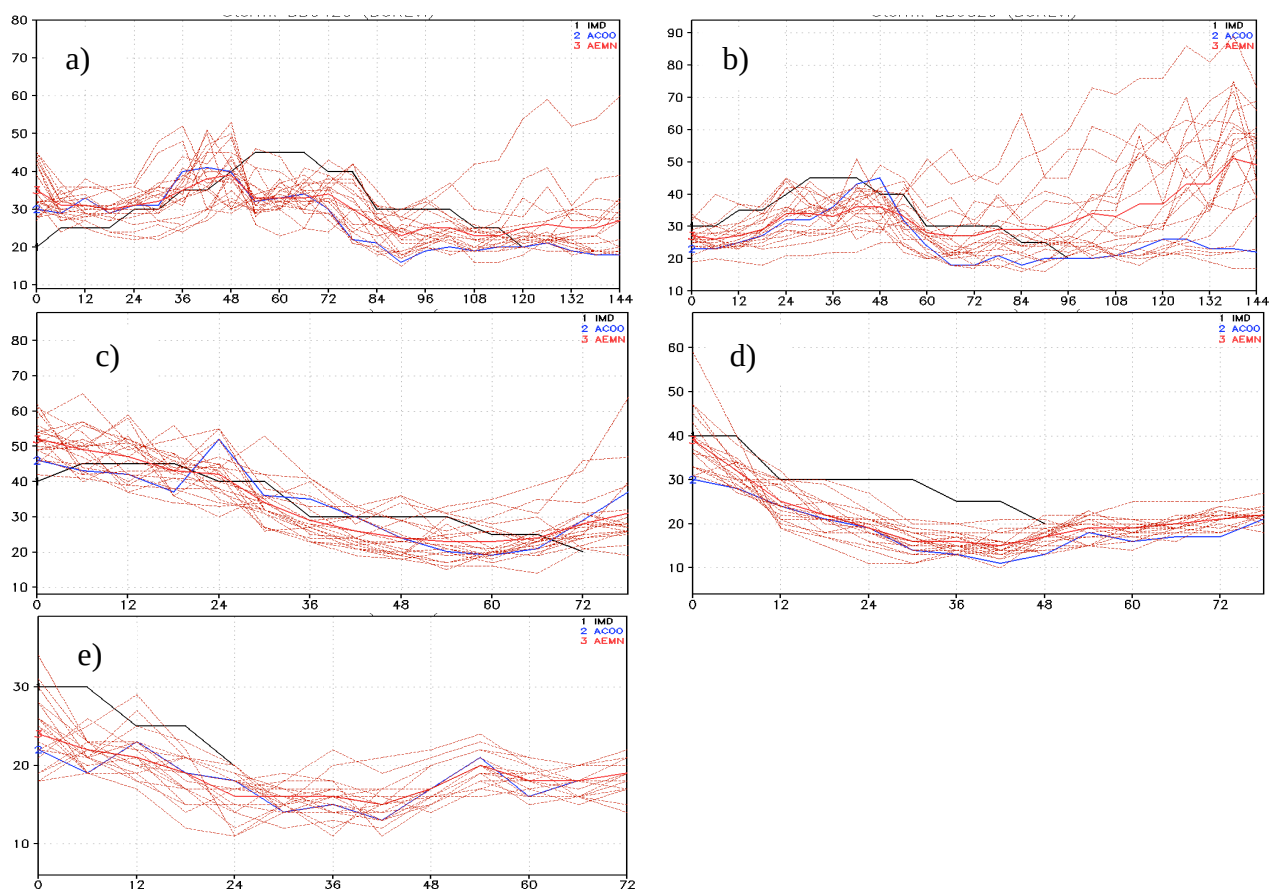


Fig. 3.6.7 Intensity in terms of MSW (knots) based on a) 00UTC of 30 November 2020 b) 00UTC of 01 December 2020 c) 00UTC of 02 December 2020 d) 00UTC of 03 December 2020 e) 00UTC of 04 December 2020.

Table-3.6.2 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	84 Hr	96 Hr	108 Hr	120 Hr
IMD-SCIP (AAE)	1.3(6)	2.0(5)	4.5(4)	6.7(3)	9.0(2)	11.0(1)				
HWRF (AAE)	7.8 (19)	4.4 (17)	4.5 (15)	5.0 (13)	4.5 (11)	5.0 (9)	6.1 (7)	12.1 (4)	12.7 (2)	16.0 (1)
GFS(AAE)	3.5	4.0	5.0	5.5	5.5	4.8	5.0	8.5	4.0	5.0
NCUM(R) (AAE)	12	06	09	08	09	5.5				
NCUM(G) (AAE)	05	05	04	04	07	10	06	04	05	07
GEFS_CNTL(AAE)	5(10)	7(9)	7(8)	7(7)	7(6)	8(5)	7(4)	6(3)	4(2)	0(1)
GEFS_MEAN(AAE)	4(10)	5(9)	6(8)	5(7)	5(6)	5(5)	3(4)	5(3)	5(2)	5(1)
NEPS(G)	04	04	03	03	04	05	05	4.5	05	06
IMD-SCIP (RMSE)	1.6	2.2	4.6	10.0	10.3	11.0				
HWRF (RMSE)	9.8 (19)	5.1 (17)	5.4 (15)	6.5 (13)	5.3 (11)	6.4 (9)	7.2 (7)	11.9 (4)	18.7 (2)	16.0 (1)
GFS(RMSE)	6.0	8.5	7.5	7.0	7.5	8.5	7.5	7.5	4.5	-

GEFS_CNTL(RMSE)	6(10)	8(9)	8(8)	8(7)	8(6)	9(5)	8(4)	8(3)	4(2)	0(1)
GEFS_MEAN(RMSE)	5(10)	6(9)	7(8)	6(7)	7(6)	5(5)	4(4)	7(3)	5(2)	5(1)

3.6.4.4 Track, Intensity and Landfall Forecast Errors by GEFS model:

The average track forecast errors (Direct Position Error) in km at different lead period (hrs) for GEFS (Control (CNTL) and Ensemble mean (GEFS_MEAN) models are presented in Table 3.3.1. The Track error is less in GEFS_MEAN than control. Table 3.3.5 represents intensity forecast errors in knots. The Average absolute errors (AAE) and Root Mean Square (RMSE) errors in kts from GEFS model are given in Table 3.3.2. Table 3.3.7 and Table 3.3.8 gives the landfall errors in time and km.

Table 3.6.4 Average Intensity Forecast Errors in knots (Number of forecasts verified is given in the parentheses). Negative sign indicates underestimation of intensity and vice versa

Lead Time	12H	24H	36H	48H	60H	72H	84H	96H	108H	120H
CNTL	3(10)	4(9)	5(8)	5(7)	5(6)	5(5)	5(4)	6(3)	4(2)	0(1)
ENS_MEAN	2(10)	5(9)	6(8)	5(7)	5(6)	1(5)	-1(4)	-2(3)	-3(2)	-5(1)

Table 3.6.6 Landfall time forecast errors (hour) at different lead time (hr) ('+' indicates delay landfall, '-' indicates early landfall)

Forecast Lead Time (h)	63h 00Z30Nov	39h 00Z01Dec	15h 00Z02Dec
CNTL	-17	-11	+1
ENS_MEAN	-17	-11	-5

Table 3.6.7 Landfall point forecast errors (km) of NWP Models at different lead time (hour)

Forecast Lead Time (h)	63h 00Z30Nov	39h 00Z01Dec	15h 00Z02Dec
CNTL	113	89	125
ENS_MEAN	116	71	32

CHAPTER-IV
PERFORMANCE OF RSMC, NEW DELHI
IN TRACK AND INTENSITY PREDICTION OF CYCLONES DURING 2020

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 2020. It issued 3 hourly forecast and warning/advisory bulletins to various national and international disaster management agencies including National Disaster Management Authority (NDMA), 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 and predicted cyclogenesis, track, intensity and structure of cyclones. The genesis forecast in probabilistic terms 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, warnings are issued regularly. The above structured track and intensity forecasts were issued from the stage of deep depression onwards. However, from 2019 onwards, the quantitative track & intensity forecast for +12, +24, +36, +48, +60, +72 hrs. lead period is being 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 in .png format. These products were also made available on GIS platform from severe cyclonic storm "Nisarga" in June, 2020. The storm surge guidance was provided as and when required to the member countries of WMO/ESCAP Panel based on AD-CIRC model run by INCOIS under the Ministry of Earth Sciences (MoES). 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 2020 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 2020

Bulletins issued during 'AMPHAN'

Bulletins for national disaster management agencies	45
Bulletin for WMO/ESCAP Panel counties	
(Special Tropical Weather Outlook and Tropical Cyclone Advisory)	45
Tropical cyclone advisory for international civil aviation	22

Bulletins issued during 'NISARGA'

Bulletins for national disaster management agencies	24
Bulletin for WMO/ESCAP Panel counties	
(Special Tropical Weather Outlook and Tropical Cyclone Advisory)	24
Tropical cyclone advisory for international civil aviation	8

Bulletins issued during 'GATI'

Bulletins for national disaster management agencies	17
Bulletin for WMO/ESCAP Panel counties	
(Special Tropical Weather Outlook and Tropical Cyclone Advisory)	18
Tropical cyclone advisory for international civil aviation	08

Bulletins issued during 'NIVAR'

Bulletins for national disaster management agencies	21
Bulletin for WMO/ESCAP Panel counties	
(Special Tropical Weather Outlook and Tropical Cyclone Advisory)	35
Tropical cyclone advisory for international civil aviation	13

Bulletins issued during 'BUREVI'

Bulletins for national disaster management agencies	:	36
Bulletin for WMO/ESCAP Panel counties		
(Special Tropical Weather Outlook and Tropical Cyclone Advisory)	:	36
Tropical cyclone advisory for international civil aviation	:	11

Bulletins issued for all cyclonic storm during 2020

Bulletins for national disaster management agencies	:	143
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RSMC bulletin for WMO/ESCAP Panel member countries

(Special Tropical Weather Outlook and Tropical Cyclone Advisory) : 158

TCAC bulletin for international civil aviation : 66

***Bulletins issued for all cyclonic disturbances (depression and above) during 2020**

Bulletins for national disaster management agencies : 197

RSMC bulletin for WMO/ESCAP Panel member countries

(Special Tropical Weather Outlook and Tropical Cyclone Advisory) : 202

TCAC bulletin for international civil aviation : 66

The number of bulletins issued during 2009-2020 for all cyclones over the NIO is shown in Fig.4.1.1 for comparison.

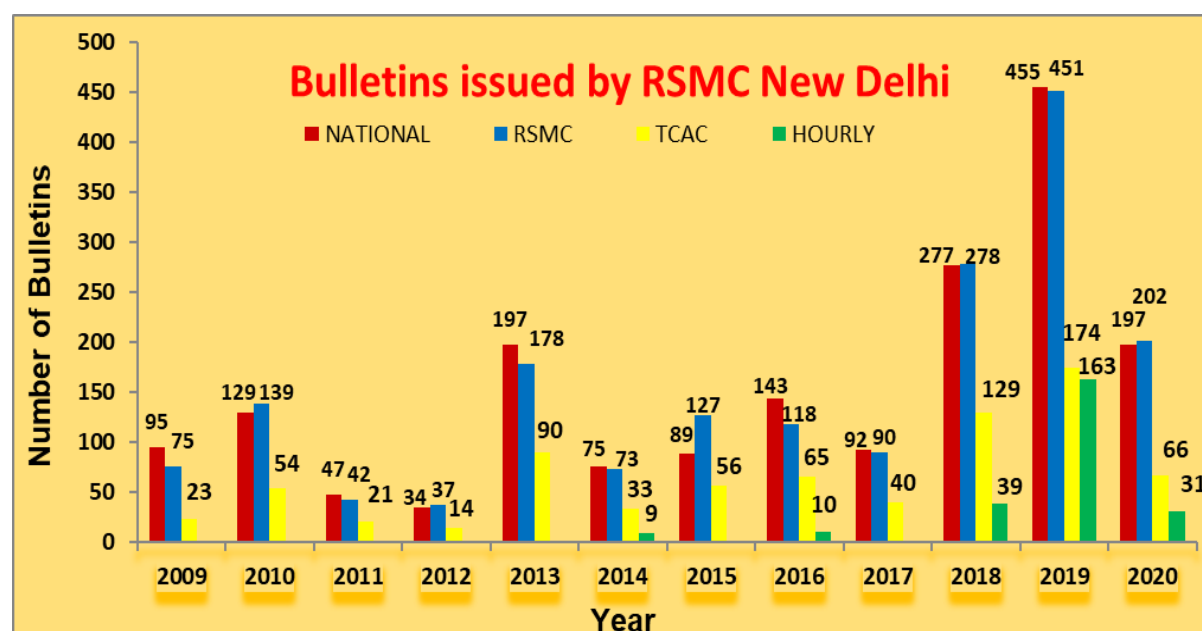


Fig 4.2.1: Total Number of bulletins issued by RSMC, New Delhi for all cyclonic disturbances during 2009-2020

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 2020 is described in following sections:

4.3.1 Super Cyclonic Storm “AMPHAN” over the Bay of Bengal (16-21 May)

4.3.1.1 Genesis Forecast

- The system was monitored since 23rd April about three weeks prior to the formation of Low Pressure Area over the southeast BoB on 13th May. A Low Pressure Area formed over south Andaman Sea and adjoining southeast Bay of Bengal on 1st May. It meandered over the region for next 5 days and became less marked on 6th. However, associated cyclonic circulation persisted over the region till 12th. Continuous watch of this circulation was maintained.
- In the extended range outlook issued on 7th May, cyclogenesis (formation of Depression) was predicted with low probability in the later part of week during 8th-14th May 2020. It was also predicted that the system would intensify further and move initially north-northwestwards and recurve north-northeastwards thereafter towards north BoB.
- In the Tropical Weather Outlook issued on 9th May, it was indicated that a Low Pressure Area would form over the region on 13th May (96 hours prior to formation of the system) under the influence of the remnant cyclonic circulation persisting over the region during 6th-12th.
- In the Tropical Weather Outlook issued on 11th May, it was indicated that cyclogenesis (formation of depression) would occur around 16th May (48 hours prior to formation of the Low Pressure Area and 120 hours prior to formation of depression) over the BoB. The Low pressure area formed on 13th May and concentrated into a Depression on 16th May morning.

4.3.1.2 Track, Intensity and Landfall Forecast

- First information was provided in the **extended range outlook issued on 7th May (about 6 days prior to formation of LPA, 9 days prior to formation of depression and 13 days prior to Landfall)** indicated that the system would intensify into a cyclonic storm and move initially northwestwards and recurve north-northeastwards towards north BoB
- In the **Tropical Weather Outlook, Press release and inforamatory message to the Government of India issued on 13th April (on the day of development of LPA, 3 days prior to formation of depression and 7 days prior to Landfall)**, it was indicated that the system would intensify into a cyclonic storm by 16th evening and would move initially northwestwards till 17th and then recurve north-northeastwards towards north BoB.
- Actually, the depression formed in the morning (0000 UTC) of 16th, cyclonic storm in the evening (1200 UTC) of 16th and the system moved north-northwestwards till 17th evening (1200 UTC) followed by north-northeastward recurvature thereafter and crossed West Bengal coast on 20th Afternoon.
- **In the first bulletin issued at 0845 IST of 16th May (104 hrs prior to landfall)** with the formation of Depression, it was indicated that the system would intensify into a cyclonic storm and will move north-northwestwards till 17th May followed by

north-northeastward re-curvature towards West Bengal coast during 18th-20th May and cross West Bengal coast with maximum sustained wind speed of 155-165 kmph gusting to 180 kmph.

- In the bulletin issued at 1645 hrs IST of 16th May (24 hrs prior to rapid intensification), rapid intensification of the system was predicted and the system rapidly intensified from 17th afternoon onwards.
- In the bulletin issued at 0845 hrs IST of 17th May (80 hrs prior to landfall), it was precisely mentioned that the system would cross West Bengal-Bangladesh coasts between Sagar Island (West Bengal) and Hatiya Islands (Bangladesh coast) during afternoon to evening of 20th May with maximum sustained wind speed of 155-165 kmph gusting to 185 kmph. The predicted track indicated Landfall across Sunderbans on 20th Afternoon.
- Observed & forecast track based on 0600 UTC of 17th May, 0300 UTC of 18th May and 0300 UTC of 19th May about 84, 60 & 36 hrs prior to landfall respectively of SuCS Amphan indicating accurate track, landfall and intensity prediction is presented in **Fig.4.3.1 (a-c)**. It also indicates the consistency in the forecast track & intensity of the Cyclone.
- IMD continuously predicted since 16th May that Amphan will cross West Bengal coast as a very severe cyclonic storm (VSCS) with wind speed of 155-165 kmph gusting to 180 kmph on 20th May.

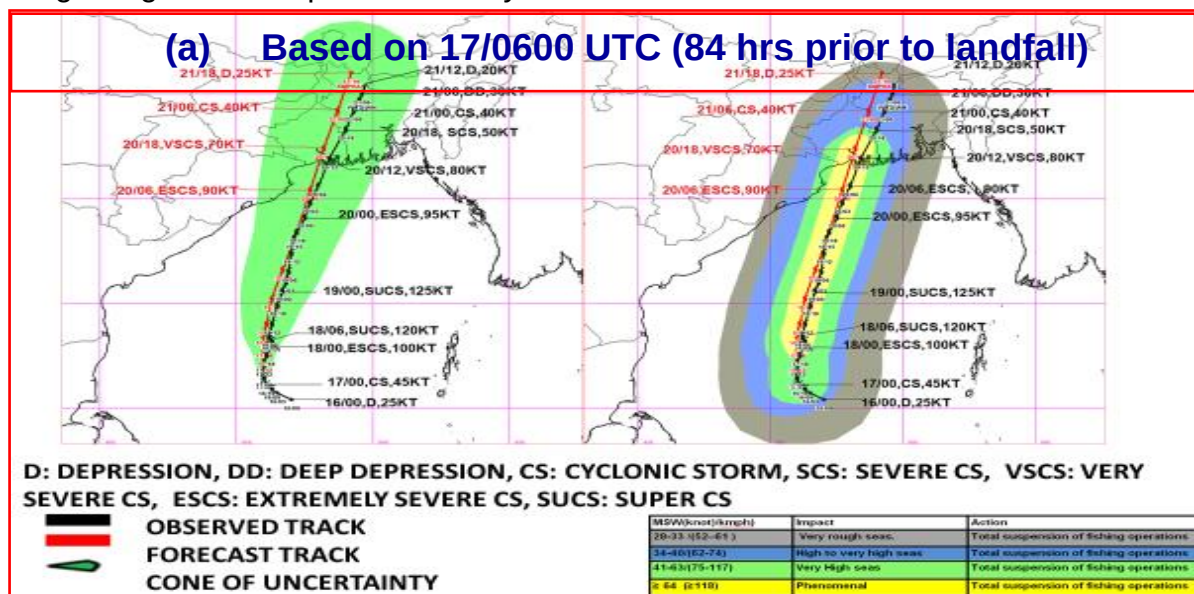


Fig.4.3.1.1(a): Observed and forecast track along with cone of uncertainty and quadrant wind distribution based on 0600 UTC of 17th May (84 hrs prior to landfall) of SuCS AMPHAN indicating accuracy in landfall, track & intensity predictions

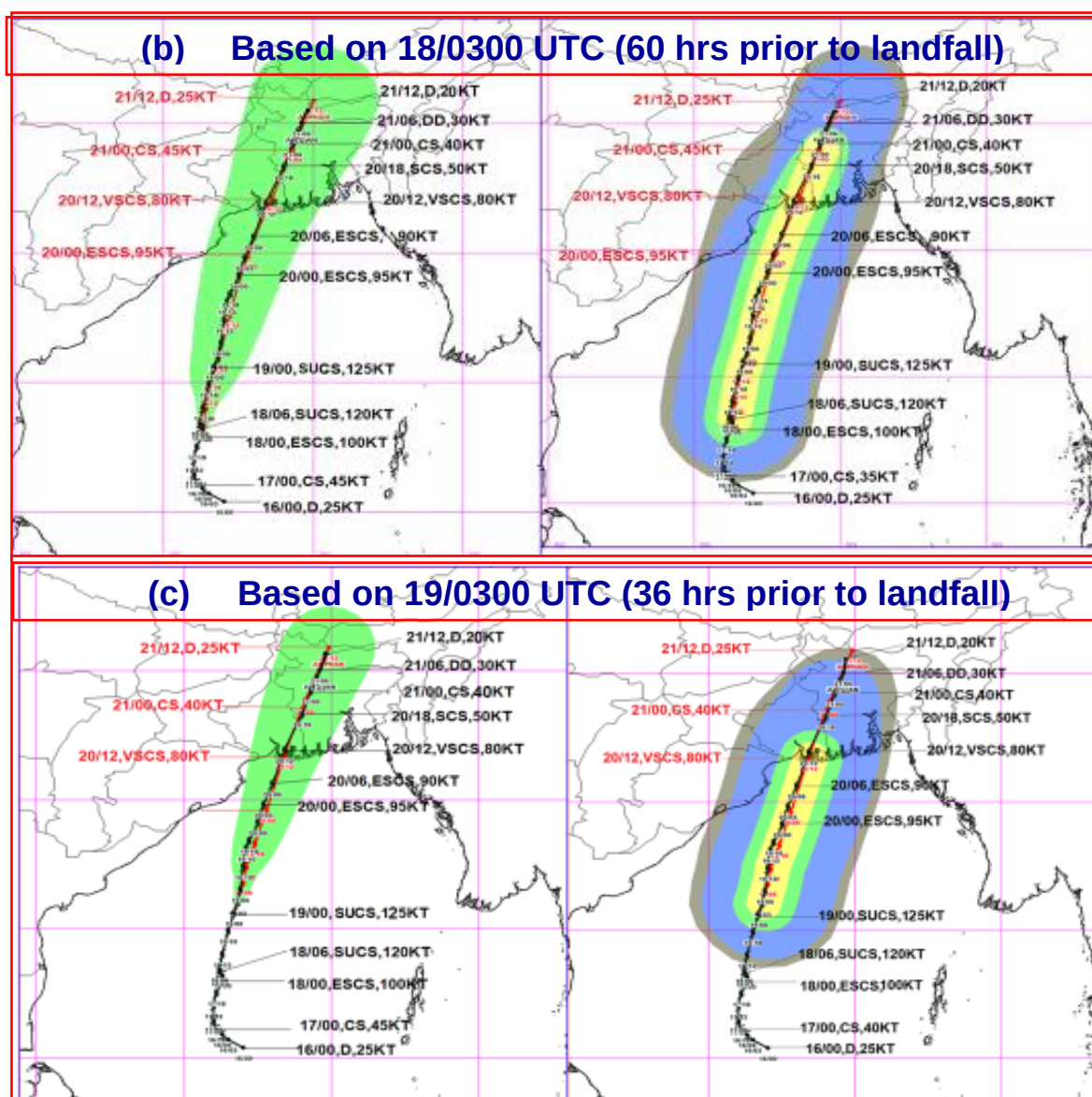


Fig. 4.3.1.1(b) &(c): Observed and forecast track alongwith cone of uncertainty and quadrant wind distribution based on (b) 0300 UTC of 18th May (60 hours prior to landfall) and (c) 0300 UTC of 19th May (36 hours prior to landfall) of SuCS AMPHAN indicating accuracy in landfall, track & intensity predictions

4.3.1.3 Landfall Forecast Error

The landfall point and time Forecast errors compared to long period average (LPA) errors during 2015-19 are presented in Table 4.3.1.1 and Fig. 4.3.1.2 (a-b).

- The landfall point forecast errors for 24, 48 and 72 hrs lead period were 5.5, 11.0, and 35.2 km respectively against the LPA errors of 44.7, 69.4 and 109.3 km during 2015-19 respectively (Fig. 4.3.1.2a).

- The landfall time forecast errors for 24, 48 and 72 hrs lead period were 0.5, 0, and 2.0 hours respectively against the LPA errors of 3.0, 5.4 and 8.6 hours during 2015-19 respectively (Fig. 4.3.1.2b).
- For all lead periods, the landfall errors were exceptionally less than the LPA errors during 2015-19. Considering the Eye (Centre) Diameter of Cyclone ‘Amphan’ as 15 km at the time of landfall, there was almost zero error in landfall time and point forecast upto 48 hrs lead period.

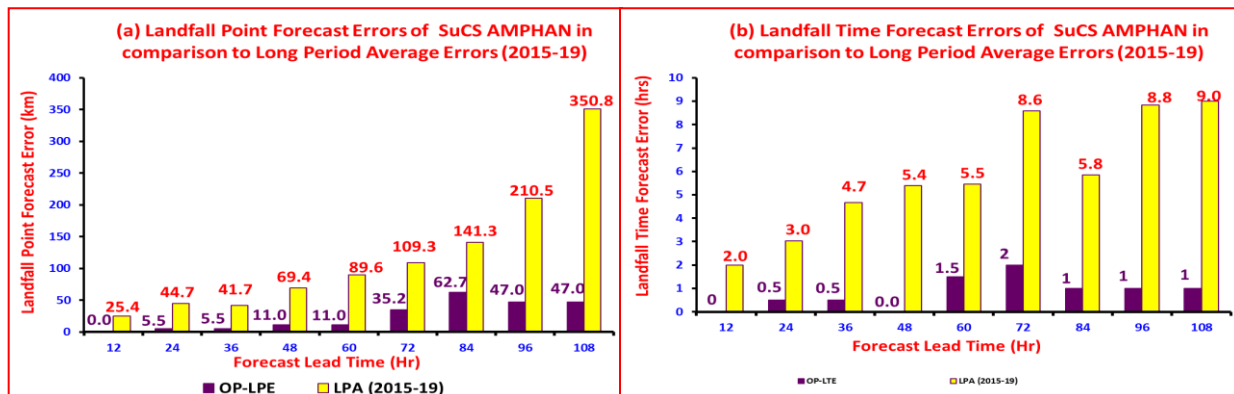


Fig. 4.3.1.2: Landfall (a) point and (b) time forecast errors of SUCS AMPHAN as compared to long period average (2015-19)

Table 4.3.1.1: Landfall point and time forecast errors of SuCS Amphan as compared to long period average (LPA) errors during 2015-19

Lead Period (hrs)	Base Time	Landfall Point ($^{\circ}$ N/ $^{\circ}$ E)		Landfall Time (hours)		Operational Error		LPA error (2015-19)	
		Forecast	Actual	Forecast	Actual	LPE (km)	LTE (hours)	LPE (km)	LTE (hours)
12	20/00	21.65/88.30	21.65/88.30	20/1100	20/1100	0.0	0.0	25.4	2.0
24	19/12	21.70/88.30	21.65/88.30	20/1130	20/1100	5.5	+0.5	44.7	3.0
36	19/00	21.65/88.35	21.65/88.30	20/1130	20/1100	5.5	+0.5	41.7	4.7
48	18/12	21.65/88.40	21.65/88.30	20/1100	20/1100	11.0	0.0	69.4	5.4
60	18/00	21.65/88.40	21.65/88.30	20/0930	20/1100	11.0	-1.5	89.6	5.5
72	17/12	21.90/88.10	21.65/88.30	20/1300	20/1100	35.2	+2.0	109.3	8.6
84	17/00	21.63/88.87	21.65/88.30	20/1200	20/1100	62.7	+1.0	141.3	5.8
96	16/12	21.80/87.90	21.65/88.30	20/1000	20/1100	47.0	-1.0	210.5	8.8
108	16/00	21.80/87.90	21.65/88.30	20/1200	20/1100	47.0	+1.0	350.8	9.0

“+” indicates delayed prediction and “-” indicates early prediction

4.3.1.4 Track Forecast Error

The track forecast errors (Forecast position – Actual position of Cyclone centre) and skill as compared to Climatological and Persistence forecast are presented in Table 4.3.2 and Fig. 4.3.3 (a-b).

