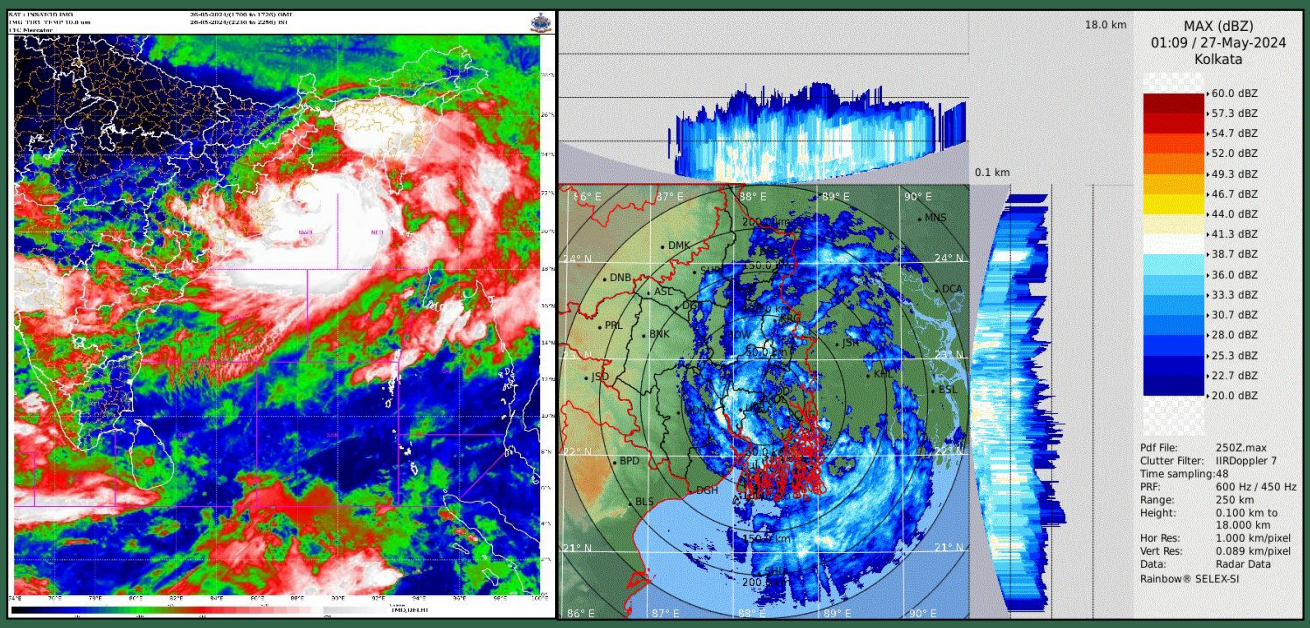
World Meteorological Organisation

Government of India
Ministry of Earth Sciences
India Meteorological Department

ESSO/MoES/IMD/RSMC-Tropical Cyclone Report/01(2025)/15

REPORT ON CYCLONIC DISTURBANCES OVER NORTH INDIAN OCEAN DURING 2024



SATELLITE AND RADAR IMAGERY OF SEVERE CYCLONIC STORM, "REMAL"

RSMC-TROPICAL CYCLONES, NEW DELHI

MARCH 2025

WMO

INDIA METEOROLOGICAL DEPARTMENT

RSMC- TROPICAL CYCLONES, NEW DELHI

INDIA METEOROLOGICAL DEPARTMENT

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

1.	ESSO Report Number	ESSO/MoES/IMD/RSMC-Tropical Cyclone Report/01(2025)/15
2.	Title of The Report	Report on cyclonic disturbances over the north Indian Ocean during 2024
3.	Authors	RSMC-Tropical Cyclones, New Delhi
4.	Originating Unit	RSMC-Tropical Cyclones, New Delhi
5.	Type of Document	Technical Report
6.	No. of Pages	411
7.	No. of references	0
8.	Key words	Cyclogenesis, intensity, track, landfall, NWP model, forecast verification
9.	Security classification	Open
10.	Distribution	Open
11.	Funding Agency	India Meteorological Department
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 2024. 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 40^0E and 100^0E and includes the member countries of WMO/ESCAP Panel on Tropical Cyclones viz, Bangladesh, India, Iran, Maldives, Myanmar, Oman, Pakistan, Qatar, Saudi Arabia, Sri Lanka, Thailand, United Arab Emirates and Yemen as shown in Fig. 1.1.