- The track forecast errors for 24, 48 and 72 hrs lead period were 59.4, 59.9, and 61.0 km respectively against the LPA errors of 80.6, 125.5, and 171.2 km respectively (**Fig. 4.3.3a**).
- The track forecast skill was about 60%, 78%, and 88% against the LPA skill of 61%, 73%, and 74% for 24, 48 and 72 hrs lead period respectively (**Fig. 4.3.3b**).
- **Track forecast errors were exceptionally less than the past five years average errors for all lead periods. Similarly, track forecast skill was higher than the past five years average skill for all lead periods beyond 24 hours.**

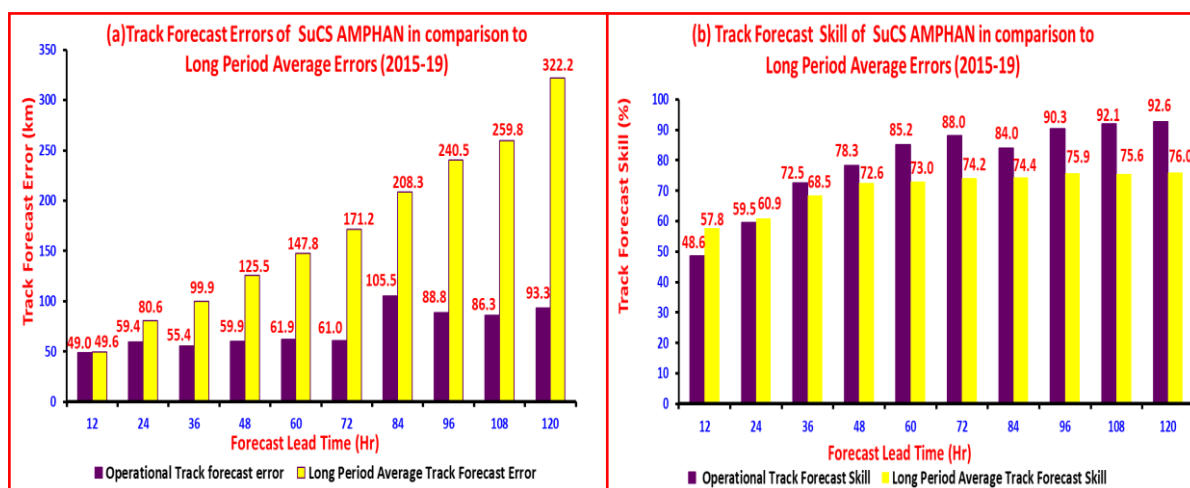


Fig. 4.3.1.3 (a): Track forecast errors and (b) skill of SuCS AMPHAN as compared to long period average (2015-19)

Table 4.3.1.2: Operational track forecast errors (km) & Skill (%) compared to long period average during 2015-19

Lead Period (hrs)	No. of obs. Verified	Operational Track Forecast		Long Period Average (2015-19) Track Forecast	
		Error (km)	Skill (%)*	Error (km)	Skill (%)*
12	18	49.0	48.6	49.6	57.8
24	16	59.4	59.5	80.6	60.9
36	15	55.4	72.5	99.9	68.5
48	13	59.9	78.3	125.5	72.6
60	11	61.9	85.2	147.8	73.0
72	9	61.0	88.0	171.2	74.2
84	7	105.5	84.0	208.3	74.4
96	5	88.8	90.3	240.5	75.9
108	3	86.3	92.1	259.8	75.6
120	1	93.3	92.6	322.2	76.0

4.3.1.5 Intensity Forecast Error

The intensity forecast errors (Forecast wind – Actual wind) and skill based on absolute errors and root mean square errors are presented in Table 4.3.3 and Fig. 4.3.4 & 4.3.5 respectively.

- The absolute error (AE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 13.4, 15.0 and 9.0 knots against the LPA errors of 8.9, 13.0, and 15.4 knots during 2015-19 respectively (**Fig. 4.3.1.4 a**).
- The root mean square error (RMSE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 18.8, 22.1 and 12.2 knots against the LPA errors of 11.5, 16.7, and 19.2 knots respectively (**Fig. 4.3.1.4 b**).

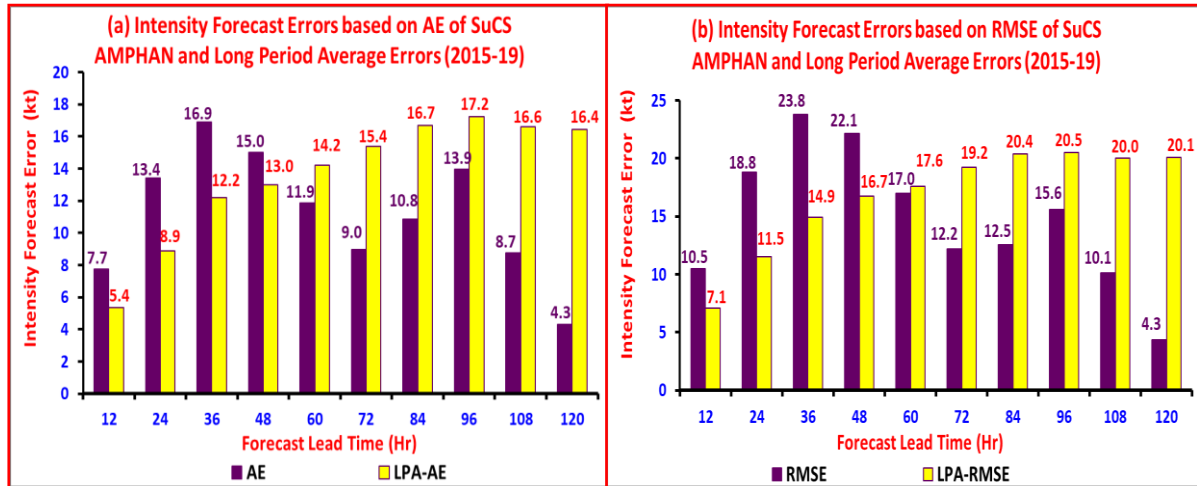


Fig. 4.3.1.4: Absolute errors (AE) and Root Mean Square errors (RMSE) in intensity forecast (winds in knots) of SuCS AMPHAN as compared to long period average (2015-19)

- The skill (%) in intensity forecast as compared to persistence forecast based on AE for 24, 48 and 72 hrs lead period was 56%, 80% and 94% against the LPA of 45%, 69% and 72% respectively (**Fig. 4.3.1.5a**).
- The skill (%) in intensity forecast based on RMSE for 24, 48 and 72 hrs lead period was 50%, 76% and 93% against the LPA of 49%, 63% and 72% respectively (**Fig. 4.3.1.5b**).
- Thus even being a Super cyclone, the intensity forecast was skill full and better than the Long Period Average.

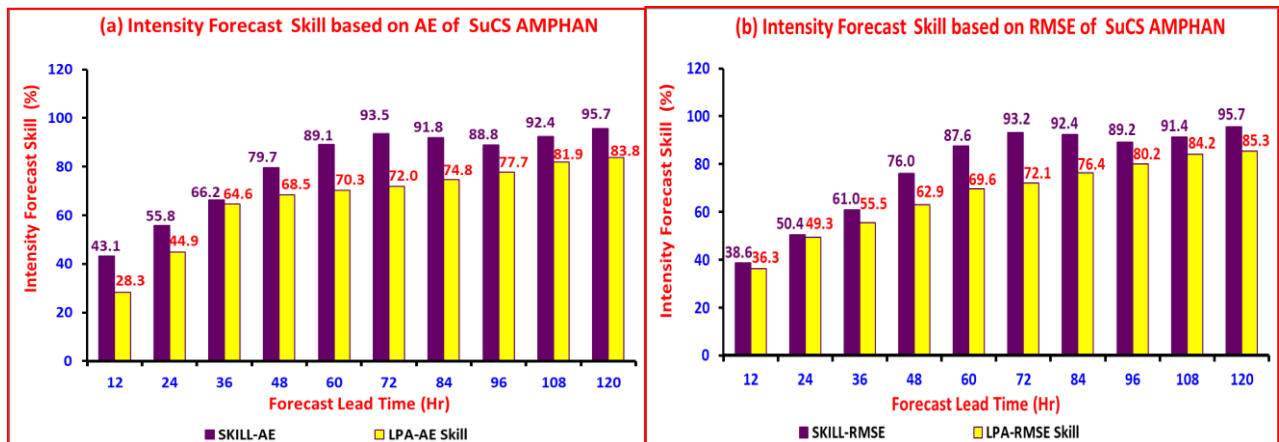


Fig. 4.3.1.5a: Skill (%) in intensity forecast based on (a) Absolute errors (AE) and (b) Root Mean Square errors (RMSE) of SuCS AMPHAN as compared to long period average (2015-19)

Table 4.3.1.3: Mean Intensity forecast errors (kt) and Skill (%) in association with SUCS AMPHAN compared to long period average errors and skill during 2015-19

Lead Period (hrs)	N	Average error in Intensity forecast (kts)		LPA (2015-19) Intensity forecast error (kts)		Operational Skill* (%) in intensity forecast		LPA (2015-19) Skill* (%) in intensity forecast	
		AE	RMSE	AE	RMSE	AE	RMSE	AE	RMSE
12	18	7.7	10.5	5.4	7.1	43.1	38.6	28.3	36.3
24	16	13.4	18.8	8.9	11.5	55.8	50.4	44.9	49.3
36	15	16.9	23.8	12.2	14.9	66.2	61.0	64.6	55.5
48	13	15.0	22.1	13.0	16.7	79.7	76.0	68.5	62.9
60	11	11.9	17.0	14.2	17.6	89.1	87.6	70.3	69.6
72	9	9.0	12.2	15.4	19.2	93.5	93.2	72.0	72.1
84	7	10.8	12.5	16.7	20.4	91.8	92.4	74.8	76.4
96	5	13.9	15.6	17.2	20.5	88.8	89.2	77.7	80.2
108	3	8.7	10.1	16.6	20.0	92.4	91.4	81.9	84.2
120	1	4.3	4.3	16.4	20.1	95.7	95.7	83.8	85.3

N: No. of observations verified; AE: Absolute Error; RMSE: Root Mean Square Error, LPA: Long Period Average (2015-19).

4.3.1.6 Adverse weather forecast verification

The verifications of adverse weather like heavy rainfall, gale wind and storm surge forecast issued by IMD are presented in Tables 4.3.1.4-6. It is found that all the three types of adverse weather were predicted accurately and well in advance.

Table 4.3.1.4: Verification of Heavy Rainfall Forecast

Date/Base Time of forecast (UTC)	24 hr Heavy rainfall warning ending at 0300 UTC of next day	Realised 24-hour heavy rainfall ending at 0300 UTC of date
16.05.2020/0300	Andaman & Nicobar Islands Heavy falls at isolated places is very likely over Andaman & Nicobar Islands on 16th May. Odisha & Gangetic West Bengal Heavy falls at isolated places from 18th May evening, heavy to very heavy rainfalls at a few places on 19th May and isolated heavy rainfall over northeast Odisha on 20th May 2020. Coastal districts of Gangetic West Bengal are likely to experience heavy falls at a few places on 19th May, heavy to very heavy falls at a few places with extremely heavy falls at isolated places over Gangetic West Bengal on 20th May.	17 May 2020 A & N Island: Nancowary-2 and IAF Carnicobar & Car Nicobar-1 each 18 May 2020 A & N Island: Car Nicobar-5, IAF Carnicobar-4 and Nancowary-1, Odisha: Jhumpura-10 and Gurundia -8 19 May 2020 SHWB & Sikkim: Mangan-7 20 May 2020
17.05.2020/0300	(i) Rainfall (over Andaman & Nicobar Islands): •Light to moderate rainfall at most places is very likely over Andaman & Nicobar Islands during next	

	24 hours. •Rainfall (over Odisha & Gangetic West Bengal) heavy falls at isolated places from 18th May evening. Rainfall at most places with heavy to very heavy rainfall at a few places on 19th May and isolated heavy rainfall over north coastal Odisha on 20th May 2020. Coastal districts of Gangetic West Bengal are likely to experience heavy falls at isolated places on 19th May. Heavy to very heavy falls at a few places & extremely heavy falls at isolated places likely over coastal districts of West Bengal on 20th May.	Gangetic West Bengal: Contai-11, Digha-9, Odisha: Paradeep-21, Balikuda-18, Kakatpur & Kujanga-16 each, Astaranga & Alipingal-14 each, Niali-12, Raghunathpur, Puri, Marsaghai, Nilgiri, Kantapada & Garadapur-9 each, Gop, Chandanpur, Betanati, Rajkanika, Jagatsinghpur, Tirtol & Baripada-8 each and Binjharpur, Satyabadi, Nischintakoili, Chandbali, Bhograi, Jajpur, Dhamnagar, Soro, Tihidi, Bari & Basudevpur-7 each, 21 May 2020 Assam & Meghalaya: Williamnagar-23, Mawsynram-15, Sohra (RKM)-13, Bhaghmara-11 and Sohra & Shillong-9 each SHWB & Sikkim: Sevoke-7, Gangetic West Bengal: Alipore-24, Dum Dum-20, Harinkhola & Debagram-13 each, Burdwan-10, Manteswar & Digha-9 each and Mohanpur, Kharagpur, Suri, Mangalkote, Bankura, Lalgah & Midnapore-7 each, Odisha: Bhograi-13, Rajghat & Jaleswar-12 each and Chandanpur & Bangiriposi-11 each, Paradeep, Samakhunta, Betanati & Baripada-9 each and Chandikhol, Joshipur & Danagadi-7 each, 22 May 2020
18.05.2020/0300	Odisha Coastal Odisha is likely to experience heavy falls at isolated places over coastal Odisha (Gajapati, Ganjam, Puri, Jagatsinghpur & Kendrapara Districts) on 18th May, 2020. Heavy to very heavy rainfall at a few places over north coastal Odisha (Jagatsinghpur, Kendrapara, Jajpur, Balasore, Bhadrak & Mayurbhanj Districts) and isolated heavy falls over Khordha & Puri districts on 19th May and isolated heavy rainfall over north Odisha (Bhadrak, Balasore, Mayurbhanj, Jajpur, Kendrapara and Keonjhar Districts) on 20th May 2020. West Bengal Coastal districts of Gangetic West Bengal (East Medinipur, South & North 24 Parganas) are likely to experience heavy falls at isolated places on 19th May. Rainfall at most places with heavy to very heavy falls at a few places & extremely heavy falls at isolated places likely over Gangetic West Bengal (east & west Medinipur, south & north 24 Parganas, Howrah, Hoogli, Kolkata and adjoining districts) on 20th May and isolated heavy rain over interior districts on 21st May, 2020. Sub-Himalayan West Bengal and Sikkim Heavy to very heavy falls at a few places over Malda & Dinajpur districts on 20th May and over most of the districts of Sub-Himalayan West Bengal & Sikkim on 21st May, 2020. Assam & Meghalaya Heavy to very heavy falls at a few places over the western districts of Assam & Meghalaya on 21st May.	
19.05.2020/0300	Odisha Coastal Odisha to experience heavy to very heavy rainfall at isolated places Jagatsinghpur, Kendrapara and Bhadrak Districts and isolated heavy falls over Jajpur, Balasore, Cuttack, Mayurbhanj, Khordha & Puri districts on 19th May and isolated heavy to very heavy rainfall at isolated places over north coastal Odisha	

	(Jagatsinghpur, Bhadrak and Keonjhar Districts) on 20th May 2020. West Bengal Coastal districts of Gangetic West Bengal (East Medinipur, South & North 24 Parganas) are likely to experience light to moderate rainfall at many places commencing from today, the 19th May afternoon. Rainfall intensity is likely to increase gradually and become maximum on 20th May. Heavy to very heavy falls at a few places & extremely heavy falls at isolated places likely over Gangetic West Bengal (east & west Medinipur, south & north 24 Parganas, Howrah, Hoogli, Kolkata and adjoining districts) on 20th May and isolated heavy rain over interior districts on 21st May, 2020. Sub-Himalayan West Bengal and Sikkim Heavy to very heavy falls at a few places over Malda & Dinajpur districts on 20th May and over most of the districts of Sub-Himalayan West Bengal & Sikkim on 21st May, 2020. Assam & Meghalaya Heavy to very heavy falls at a few places over the western districts of Assam & Meghalaya on 21st May.	Arunachal Pradesh: Bhalukpong-12, Bomdila-10, Itanagar & Ziro-9 each, Roing-8, Pasighat Aero-7, Assam & Meghalaya: Sohra (RKM)-25, Mawsynram-22, Sohra-21, Khliehriat-15, Goalpara-12, Goalpara-11, Nongstein, Dhubri & Mela bazar -10 each, Goibargaon, N.Lakhimpur/Lilabari & Shillong-8 each and Tamulpur, Barapani, Williamnagar, DRF & Tezpur-7 each, Nagaland, Manipur, Mizoram & Tripura: Sabroom-13, SHWB & Sikkim: Buxaduar-8,
20.05.2020/0300	Odisha Heavy to very heavy rainfall very likely at isolated places over north coastal Odisha (Balasore, Bhadrak, Mayurbhanj, Jajpur, Kendrapara and Keonjhar Districts) and isolated heavy falls over Jagatsinghpur district on 20th May 2020. West Bengal Heavy to very heavy falls at a few places & extremely heavy falls at isolated places likely over Gangetic West Bengal (east & west Medinipur, south & north 24 Parganas, Howrah, Hoogli, Kolkata and adjoining districts) on 20th May and isolated heavy rain over interior districts on 21st May, 2020. Sub-Himalayan West Bengal and Sikkim Heavy to very heavy falls at a few places over Malda & Dinajpur districts on 20th May and over most of the districts of Sub-Himalayan West Bengal & Sikkim on 21st May, 2020. Assam & Meghalaya Heavy to very heavy falls at a few places over the western districts of Assam & Meghalaya on 21st May.	
21.05.2020/0300	Assam & Meghalaya Heavy to very heavy & extremely heavy falls (≥ 20 cm) at isolated places very likely on 21st May, 2020. Arunachal Pradesh	

	Heavy to very heavy falls at isolated places very likely on 21st May, 2020.	
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Table 4.3.1.5: Verification of Squally/Gale wind forecast (16-21 May)

Date/Base Time of Forecast (UTC)	Gale/ Squally wind Forecast at 0300 UTC of date	Realised wind
16.05.2020/0300	- Squally wind speed reaching 45 to 55 kmph gusting to 65 kmph is likely along and off Odisha coast from 19th morning and along and off West Bengal coast from 19th afternoon. The wind speed will gradually increase becoming gale wind speed reaching 75 to 85 kmph gusting to 95 kmph from 20th morning along and off north Odisha and West Bengal coast. It will gradually increase thereafter. - Squally wind speed reaching 45 to 55 kmph gusting to 65 kmph is likely over Andaman Sea during next 48 hours. - Squally wind speed reaching 45 to 55 kmph gusting to 65 kmph is prevailing over southeast and adjoining southwest Bay of Bengal. It is likely to increase becoming 90-100 gusting to 110 kmph over eastcentral and adjoining west central Bay of Bengal by 17th morning, 120-130 gusting to 145 kmph over southern parts of central Bay of Bengal by 18th morning, 155-165 gusting to 180 kmph over northern parts of central Bay of Bengal and adjoining north Bay of Bengal on 19th , and 160-170 gusting to 190 kmph over north Bay of Bengal by 20th morning.	155-165kmph gusting to 185 kmph along & off coastal Districts of West Bengal and 100-110 kmph gusting to 120 kmph along & off north coastal Districts of Odisha. Kolkata (Dum Dum) reported 130 kmph at 1855 hrs IST and Kolkata (Alipore) 112 kmph at 1752 hrs IST of 20th May. Also Canning reported 85 knots (9157 kmph), Nimpith 84 knots (155 kmph) and Sagar islands 60 knots (111 kmph)
17.05.2020/0300	- Squally wind speed reaching 45 to 55 kmph gusting to 65 kmph is likely to commence along and off south Odisha coast from 18th evening, extend to along & off north Odisha coast from 19th morning and along and off West Bengal coast from 19th afternoon. The wind speed will gradually increase becoming gale wind speed reaching 75 to 85 kmph gusting to 95 kmph from 20th morning along and off north Odisha and West Bengal coasts. It will gradually increase thereafter along & off West Bengal coast. - Squally wind speed reaching 45 to 55 kmph gusting to 65 kmph is likely over Andaman Sea during next 24 hours. - Squally wind speed reaching 80 to 90 kmph gusting to 100 kmph is prevailing over southeast and adjoining southwest Bay of Bengal. It is likely to increase becoming 125-135 gusting to 150 kmph over southern parts of central Bay of Bengal by 18th morning, 160-170 gusting to 190 kmph over northern parts of central Bay of Bengal and adjoining North Bay of Bengal on	Paradip reported 106 kmph at 0630 hrs IST (0100 UTC) , Chandbali, 80 kmph at 0830 hrs. IST (0300 UTC) and Balasore 91 kmph during 1330 – 1430 hrs. IST (0800 & 0900 UTC) of 20th May.

	19th, and 155-165 gusting to 180 kmph over north Bay of Bengal during 20th May.	
18.05.2020/0300	West Bengal & Odisha • Squally wind speed reaching 45 to 55 kmph gusting to 65 kmph is likely to commence along and off south Odisha coast from 18th evening, increase becoming 55 to 65 kmph gusting to 75 kmph extend to along & off north Odisha coast from 19th morning and along and off West Bengal coast from 19th afternoon. • The wind speed will gradually increase becoming gale wind speed reaching 75 to 85 kmph gusting to 95 kmph from 20th morning along and off north Odisha (Jagatsinghpur, Kendrapara, Bhadrak, Balasore and Mayurbhanj districts) and West Bengal (east & west Medinipur, south & north 24 Parganas, Howrah, Hoogli, Kolkata Districts). It will gradually increase thereafter becoming 110 to 120 kmph gusting to 135 kmph along & off the above-mentioned districts of North Odisha. • Gale wind speed reaching 155 to 165 kmph gusting to 185 kmph very likely along & off east Medinipur and north & south 24 Parganas districts and 100-110 kmph gusting to 120 kmph over Kolkata, Hoogli, Howrah and West Mednipur Districts of West Bengal during the time of landfall (20th afternoon to night). • Squally wind speed reaching 55-65 kmph gusting to 75 kmph likely to prevail over Puri, Khordha, Cuttack, Jajpur districts of Odisha during 20th May 2020. Deep Sea area • Gale wind speed reaching 210-220 gusting to 240 kmph is prevailing over west-central and adjoining central parts of south Bay of Bengal. It is likely to increase becoming 220-230 gusting to 250 kmph over northern parts of central Bay of Bengal and adjoining North Bay of Bengal from tonight to 19th May morning, likely to increase further becoming 230-240 gusting to 255 kmph by tonight. • Gale wind speed reaching 220-230 gusting to 255 kmph over north Bay of Bengal from 19th morning and gradually decrease becoming 155-165 kmph gusting to 180 kmph by 20th evening.	
19.05.2020/0300	West Bengal & Odisha • Squally wind speed reaching 45 to 55 kmph gusting to 65 kmph is prevailing along & off south Odisha coast. It is very likely to increase and extend northwards becoming 55 to 65 kmph gusting to 75 kmph northwards to north Odisha coast by today afternoon and along & off West Bengal coast by tonight.	

	• The wind speed will gradually increase becoming gale wind speed reaching 75 to 85 kmph gusting to 95 kmph from 20th morning along and off north Odisha (Jagatsinghpur, Kendrapara, Bhadrak, Balasore and Mayurbhanj districts) coast and West Bengal (east & west Medinipur, south & north 24 Parganas, Howrah, Hoogli, Kolkata Districts) coast. It will gradually increase thereafter becoming 100 to 110 kmph gusting to 125 kmph along & off the above mentioned districts of North Odisha. • Gale wind speed reaching 155 to 165 kmph gusting to 185 kmph very likely along & off east Medinipur and north & south 24 Parganas districts and 110-120 kmph gusting to 130 kmph over Kolkata, Hoogli, Howrah and West Medinipur Districts of West Bengal during the time of landfall (20th afternoon to night). • Squally wind speed reaching 55-65 kmph gusting to 75 kmph likely to prevail over Puri, Khordha, Cuttack, Jajpur districts of Odisha during 20th May 2020. Deep Sea area • Gale wind speed reaching 225-235 gusting to 255 kmph is prevailing over westcentral Bay of Bengal. It is likely to prevail over northern parts of central Bay of Bengal and adjoining North Bay of Bengal during 19th May. • Gale wind speed reaching 180-190 gusting 210 kmph over north Bay of Bengal from 19th afternoon. It will gradually decrease becoming 165-175 kmph gusting to 195 kmph by 20th afternoon.	
20.05.2020/0300	West Bengal & Odisha • Gale wind, speed reaching 90 to 100 kmph gusting to 110 kmph is prevailing along and off Jagatsinghpur, Kendrapara, Bhadrak, Balasore and Mayurbhanj districts of Odisha and squally wind speed reaching 55 to 65 kmph gusting to 75 kmph is prevailing along & off remaining coastal districts of Odisha (Puri, Khordha, Cuttack, Jajpur) during 20th May 2020. • It will gradually increase becoming 100 to 110 kmph gusting to 125 kmph along & off the above mentioned districts of North Odisha during forenoon to afternoon of 20th May 2020. • Gale wind speed reaching 80 to 90 kmph gusting to 100 kmph is prevailing along and off West Bengal coast (east & west Medinipur, south & north 24 Parganas, Howrah, Hoogli, Kolkata Districts). • Gale wind speed reaching 155 to 165 kmph gusting to 185 kmph very likely along & off east	

	Medinipur and north & south 24 Parganas districts and 110-120 kmph gusting to 130 kmph over Kolkata, Hoogli, Howrah and West Medinipur Districts of West Bengal during the time of landfall (20th afternoon to night). Deep Sea area Gale wind speed reaching 165-175 gusting to 195 kmph is prevailing over northwest and adjoining westcentral Bay of Bengal. Gale wind, speed reaching 150-160 gusting to 175 kmph is prevailing over northern parts of central Bay of Bengal. It will gradually decrease becoming 155-165 kmph gusting to 185 kmph over North Bay of Bengal during the evening hours of today, the 20th May.	
21.05.2020/0300	Squally wind speed reaching 50 to 60 kmph gusting to 70 kmph very likely over Western Assam & Western Meghalaya till evening and reduce gradually thereafter.	

Table 4.3.1.6: Verification of Storm Surge Forecast

Date/Base Time of observation	Storm Surge Forecast at 0300 UTC of date	Realised surge
18.05.2020/0300	Storm Surge of about 4-5 meters above Astronomical Tide is likely to inundate low lying areas of south & north 24 Parganas and about 3-4 meters over the low lying areas of East Medinipur District of West Bengal during the time of Landfall.	Maximum tidal wave of 4.6 meters height inundated the low lying areas of South & North
19.05.2020/0300	Storm Surge of about 4-5 meters above Astronomical Tide is likely to inundate low lying areas of south & north 24 Parganas and about 3-4 meters over the low lying areas of East Medinipur District of West Bengal during the time of Landfall.	24 Parganas districts and adjoining areas of east Medinipur district of West Bengal as
20.05.2020/0300	Storm Surge of about 4-5 meters above Astronomical Tide is likely to inundate low lying areas of south & north 24 Parganas and about 3-4 meters over the low lying areas of East Medinipur District of West Bengal during the time of Landfall.	estimated by the post Cyclone landfall survey Team of ACWC Kolkata. No significant Storm Surge has been reported along Odisha coast.

4.3.2 Severe Cyclonic Storm “NISARGA” over the east-central and adjoining southeast Arabian Sea (01st-04th June)

4.3.2.1 Genesis Forecast

- First information about development of low pressure area over southeast Arabian Sea was given in the extended range outlook issued on 21st May about **10 days prior** to the formation of low pressure area over the southeast & adjoining eastcentral Arabian Sea and Lakshadweep on 31st May.
- First information about development of depression over southeast Arabian Sea was issued in the tropical weather outlook and national weather forecast bulletin issued at 0630 UTC of 29th May about **3 days prior** to the formation of depression over southeast & adjoining eastcentral Arabian Sea on 1st June morning.

4.3.2.2 Track, Intensity and Landfall Forecast

- **With the formation of** low pressure area over southeast & adjoining eastcentral Arabian Sea on 31st May morning, IMD **issued first bulletin at 0630 UTC of 31st May and** indicated that the system would intensify into a cyclonic storm and reach north Maharashtra and Gujarat coasts by 3rd June, **(about 77 hours prior to landfall of SCS NISARGA).**
- **In the bulletin issued at 0400 UTC of 1st June,** it was indicated that the system would intensify upto severe cyclonic storm stage with maximum sustained wind speed of 105-115 kmph gusting to 125 kmph and cross north Maharashtra and south Gujarat coasts between Harihareshwar (Raigad), Maharashtra and Daman during evening/ night of 3rd June **(about 52 hours prior to landfall of SCS NISARGA).**
- **In the bulletin issued at 0600 UTC of 2nd June, it was indicated that the system would cross** close to Alibag (Raigad District, Maharashtra) during the afternoon of 03rd June as a Severe Cyclonic Storm with a maximum sustained wind speed of 100-110 kmph gusting to 120 kmph **(about 28 hours prior to landfall of SCS NISARGA).**
- **Actually, the severe cyclonic storm Nisarga** crossed north Maharashtra coast close to south of Alibag with a maximum sustained wind speed of 110-120 kmph gusting to 130 kmph between 0700 & 0900 UTC of 03rd June.
- Thus, the track, landfall point & time, intensity and associated adverse weather like heavy rainfall, gale wind and storm surge were predicted well in advance by IMD.
- Typical observed & forecast track along with cone of uncertainty and quadrant wind distribution based on 1200 UTC of 1st June about 45 hours prior to landfall is presented in **Fig.4.3.2.1.**

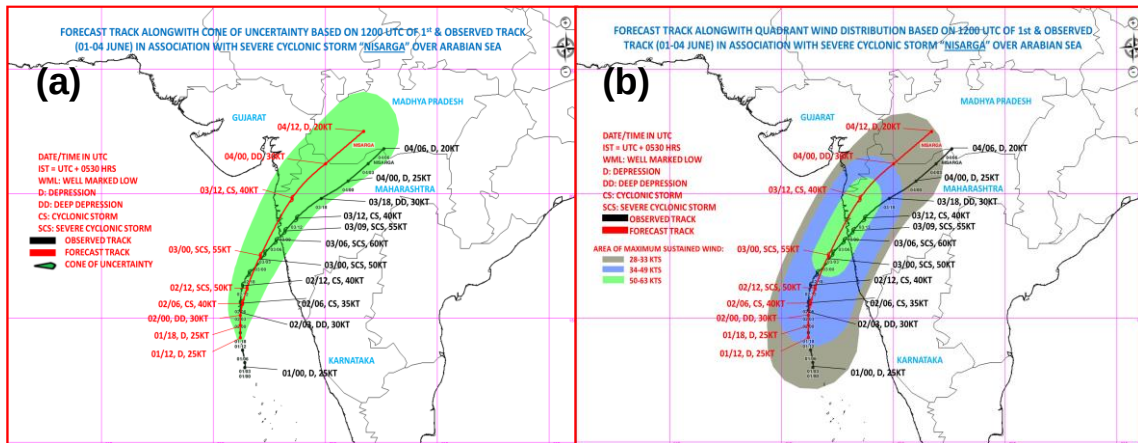


Fig. 4.3.2.1: Typical observed and forecast track alongwith cone of uncertainty and quadrant wind distribution based on 1200 UTC of 1st June (45 hrs prior to landfall) of SCS NISARGA

4.3.2.3 Landfall Forecast Errors:

The landfall point and time errors during SCS Nisarga compared to long period average (LPA) errors during 2015-19 are presented in Table 4.3.2.1 and Fig. 4.3.2.2 (a-b).

- The landfall point forecast errors for 12, 24 and 48 hrs lead period were 7.8, 33.1 and 80.1 km respectively against the LPA errors of 25.4, 44.7 and 69.4 km during 2015-19 respectively (**Fig. 4.3.2.2a**).
- The landfall time forecast errors for 12, 24 and 48 & 72 hrs lead period were 0, 0.5, 0 & 1.0 hours respectively against the LPA errors of 2.0, 3.0 & 5.4 hours during 2015-19 respectively (**Fig. 4.3.2.2b**).

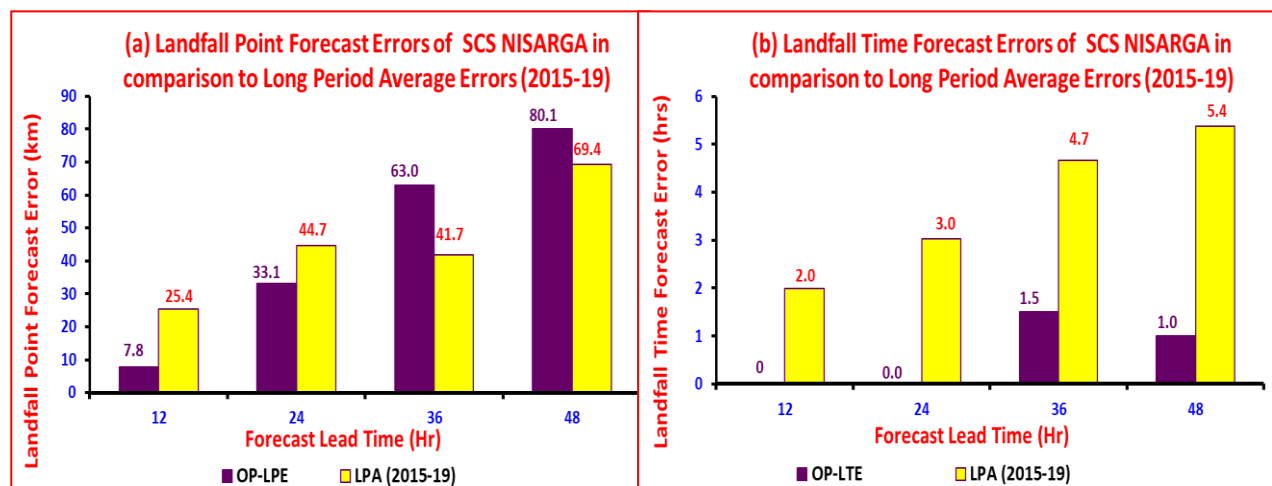


Fig. 4.3.2.2: Landfall (a) point and (b) time forecast errors of SCS NISARGA as compared to long period average (2015-19)

Table 4.3.2.1: Landfall point and time errors of SCS NISARGA compared to long period average errors during 2015-19

Lead Period (hrs)	Base Time	Landfall Point ($^{\circ}$ N/ $^{\circ}$ E)		Landfall Time (hours)		Operational Error		LPA error (2015-19)	
		Forecast	Actual	Forecast	Actual	LPE (km)	LTE (hours)	LPE (km)	LTE (hours)
12	02/18	18.40/72.90	18.35/72.95	03/0800	03/0800	7.8	0	25.4	2.0
24	02/06	18.64/72.87	18.35/72.95	03/0800	03/0800	33.1	0	44.7	3.0
36	01/18	18.92/72.89	18.35/72.95	03/0930	03/0800	63.0	+1.5	41.7	4.7
48	01/06	19.06/72.79	18.35/72.95	03/0700	03/0800	80.1	-1.0	69.4	5.4

“+” indicates delayed prediction and “-” indicates early prediction

4.3.2.3 Track Forecast Errors:

The track forecast errors and skill compared to long period average errors during 2015-19 are presented in Table 4 and Fig. 4.3.2.3(a-b).

- The track forecast errors for 12, 24 & 48 hrs lead period were 59.7, 111.6, and 212.0 km respectively against the LPA errors of 49.6, 80.6 & 125.5 km respectively (**Fig. 4.3.2.3a**). The relatively higher forecast error was due to recurving nature of the track.
- The track forecast skill was about 67%, 73%, and 78% against the LPA skill of 58%, 61% & 73% for 12, 24 & 48 hrs lead period respectively (**Fig. 4.3.2.3b**). Thus, the track forecast skill was higher than the past five years average skill during 2015-19 for all lead periods.

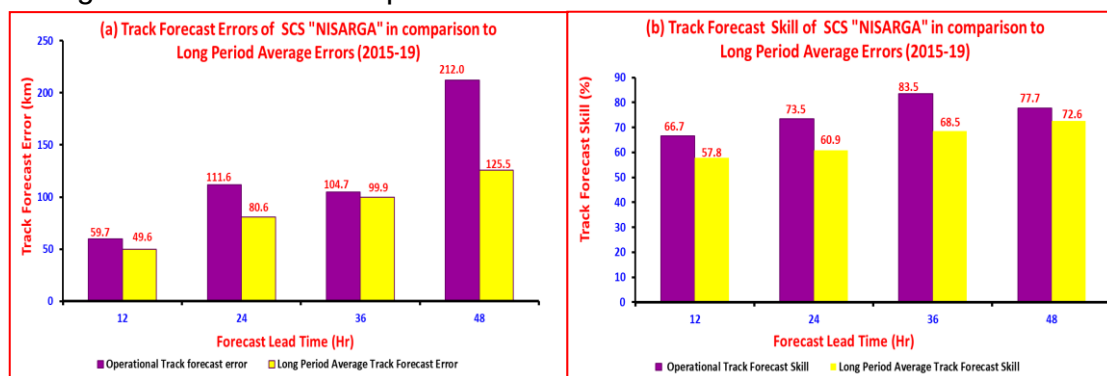


Fig. 4.3.2.3: Track forecast errors and skill of SCS NISARGA as compared to long period average (2015-19)

Table 4.3.2.2: Operational track forecast errors (km) & Skill (%) compared to long period average during 2015-19

Lead Period(hrs)	No. of obs. verified	Operational Track Forecast		Long Period Average (2015-19) Track Forecast	
		Error (km)	Skill (%)*	Error (km)	Skill (%)*
12	7	59.7	66.7	49.6	57.8
24	6	111.6	73.5	80.6	60.9
36	3	104.7	83.5	99.9	68.5
48	2	212.0	77.7	125.5	72.6

* Skill is calculated by comparing the operational track forecast error with the forecast error based on climatology and persistence (CLIPER) model.

4.3.2.4 Intensity Forecast Errors:

The intensity forecast errors and skill based on absolute errors and root mean square errors are presented in Table 4.3.2.3 and Fig. 4.3.2.4 & 4.3.2.5 respectively.

- The absolute error (AE) of intensity (wind) forecast for 12, 24 & 48 hrs lead period were 2.9, 3.3 and 7.5 knots against the LPA errors of 5.4, 8.9 & 13.0 knots during 2015-19 respectively (Fig. 4.3.2.4).
- The root mean square error (RMSE) of intensity (wind) forecast for 12, 24 & 48 hrs lead period were 4.6, 5.8 & 7.9 knots against the LPA errors of 7.1, 11.5 & 16.7 knots respectively (Fig. 4.3.2.4).

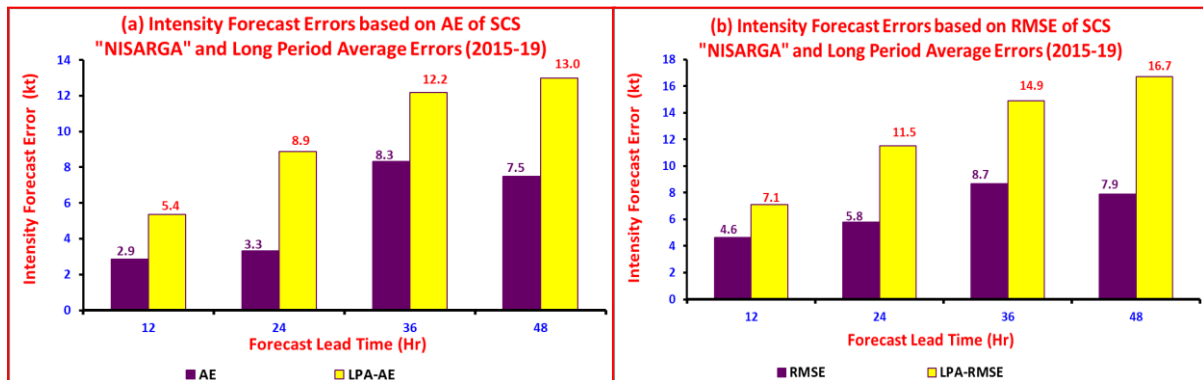


Fig. 4.3.2.4: Absolute errors (AE) and Root Mean Square errors (RMSE) in intensity forecast (winds in knots) of SCS NISARGA as compared to long period average (2015-19)

- The skill (%) in intensity forecast based on AE for 12, 24 & 48 hrs lead period was 80%, 89% and 81% against the LPA of 29%, 43% & 68% respectively (Fig. 4.3.2.5a).
- The skill (%) in intensity forecast based on RMSE for 12, 24 & 48 hrs lead period was 78%, 85% and 82% against the LPA of 36%, 49% & 59% respectively (Fig. 4.3.2.5b).

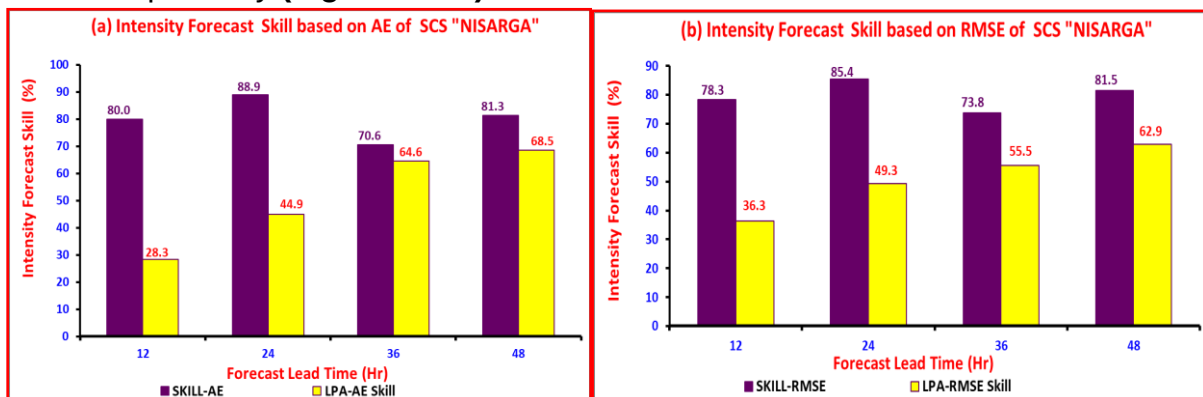


Fig. 4.3.2.5: Skill (%) in intensity forecast based on (a) Absolute errors (AE) and (b) Root Mean Square errors (RMSE) of SCS NISARGA as compared to long period average (2015-19) updated

Table 4.3.2.3: Mean Intensity forecast errors (kt) and Skill (%) in association with SCS NISARGA compared to long period average errors and skill during 2015-19

Lead Period (hrs)	N	Average error in Intensity forecast (kts)		LPA (2015-19) Intensity forecast error (kts)		Operational Skill* (%) in intensity forecast		LPA (2015-19) Skill* (%) in intensity forecast	
		AE	RMSE	AE	RMSE	AE	RMSE	AE	RMSE
12	7	2.9	4.6	5.4	7.1	80.0	78.3	28.3	36.3
24	6	3.3	5.8	8.9	11.5	88.9	85.4	44.9	49.3
36	3	8.3	8.7	12.2	14.9	70.6	73.8	64.6	55.5
48	2	7.5	7.9	13.0	16.7	81.3	81.5	68.5	62.9

N: No. of observations verified; AE: Absolute Error; RMSE: Root Mean Square Error, LPA: Long Period Average (2015-19). * Skill of forecast is calculated by comparing the operational forecast error with the forecast error based on persistence method

4.3.2.5 Adverse weather forecast verification

The verifications of adverse weather like heavy rainfall, gale wind and storm surge forecast issued by IMD are presented in Table 6-8. It is found that all the three types of adverse weather were predicted accurately and well in advance.

Table 4.3.2.4: Verification of Heavy Rainfall Forecast

Date/Base Time of observation	24 hr Heavy rainfall warning ending at 0300 UTC of next day	Realised 24-hour heavy rainfall ending at 0300 UTC of date
01.06.2020/0300	➤ Isolated heavy falls very likely over Lakshadweep area, north Kerala and coastal Karnataka on 1st June. Isolated heavy to very heavy falls over south Konkan & Goa on 1st June. Isolated heavy to very heavy falls very over Konkan & Goa on 02nd June and over south Konkan & Goa on 03rd June. ➤ Heavy to very heavy falls at a few places and extremely heavy falls at isolated places over north Konkan and north Madhya Maharashtra on 03rd & 04th June. ➤ Isolated heavy to very heavy falls very likely over south Gujarat state, Daman, Diu, Dadra & Nagar Haveli on 03rd June and with heavy to very heavy falls at a few places and extremely heavy falls at isolated places over south Gujarat state, Daman, Diu, Dadra & Nagar Haveli and on 04th June.	1 June 2020 Coastal Karnataka: Kota-10 and Kundapur-7 3 June 2020 Konkan & Goa: Mormugao & Panjim-13 each, Quepem & Malvan-11 each, Valpoi & Sanguem-9 each, Sawantwadi, Dodamarg, Canacona & Devgad-8 each and Kudal-7 Madhya Maharashtra: Khed Rajgurunagar-7 4 June 2020 Konkan & Goa: Pen-16, Poladpur-15, Mangaon-14, Lanja, Mandangad & Dapoli-13 each, Tala-12, Vaibhavwadi & Alibag-11 each, Chiplun-10, Roha, Rajapur & Harnai -9 each, Guhagarh & Khed-8 each and Shahapur, Murud,
02.06.2020/0300	➤ Heavy to very heavy falls at isolated places	

	over Konkan & Goa during next 24 hours. Isolated heavy falls over Coastal Karnataka, Madhya Maharashtra and Marathwada during next 24 hours. ➤ Heavy to very heavy falls at a few places and extremely heavy falls (≥ 20 cm in 24 hours) at isolated places over north Konkan (Mumbai, Palghar, Thane, Raigad districts) and north Madhya Maharashtra ➤ Heavy to very heavy falls at isolated places over south Konkan (Ratnagiri & Sindhudurg districts) & Goa and south Gujarat region (Valsad, Navsari, Dang, Daman, Dadra & Nagar Haveli and Surat districts) ➤ Heavy falls at isolated places over west Madhya Pradesh on 03rd June.	Sangameshwar Devrukh, Khalapur, Jawhar & Ulhasnagar-7 each Madhya Maharashtra: Mahabaleshwar-19, Gaganbawada-15, Nashik-14, Sinnar, Bhusawal & Igatpuri-11 each, Akole, Devla, Satna Baglan & Chandgad-9 each, Javali Medha, Patan & Khed Rajgurunagar-8 each and Girnadam, Malegaon Camp, Sakri, Kalvan, Dindori, Yaval, Shahuwadi, Surgana & Radhanagari-7 each Vidarbha: Mangrulpir, Karanjilad, Jalgaon Jamod & Washim-8 each and Manora & Malegaon-7 each
03.06.2020/0300	➤ Heavy to very heavy falls at a few places and extremely heavy falls (≥ 20 cm in 24 hours) at isolated places very likely over north Konkan (Mumbai, Palghar, Thane, Raigad districts) and north Madhya Maharashtra during next 24 hours. ➤ Heavy to very heavy falls at isolated places over south Konkan (Ratnagiri & Sindhudurg districts) & Goa and south Gujarat region (Valsad, Navsari, Dang, Daman, Dadra & Nagar Haveli and Surat districts) during next 24 hours. ➤ Heavy falls at isolated places over west Madhya Pradesh and Vidarbha during next 24 hours.	
04.06.2020/0300	➤ Heavy to very heavy falls at isolated places very likely over east Madhya Pradesh and Chhattisgarh. ➤ Heavy falls at isolated places very likely over Vidarbha and west Madhya Pradesh during next 24 hours.	

Table 4.3.2.5: Verification of Squally/Gale wind forecast

Date/Base Time of observation	Gale/ Squally wind Forecast at 0300 UTC of date	Realised wind (kmph)
01.06.2020/0300	➤ Squally wind, speed reaching 40-50 kmph gusting to 60 kmph, is prevailing over Eastcentral and adjoining southeast Arabian Sea. It is very likely to become 50-60 kmph gusting	Reported on 3 rd June during and after the landfall in

	to 70kmph over Eastcentral and adjoining southeast Arabian Sea during next 48 hours. It will gradually increase becoming Gale wind speed reaching 60-70 kmph gusting to 80 kmph over eastcentral Arabian Sea and along and off south Maharashtra coast from 2nd June morning and further becoming 105-115 kmph gusting to 125 kmph over eastcentral and northeast Arabian Sea along & off Maharashtra coast (Raigad, Mumbai, Palghar, Thane), 90-100 kmph gusting to 110 kmph along & off Valsad, Navsari districts of Gujarat, and 80-90 kmph gusting to 100 kmph along & off Ratnagiri, Sindhudurg districts of Maharashtra, 70-80 kmph gusting to 90 kmph along & off Surat & Bharuch districts of south Gujarat from 3rd June evening. ➤ Squally wind, speed reaching 50-60 kmph gusting to 70 kmph is likely prevail over eastcentral Arabian Sea along and off Karnataka-Goa coasts during next 48 hours. ➤ Squally wind, speed reaching 40-50 kmph gusting to 60 kmph is likely to prevail over Lakshadweep area and along & off Kerala coast during next 48 hours.	kmph are as given below: Devgad -92, Ratnagiri – 110, Harnai – 74, Alibag – 102, Mumbai (Colaba) – 92, Thane – 75, Rajgurunagar (Pune) – 65, Ahmadnagar – 50, Satara - 59
02.06.2020/0300	➤ Squally wind speed reaching 55-65 kmph gusting to 75 kmph, is prevailing over Eastcentral Arabian Sea. To increase becoming gale wind, speed reaching 60-70 kmph gusting to 80 kmph, over eastcentral Arabian Sea off south Maharashtra & Goa coasts from 2nd afternoon and further becoming 100-110 kmph gusting to 120 kmph over eastcentral Arabian Sea along & off Maharashtra (Raigad, Mumbai, Palghar, Thane) coast from 03rd June morning. Gale wind, speed reaching 80-90 kmph gusting to 100 kmph, likely along & off Valsad, Navsari districts of Gujarat, Daman ad along & off northeast Arabian Sea, Ratnagiri, Sindhudurg districts of Maharashtra and 70-80 kmph gusting to 90 kmph along & off Surat & Bharuch districts of south Gujarat, Dadra & Nagar Haveli from 03rd June noon. ➤ Squally wind, speed reaching 50-60 kmph gusting to 70 kmph is likely to prevail over northeast Arabian Sea along & off remaining districts of south Gujarat coast on 03rd June. ➤ Squally wind, speed reaching 50-60 kmph gusting to 70 kmph is likely prevail over eastcentral Arabian Sea along and off Karnataka-Goa coasts during next 24 hours.	
03.06.2020/0300	➤ Gale wind, speed reaching 100-110 kmph gusting to 120 kmph, is prevailing over Eastcentral Arabian Sea. From the Noon of today, the 3rd June, it will become Gale wind, speed reaching 100-110 kmph gusting to 120 kmph over eastcentral Arabian Sea along & off north Maharashtra coast (Raigad, Mumbai and adjoining Thane), 85-95 kmph gusting to 105 kmph	

	along & off Ratnagiri, Sindhudurg, Palghar and remaining areas of Thane. Gale wind, speed reaching 60-80 kmph gusting to 90 kmph, likely along & off Valsad, Navsari districts of Gujarat, Daman, Dadra & Nagar Haveli and along & off northeast Arabian Sea and 60-70 kmph gusting to 80 kmph along & off Surat & Bharuch districts of south Gujarat from today the 03rd June noon. ➤ Squally wind, speed reaching 50-60 kmph gusting to 70 kmph is likely to prevail over northeast Arabian Sea along & off remaining districts of south Gujarat coast on 03rd June. ➤ Squally wind, speed reaching 50-60 kmph gusting to 70 kmph is likely prevail over eastcentral Arabian Sea along and off Karnataka-Goa coasts during next 12 hours.	
04.06.2020/0300	➤ Squally wind, speed reaching 35-45 kmph gusting to 55 kmph, is prevailing over western Districts of Vidarbha and adjoining Madhya Pradesh. ➤ It is likely reduce gradually during next 12 hours.	

Table 4.3.2.6: Verification of Storm Surge Forecast

Date/Base Time of observation	Storm Surge Forecast at 0300 UTC of date	Realised surge
02.06.2020/0300	Storm surge of about 1-2 meters height above astronomical tide to inundate low lying areas of Mumbai up to about 1.0 to 1.5 km, Thane and Raigad districts and 0.5-1.0 meter height above the astronomical tide likely to inundate low lying areas of Ratnagiri district during the time of landfall.	Storm surge of 0.5 – 1.0 m height occurred over the low lying areas of Raigad District during the time of landfall.
03.06.2020/0300	Storm surge of about 1-2 meters height above astronomical tide to inundate low lying areas of Mumbai, Thane and Raigad districts and 0.5-1.0 meter height above the astronomical tide likely to inundate low lying areas of Ratnagiri district during the time of landfall.	