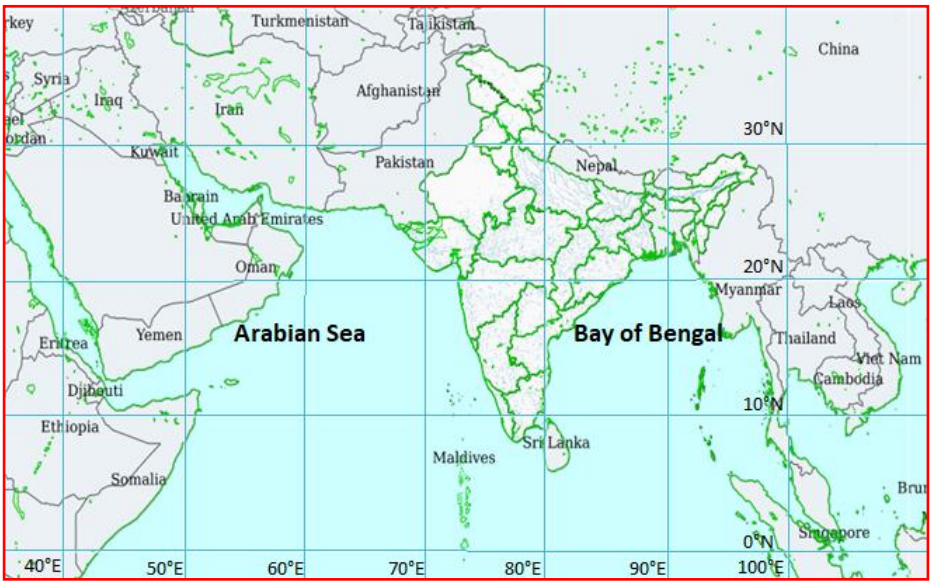


Fig. 1.1 Area of responsibility of RSMC- Tropical Cyclone, New Delhi

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 of a table has been prepared. The names of Panel members who contributed cyclone names, have arranged in rows. The RSMC (tropical cyclones) New Delhi gives a tropical cyclone an identification name from the table of names. 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 the 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. Till the end of year 2023, a total of 18 names have already been utilized for naming the Tropical Cyclones over North Indian Ocean. The same 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

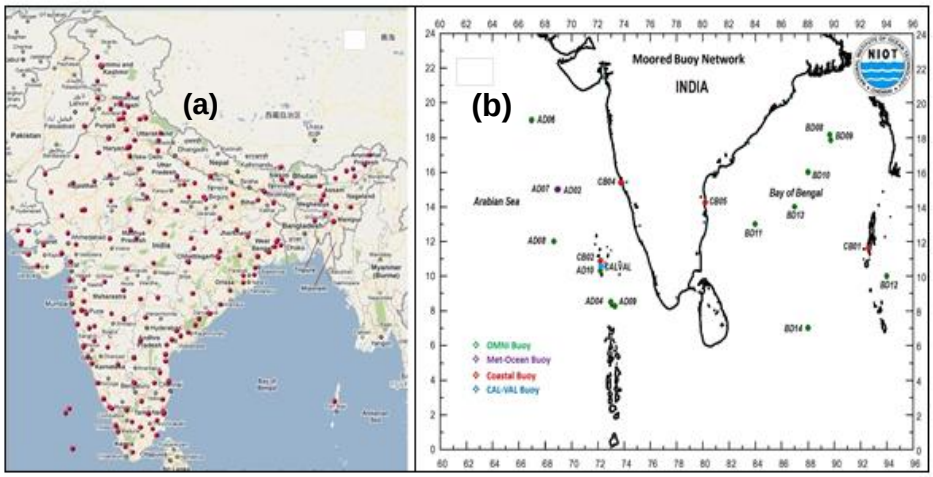


Fig.1.2. (a) The surface Observatory Network of IMD (b) Buoy network of NIOT

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.