4.3.3 Very severe cyclonic storm GATI over the Arabian Sea (21st – 24th November 2020)

4.3.3.1 Genesis Forecast

- The extended range outlook issued on 12th November indicated that a depression would form over southwest AS during the week (20-26 November) (about 9 days prior to formation of depression). Actually depression formed over southwest AS on 21st November.
- The tropical weather outlook issued on 17th November, indicated that a low pressure area would form over south Arabian Sea around 19th with moderate probability of it's intensification into depression (26-50%) around 21st. It was also indicated that the system would move gradually west-northwestwards towards Gulf of Aden by 24th November.
- The first press release issued in association with this system at 1730 hrs IST of 18th November indicated that a depression would form over southwest AS around 21st. It also indicated that, it would move west-northwestwards away from Indian coast (about 3 days and 6 hours prior to formation of depression). Wind warnings for deep sea areas of Arabian Sea were released in the Press Release alongwith the advisories for fishermen.
- On 18th November, the National Operation Centre Report issued by IMD under the Forecast Demonstration Project (FDP) indicated that a low pressure area would form over south Arabian Sea around 19th with moderate probability of it's intensification into depression around 21st. It was also indicated that the system would move gradually west-northwestwards towards Gulf of Aden by 24th November. Intense observation period was declared for Lakshadweep on 18th November and for South Oman and Yemen during 22nd to 25th November. This bulletin is uploaded every day on RSMC website and sent by email to all the beneficiaries of RSMC advisories everyday during FDP Phase (October-December).
- First information that the system would cross north Somalia coast around 10.5°N during early morning hours of 23rd was issued at 0900 hrs IST of 22nd November as a severe cyclonic storm with wind speed of 100-110 kmph gusting to 120 kmph. Warnings were further upgraded and the bulletin issued at 2000 hrs IST of 22nd indicated that the system would cross coast as a very severe cyclonic storm with speed of 130-140 kmph gusting to 155 kmph. Actually, the system crossed north Somalia coast near 10.5°N/51.1°E around 1500 UTC with maximum sustained wind speed of 130-140 kmph gusting to 155 kmph.
- Since 18th November onwards, regular updates about the state of Arabian Sea and advisories for fishermen were issued for the states along the west coast of India and Lakshadweep Islands.

4.3.3.2 Track and Intensity Forecast

- A low pressure area formed over central parts of south Arabian Sea (AS) in the morning (0300 UTC) 19th November.
- It lay as a well marked low pressure area over southwest AS & neighbourhood in the early morning (0000 UTC) 21st.
- It concentrated into a depression over the same region in the midnight (1800 UTC) of 21st.
- Moving west-southwestwards, it explosively intensified into a deep depression in the early morning (0000 UTC) of 22nd and further into the cyclonic storm “**GATI**” in the same morning (0300 UTC), into a severe cyclonic storm in the noon (0600 UTC) and into very severe cyclonic storm in the afternoon (0900 UTC) over southwest AS. It reached it’s peak intensity of 75 knots in the same evening (1200 UTC) over the southwest AS.
- Continuing to move westwards, it crossed Somalia coast near latitude 10.45°N and longitude 51.10°E between 1400 and 1500 UTC of 22nd as a very severe cyclonic storm with estimated wind speed of 130-140 kmph gusting to 155 kmph.
- Continuing to move nearly westwards, it weakened into a severe cyclonic storm in the early morning (2100 UTC of 22nd) of 23rd, into a cyclonic storm in the early morning (0000 UTC) and into a deep depression in the same noon (0600 UTC) over north Somalia.
- Thereafter, it moved west-northwestwards and emerged into Gulf of Aden in the evening (1200 UTC) of 23rd.
- Continuing to move west-northwestwards, it weakened into a depression in the early morning (0000 UTC) of 24th over Gulf of Aden and adjoining north Somalia and into a well marked low pressure area in the noon (0600 UTC) of 24th over the same region.

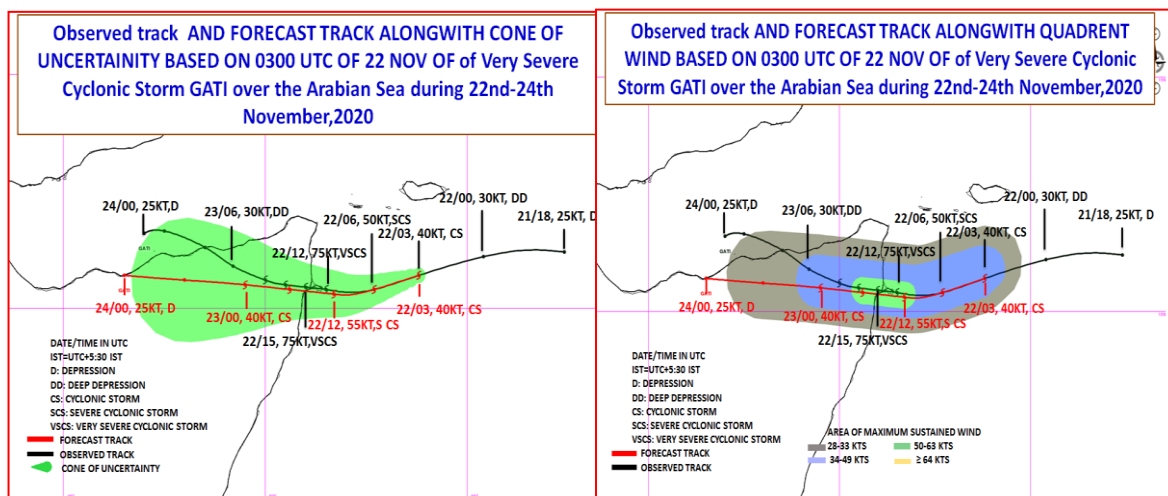


Fig 4.3.3.1: Observed and forecast track of VSCS GATI based on 0830 hours IST of 22nd November (12hrs in advance of landfall) demonstrating accuracy in track, landfall and intensity forecast

- As per media reports, intense rainfall activity occurred over north Somalia, more than 20 cm rainfall in just a few days against about 10 cm of annual rainfall.
- The observed and forecast track based on 0830 hrs IST of 22nd about 12 hrs prior to landfall demonstrating accuracy in track and landfall prediction is presented in Fig. 4.3.3.1. The black and red lines indicate the observed (actual) track and forecast track respectively. The closeness of these two lines indicate very accurate forecast of track (movement) and landfall point of cyclone, GATI.

4.3.3.3 Landfall Forecast Errors:

The 12 hr landfall point forecast errors for was 37km against the LPA errors (2015-19) of 25.4 km during 2015-19 respectively. The landfall time forecast errors for 12 hrs lead period was 0.5 hours against the LPA errors (2015-19) of 2.0.

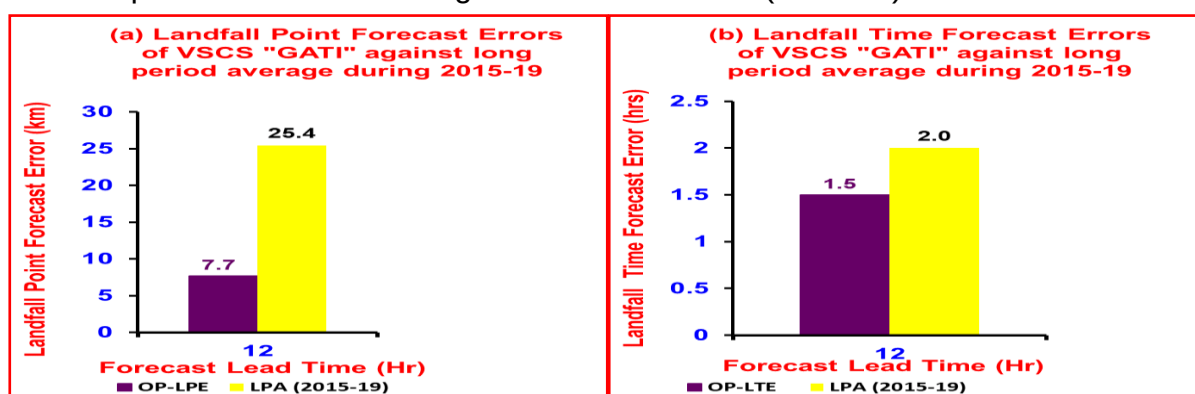


Fig.4.3.3.2: Landfall (a) point and (b) time forecast errors of of VSCS 'GATI' as compared to long period average (2015-19)

Table 4.3.3.1: Landfall point and time forecast errors of VSCS 'GATI' as compared to long period average (LPA) errors during 2015-19

Lead Period (hrs)	Base Time	Landfall Point (⁰ N/ ⁰ E)		Landfall Time (hours)		Operational Error		LPA error (2015-19)	
		Forecast	Actual	Forecast	Actual	LPE (km)	LTE (hours)	LPE (km)	LTE (hours)
12	22/03	10.38/ 51	10.45/51	22/1530	22/1430	7.7	1.5	25.4	2.0

“+” indicates delayed prediction and “-” indicates early prediction

4.3.3.4 Track Forecast Errors:

The track forecast errors (Forecast position – Actual position of Cyclone centre) and skill as compared to Climatological and Persistence forecast are presented in Fig. 4.3.3.3 (a-b). The track forecast errors for 12, 24 and 48 hrs lead period were 61.2, 100.6, and 113.3 km respectively against the LPA errors (2015-19) of 49.6, 80.6 and 125.5 km respectively. (Fig.5a). The track forecast skill was about 63%, 67% and 78% against the LPA skill of 58%, 61%, and 73% for 12, 24 and 48 hrs lead period respectively (Fig.4.3.3.3b).

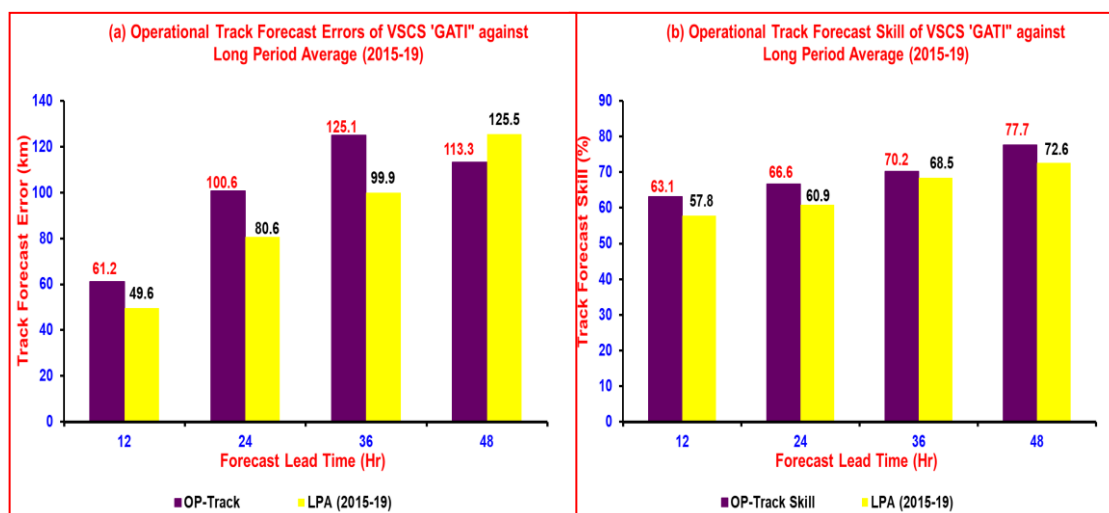


Fig.4.3.3.3: Track forecast (a) errors and (b) skill of VSCS 'GATI' as compared to long period average (2015-19)

Table 4.3.3.2: Operational track forecast errors (km) & Skill (%) compared to long period average during 2015-19

Lead Period(hrs)	No. of obs. verified	Operational Track Forecast		Long Period Average (2015-19) Track Forecast	
		Error (km)	Skill (%)*	Error (km)	Skill (%)*
12	6	61.2	63.1	49.6	57.8
24	3	100.6	66.6	80.6	60.9
36	2	125.1	70.2	99.9	68.5
48	1	113.3	77.7	125.5	73.4

* Skill is calculated by comparing the operational track forecast error with the forecast error based on climatology and persistence (CLIPER) model.

4.3.3.5 Intensity Forecast Errors:

The intensity forecast errors (Forecast wind – Actual wind) and skill based on absolute errors and root mean square errors are presented in Fig. 4.3.3.4 & 4.3.3.5 respectively.

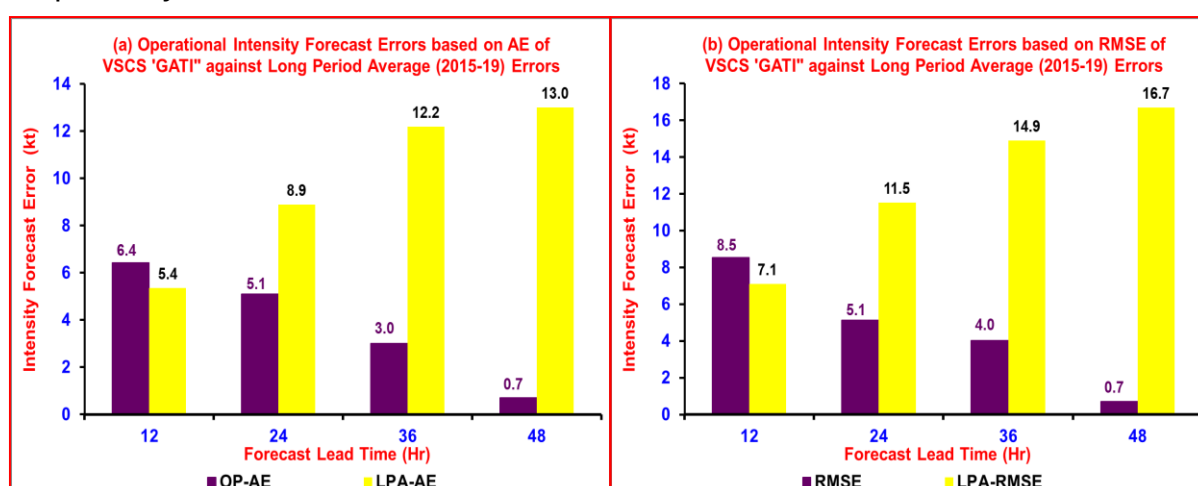


Fig. 4.3.3.4: Absolute errors (AE) and Root Mean Square errors (RMSE) in intensity forecast (winds in knots) of VSCS 'GATI' as compared to long period average (2015-19)

- The absolute error (AE) of intensity (wind) forecast for 12, 24 and 48 hrs lead period were 6.4, 5.1 and 0.7 knots against the LPA errors of 5.4, 8.9 and 13.0 knots during 2015-19 respectively (Fig. 4.3.3.4a). The root mean square error (RMSE) of intensity (wind) forecast for 12, 24 and 48 hrs lead period were 8.5, 5.1 and 0.7 knots against the LPA errors of 7.1, 11.5 and 16.7 knots respectively (Fig. 4.3.3.4b).
- The skill (%) in intensity forecast as compared to persistence forecast based on AE for 12, 24 and 48 hrs lead period was 78%, 94% and 99% against the LPA of 29%, 45% and 69% respectively (Fig. 4.3.3.5a). The skill (%) in intensity forecast based on RMSE for 12, 24 and 48 hrs lead period was 78%, 94% and 99% against the LPA of 36%, 49% and 63% respectively (Fig. 4.3.3.5b).

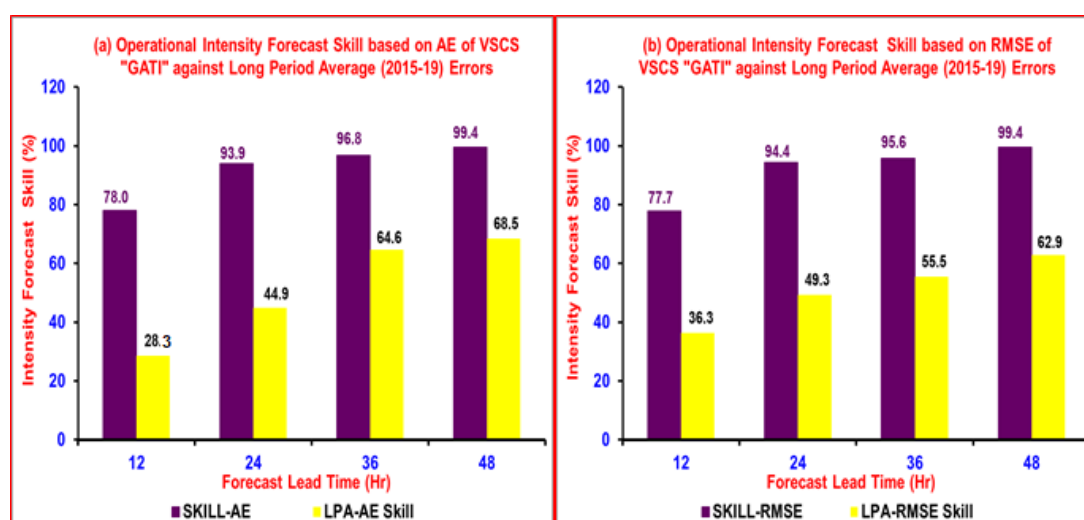


Fig. 4.3.3.5: Skill (%) in intensity forecast based on (a) AE and (b) RMSE of VSCS ‘GATI’ as compared to long period average (2015-19)

Table 4.3.3.3: Mean Intensity forecast errors (kt) and Skill (%) in association with VSCS ‘GATI’ compared to long period average errors and skill during 2015-19

Lead Period (hrs)	N	Average error in Intensity forecast (kts)		LPA (2015-19) Intensity forecast error (kts)		Operational Skill* (%) in intensity forecast		LPA (2015-19) Skill* (%) in intensity forecast	
		AE	RMSE	AE	RMSE	AE	RMSE	AE	RMSE
12	6	8.2	12.6	5.4	7.1	78.0	67.1	28.3	36.3
24	3	5.1	5.1	8.9	11.5	93.9	94.4	44.9	49.3
36	2	3.0	4.0	12.2	14.9	96.8	95.6	64.6	55.5
48	1	0.0	0.0	13.0	16.7	99.4	99.4	68.5	62.9

N: No. of observations verified; AE: Absolute Error; RMSE: Root Mean Square Error, LPA: Long Period Average (2015-19). * Skill of forecast is calculated by comparing the operational forecast error with the forecast error based on persistence method

4.3.4 Very severe cyclonic storm “NIVAR” over the Bay of Bengal (22-27 November)

4.3.4.1 Genesis, Track, Intensity and Landfall Forecast

- The extended range outlook issued on 12th November, indicated that a low pressure area would form over BoB during first half of week (20-26 November) and depression would form over south Bay of Bengal later half of the week. Actually, low pressure area formed over EIO and adjoining central parts of south BoB on 21st November and depression formed over central parts south BoB in on 23rd November. Thus, the genesis of “NIVAR” was predicted by IMD about 12 days in advance.
- The daily national bulletin issued at 1210 hrs IST of 20th November indicated that a low pressure area would form over central parts of south Bay of Bengal around 23rd November, 2020. It was also indicated that it would concentrate into a depression over southwest Bay of Bengal and move west-northwestwards towards Tamilnadu coast by 25th. Actually, the system moved northwestwards towards Tamilnadu coast and crossed the coast in the late night of 25th. Thus, track of “NIVAR” was predicted correctly by IMD about 5 days in advance.
- The first special bulletin and press release issued at 1500 hrs IST of 21st November indicated that a depression would form over southwest BoB around 23rd. It was also indicated that, it would intensify further and move west-northwestwards towards Sri Lanka-south Tamil Nadu coast and reach near Tamil Nadu & Puducherry coast on 25th November, 2020 (about 4 days and 8 hours prior to landfall near Puducherry).
- In the bulletin issued at 1130 hrs IST of 22nd November. It was indicated that the cyclone would cross Tamilnadu and Puducherry coasts between Karaikal and Mammalapuram during 25th afternoon (3 days and 12 hours prior to landfall). **For the first time IMD indicated landfall area of the cyclone, when the system was in the stage of low pressure area.**
- First information that the system would cross Tamilnadu coast close to Puducherry in the evening of 25th with a wind speed of 100-110 kmph gusting to 120 kmph was released in the bulletin issued at 0830 hrs IST of 23rd (about 2 days and 18 hours prior to landfall). The cyclone crossed coast near Puducherry during midnight of 25th to early hours of 26th November with a wind speed of about 120 kmph.
- Since 20th November, regular warnings about the heavy rainfall and strong winds were issued for the states of Tamilnadu, Puducherry and Andhra Pradesh.
- The observed and forecast track based on 0530 hrs IST of 23rd about 72 hrs prior to landfall demonstrating accuracy in track, landfall and intensity prediction is presented in Fig. 4.3.4.1. The black and red lines indicate the observed (actual) track and forecast track respectively. The closeness of these two lines indicate very accurate forecast of track (movement) and landfall point of cyclone, NIVAR.

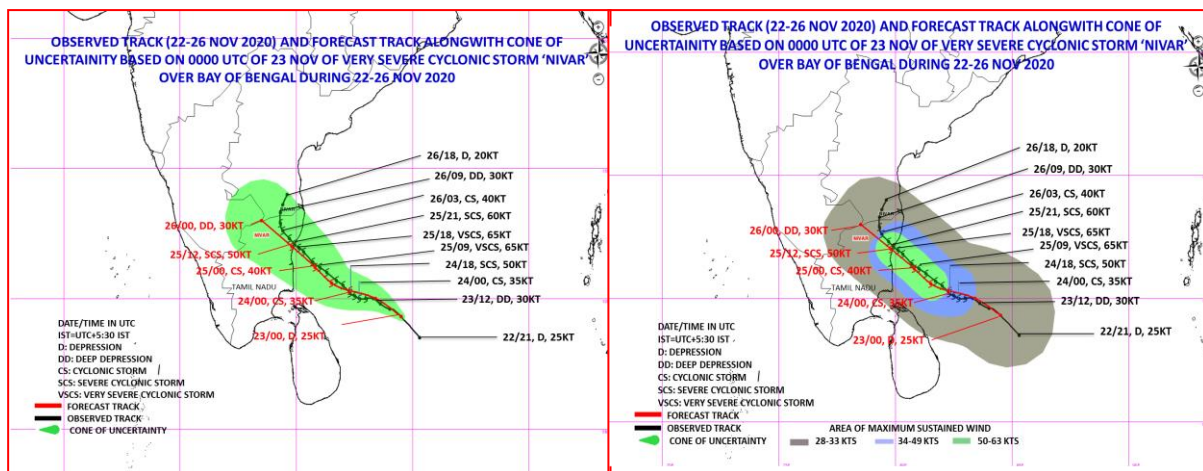


Fig 4.3.4.1: Observed and forecast track of VSCS NIVAR based on 0530 hours IST of 23rd (72hrs in advance of landfall) demonstrating accuracy in track, landfall and intensity forecast

4.3.4.2 Landfall Forecast Errors:

The landfall point and time Forecast errors compared to long period average (LPA) errors during 2015-19 are presented in Fig. 4.3.4.2 (a-b). The landfall point forecast errors for 24, 48 and 72 hrs lead period were 25, 25 and 16 km respectively against the LPA errors (2015-19) of 44.7, 69.4 and 109.3 km during 2015-19 respectively. The landfall time forecast errors for 24, 48 and 72 hrs lead period were 0.5, 5.0, and 8.5 hours respectively against the LPA errors (2015-19) of 3.0, 5.4 and 8.6 hours during 2015-19 respectively. **For all lead periods, the landfall point errors were exceptionally less than the LPA errors during 2015-19.**

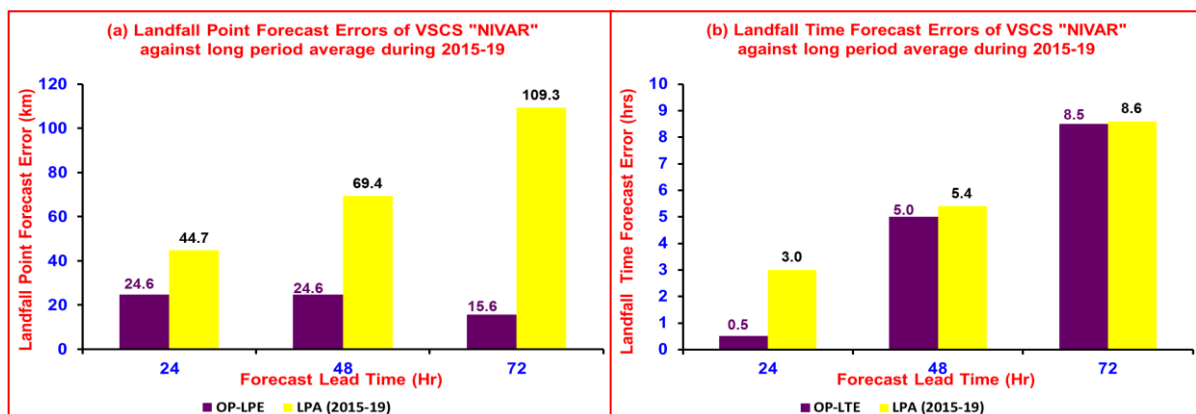


Fig. 4.3.4.2: Landfall (a) point and (b) time forecast errors of VSCS 'NIVAR' as compared to long period average (2015-19)

Table 4.3.4.1: Landfall point and time forecast errors of VSCS ‘NIVAR’ as compared to long period average (LPA) errors during 2015-19

Lead Period (hrs)	Base Time	Landfall Point ($^{\circ}$ N/ $^{\circ}$ E)		Landfall Time (hours)		Operational Error		LPA error (2015-19)	
		Forecast	Actual	Forecast	Actual	LPE (km)	LTE (hours)	LPE (km)	LTE (hours)
24	25/00	11.9/ 79.8	12.1/79.9	25/1930	25/2000	24.6	0.5	44.7	3.0
48	24/00	11.9/ 79.8	12.1/79.9	25/1400	25/2000	24.6	5.0	69.4	5.4
72	23/00	12/ 79.8	12.1/79.9	25/1130	25/2000	15.6	8.5	109.3	8.6

“+” indicates delayed prediction and “-” indicates early prediction

4.3.4.3 Track Forecast Error and Skill

The track forecast errors (Forecast position – Actual position of Cyclone centre) and skill as compared to Climatological and Persistence forecast are presented in Fig. 4.3.4.3 (a-b). The track forecast errors for 24, 48 and 72 hrs lead period were 86.1, 126.8, and 185.0 km respectively against the LPA errors (2015-19) of 80.6, 125.5, and 171.2 km respectively (Fig. 4.3.4.3a). The track forecast skill was about 61%, 72%, and 79% against the LPA skill of 61%, 73%, and 74% for 24, 48 and 72 hrs lead period respectively (Fig. 4.3.4.3b).

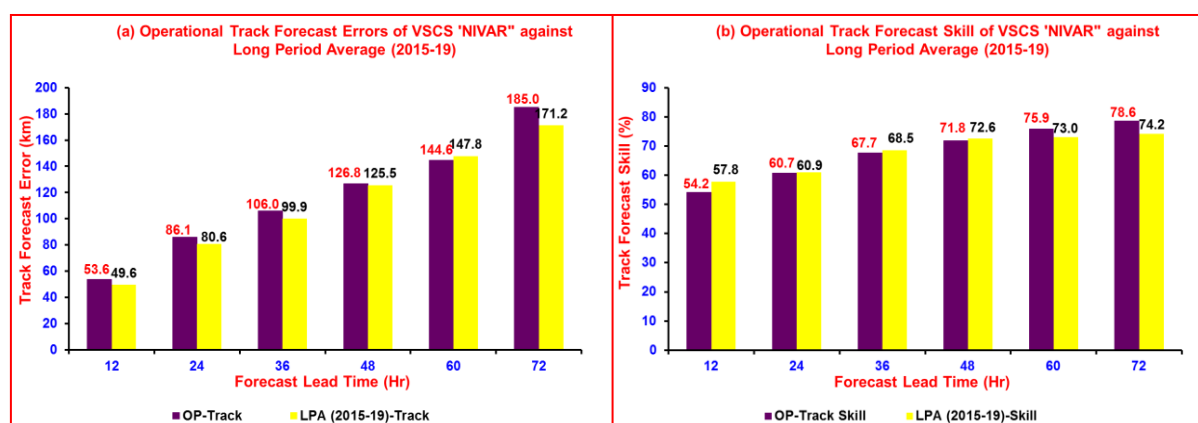


Fig. 4.3.4.3: Track forecast (a) errors and (b) skill of VSCS ‘NIVAR’ as compared to long period average (2015-19)

Table 4.3.4.2: Operational track forecast errors (km) & Skill (%) compared to long period average during 2015-19

Lead Period(hrs)	No. of obs. verified	Operational Track Forecast		Long Period Average (2015-19) Track Forecast	
		Error (km)	Skill (%)*	Error (km)	Skill (%)*
12	14	53.6	54.2	49.6	57.8
24	11	86.1	60.7	80.6	60.9
36	10	106.0	67.7	99.9	68.5
48	8	126.8	71.8	125.5	72.6
60	6	144.6	75.9	147.8	73.0
72	4	185.0	78.6	171.2	74.2

* Skill is calculated by comparing the operational track forecast error with the forecast error based on climatology and persistence (CLIPER) model.

4.3.4.3 Intensity Forecast Error and skill

The intensity forecast errors (Forecast wind – Actual wind) and skill based on absolute errors and root mean square errors are presented in Fig. 4.3.4.4 & 4.3.4.5 respectively.

The absolute error (AE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 4.3, 6.5 and 10.2 knots against the LPA errors of 8.9, 13.0, and 15.4 knots during 2015-19 respectively (Fig. 4.3.4.4a). The root mean square error (RMSE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 5.0, 9.2 and 11.8 knots against the LPA errors of 11.5, 16.7, and 19.2 knots respectively (Fig. 4.3.4.4b).

The skill (%) in intensity forecast as compared to persistence forecast based on AE for 24, 48 and 72 hrs lead period was 79%, 76% and 59% against the LPA of 45%, 69% and 72% respectively (Fig. 4.3.4.5a). The skill (%) in intensity forecast based on RMSE for 24, 48 and 72 hrs lead period was 82%, 75% and 65% against the LPA of 49%, 63% and 76% respectively (Fig. 4.3.4.5b).

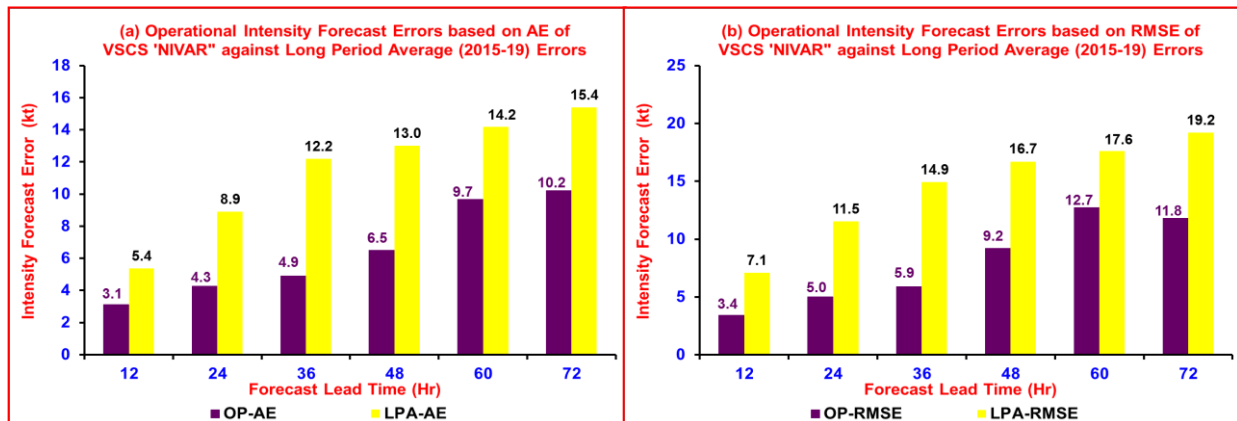


Fig. 4.3.4.4: Absolute errors (AE) and Root Mean Square errors (RMSE) in intensity forecast (winds in knots) of VSCS 'NIVAR' as compared to long period average (2015-19)

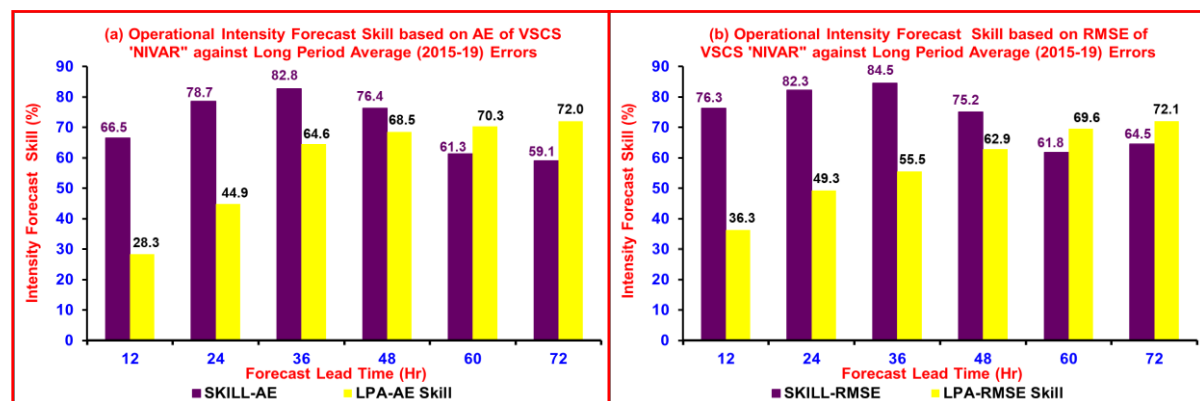


Fig. 4.3.4.5: Skill (%) in intensity forecast based on (a) Absolute errors (AE) and (b) Root Mean Square errors (RMSE) of VSCS 'NIVAR' as compared to long period average (2015-19) updated

Table 4.3.4.3: Mean Intensity forecast errors (kt) and Skill (%) in association with VSCS ‘NIVAR’ compared to long period average errors and skill during 2015-19

Lead Period (hrs)	N	Average error in Intensity forecast (kts)		LPA (2015-19) Intensity forecast error (kts)		Operational Skill* (%) in intensity forecast		LPA (2015-19) Skill* (%) in intensity forecast	
		AE	RMSE	AE	RMSE	AE	RMSE	AE	RMSE
12	14	3.1	3.4	5.4	7.1	66.5	76.3	28.3	36.3
24	11	4.3	5.0	8.9	11.5	78.7	82.3	44.9	49.3
36	10	4.9	5.9	12.2	14.9	82.8	84.5	64.6	55.5
48	8	6.5	9.2	13.0	16.7	76.4	75.2	68.5	62.9
60	6	9.7	12.7	14.2	17.6	61.3	61.8	70.3	69.6
72	4	10.2	11.8	15.4	19.2	59.1	64.5	72.0	72.1

N: No. of observations verified; AE: Absolute Error; RMSE: Root Mean Square Error, LPA: Long Period Average (2015-19). * Skill of forecast is calculated by comparing the operational forecast error with the forecast error based on persistence method

4.3.4.4 Adverse weather forecast verification

The verification of adverse weather like heavy rainfall, gale wind and storm surge forecast issued by IMD are presented in Table 4.3.4.4 - 6. It is found that all the three types of adverse weather were predicted accurately and well in advance.

Table 4.3.4.4: Verification of Heavy Rainfall Forecast

Date/Base Time of observation	24 hr Heavy rainfall warning ending at 0300 UTC of next day	Realised 24-hour heavy rainfall ending at 0300 UTC of date
23.11.2020/0300UTC	Fairly widespread to widespread rainfall/thunderstorm activity very likely over Tamilnadu, Puducherry & Karaikal during 24 th to 26 th November and over south Coastal Andhra Pradesh, Rayalaseema during 25 th to 26 th and Telangana during 26 th to 27 th November, 2020. Isolated extremely heavy rainfall activity also very likely over Tamilnadu & Puducherry (Pudukottai, Thanjavur, Tiruvarur, Karaikal,	24 November 2020 Tamilnadu, Puducherry & Karaikal: Tambaram-9, Mgr Nagar, Chennai-8 each, Chennai, Alandur-7 each. 25 November 2020 Tamilnadu, Puducherry & Karaikal: Chennai (N)-16, Anna University, Chennai, Sholinganallur-15 each, Taramani, Anna University, dgp Office, Mgr Nagar-14 each, Mahabalipuram, Alandur, Hindusthan University, Puzhal, Chembarambakkam-12 each, Tambaram, Ambathur-11 each, Perambur,

	Nagapattinam, Cuddalore, Ariyalur & Perabalu districts during 24 th and Kadalur, Kallakurchi, Puducherry, Villupuram, Tiruvannamalai, Chengalpattu to Ariyalur, Perambalur and Karaikal districts during 25 th) and over south Coastal Andhra Pradesh & Rayalaseema (Nellore and Chittoor districts) on 25 th & 26 th and over Telangana on 26 th November, 2020.	Chembarabakkam, Red Hills, Kolapakkam, Poonamallee-10 each, Ennore, Thirupporur, Cholavaram-9 each, Maduranthagam, Kelambakkam-8 each, Sriperumbudur-7. 26 November 2020 Andhra Pradesh: Kodur-25, Venkatagiri-24, Gudur-19, Rapur-16, Atmakur, Sullurpeta-15 each, Nellore, Kavali, Satyavedu, Sambepalle-14 each, Nagari, Rajampet, Tirupati-13 each, Thottambedu, Puttur-12 each, Palamaner, Srikalahasti, Tada-11 each, Penagaluru, Kalakada-10 each, Palasamudram, Royachoti, Amalapuram-9 each, Vinjamur, Udayagiri, Pullampeta, Pakala-8 each, Chittoor, Chinnamandem, Cuddapah, Madanapalle-7 each. Tamilnadu, Puducherry & Karaikal: Tambaram-31, Pondicherry-30, Vilupuram-28, Cuddalore-27, DGP Office, Chennai-26, Sholinganallur-22, Thamarapakkam-19, Parangipettai-18, Pallipattu-17, Cholavaram-16, Gingee, Poonamallee, Ambathur, Tiruvallur, Mahabalipuram, Gummidipoondi-15 each, Tindivanam, Maduranthagam, Chembarabakkam, Anna University, Vanur, Kollidam, Bhuvanagiri-14 each, Mgr Nagar, Kancheepuram, Kurinjipadi, Alandur, Chidambaram, Red Hills, Marakkanam, Chengalpattu, Tiruttani, Chidambaram-13 each, Ulundurpet, Poondi, Keelpennathur, Vadapudupattu, Koratur, Sirkali-12 each, Chennai Airport, Vandavasi, Sethiyathope, Vembakkam, Poonamalle-11, Arakonam, Thirukalukundram,
24.11.2020/0300	Fairly widespread to widespread rainfall/thunderstorm activity very likely over coastal and north interior Tamilnadu, Puducherry & Karaikal during 24 th to 26 th November and over south coastal Andhra Pradesh, Rayalaseema during 25 th to 26 th and southeast Telangana during 26 th November, 2020. Isolated extremely heavy rainfall activity also very likely over coastal & north interior Tamilnadu & Puducherry (Pudukottai, Thanjavur, Tiruvarur, Karaikal, Nagapattinam, Cuddalore, Ariyalur & Perabalu districts during 24 th and Kadalur, Kallakurchi, Puducherry, Villupuram, Tiruvannamalai, Chengalpattu to Ariyalur,	

	Perambalur and Karaikal districts during 25 th) and over Nellore and Chittoor districts of Andhra Pradesh on 25 th and over Rayalseema & southeast Telangana on 26 th November, 2020.	Sriperumbudur, Panruti-11 each, Ponneri, Arcot, Taramani, Perambur, Uthiramerur, Sholingur, Cheyyur-10 each, Anna University, Chembarambakkam, Thiruvallangadu, Tirukoilur, Polur, Mayiladuthurai, Thirupporur, Kelambakkam, Karaikal, Manalmedu, Puzhal-9 each, Arani, Chennai (Nungambakkam), Vridhachalam, Vepur, Hindusthan University, Ammundi, Vellore, R.K.Pet, Kodavasal, Manjalaru-8 each, Uthukottai, Ambur, Kaveripakkam, Agaram Seegoor, Tiruttani, Tozhudur, Tarangambadi, Pelandurai, Tiruvannamalai, Srimushnam, Ennore, Needamangalam, Sendurai, Katpadi, Cheyyar, Aduthurai-7 each.
25.11.2020/0300	Fairly widespread to widespread rainfall/thunderstorm activity very likely over coastal and north interior Tamilnadu, Puducherry & Karaikal, south coastal Andhra Pradesh and Rayalaseema during 25th and 26th November and southeast Telangana on 26th November, 2020. Isolated extremely heavy rainfall activity also very likely over coastal & north interior Tamilnadu; Puducherry (Thanjavur, Tiruvarur, Nagapattinam, Cuddalore, Chennai, Kanchipuram, Chengalpattu, Myladuthirai, Ariyalur, Perambalur, Kallakurchi, Villupuram, Tiruvannamalai, Puducherry and Karaikal districts) during 25th ; over Nellore and Chittoor districts of Andhra Pradesh on 25th and over Rayalaseema & southeast Telangana on 26th November, 2020.	27 November 2020 Andhra Pradesh: Kavali-27, Nambulipulikunta-25, Gurramkonda-21, Sambepalle-20, Royachoti, Madanapalle, Chinnamandem, Kalakada-18 each, Punganur, Udayagiri, Vinjamur- 17 each, Atmakur, Pullampeta, Thambalapalle, Palamaner-16 each, Chapad, Chittoor, Proddutur, Arogyavaram, Avanigada, Ongole, Amalapuram-15 each, Yanam, Marripudi, Podili, Veligandla, Kandukur, Utukuru(A), Vempalle, Kamalapuram-14 each, Atlur-13, Kakinada, Palakoderu, Cuddapah -12 each, Bheemavaram, Bapatla, Vijayawada Airport, Gudivada, Narsapuram, Chimakurthi, Duvvur-11, Raju Palem, Pakala, Palasamudram-11 each, Vallur, Kodur, Rajampet, Karamchedu, Repalle, Seetharamapuram, Tanuku-10 each, Mundlamuru, Addanki, Mangalagiri,
26.11.2020/0300	Rainfall at most/many places with heavy to very heavy falls at a few places and isolated extremely heavy falls likely to occur over Chittoor, Kurnool, Prakasam; Cuddappa districts of Andhra Pradesh and adjoining southeast Telangana on 26th Nov. Heavy to very heavy rainfall at isolated places are very likely	

	over north Tamilnadu, remaining districts of Andhra Pradesh and southeast Telangana.	Tadepalligudem, Masulipatnam, Peddapuram, Kaikalur, Jammalamadugu, Badvel, Porumamilla, Puttur-9 each, Pulivendla, Muddanur, Lakkireddipalle, Konakanamitla, Cumbum, Bestavaripeta, Markapur, Nellore, Darsi-8 each, Vijayawada, Tuni, Anakapalle, Rapur, Santhamaguluru, Guntur, Bhimadole, Racherla, Prathipadu, Visakhapatnam, Eluru, Penagaluru, Kadiri, Tanakal, Venkatagiri Kota-7 each.
27.11.2020/0000 UTC	Light to moderate rainfall at many places with heavy falls at isolated places is likely over coastal Andhra Pradesh during next 24 hours.	Tamilnadu, Puducherry & Karaikal: Sholingur-23, Vadapudupattu-16, Vellore, Ponnai Dam, Ammundi-14 each, Ambur, R.K.Pet-13 each, Alangayam, Katpadi-12 each, Vaniyambadi, Tirupuvanam, Kaveripakkam-9 each, Wallajah, Gudiyatham, Virinjipuram-8 each, Devakottai, Vembakkam, Melalathur-7 each.

Table 4.3.4.5: Verification of Gale/Squally Wind Forecast issued by IMD

Date/Base Time of observation	Gale/ Squally wind Forecast at 0300 UTC of date	Realised wind
24.11.2020/0300UTC	- Gale wind speed reaching 70-80 kmph gusting to 90 kmph is prevailing over Southwest Bay of Bengal. It would further increase becoming 100-110 kmph gusting to 120 kmph over the southwest Bay of Bengal from 25th November morning for subsequent 18 hours. - Squally wing speed reaching 30-40 kmph gusting to 50 kmph is prevailing along & off Tamil Nadu, Puducherry and adjoining South Andhra Pradesh coast and over Gulf of Mannar. It will gradually increase and become 100-110 kmph gusting to 120 kmph along & off coastal districts of north Tamil Nadu and Puducherry (Nagapattinam, Karaikal, Myladuthurai, Cuddalore, Puducherry,	It crossed Tamilnadu & Puducherry coasts as a very severe cyclonic storm with estimated wind speed of 120 kmph gusting to 135 kmph

	Villupuram; Chengalpattu districts; 80-90 gusting to 100 kmph very likely over Tiruvarur, Kanchipuram, Chennai, Tiruvallur districts) during forenoon to night of 25th November, 2020. • Gale wind speed reaching 65-75 kmph gusting to 85 kmph very likely over adjoining westcentral Bay of Bengal and along & off South Andhra Pradesh (Nellore & Chittoor districts), Gulf of Mannar and along and off districts of south coastal districts of Tamil Nadu during forenoon to night of 25th November, 2020.	
25.11.2020/0300UTC	Gale wind speed reaching 105-115 kmph gusting to 130 kmph is prevailing over Southwest Bay of Bengal. It would further increase becoming 120-130 kmph gusting to 145 kmph during afternoon of 25th to early hours of 26th November. □ Squally wind speed reaching 55-65 kmph gusting to 75 kmph is prevailing along & off Tamil Nadu, Puducherry and adjoining South Andhra Pradesh coast and over Gulf of Mannar. It will gradually increase and become gale wind speed reaching 120-130 kmph gusting to 145 kmph along & off coastal districts of north Tamil Nadu and Puducherry (Nagapattinam, Karaikal, Myladuthurai, Cuddalore, Puducherry, Villupuram & Chengalpattu) and 80-90 gusting to 100 kmph very likely over Tiruvarur, Kanchipuram, Chennai, Tiruvallur districts during afternoon of 25th to early hrs of 26th November, 2020. □ Gale wind speed reaching 65-75 kmph gusting to 85 kmph very likely over adjoining westcentral Bay of Bengal and along & off South Andhra Pradesh (Nellore & Chittoor districts), Gulf of Mannar and along and off south coastal districts of Tamil Nadu during afternoon of 25th to early hrs of 26th November, 2020.	
26.11.2020/0300UTC	Gale wind speed reaching 70-80 kmph gusting to 90 kmph is prevailing over Southwest Bay of Bengal. It will gradually decrease becoming 50-60 kmph gusting to 70 kmph by evening of today, the 26 th November, 2020. □ Gale wind speed reaching 70-80 kmph	

	gusting to 90 kmph is prevailing along & off Puducherry, Villupuram, Chengalpattu, Kanchipuram, Chennai & Tiruvallur districts of north Tamil Nadu. It will gradually decrease becoming 50-60 kmph gusting to 70 kmph by evening and squally wind speed reaching 35-45 kmph gusting to 55 kmph by night of today, the 26 th November, 2020. □ Squally wind speed reaching 45-55 gusting to 65 kmph very likely to prevail over interior districts (Ranipet, Tiruvannamalai, Tirupattur, Vellore) of Tamilnadu and Chittoor district of Andhra Pradesh till noon of today, 26th November, 2020 and gradual decrease thereafter. □ Squally wind speed reaching 35-45 gusting to 55 kmph very likely over Nagapattinam, Karaikal, Myladuthurai, Cuddalore & Tiruvarur districts of Tamilnadu during next 06 hours and gradual decrease thereafter.	
27.11.2020/0000UTC (last bulletin)	□ Squally wind speed reaching 40-50 kmph gusting to 60 kmph is likely to prevail over westcentral Bay of Bengal and along & off south Andhra Pradesh coast during next 12 hours.	

Table 4.3.4.6: Verification of Storm Surge Forecast issued by IMD

Date/Base Time of observation	Storm Surge Forecast at 0300 UTC of date	Realised surge
24.11.2020/0300UTC	□ Tidal wave of about 1m height above the astronomical tide is very likely to inundate the low lying areas of north coastal districts of Tamilnadu & Puducherry near the place of landfall.	No report of any significant Storm surge
25.11.2020/0300UTC	Tidal wave of about 1-1.5m height above the astronomical tide is very likely to inundate the low lying areas of north coastal districts of Tamilnadu & Puducherry near the place of landfall.	

4.3.5 Cyclonic Storm “BUREVI” over the Bay of Bengal (30th November - 05th December 2020)

4.3.5.1 Genesis Forecast

- The extended range outlook issued on 26th November, indicated that there is a ‘High’ (68 – 100 %) probability for cyclogenesis over southwest Bay of Bengal during the second half of week (27th November – 03rd December). Actually, the Depression formed over southeast BoB on 30th November.
- First information that a low pressure area would form over southeast Bay of Bengal around 28th November with high (76-100%) probability of its intensification into depression around 30th was issued in the Tropical Weather Outlook at 1130 hrs IST of 27th November. Actually low pressure area formed over south Andaman Sea on 28th November (0830 hrs IST) and it concentrated into a depression over southwest Bay of Bengal on 30th (0530 hrs IST).
- The information that a low pressure area would form over southeast Bay of Bengal around 29th November was also provided in the Press Release issued at 1600 hrs IST of 27th November. All warnings w.r.t. heavy rainfall, strong wind, state of Sea and advisory for fishermen was issued in the Press Release. Extremely heavy rainfall warning over Tamil Nadu & Puducherry on 2nd & 3rd December was also indicated in the Press Release. Special bulletins were issued by Area Cyclone Warning Centre, Chennai and Cyclone Warning Centre, Thiruvananthapuram also.
- In the first Press Release issued on 27th November, it was also indicated that the system would intensify further and move towards Tamil Nadu-Puducherry coasts.

4.3.5.2 Track, Intensity and Landfall Forecast

- The bulletin issued at 0930 hrs IST of 30th, indicated that the system would intensify upto cyclonic storm stage, cross Sri Lanka coast between 7.5° & 9.0° N around evening of 2nd December. It was also indicated that the system would emerge into Gulf of Mannar and Comorin area on 3rd December morning. Actually, the system crossed Sri Lanka coast as a cyclonic storm near 08.85 N and Log 81.0 E during 2230 – 2330 UTC of 02nd December 2020. It emerged into Gulf of Mannar during forenoon of 3rd December.
- The warnings were further updated and at 0210 hrs IST of 1st December, it was indicated that the system would emerge into Gulf of Mannar- Comorin area on 3rd December morning and move towards south Tamil Nadu coast.
- The warnings were further updated and at 1430 hrs IST of 1st December, it was indicated that the system would emerge into Gulf of Mannar and adjoining Comorin area on 3rd December morning and cross south Tamil Nadu coast between Kanniyakumai and Pamban around early morning of 4th December.

- At 1130 hrs IST of 2nd December, it was further indicated that the system would be centered very close to Pamban around noon of 3rd December and its impact over Ramanathapuram district will commence from 3rd December forenoon.
- The observed and forecast track of cyclonic storm “BUREVI” based on 0000 UTC of 30th November and 0000 UTC of 2nd December along with cone of uncertainty and wind distribution are presented in Fig. 4.3.5.1 and Fig. 4.3.5.2.

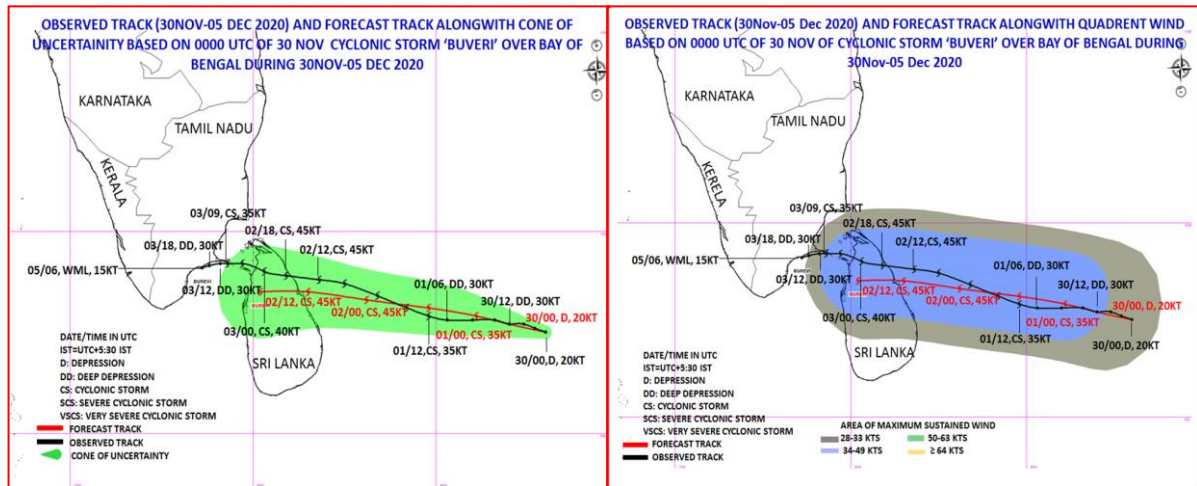


Fig 4.3.5.1: The observed and forecast track of cyclonic storm “BUREVI” based on 0000 UTC of 30th November demonstrating accuracy in landfall, track and intensity prediction (about 60 hrs prior to landfall over Sri Lanka)

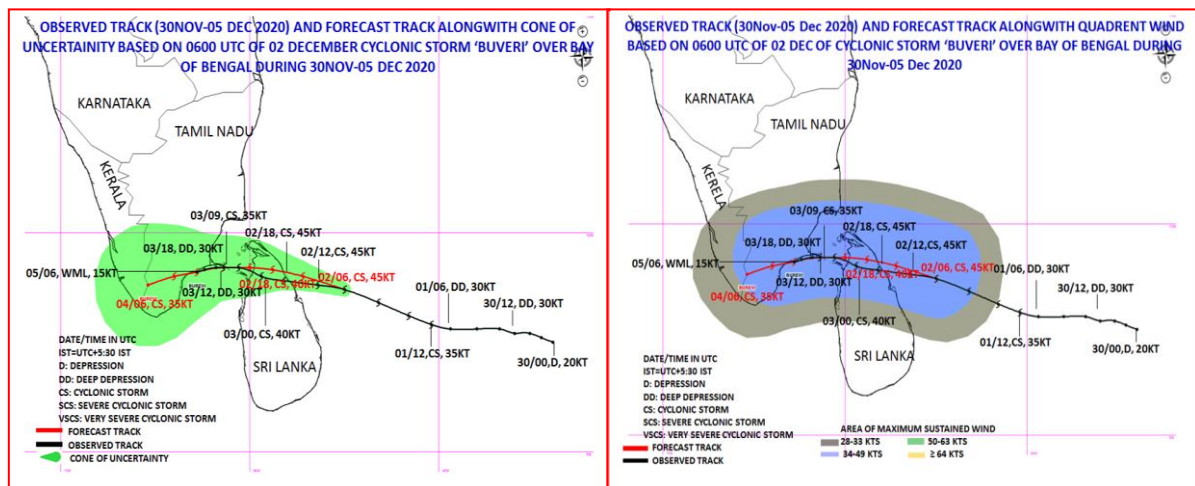


Fig. 4.3.5.2: The observed and forecast track of cyclonic storm “BUREVI” based on 0600 UTC of 2nd December demonstrating accuracy in landfall, track and intensity prediction (about 24 hrs prior to landfall over Pamban Area)

4.3.5.3 Landfall Forecast Errors

Cyclonic storm ‘BUREVI’ made landfall over Sri Lanka coast close to north of Trincomalee near latitude 08.85°N and longitude 81.0°E , during 1700 – 1800 UTC of

02nd December 2020 and Pamban area near latitude 09.2⁰N and longitude 79.35⁰ E during 0800 UTC of 03rd December 2020.