A fairly dense network of 1008 AWSs as shown in Fig. 1.3 is now available for operational utilization. In addition to AWS, a network of 1382 ARG Stations has been established in different states. Recently different state government AWS/ARG data is also integrated with IMD Server for optimum utilization of AWS data. The recent imitative to strengthen further the observational network in Ladakh will very helpful.

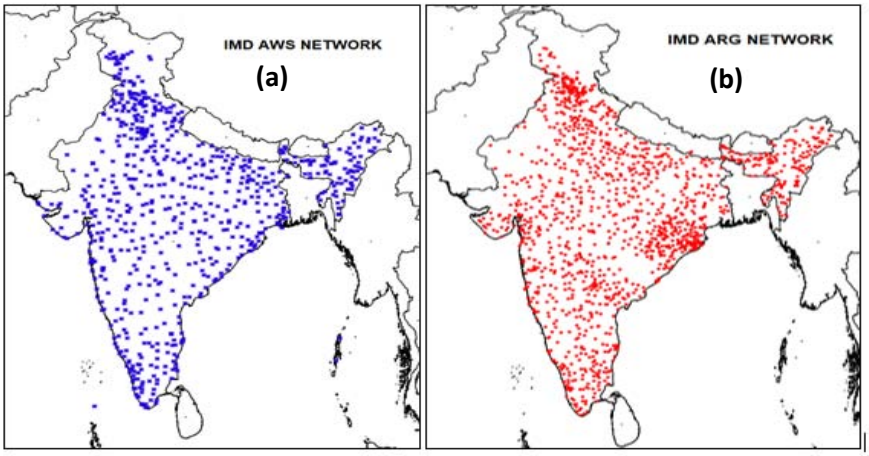
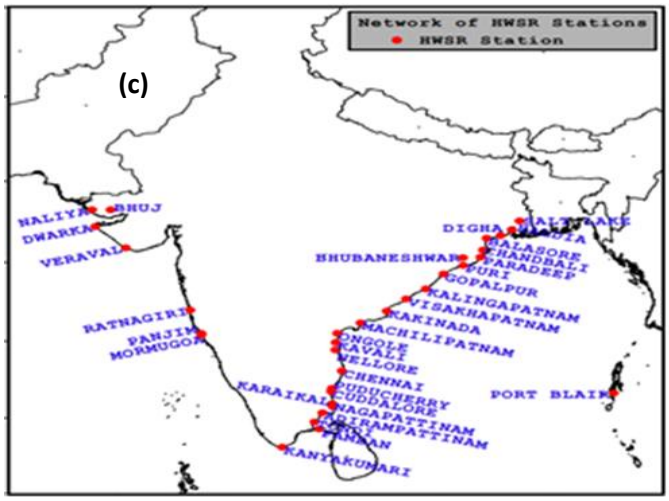


Fig. 1.3 (a) Network of 1008 AWS and (b) 1382 ARGs.

As a part of addressing the Impact of severe weathers over Megacities in the country; Meso scale observational networks of AWS/ARG are established in Mumbai and Pune for location specific real-time weather updates on web and on Mobile App recently. This was done jointly with local state government authorities. Further more cities will be taken up in coming time.

In addition, 35 Nos. of High Wind Speed Recorders (HWSRs) are installed for continuous monitoring of High wind speed and Station Level Pressure along East & West coast of India during cyclone and severe weather. The HWSR system have wind sampling capacity (every second data sample) using state-of-the-art Ultrasonic wind sensor and data is made available in real time to users. Some HWSRs are also planned in the interior of country specifically monitoring Gusty wind during severe Thunderstorm.



Future Plans:

- AWS network is further being strengthened with 400 AWSs across the country. The 170 AWS network have been established out of 400 AWSs and will be completed by 2025. In addition, network of Agro-AWS will also be further augmented by installation of 330 Agro-AWSs by 2024-2026.

- By 2025, additional 100 HWSR stations will be installed across the country. One HWSR station (at least) in each coastal district of India will be installed. The HWSR stations will also be installed in contiguous coastal districts of India. A new web portal for HWSR stations already developed and will be made operational soon for monitoring and retrieval of data in real time.