The landfall point and time forecast errors compared to long period average (LPA) errors during 2015-19 for landfall over Sri Lanka are presented in Fig. 11 (a-b). The landfall point forecast errors for 12, 24, 48 and 60 hrs lead period were 20, 25, 35 and 44 km respectively against the LPA errors (2015-19) of 25, 45, 69 and 99 km during 2015-19 respectively. The landfall time forecast errors for 12, 24, 48 and 60 hrs lead period were 1.5, 4.0, 2.0 and 3.0 hours respectively against the LPA errors (2015-19) of 1.5, 3.0, 5.4 and 5.5 hours during 2015-19 respectively. **For all lead periods, the landfall point and time errors were exceptionally less than the LPA errors during 2015-19.**

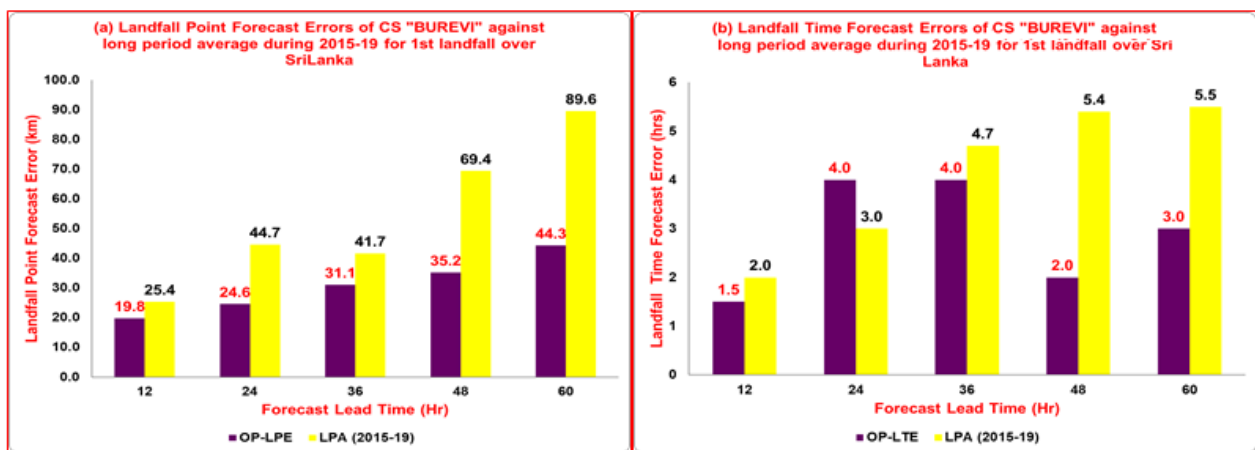


Fig. 4.3.5.3: Landfall (a) point and (b) time forecast errors of CS 'BUREVI' as compared to long period average (2015-19) for landfall over Sri Lanka

Table 4.3.5.1(a): Landfall point and time forecast errors CS 'BUREVI' as compared to long period average (2015-19) for landfall over Sri Lanka

Lead Period (hrs)	Base Time	Landfall Point (⁰ N/ ⁰ E)		Landfall Time (hours)		Operational Error		LPA error (2015-19)	
		Forecast	Actual	Forecast	Actual	LPE (km)	LTE (hours)	LPE (km)	LTE (hours)
12	02/00	9/ 80.9	8.85/81	02/1600	02/1730	19.8	1.5	25.4	2.0
24	01/12	8.75/ 81.2	8.85/81	02/1330	02/1730	24.6	4.0	44.7	3.0
36	01/00	8.65/ 81.2	8.85/81	02/1330	02/1730	31.1	4.0	41.7	4.7
48	30/12	8.6/ 81.2	8.85/81	02/1530	02/1730	35.2	2.0	69.4	5.4
60	30/00	8.5/ 81.2	8.85/81	02/1430	02/1730	44.3	3.0	89.6	5.5

“+” indicates delayed prediction and “-” indicates early prediction

The landfall point and time forecast errors for second landfall of “BUREVI” over Pamban area compared to long period average (LPA) errors during 2015-19 are presented in Fig. 12 (a-b). The landfall point forecast errors for 12, 24 and 48 hrs lead period were 0, 0 and 150 km respectively against the LPA errors (2015-19) of 25, 45 and 69 km during 2015-19 respectively. The landfall time forecast errors for 12, 24 and 48 hrs lead period were 1.0, 2.5, and 8.0 hours respectively against the

LPA errors (2015-19) of 2.0, 3.0, and 5.4 hours during 2015-19 respectively. The landfall over Pamban area could be successfully predicted **24 hours prior to landfall** and the errors in prediction were exceptionally less than the LPA errors during 2015-19.

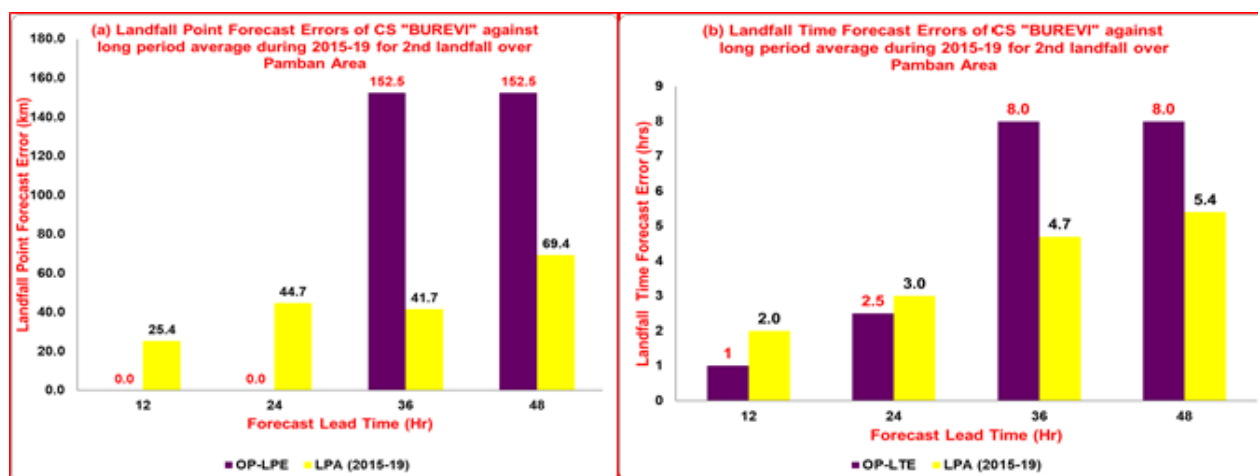


Fig. 4.3.5.4: Landfall (a) point and (b) time forecast errors of CS 'BUREVI' as compared to long period average (2015-19) for landfall over Pamban Area

Table 4.3.5.1(b): Landfall point and time forecast errors CS 'BUREVI' as compared to long period average (2015-19) for landfall over Pamban Area

Lead Period (hrs)	Base Time	Landfall Point (⁰ N/ ⁰ E)		Landfall Time (hours)		Operational Error		LPA error (2015-19)	
		Forecast	Actual	Forecast	Actual	LPE (km)	LTE hours	LPE (km)	LTE (hours)
12	02/18	9.2/ 79.35	9.20/79.35	03/0700	03/0800	0.0	1	25.4	2.0
24	02/06	9.2/ 79.35	9.20/79.35	03/0530	03/0800	0.0	2.5	44.7	3.0
36	01/18	8.6/ 78.10	9.20/79.35	04/0000	03/0800	152.5	8.0	41.7	4.7
48	01/06	8.6/ 78.10	9.20/79.35	04/0000	03/0800	152.5	8.0	69.4	5.4

“+” indicates delayed prediction and “-” indicates early prediction

4.3.5.3 Track Forecast Errors:

The track forecast errors (Forecast position – Actual position of Cyclone centre) and skill as compared to Climatological and Persistence forecast are presented in Fig. 13 (a-b). The track forecast errors for 24, 48 and 72 hrs lead period were 55.3, 61.6, and 131.2 km respectively against the LPA errors (2015-19) of 80.6, 125.5, and 171.2 km respectively (Fig. 4.3.5.5a). The track forecast skill was about 67%, 78%, and 72% against the LPA skill of 61%, 73%, and 74% for 24, 48 and 72 hrs lead period respectively (Fig. 4.3.5.5b).

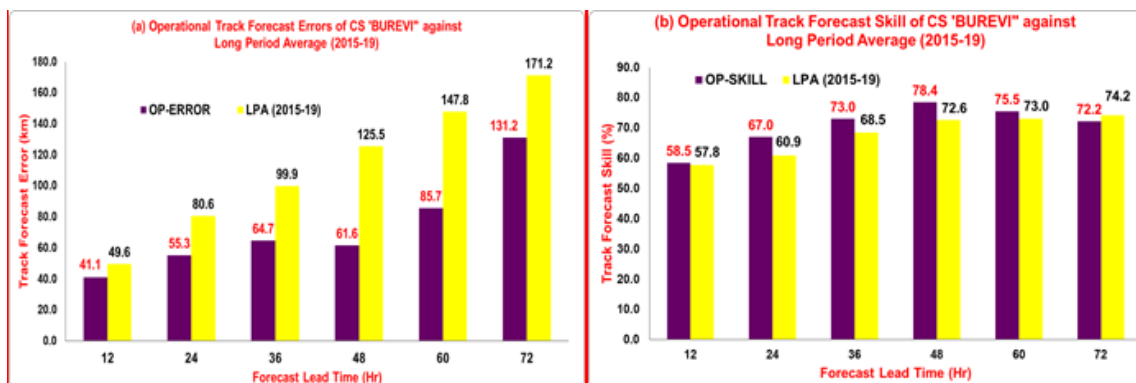


Fig. 4.3.5.5: Track forecast (a) errors and (b) skill of CS 'BUREVI' as compared to long period average (2015-19)

Table 4.3.5.2: Operational track forecast errors (km) & Skill (%) compared to long period average during 2015-19

Lead Period(hrs)	No. of obs. verified	Operational Track Forecast		Long Period Average (2015-19) Track Forecast	
		Error (km)	Skill (%)*	Error (km)	Skill (%)*
12	17	41.1	64.9	49.6	57.8
24	15	55.3	74.7	80.6	60.9
36	14	64.7	80.3	99.9	68.5
48	12	61.6	86.3	125.5	72.6
60	10	85.7	85.7	147.8	73.0
72	8	131.2	84.8	171.2	74.2

* Skill is calculated by comparing the operational track forecast error with the forecast error based on climatology and persistence (CLIPER) model.

4.3.5.4 Intensity Forecast Errors:

The intensity forecast errors (Forecast wind – Actual wind) and skill based on absolute errors and root mean square errors are presented in Fig. 4.3.5.6 & 4.3.5.7 respectively. The absolute error (AE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 4.2, 4.7 and 9.3 knots against the LPA errors of 8.9, 13.0, and 15.4 knots during 2015-19 respectively (Fig. 4.3.5.6a). The root mean square error (RMSE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 5.2, 5.9 and 9.7 knots against the LPA errors of 11.5, 16.7, and 19.2 knots respectively (Fig. 4.3.5.6b).

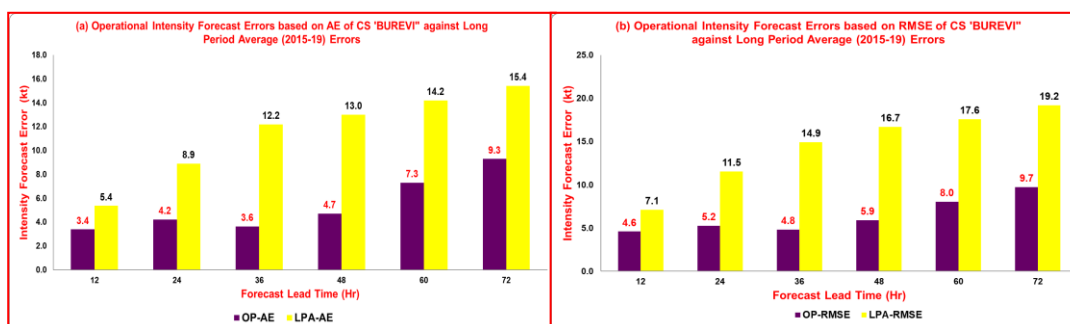


Fig. 4.3.5.6: Absolute errors(AE) and Root Mean Square errors(RMSE) in intensity forecast (winds in knots) of CS 'BUREVI' as compared to long period average (2015-19)

The skill (%) in intensity forecast as compared to persistence forecast based on AE for 24, 48 and 72 hrs lead period was 47%, 78% and 66% against the LPA of 45%, 69% and 72% respectively (Fig. 4.3.5.7a). The skill (%) in intensity forecast based on RMSE for 24, 48 and 72 hrs lead period was 56%, 70% and 77% against the LPA of 49%, 63% and 76% respectively (Fig. 4.3.5.7b).

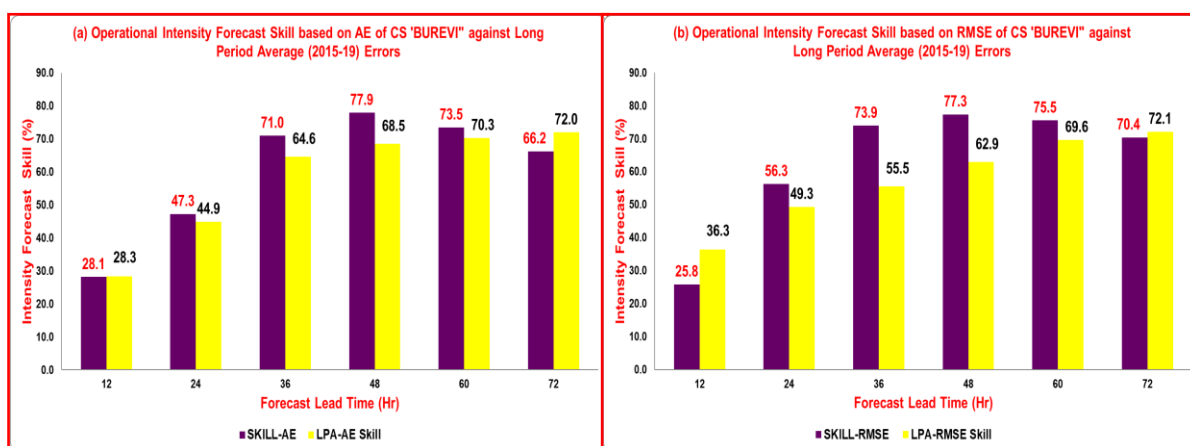


Fig. 4.3.5.7: Skill (%) in intensity forecast based on (a) Absolute errors (AE) and (b) Root Mean Square errors (RMSE) of CS 'BUREVI' as compared to long period average (2015-19)

Table 4.3.4.3: Mean Intensity forecast errors (kt) and Skill (%) in association with CS 'BUREVI' compared to long period average errors and skill during 2015-19

Lead Period (hrs)	N	Average error in Intensity forecast (kts)		LPA (2015-19) Intensity forecast error (kts)		Operational Skill* (%) in intensity forecast		LPA (2015-19) Skill* (%) in intensity forecast	
		AE	RMSE	AE	RMSE	AE	RMSE	AE	RMSE
12	17	3.4	4.6	5.4	7.1	28.1	25.8	28.3	36.3
24	15	4.2	5.2	8.9	11.5	47.3	56.3	44.9	49.3
36	14	3.6	4.8	12.2	14.9	71.0	73.9	64.6	55.5
48	12	4.7	5.9	13.0	16.7	77.9	77.3	68.5	62.9
60	10	7.3	8.0	14.2	17.6	73.5	75.5	70.3	69.6
72	8	9.3	9.7	15.4	19.2	66.2	70.4	72.0	72.1

N: No. of observations verified; AE: Absolute Error; RMSE: Root Mean Square Error, LPA: Long Period Average (2015-19). * Skill of forecast is calculated by comparing the operational forecast error with the forecast error based on persistence method

4.3.5.5 Adverse weather forecast verification

The verifications of adverse weather like heavy rainfall, gale wind and storm surge forecast issued by IMD are presented in Tables 4.3.5.4 - 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	24 hr Heavy rainfall warning ending at 0300 UTC of next day	Realised 24-hour heavy rainfall ending at 0300 UTC of date
30.11.2020/0300UTC	• Heavy to very heavy rainfall at a few places with isolated Extremely heavy falls very likely over south Tamilnadu(Kanniyakumari, Tirunelveli, Thoothukudi, Tenkasi, Ramanathapuram and Sivagangai; south Kerala(Thiruvananthapuram, Kollam, Pathanamthitta and Alappuzah) on 2nd and 3rd December, 2020 and Isolated heavy to very heavy rainfall likely over these regions on 1st and 4th December 2020. • Heavy to very heavy rainfall at Isolated places very likely over north Tamilnadu, Puducherry, Mahe & Kariakal and north Kerala during 2 nd and 3rd December, 2020 and isolated heavy rainfall during 1st and 4th December. • Heavy rainfall at isolated places very likely over south Coastal Andhra Pradesh during 2 nd & 03rd December and over Lakshadweep during 03rd and 4th December, 2020.	<u>2nd December:</u> Vedaranyam (dist Nagapattinam) - 20, Karaikal (dist Karaikal)- 16, Thalaigaiyay (dist Nagapattinam) & Tirupoondi (dist Nagapattinam) -15 each, Nagapattinam (dist Nagapattinam)- 14, Thiruthuraipoondi (dist Tiruvarur) -13, Mayiladuthurai (dist Nagapattinam) , Rameswaram (dist Ramanathapuram)- 12 each, Mudukulatur (dist Ramanathapuram) - 11, Sirkali (dist Nagapattinam), Kodavasal (dist Tiruvarur) , Adirampatnam (dist Thanjavur) , Manjalaru (dist Thanjavur) - 10 each, Tiruvarur (dist Tiruvarur) ,Aduthurai (dist Thanjavur) , Tambaram (dist Chengalpattu) , Pattukottai (dist Thanjavur) - 9 each, Nannilam (dist Tiruvarur), Marakkanam (dist Villupuram), Pamban (dist Ramanathapuram), Thiruvidadaimaruthur (dist Thanjavur), Thirukalukundram (dist Chengalpattu), Puducherry (dist Puducherry), Valangaiman (dist Tiruvarur) -8 each, Manalmedu (dist Nagapattinam), Kollidam (dist Nagapattinam), Kelambakkam (dist Chengalpattu), K.M.koil (dist Cuddalore), Vanur (dist Villupuram), Mannargudi (dist Tiruvarur), Taramani (dist Chennai), Madukkur (dist Thanjavur), Parangipettai (dist Cuddalore), Ayyampettai (dist Thanjavur), ThanjaiPapanasam (dist Thanjavur), Cuddalore (dist Cuddalore), Needamangalam (dist Tiruvarur) -7 each <u>3rd December:</u> Kollidam (dist Nagapattinam) -
01.12.2020/0300	•Heavy to very heavy rainfall at a few places with isolated Extremely heavy falls very likely over south Tamilnadu (Kanniyakumari, Tirunelveli, Thoothukudi, Tenkasi, Ramanathapuram and Sivagangai) on 2nd and 3rd December, 2020; over south Kerala(Thiruvananthapuram, Kollam, Pathanamthitta and Alappuzah) on 3rd December and isolated heavy to very	

	heavy rainfall likely over south Tamilnadu on 2 nd & 4 th December 2020 and south Kerala on 3 rd & 4 th December, 2020. • Heavy to very heavy rainfall at Isolated places very likely over north Tamilnadu, Puducherry, Mahe & Kariakal and north Kerala during 2nd & 3 rd December, isolated heavy rainfall on 4th December and isolated heavy rainfall over coastal Tamilnadu on 1st December. • Heavy rainfall at isolated places very likely over south Coastal Andhra Pradesh during 2nd & 03rd December and over Lakshadweep during 03rd and 4th December, 2020.	36, Chidambaram (dist Cuddalore) - 34, Parangipettai (dist Cuddalore) - 26, Manalmedu (dist Nagapattinam), Kurinjipadi (dist Cuddalore) - 25 each, Thiruthuraipoondi (dist Tiruvarur) - 22, Sirkali (dist Nagapattinam) , Kodavasal (dist Tiruvarur) - 21 each, Rameswaram (dist Ramanathapuram) - 20, Peravurani (dist Thanjavur), Manjalaru (dist Thanjavur), Bhuvanagiri (dist Cuddalore), Mayiladuthurai (dist Nagapattinam)-19 each, Karambakudi (dist Pudukkottai), Pattukottai (dist Thanjavur)-17 each, Madukkur (dist Thanjavur)-16, Srimushnam (dist Cuddalore)-15, Tindivanam (dist Villupuram), Nannilam (dist Tiruvarur), Thiruvudaimaruthur (dist Thanjavur)-14 each, Kumbakonam (dist Thanjavur), Ayyampettai (dist Thanjavur), Valangaiman (dist Tiruvarur), Panruti (dist Cuddalore), Ulundurpet (dist Villupuram)-13 each, Aduthurai (dist Thanjavur), Alangudi (dist Pudukkottai), Pandavaaiyar Head (dist Tiruvarur) 12 each, Tiruvarur (dist Tiruvarur), Budalur (dist Thanjavur), Mahabalipuram (dist Chengalpattu), Mannargudi (dist Tiruvarur)-11 each, Vallam (dist Thanjavur), Perambalur (dist Perambalur), Thanjavur (dist Thanjavur), Thirumanur (dist Ariyalur) , Needamangalam (dist Tiruvarur)-10 each, Sendurai (dist Ariyalur) , Tirukattupalli (dist Thanjavur) , Vilupuram (dist Villupuram) , Mylam Aws (dist Villupuram) , Cholavaram (dist Tiruvallur) , Vanur (dist Villupuram) , Gandarvakottai (dist Pudukkottai) , Marakkanam (dist Villupuram) , Chengalpattu (dist Chengalpattu) , Gingee (dist Villupuram) - 9 each, Keeranur (dist Pudukkottai) , Thalaigayner (dist Nagapattinam) , Agaram Seegoor (dist Perambalur)
02.12.2020/0300	• Heavy to very heavy rainfall at a few places with isolated Extremely heavy falls very likely over south Tamilnadu (Ramanathapuram, Thoothukudi, Tirunelveli, Kanniyakumari, Tenkasi and Sivagangai districts) on 2nd & 3 rd December, 2020; over south Kerala (Thiruvananthapuram, Kollam, Pathanamthitta and Alappuzah) on 3rd December and isolated heavy to very heavy rainfall likely over south Tamilnadu on 4 th December 2020 and south Kerala on 2 nd & 4 th December, 2020. • Heavy to very heavy rainfall at isolated places very likely over north Tamilnadu, Puducherry, Mahe & Karaikal and north Kerala on 3 rd December, isolated heavy rainfall on 2 nd & 4 th December.	

	• Heavy rainfall at isolated places very likely over south Coastal Andhra Pradesh and Lakshadweep on 3 rd & 04 th December.	, Eraiyur (dist Perambalur) , Gummidipoondi (dist Tiruvallur) , Adirampatnam (dist Thanjavur) , Manamelkudi (dist Pudukkottai) , Pullambadi (dist Trichy) , Annavasal (dist Pudukkottai) , Samayapuram (dist Trichy) , Pamban (dist Ramanathapuram) , Perungalur (dist Pudukkottai) , Tarangambadi (dist Nagapattinam) - 8 each , Labbaikudikadu (dist Perambalur) , Tozhudur (dist Cuddalore) , Tirukoilur (dist Villupuram) , Thuvakudi Imti (dist Trichy) , Uthukottai (dist Tiruvallur) , Ariyalur (dist Ariyalur) , Anna UTY (dist Chennai) , Uthiramerur (dist Chengalpattu) , Tirupoondi (dist Nagapattinam) , Tirumayam (dist Pudukkottai) , Tondi (dist Ramanathapuram) , TRP Town (dist Trichy) - 7 each
03.12.2020/0300	• Heavy to very heavy rainfall at a few places with isolated Extremely heavy falls very likely over south Tamilnadu (Ramanathapuram, Thoothukudi, Tirunelveli, Kanniyakumari, Tenkasi, Virudhunagar, Theni, Madurai and Sivagangai districts) and over south Kerala (Thiruvananthapuram, Kollam, Pathanamthitta, Idukki and Alappuzah) on 3rd December and isolated heavy to very heavy rainfall likely over south Tamilnadu and south Kerala on 4th December, 2020. • Heavy to very heavy rainfall at isolated places very likely over north Tamilnadu, Puducherry, Mahe & Karaikal and north Kerala on 3 rd December, isolated heavy rainfall on 4 th December. • Heavy rainfall at isolated places very likely over south Coastal Andhra Pradesh and Lakshadweep on 3rd & 04th December.	<u>4th December:</u> Nagapattinam (Nagapattinam) and Karaikal (Karaikal)-16 each, Kodavasal (Tiruvarur) and Bhuvanagiri (Cuddalore)- 15 each, Sethiyathope (Cuddalore)-14, Tarangambadi (Nagapattinam)-13, Sirkali (Nagapattinam), DGP Office (Chennai), Vembakkam (Tiruvannamalai) and Srimushnam (Cuddalore)- 12 each, Rameswaram (Ramanathapuram), Anna University (Chennai), Tirupoondi (Nagapattinam) and Kayalpattinam (Toothukudi)-11 each, Sriperumbudur (Kancheepuram), Kollidam (Nagapattinam), Mgr Nagar (Chennai) and Pelandurai (Cuddalore)-10 each, Uthukottai (Tiruvallur), Chembarambakkam (Tiruvallur), Tuticorin (Toothukudi), Thalaigayyer (Nagapattinam)-9 each <u>5th December:</u> Muthupet (dist Tiruvarur)-
04.12.2020/0000 UTC	• Heavy to very heavy rainfall at isolated places with extremely heavy falls at isolated places very likely over Tamilnadu, Puducherry and Karaikal today, the 4th December and heavy to very heavy rainfall at isolated places on 05th December. • Heavy to very heavy rainfall at isolated places very likely over Kerala & Mahe on 04th & 05th December. India Meteorological Department (Ministry of Earth	

	Sciences) Spatial rainfall distribution: Isolated: $\leq 25\%$, A few: 26-50%, Many: 51-75%, Most: 76-100% Rainfall amount (mm): Heavy rain: 64.5 – 115.5, Very heavy rain: 115.6 – 204.4, Extremely heavy rain: 204.5 or more. • Heavy rainfall at isolated places very likely over south coastal Andhra Pradesh on 04 th & 05th December and over Lakshadweep on 05th December.	10, Mahabalipuram (dist Chengalpattu)-7 each, Kodavasal (dist Tiruvarur), Nannilam (dist Tiruvarur) & Thalaignayer (dist Nagapattinam)-6 each and Thiruthuraipoondi (dist Tiruvarur), Cheyyur (dist Chengalpattu), Kollidam (dist Nagapattinam), Cholavaram (dist Tiruvallur), Tirupoondi (dist Nagapattinam) and Chidambaram (dist Cuddalore) 5 each. 6th December: Maniyachi (dist Toothukudi) -16, Vaippar (dist Toothukudi) -12, Kadambur (dist Toothukudi) -11, Kayathar (dist Toothukudi), Sirkali (dist Nagapattinam), Karaikal (dist Karaikal), Chittar (dist Kanyakumari) - 9 each, Thalaignayer (dist Nagapattinam), Mayiladuthurai (dist Nagapattinam), Valinokam (dist Ramanathapuram), Needamangalam (dist Tiruvarur) - 8 each, Kodavasal (dist Tiruvarur), Manalmedu (dist Nagapattinam), Palayamkottai (dist Tirunelveli), Vilathikulam (dist Toothukudi) - 7 each
05.12.2020/0000 UTC	• Heavy to very heavy rainfall at isolated places very likely over Tamilnadu & Puducherry on 05th & 06th December. • Heavy rainfall at isolated places over south Kerala & Mahe on 05th and heavy to very heavy rainfall at isolated places very likely over Kerala on 06th December. • Heavy to very heavy rainfall at isolated places very likely over Lakshadweep on 05th & 06th December.	

Table 4.3.5.5 Verification of Gale/Squally Wind Forecast issued by IMD

Date/Base Time of observation	Gale/ Squally wind Forecast at 0300 UTC of date	Realised wind speed
30.11.2020/0300UTC	• Squally wind speed reaching 45-55 kmph gusting to 65 kmph very likely over central parts of South Bay of Bengal on 30th November. • It would gradually increase becoming 55-65 kmph gusting to 75 kmph over southeast and adjoining southwest Bay of Bengal from 1st December night and 70-80 kmph gusting to 90 kmph over southwest Bay of Bengal, along & off Sri Lanka coast and 45-55 kmph gusting to 65 kmph over Comorin Area, Gulf of Mannar and south Tamilnadu-Kerala coasts from 2nd	Crossed Sri Lanka coast close to north of as a Cyclonic Storm with maximum sustained wind speed of 80-90 kmph gusting to 100 kmph. Crossed Pamban area as a cyclonic storm with maximum sustained wind speed of 60-70

	December forenoon for subsequent 24 hours. The squally wind speed reaching 55-65 kmph gusting to 75 kmph is very likely to prevail over Gulf of Mannar, along & off south Tamilnadu & Kerala coasts, Comorin Area, Lakshadweep-Maldives area and adjoining southeast Arabian Sea from 3rd December morning for subsequent 48 hours.	kmph gusting to 80 kmph
01.12.2020/0300UTC	- Squally wind speed reaching 50-60 kmph gusting to 70 kmph very likely over central parts of South Bay of Bengal during next 12 hours. - It would gradually increase becoming gale wind speed reaching 60-70 kmph gusting to 80 kmph over southwest and adjoining southeast Bay of Bengal from 1 st December evening. It would gradually increase becoming 70-80 kmph gusting to 90 kmph over southwest Bay of Bengal, along & off Sri Lanka coast from 2nd December morning for subsequent 24 hours. - Squally wind speed reaching 45-55 kmph gusting to 65 kmph very likely over Comorin Area, Gulf of Mannar and south Tamilnadu-Kerala coasts from 2nd December forenoon. It will gradually increase becoming 55-65 kmph gusting to 75 kmph over Gulf of Mannar, along & off south Tamilnadu & Kerala coasts, over Comorin Area, Lakshadweep-Maldives area and adjoining southeast Arabian Sea from 3rd December morning and 70-80 kmph gusting to 90 kmph from evening of 3rd December for subsequent 24 hours.	
02.12.2020/0300UTC	- Gale wind speed reaching 75-85 kmph gusting to 95 kmph prevails over southwest Bay of Bengal and along & off Sri Lanka coast. It is very likely to increase becoming 80-90 kmph gusting to 100 kmph from afternoon for subsequent 12 hours. It will gradually decrease thereafter. - Squally wind speed reaching 45-55 kmph gusting to 65 kmph very likely over Comorin Area, Gulf of Mannar and along and off south Tamilnadu coast (Ramanathapuram, Thoothukudi, Tirunelveli and Kanniyakumari districts) and south Kerala coast (Thiruvananthapuram, Kollam, Pathanamthitta and Alappuzah districts). It will gradually increase becoming 55-65 kmph gusting to 75 kmph from	

	2nd December evening and 70-80 kmph gusting to 90 kmph from 3rd December forenoon for subsequent 24 hours and decrease thereafter. • Squally wind speed reaching 45-55 kmph gusting to 65 kmph very likely over Lakshadweep-Maldives area and adjoining southeast Arabian Sea from 3 rd December morning for next 48 hours.	
03.12.2020/0300UTC	• Gale wind speed reaching 70-80 kmph gusting to 90 kmph prevails around the system centre covering extreme north Sri Lanka and adjoining areas of Gulf of Mannar & southwest Bay of Bengal. • Squally wind speed reaching 55-65 kmph gusting to 75 kmph prevails along and off south Tamilnadu coast (Ramanathapuram, Thoothukudi, Tirunelveli and Kanniyakumari districts) and 30-40 kmph gusting to 50 kmph prevails along & off south Kerala coast (Thiruvananthapuram, Kollam, Pathanamthitta and Alappuzah districts). • It will gradually increase becoming 70-80 kmph gusting to 90 kmph from 3rd December noon for subsequent 24 hours along and off south Tamilnadu coast (Ramanathapuram, Thoothukudi, Tirunelveli and Kanniyakumari districts) and 55-65 kmph gusting to 75 kmph prevails along & off south Kerala coast (Thiruvananthapuram, Kollam, Pathanamthitta and Alappuzah districts). and decrease thereafter. • Squally wind speed reaching 45-55 kmph gusting to 65 kmph very likely over Lakshadweep-Maldives area and adjoining southeast Arabian Sea on 3 rd and 4th December.	
04.12.2020/0300UTC	• Squally wind speed reaching 50-60 kmph gusting to 70 kmph is very likely during next 12 hours along and off south Tamilnadu coast (Ramanathapuram, Thoothukudi, Tirunelveli and Kanniyakumari districts) and it will gradually decrease to 40-50 kmph gusting to 60 kmph by night of 4th December. • Squally wind speed reaching 35-45 kmph gusting to 55 kmph very likely to prevail along & off south Kerala coast (Thiruvananthapuram, Kollam, Pathanamthitta and Alappuzah districts) from	

	tonight for subsequent 12 hours. • Squally wind speed reaching 35-45 kmph gusting to 55 kmph very likely over Lakshadweep-Maldives area and adjoining southeast Arabian Sea from early morning of 05th December.	
05.12.2020/0300 UTC	• Squally wind speed reaching 40-50 kmph gusting to 60 kmph is very likely over Gulf of Mannar & adjoining southwest Bay of Bengal, along & off south Tamilnadu coast (Ramanathapuram, Thoothukudi, Tirunelveli and Kanniyakumari districts) during next 12 hours. It will gradually decrease to 35-45 kmph gusting to 55 kmph for subsequent 12 hours. • Squally wind speed reaching 35-45 kmph gusting to 55 kmph very likely over Lakshadweep-Maldives & Comorin area, southeast Arabian Sea and along & off south Kerala coast on 5th and 6th December.	

Table 4.3.2.6: Verification of Storm Surge Forecast

Date/Base Time of observation	Storm Surge Forecast at 0300 UTC of date	Realised surge
02.12.2020/0300UTC	• Storm surge of about 1.0 m height above astronomical tide is very likely to inundate low lying areas of south coastal Tamilnadu (Ramanathapuram, Thoothukudi, Tirunelveli and Kanniyakumari districts) during the time of landfall.	No significant storm Surge reported
03.12.2020/0300UTC TC	• Storm surge of about 1.0 m height above astronomical tide is very likely to inundate low lying areas of south coastal Tamilnadu (Ramanathapuram, Thoothukudi, Tirunelveli and Kanniyakumari districts) during the time of landfall and northwest Sri Lanka coast during next 06 hours.	

4.4 Performance of cyclone landfall, track and intensity forecast during 2020

4.4.1 Track forecast

The annual average track forecast errors in 2020 have been 72 km, 85 km and 111 km, respectively for 24, 48 and 72hrs against the past five year average error of 80, 125 and 177 km based on data of 2015-2020. The errors have been significantly lower during this year as compared to long period average (2015-19) for all lead periods upto 120 hours. The track forecast skills compared to climatology and persistence forecast are 68%, 79% and 84% respectively for the 24, 48 and 72 hrs lead period which is comparatively higher than long period average of 2015-2020 (58%, 80% & 84% respectively). The track forecast errors and skill during 2020 are presented in Table and Fig.4.4.1. The average track forecast error and skill of all TCs alongwith annual average during 2020 in comparison to long period average errors and skill during 2015-19 are presented in tables 4.4.1. (a and b).

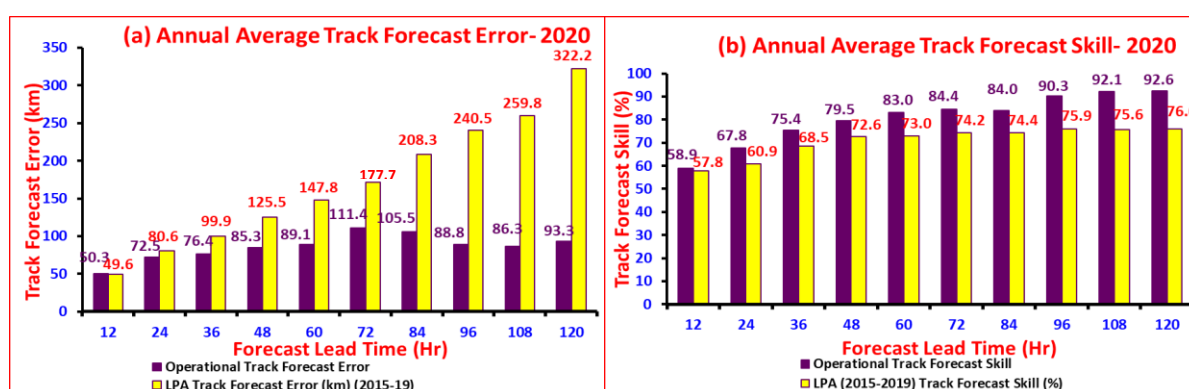


Fig. 4.4.1. Annual average (a) track forecast error (km) and (b) track forecast skill against the climatology and persistence forecast during 2020 as compared to that during 2015-2020

4.4.2 Landfall forecast

The annual average landfall point forecast errors for the year 2020 have been 18 km, 70 km and 43 km for 24, 48 and 72 hrs lead period against the long period average of past five years during 2015-19 of 47 km, 70 km and 110 km (Tables 4.4.2 a & b, Fig. 4.4.2 a & b)

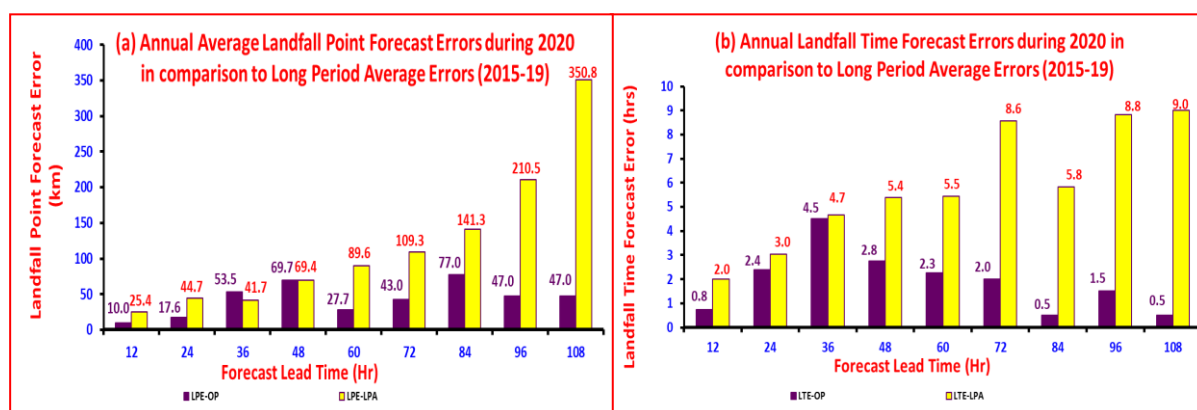


Fig. 4.4.2. Annual average (a) landfall point forecast error (km) and (b) landfall time (hrs) during 2020 as compared to that during 2015-2020

The landfall time forecast errors have been 2.4, 2.8 and 2.0 hrs for 24, 48 and 72 hrs lead period during 2020 against the average of past five years of 3.0, 5.4 and 8.6 hrs during 2015-2019

4.4.3 Intensity forecast

The average absolute errors during 2020 have been 7.1 knots, 8.8 knots and 9.3 knots respectively for 24, 48 and 72 hrs lead period of forecast against the long period average errors of 8.9, 13.0 and 15.4 knots during 2015-19 (Fig. 4.4.3 a & b and 4.4.4 a & b).

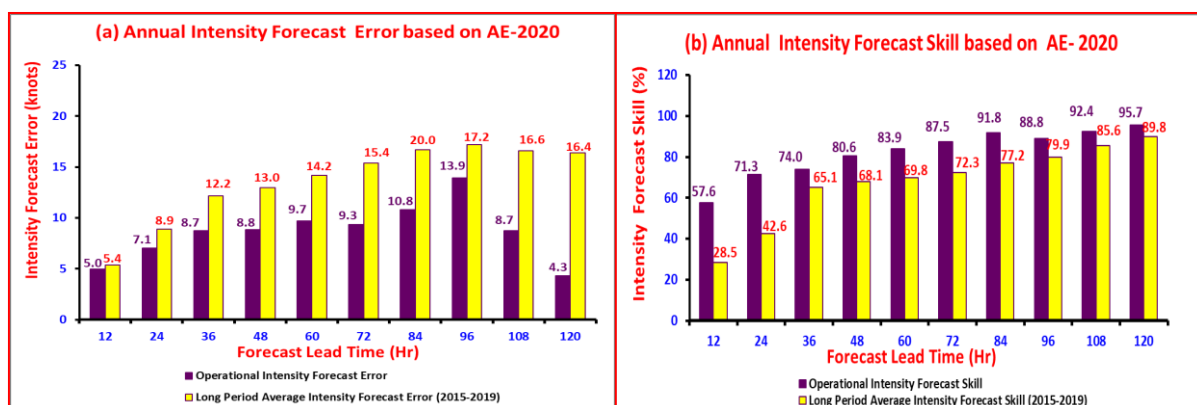


Fig. 4.4.3. Annual average intensity forecast error (knots) based on absolute errors and root mean square errors during 2020 as compared to LPA (2015-2020)

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 2020 have been 46.8, 63.5% and 69.6 % respectively for 24, 48 and 72 hrs lead period of forecast against the past five year average of 35.2, 55.7% and 66.8%. The average skill based on RMSE during 2020 have been 51.3, 67.6% and 74.3 % respectively for 24, 48 and 72 hrs lead period of forecast against the past five year average of 39, 59.6% and 72.2%.

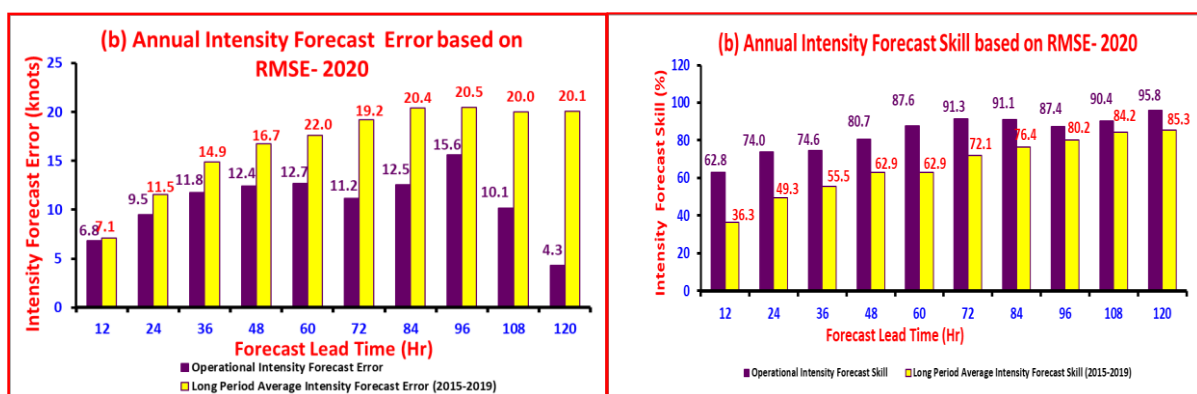


Fig. 4.4.4. Annual average intensity forecast skill (%) based on absolute errors and root mean square errors during 2020 as compared to that during 2015-2019

4.5. Interannual errors of TCs over north Indian Ocean

4.5.1. Track forecast error and skill

Inter-annual errors and skill in track forecast since 2003 are presented in Fig.4.5.1 a & b and table 4.5.1 a & b. There has been significant improvement in annual average track forecast errors and skill due to modernisation programme of IMD in 2009 with respect to observation, analysis and prediction tools & techniques which has been further augmented through improvement in observations, mainly from DWR and satellite and in terms of improved numerical modelling including enhanced data assimilation, higher resolution, improved physics etc.

There has been continuous improvement in track forecast accuracy with decrease in track forecast errors at the rate of 6.3 km/year (63 km in 10 years) for 24 hrs lead period and increase in skill at the rate of 3.4% per year (34% in 10 years) since 2003. Similarly, for 12 hrs lead period, there has been improvement in track forecast accuracy with decrease in track forecast errors at the rate of 3.7 km/year (37 km in 10 years) and increase in skill at the rate of 5.3% per year (53% in 10 years) since 2003.

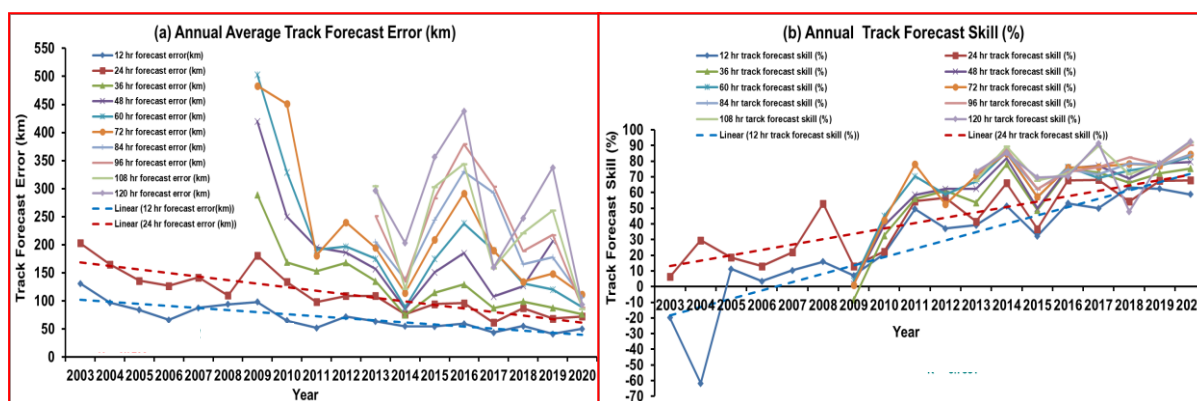


Fig. 4.5.1 Inter-annual average track forecast (a) errors and (b) skill during 2020

Table. 4.5.1 (a) Inter-annual average Track forecast errors during 2003 to 2020

(Values shown in “()” indicate number of cases verified)

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	142								

	(29)	(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)
2019	41.0 (168)	68.6 (150)	87.8 (136)	103.7 (123)	120.4 (109)	148.6 (89)	177.7 (66)	217.8 (55)	261.3 (46)	337.5 (33)
2020	50.3 (62)	72.5 (51)	76.4 (44)	85.3 (36)	89.1 (27)	111.4 (21)	105.5 (7)	88.8 (5)	86.3 (3)	93.3 (1)

Table. 4.5.1 (b) Inter-annual average track forecast skill (%) during 2003 to 2020

(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)	
2019	62.4 (168)	67.6 (150)	72.4 (136)	78.5 (123)	77.1 (109)	77.3 (89)	77.6 (66)	78.1 (55)	78.7 (46)	78.8 (33)
2020	58.9 (62)	67.8 (51)	75.4 (44)	79.5 (36)	83 (27)	84.4 (21)	84 (7)	90.3 (5)	92.1 (3)	92.6 (1)

4.5.2. Landfall point and time forecast errors

There has been an improvement in landfall point forecast accuracy at the rate of 16.4 km/year (164 km in 10 years) for 24 hrs lead period since 2003. Similarly, for 12 hrs lead period, there has been improvement in landfall point

forecast error at the rate of 8.2 km/year (82 km in 10 years) since 2003. Considering the landfall time errors, there has been an improvement at the rate of 0.21 hrs/year (2.1 hrs in 10 years) for 24 hrs lead period since 2003. Similarly, for 12 hrs lead period, there has been an improvement at the rate of 0.3 hrs/year (3.0 hrs in 10 years) for 12 hrs lead period since 2003

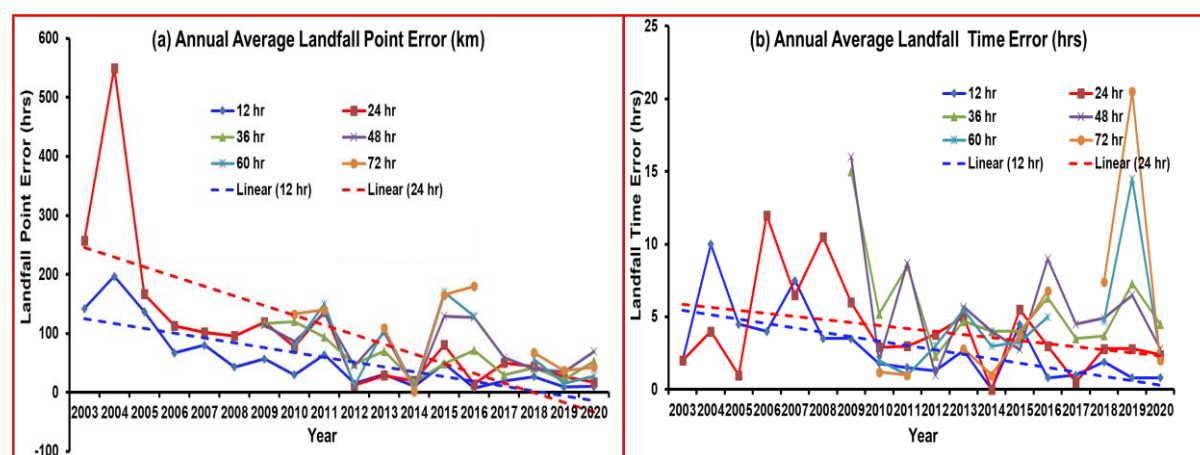


Fig. 4.5.2 Annual average (a) Landfall Point errors (b) Landfall Time errors

Table 4.5.2. (a): Inter-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)				
2019	8.9 (2)	27.1 (3)	21.9 (3)	34.7 (2)	15 (1)	37.2 (1)				
2020	10(6)	17.6(5)	53.5(5)	69.7(4)	27.7(2)	43(1)	77(1)	47(1)	47(1)	

Table 4.5.2 (b): Inter 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	5 (4)	4.7	5.7	5.5	2.8				

	(4)		(4)	(4)	(4)	(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)	
2019	0.8 (2)	2.8 (3)	7.3 (3)	6.5 (2)	14.5 (1)	20.5 (1)				
2020	0.8(6)	2.4(5)	4.5(5)	2.8(4)	2.3(2)	2(1)	0.5(1)	1.5(1)	0.5(1)	

4.5.3 Inter-annual intensity forecast error and skill

Inter-annual errors in intensity forecast since 2005 are presented in in Fig. 4.5.3 (a & b) and 4.5.4 (a & b) and Tables 4.5.3 (a & b) for skill in intensity forecast based on AE and Tables 4.5.3 (c & d) based on RSME. As regards improvement in intensity forecast, there has been decrease in errors at the rate of 0.48 knots/year (4.8 knots in 10 years) for 24 hrs lead period and increase in skill at the rate of 3.1% per year (31% in 10 years) since 2005. Similarly, for 12 hrs lead period, there has been decrease in intensity forecast errors at the rate of 0.25 knots/year (2.5 knots in 10 years) and increase in skill at the rate of 1.5% per year (15% in 10 years) since 2003.