- Under Plan Project (2021-2026), the network of 200 AWS/ARG will be enhanced in Urban City, adding 50 AWS in KV Schools, and 230 (AWS/ARG/ASG) in Himalayan States. IMD will further strengthen by adding network of around 329 AWS, 330 AGRO AWS, 242 ARG and 59 ASG all over India.

1.3.2 Upper Air Observatories

There are at present 62 Pilot Balloon Observatories (PBOs), 56 Radiosonde observatories. All the 56 stations are latest of the art- GPS based observatories. Out of these, six radiosonde stations at Regional Meteorological Centre's in New Delhi, Mumbai,

Kolkata, Chennai, Guwahati and Nagpur are of WMO-GUAN (Global Climatological Observations System Upper Air Network) standards. These have been included into GUAN. The pilot balloon observation and radiosonde observatory network of IMD is shown in Fig 1.4

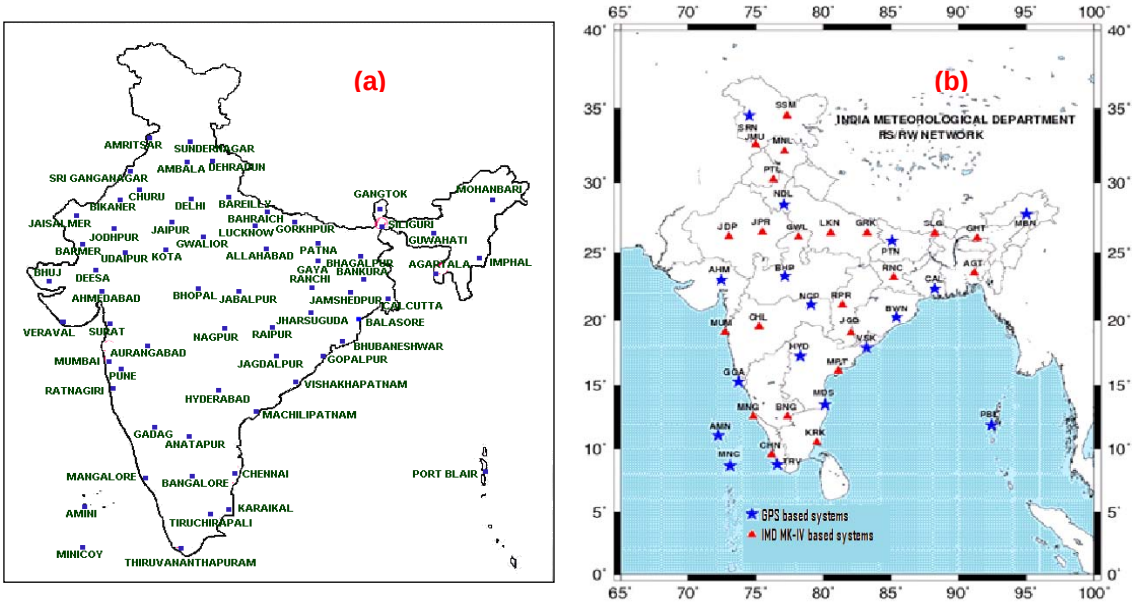


Fig.1.4 (a) Network of Pilot Balloon Observatories (PBO) and (b) Network of Radiosonde/ Radio wind observatories

To monitor the daily ascent status and the stock of various consumables the observatory performance monitoring system has been started on the intra IMD portal, https://ddgmui.imd.gov.in. The upper air meteorological data collected all over the country are used 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 39 Doppler Weather Radars (DWRs) presently, spreading across the country (Fig. 1.5). RADAR network includes 5 ISRO and 1 IITM RADARs.