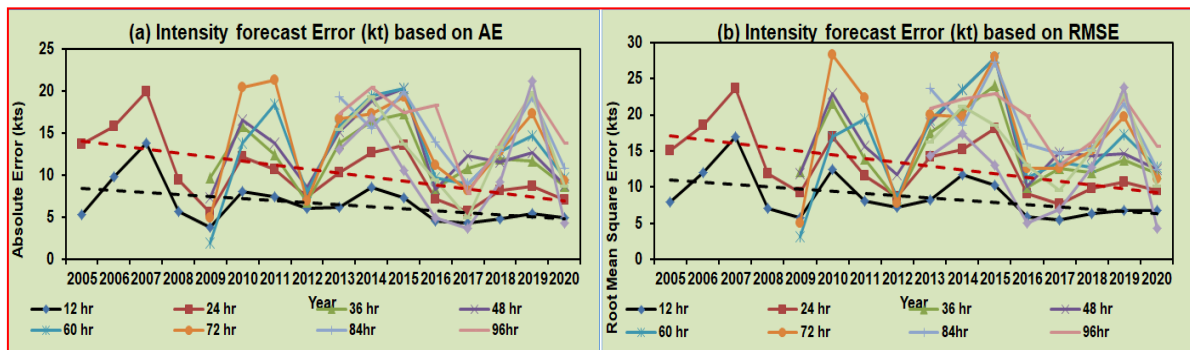


Fig. 4.5.3 Annual average Intensity forecast(kt) errors based on (a) AE (b) RMSE

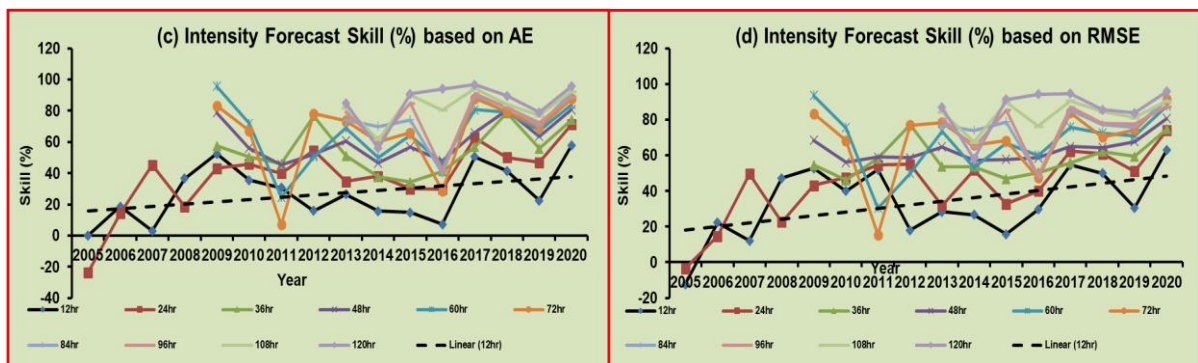


Fig. 4.5.4 Annual average Intensity forecast skill (%) based on (a) AE (b) RMSE

Table. 4.5.3 (a) Inter 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)
2019	5.5 (168)	8.7 (150)	11.7 (136)	12.7 (123)	14.7 (109)	17.4 (89)	19.3 (66)	19.8 (55)	19.9 (46)	21.2 (33)
2020	5 (62)	7.1 (51)	8.7 (44)	8.8 (36)	9.7 (27)	9.3 (21)	10.8 (7)	13.9 (5)	8.7 (3)	4.3 (1)

Table. 4.5.3 (b) Inter 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)
2019	6.8 (168)	10.7 (150)	13.8 (136)	14.6 (123)	17.3 (109)	19.7 (89)	21.6 (66)	22.3 (55)	22.7 (46)	23.8 (33)
2020	6.8 (62)	9.5 (51)	11.8 (44)	12.4 (36)	12.7 (27)	11.2 (21)	12.5 (7)	15.6 (5)	10.1 (3)	4.3 (1)

Table. 4.5.3 (c) Inter 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)
2019	22.5 (168)	46.8 (150)	55.7 (136)	63.5 (123)	67.1 (109)	69.6 (89)	69.8 (66)	71.9 (55)	76.8 (46)	78.6 (33)
2020	57.6 (62)	71.1 (51)	74.1 (44)	80.7 (36)	83.8 (27)	87.5 (21)	91.8 (7)	88.8 (5)	92.4 (3)	95.7 (1)

Table. 4.5.3 (d) Inter annual average Intensity 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)
2019	30.6 (168)	51.1 (150)	59.3 (136)	67.6 (123)	70.9 (109)	74.3 (89)	75.8 (66)	77.4 (55)	81.1 (46)	83.7 (33)
2020	62.8 (62)	73.9 (51)	74.6 (44)	80.7 (36)	87.6 (27)	91.3 (21)	91.1 (7)	87.4 (5)	90.4 (3)	95.8 (1)

4.6 Comparative analysis of forecast accuracy in recent five years (2016-20) as compared to previous five years (2011-15)

4.6.1 Landfall Forecast Error

Comparative analysis of LPE and LTE during 2016-20 vis-à-vis 2011-15 is presented in Fig. 4.6.1. The 12 and 24 hr LPEs during 2016-20 were 17.3 km and 31.9 km against 36.5 km and 56.3 km respectively during 2011-15.

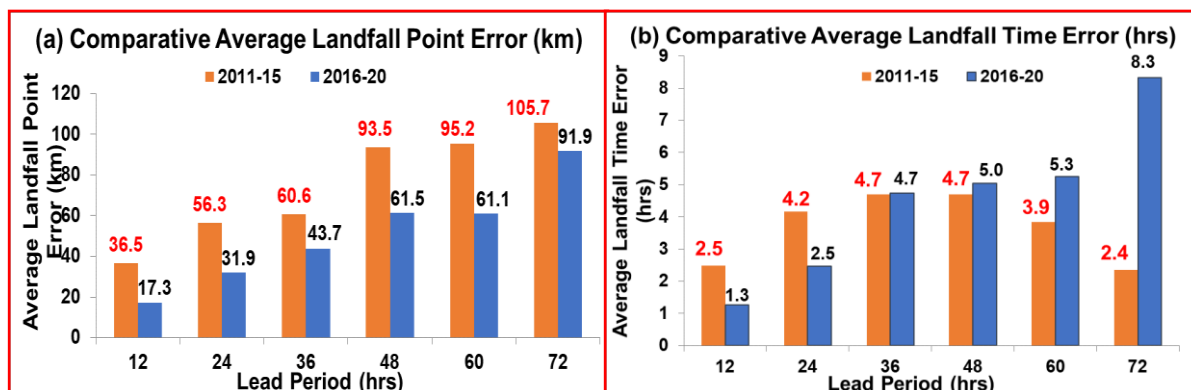


Figure 4.6.1 Comparative Average landfall (a) point and (b) time forecast errors during 2016-20 vis-à-vis 2011-15

4.6.2 Track forecast error and skill

The comparative analysis of average track forecast error and skill during 2016-20 and 2011-15 is presented in Fig.4.6.2.

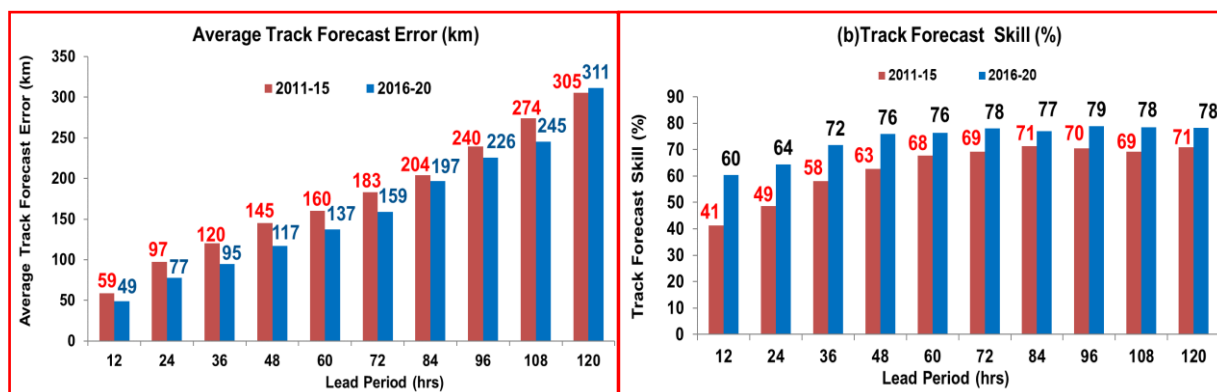


Figure 4.6.2. Comparative Average track forecast (a) error and (b) skill during 2015-19 vis-à-vis 2010-14

4.6.3 Intensity forecast error and skill

The comparative analysis of average intensity forecast error and skill based on AE and RMSE during 2016-20 and 2011-15 are presented in Fig.4.6.3 and 4.6.4 respectively. It can be seen that there has been marginal improvement in intensity forecast during recent five years (2016-20) as compared to previous five years (2011-15).

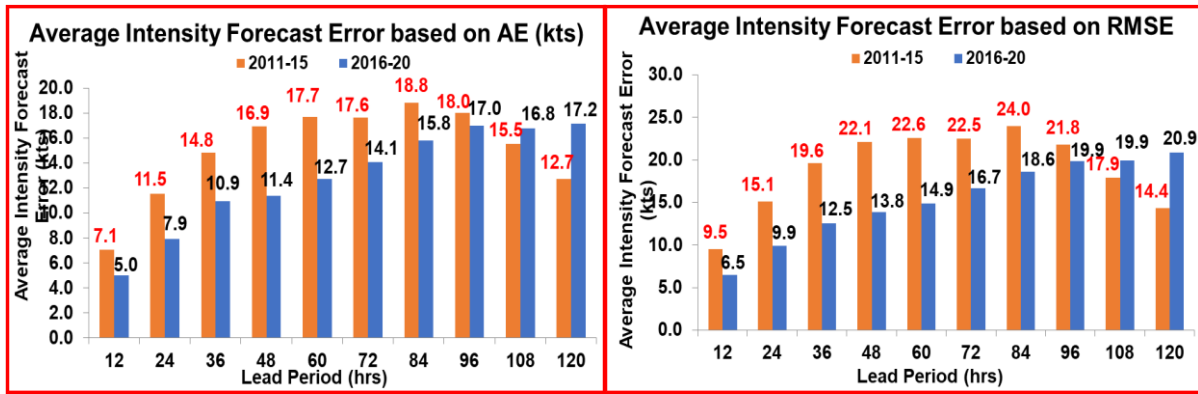


Figure 4.6.3. Comparative Average Intensity forecast errors (kts) based on (a) absolute error and (b) root mean square errors during 2016-20 vis-à-vis 2011-15

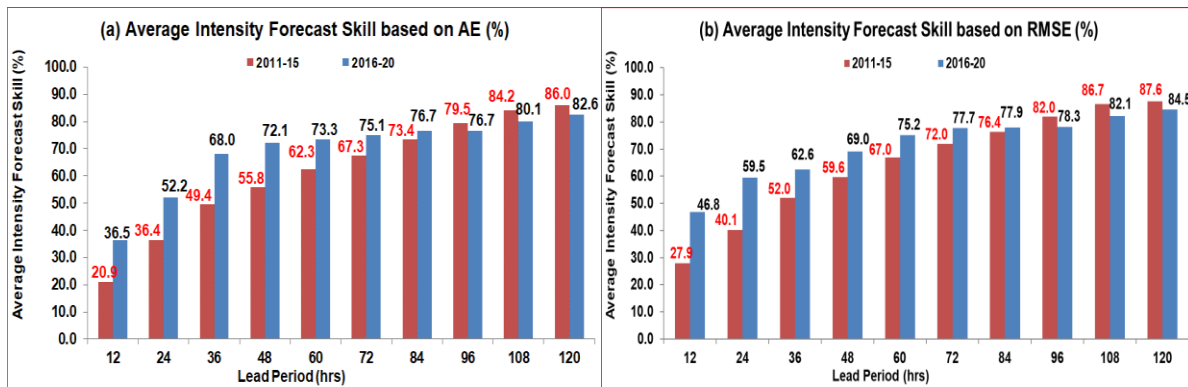


Figure 4.6.4 Comparative Average Intensity forecast skill(%) based on (a) absolute error and (b) root mean square errors during 2016-20 vis-à-vis 2011-15

4.7 Five Year Moving Average errors and skill over north Indian Ocean

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.

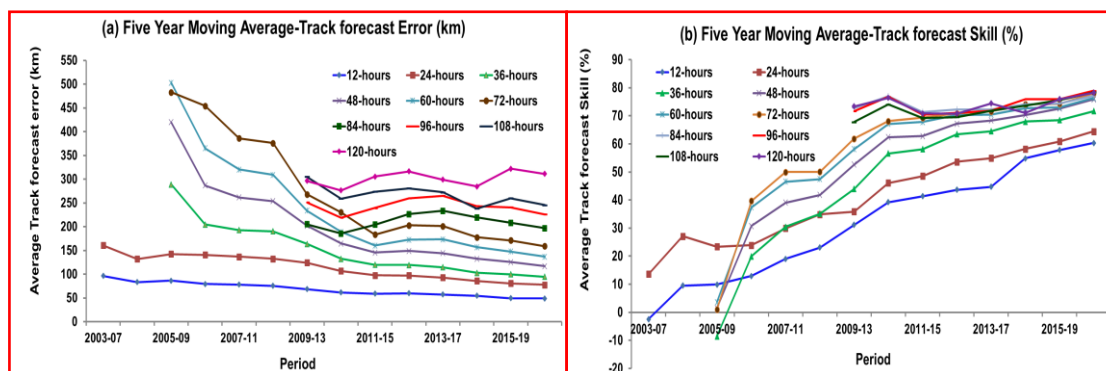


Figure 4.7.1 Five Year Moving Average (a) Track Forecast Error (km) and (b) Track Forecast Skill (%) of RSMC, New Delhi over North Indian Ocean

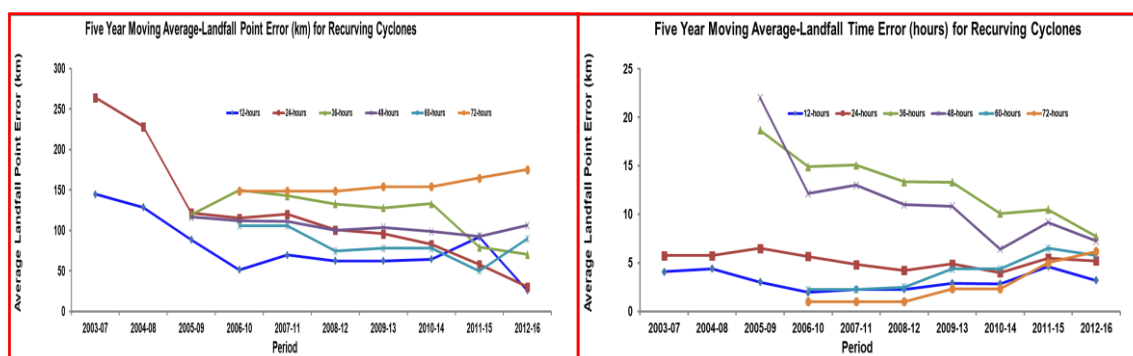


Figure 4.7.2 Five Year Moving Average Errors in (a) Landfall Point (km) and (b) Landfall Time (hrs) of RSMC, New Delhi over north Indian Ocean

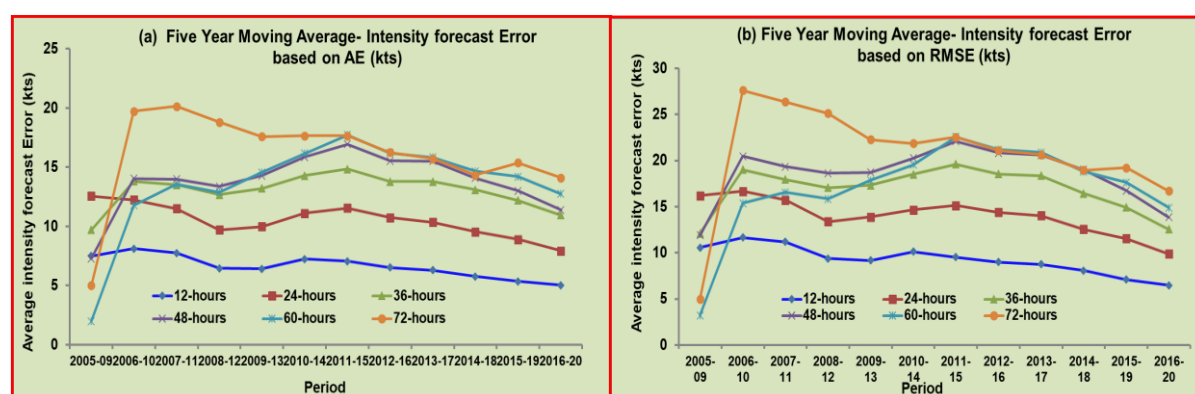


Figure 4.7.2 Five Year Moving Average Intensity Forecast (a) Absolute Error (kts) and (b) Root Mean Square Error (kts) of RSMC, New Delhi over the NIO

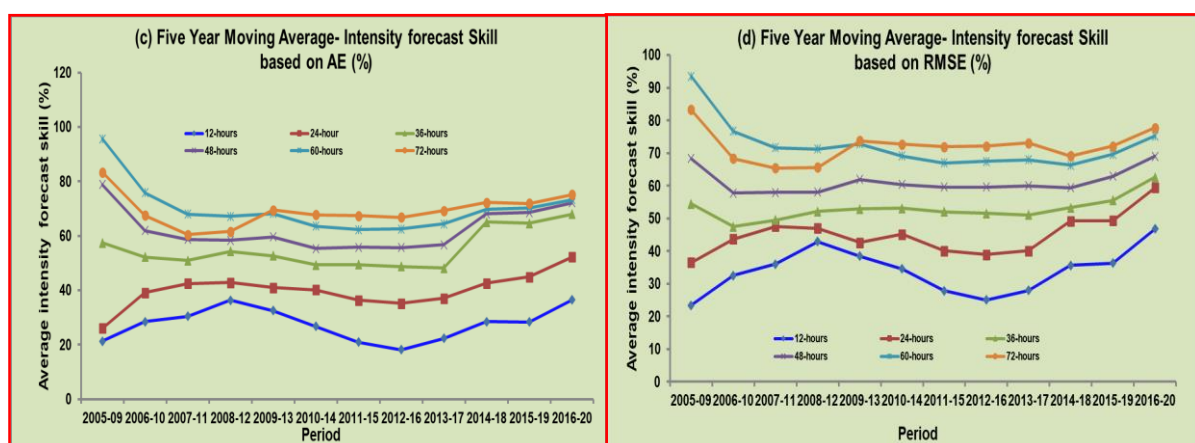


Fig. 4.7.4 Five Year Moving Average Intensity Forecast skill based on (a) AE and (b) RMSE of RSMC, New Delhi over North Indian Ocean

Table 4.7.1 Homogeneous comparison of Official Landfall Forecast Errors over north Indian Ocean in 2020 with Averages for 2015-19 and 2010-19.

Parameter	Forecast Period (hr)					
	12	24	36	48	60	72
2020						
Mean OFCL Landfall Point Error (km)	10	17.6	53.5	69.7	27.7	43
Mean OFCL Landfall Time Error (hr)	0.8	2.4	4.5	2.8	2.3	2
No. of cases	6	5	5	4	2	1
2015-19						
Mean OFCL Landfall Point Error (km)	25.4	44.7	41.7	69.4	89.6	109.3
Mean OFCL Landfall Time Error (hr)	2.0	3.0	4.7	5.4	5.5	8.6
No. of cases	17	17	17	13	10	7
2010-19						
Mean OFCL Landfall Point Error (km)	31.5	58.7	65.8	81.1	82.9	108.9
Mean OFCL Landfall Time Error (hr)	2.4	3.7	7.0	6.8	3.6	4.5
No. of cases	31	31	30	25	21	15
2020 OFCL Landfall Point Error relative to 2015-19 mean (%)	-60.6	-60.7	28.2	0.5	-69.1	-60.7
2020 OFCL Landfall Time Error relative to 2015-19 mean (%)	-59.9	-20.8	-4.3	-48.1	-58.2	-76.7
2020 OFCL Landfall Point Error relative to 2010-19 mean (%)	-68.2	-70.0	-18.7	-14.1	-66.6	-60.5
2020 OFCL Landfall Time Error relative to 2010-19 mean (%)	-66.3	-34.9	-35.6	-59.1	-36.7	-55.1

OFCL Official.The landfall forecast was issued upto 24 hrs till 2008 and 72 hrs from 2009 onwards, during 2019 forecast upto 72 hrs has been verified

Table 4.7.2 Homogeneous comparison of OFCL & CLIPER Track Forecast Errors over NIO in 2020 with Averages for 2015-19 and 2010-19

Parameter	Forecast Period (hr)									
	12	24	36	48	60	72	84	96	108	120
2020 Mean OFCL Forecast Error (km)	50.3	72.5	76.4	85.3	89.1	111.4	105.5	88.8	86.3	93.3
2020 Mean CLIPER Error (km)	122.4	225	310.1	416.8	525.4	712.8	659.9	919.6	1086.6	1260.2
2020 Mean OFCL Skill wrt CLIPER (%)	58.9	67.8	75.4	79.5	83	84.4	84	90.3	92.1	92.6
2020 No. of cases	62	51	44	36	27	21	7	5	3	1
2015-19 Mean OFCL Forecast Error (km)	49.6	80.6	99.9	125.5	147.8	171.2	208.3	240.5	259.8	322.2
2015-19 Mean CLIPER Error (km)	117.5	206.0	317.1	457.8	547.2	664.4	814.1	996.0	1067.0	1340.8
2015-19 Mean OFCL Skill wrt CLIPER (%)	57.8	60.9	68.5	72.6	73.0	74.2	74.4	75.9	75.6	76.0
2015-19 No. of cases	454	400	350	298	250	203	147	113	81	53
2010-19 Mean OFCL Forecast Error (km)	53.8	89.6	110.6	138.4	160.9	189.6	202.7	235.3	259.7	312.6
2010-19 Mean CLIPER Error (km)	111.3	216.5	341.3	475.3	596.3	732.2	881.4	1052.9	1099.3	1315.2
2010-19 Mean OFCL Skill wrt CLIPER (%)	51.7	58.6	67.6	70.9	73.0	74.1	77.0	77.6	76.4	76.2
2010-19 No. of cases	690	608	522	444	367	295	195	149	105	67
2020 relative to 2015-19 mean (%)	1.4	-10.1	-23.5	-32.1	-39.7	-34.9	-49.4	-63.1	-66.8	-49.5
2020 CLIPER error relative to 2015-19 mean (%)	4.2	9.2	-2.2	-8.9	-4.0	7.3	-18.9	-7.7	1.8	71.9
2020 Skill relative to 2015-19 mean (%)	1.9	11.4	10.1	9.5	13.7	13.7	12.9	19.0	21.7	21.9
2020 relative to 2010-19 mean (%)	-6.4	-19.1	-30.9	-38.4	-44.6	-41.2	-48.0	-62.3	-66.8	-70.2
2020 CLIPER error relative to 2010-19 mean (%)	10.0	3.9	-9.1	-12.3	-11.9	-2.7	-25.1	-12.7	-1.2	-4.2
2020 Skill relative to 2010-19 mean (%)	13.9	15.6	11.6	12.2	13.7	13.9	9.1	16.3	20.6	21.5

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 2020 with Averages for 2015-19 and 2010-19

Parameter	Forecast Period (hr)									
	12	24	36	48	60	72	84	96	108	120
2020 Mean OFCL Forecast Error (kts)	5	7.1	8.7	8.8	9.7	9.3	10.8	13.9	8.7	4.3
2020 Mean Persistence Error (kts)	11.8	24.6	33.6	45.6	60.2	74.8	132.9	125.0	115.0	100.0
2020 Mean OFCL Skill wrt Persistence (%)	57.6	71.1	74.1	80.7	83.9	87.6	91.9	88.9	92.4	95.7
2020 No. of cases	62	51	44	36	27	21	7	5	3	1
2015-19 Mean OFCL Forecast Error (kts)	5.4	8.9	12.2	13.0	14.2	15.4	16.7	17.2	16.6	16.4
2015-19 Mean Persistence Error (kts)	7.5	16.1	34.4	41.2	47.8	54.9	66.2	77.1	91.7	101.3
2015-19 Mean OFCL Skill wrt Persistence (%)	28.3	44.9	64.6	68.5	70.3	72.0	74.8	77.7	81.9	83.8
2015-19 No. of cases	454	401	351	299	250	203	147	113	81	53
2010-19 Mean OFCL Forecast Error (kts)	6.0	9.6	12.9	13.9	14.8	16.1	17.1	17.5	16.6	15.9
2010-19 Mean Persistence Error(kts)	8.3	17.0	32.3	39.4	46.7	54.8	66.5	76.5	88.4	96.0
2010-19 Mean OFCL Skill wrt Persistence (%)	27.6	43.1	60.1	64.6	68.3	70.7	74.3	77.2	81.2	83.4
2010-19 No. of cases	689	610	526	444	367	294	195	149	105	67
2020 OFCL error relative to 2015-19 mean (%)	-6.8	-20.6	-28.3	-31.9	-31.8	-39.3	-35.1	-19.0	-47.4	-73.7
2020 Persistence error relative to 2015-19 mean (%)	57.6	52.6	-2.2	10.4	25.9	36.3	100.8	62.1	25.3	-1.3
2020 Relative Skill wrt 2015-2020	103.4	58.8	14.6	17.7	19.4	21.5	22.8	14.3	12.8	14.2
2020 OFCL error relative to 2010-19 mean (%)	-16.8	-26.9	-32.2	-36.4	-34.6	-42.0	-36.7	-20.3	-47.4	-72.8
2020 Persistence error relative to 2010-19 mean (%)	41.9	44.8	4.1	15.6	28.9	36.4	99.8	63.4	30.1	4.2
2020 Relative Skill wrt 2010-19	108.6	65.5	23.2	24.8	22.9	23.8	23.6	15.2	13.8	14.7

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 2020 with Averages for 2015-19 and 2010-19

Parameter	Forecast Period (hr)									
	12	24	36	48	60	72	84	96	108	120
2020 Mean OFCL Forecast Error (km)	6.8	9.5	11.8	12.4	12.7	11.2	12.5	15.6	10.1	4.3
2020 Mean Persistence Error (km)	18.3	36.5	46.5	64.3	102.4	128.8	140.6	124.2	105.6	102.5
2020 Mean OFCL Skill wrt Persistence (%)	62.8	74.0	74.6	80.7	87.6	91.3	91.1	87.4	90.4	95.8
2020 No. of cases	62	51	44	36	27	21	7	5	3	1
2015-19 Mean OFCL Forecast Error (km)	7.1	11.5	14.9	16.7	17.6	19.2	20.4	20.5	20.0	20.1
2015-19 Mean Persistence Error (km)	11.1	22.8	33.5	45.1	57.9	68.9	86.3	103.5	126.4	136.5
2015-19 Mean OFCL Skill wrt Persistence (%)	36.3	49.3	55.5	62.9	62.9	72.1	76.4	80.2	84.2	85.3
2015-19 No. of cases	454	401	351	299	250	203	147	113	81	53
2010-19 Mean OFCL Forecast Error (km)	8.2	12.7	16.2	18.0	18.2	20.1	20.9	20.7	19.5	19.1
2010-19 Mean Persistence Error (km)	12.8	24.2	35.6	47.2	59.7	72.6	88.4	101.9	119.9	129.5
2010-19 Mean OFCL Skill wrt Persistence (%)	35.5	47.6	54.5	62.0	69.4	72.4	76.4	79.7	83.8	85.2
2010-19 No. of cases	689	610	526	444	367	294	195	149	105	67
2020 OFCL error relative to 2015-19 mean (%)	-4.1	-17.6	-21.2	-25.6	-27.8	-41.8	-38.5	-23.9	-49.3	-78.5
2020 Persistence error relative to 2015-19 mean (%)	64.2	60.2	38.7	42.4	76.9	86.9	62.9	20.0	-16.4	-24.9
2020 Relative Skill wrt 2015-2019	73.1	49.9	34.4	28.2	39.2	26.6	19.3	9.0	7.4	12.3
2020 OFCL error relative to 2010-19 mean (%)	-17.5	-25.1	-27.4	-30.7	-30.3	-44.3	-39.9	-24.6	-48.0	-77.4
2020 Persistence error relative to 2010-19 mean (%)	43.2	50.9	30.6	36.2	71.7	77.4	59.1	21.9	-11.9	-20.8
2020 Relative Skill wrt 2010-19	77.3	55.5	36.9	30.3	26.2	26.2	19.3	9.7	8.0	12.4

The intensity forecast was issued upto 24 hrs till 2008, 72 hrs during 2009-12 and 120 hrs from 2013 onwards

OFCL Official

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- Various international meteorological satellite groups/institutes providing the cloud imageries and products related to cyclonic disturbances over north Indian Ocean region through open access
- Various central and state disaster management agencies, stakeholders, press & electronic media and general public

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DAMAGE DUE TO SUPER CYCLONIC STORM 'AMPHAN'



Hanging electric pole(The Hindu,23rd May)



Damaged homes (outlookindia.com,22nd May)



Flooded Kolkata Airport (NDTV,4TH June)



Flooded area of West Bengal (cnn.com,22nd May)



A bus crashed after a tree fell on it in Kolkata(The Hindu,22nd May)



Uprooted trees (dnaindia.com,21st,May)