- India has a network of 16 RADARs covering the Indian Coast line. Eight radars (Chennai, Kolkata, Machilipatnam, Visakhapatnam, Paradip, Gopalpur, SHAR, Karaikal) on the East Coast and five radars (Kochi, Goa, Mumbai, Bhuj, and Thiruvananthapuram) on West Coast. Recently, two more indigenously developed DWRs: one X-band DWR at Pallikarnai, Chennai and one C-band at Veravali, Mumbai have been added in IMD radar network. Thus there are 16 radars along the coast.
- IMD also utilizes the data inputs from DWRs of ISRO located at VSSC Thiruvananthapuram (C-Band), Sohra / Cherrapunji (S-Band) and SHAR (Sriharikota-S Band) and radar set up by India Institute of Tropical Meteorology, Pune at Solapur, Maharashtra.

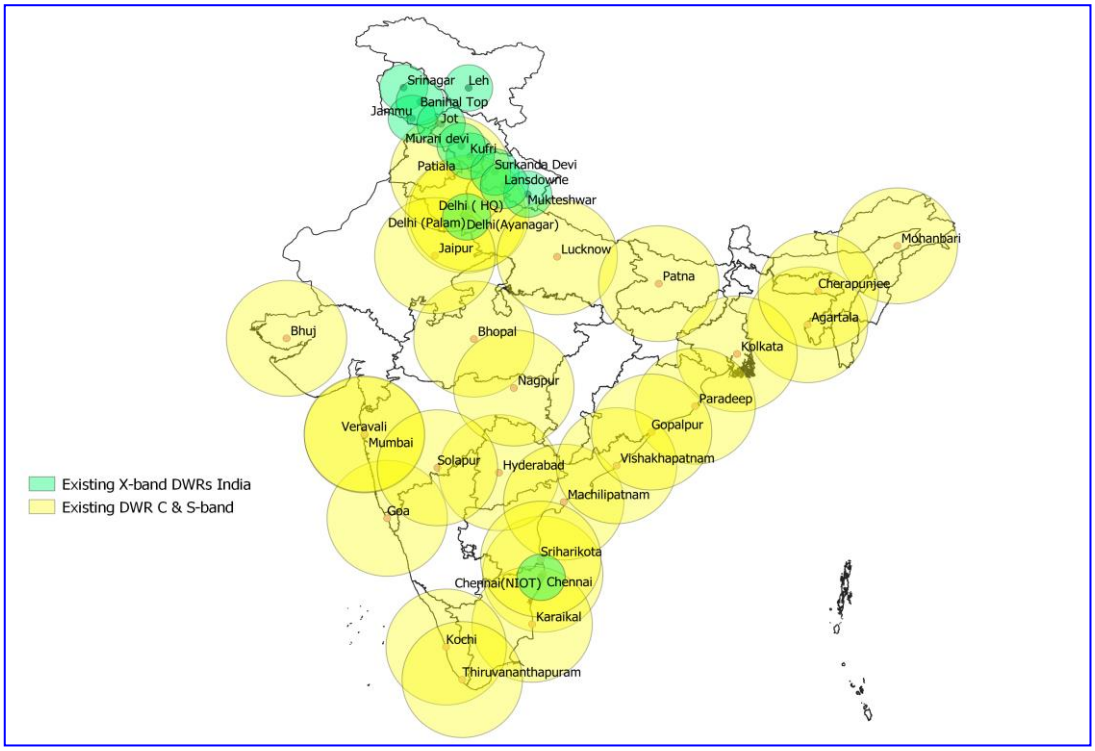


Fig. 1.5 Network of Doppler Weather Radar used for weather monitoring and forecasting

Radars of IMD are being used for detection of rainfall, hail storm, thunderstorms and for tracking of cyclonic storms. Various meteorological and hydrological products derived from radar data using software algorithms are extremely useful to the forecasters for estimating the storm's center, direction of movement, structure and intensity. The existing radars 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 (Network Common Data Format), HDF5 (Hierarchical Data Format version 5), and Opera BUFR (Binary Universal Form for Representation) 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. Open source GIS (Geographic Information System) platforms are used to display the radar data on the web pages. The radar data are combined 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.

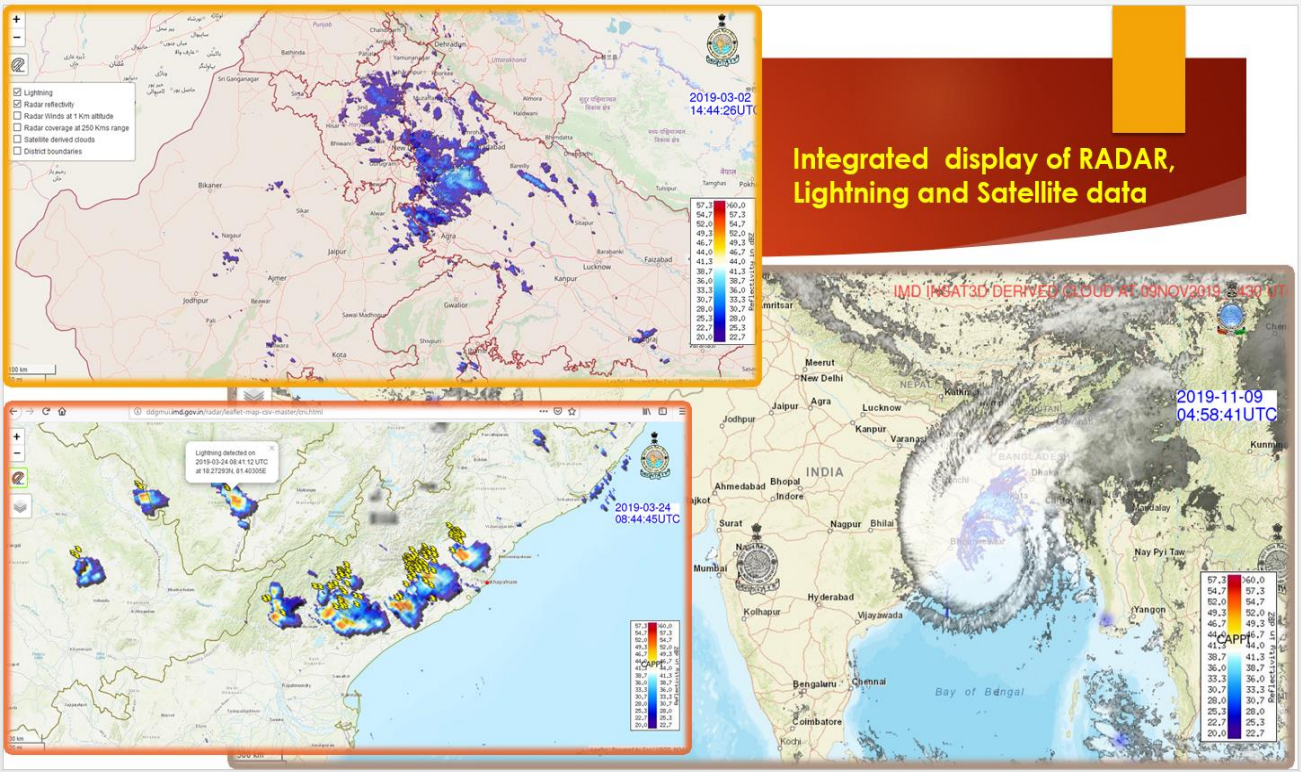


Fig. 1.6: Integrated display using RADAR, Lightning and Satellite data

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 73 DWRs in its network in the phased manner to bring entire Country and coasts under radar 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 Research & Development.

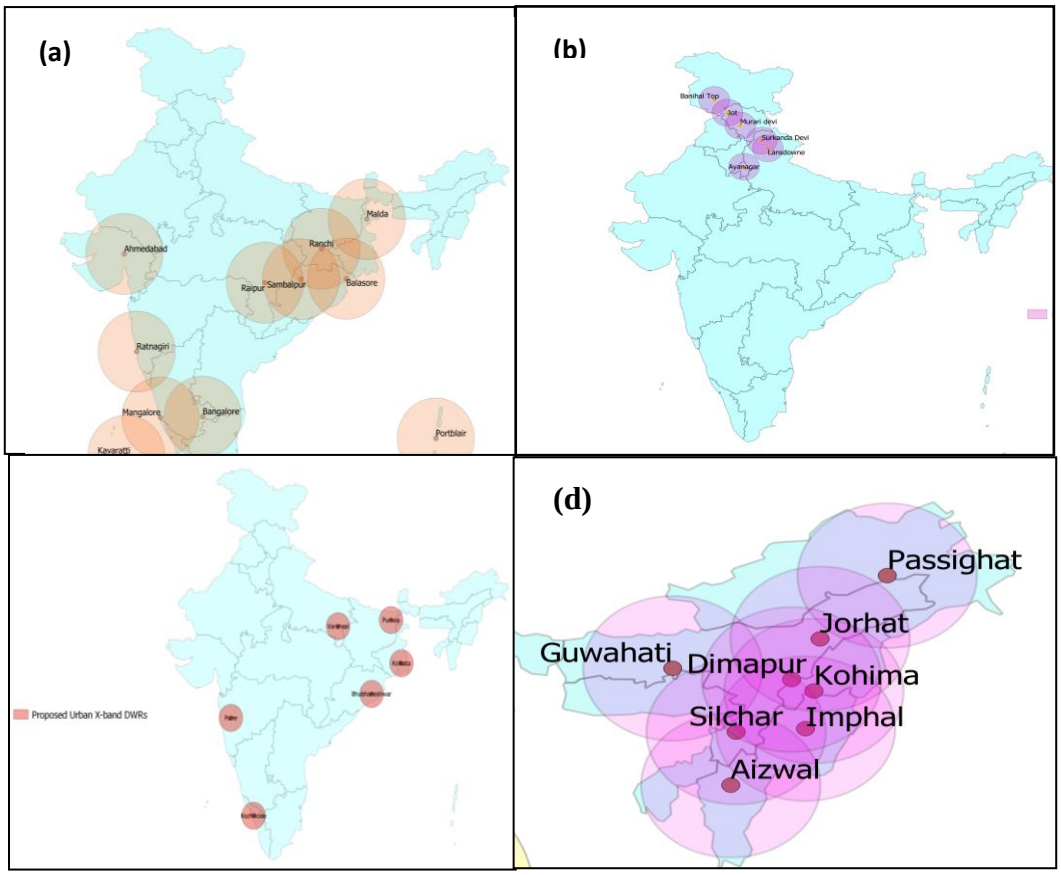


Fig. 1.7: Proposed (a) C band Doppler weather radars, (b) Radar network in Central & Western Himalayas and (c) X-band DWRs for Urban Meteorology and (d) Radar network in North East India

IMD has also planned the procurement of Wind profilers under MoU with ISRO, Bangalore. The information on wind profiles improves the weather prediction in the tropics. Therefore, wind profilers are planned to be installed at nine locations. (Fig. 1.8)

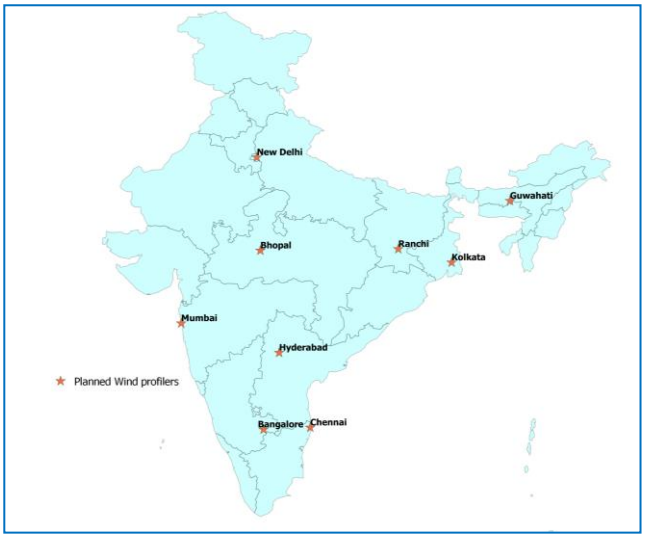


Fig. 1.8: Proposed Wind profilers

Further under Mission Mausam, 53 Radara, 10 wind profilers and 25 microwave radiometers will be procured and 60 numbers of RS/RW stations will be added to the network.

1.3.4 Satellite Monitoring

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. MMDRPS systems consist of advance & latest state of art servers capable to process the complete set of data within 7 minutes after completion of scanning along with the storage capacity of order 2.0/2.0PB (Main/ Mirror) & 324TB SSD which will facilitate online sharing of processed data for all Indian meteorological satellites to the registered users as per IMD data policy through Web based secured satellite Data Supply System.

From MMDRPS, at present IMD is receiving and processing meteorological data from two Indian satellites namely INSAT-3D & INSAT-3DR. INSAT-3D launched on 26 July 2013 is positioned at 82°E and INSAT 3DR launched on 8th Sep 2016 is located at 74°E. INSAT-3D and INSAT-3DR have an advanced imager with six imagery channels **{**Visible (0.55-0.75 μm), Short wave Infra-Red (SWIR) (1.55-1.70 μm), Medium Infra-Red (MIR) (3.80-4.00 μm), Thermal Infra-Red-1(TIR-1) (10.2-11.3 μm), TIR-2 (11.5-12.5 μm), & WV (6.50-7.10 μm)**}** and a nineteen channel sounder (18 IR & 1 Visible) for derivation of atmospheric temperature and moisture profiles. It provides 1 km. resolution imagery in visible band, 4 km resolution in IR band and 8 km in WV channel.

Imager payload of these satellites (INSAT3DS/R) are operated in a staggered mode to get images every 15 minutes. Sounder payload of INSAT 3DS and INSAT 3DR satellite is operated in an integrated mode so that every hourly data of 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. 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.
- 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 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 Application Unit is also using microwave imageries operationally from NOAA, NASA-GPM, AMSR2, Metop, 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.

ISRO successfully launched EOS-06 in November 2022. Satellite Meteorology Division, IMD had started receiving operational Scatterometer data from ISRO from May 2023. Satellite division, IMD, has indigenously devised a software module for operational handling of the Scatterometer data. Data are fetched between dual swath mode in a calendar day through file transfer protocol (FTP) and end products are generated by utilizing various Python libraries on a real time basis. Satellite division has also established a direct file transfer protocol access to the NRSC data repositories for seamless data transfer and product generation. The data output is currently generated in jpg format. The software code for this visualization has been exclusively made at SATMET division for the forecasters and end users. Typical OceanSat imagery during cyclone “Dana” is presented in Fig. 1.9.

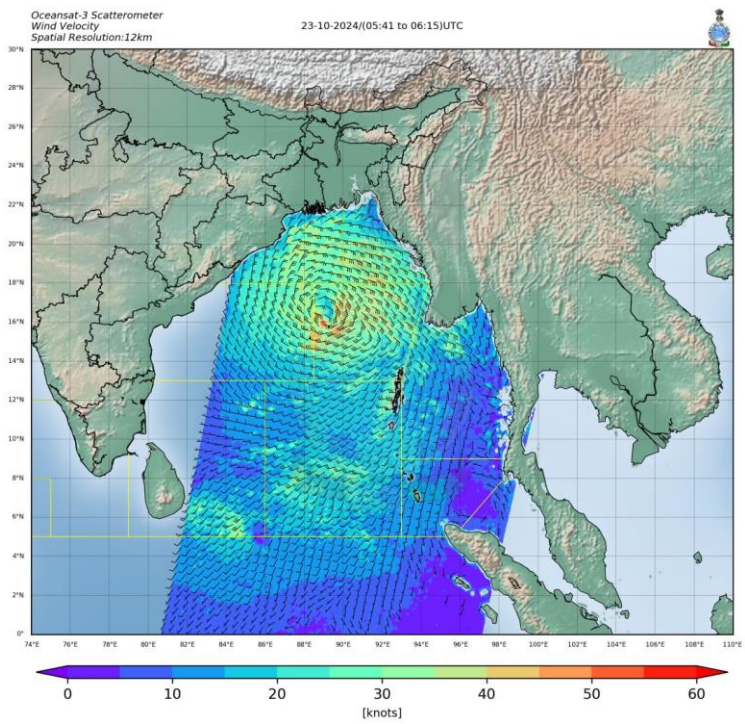


Fig.1.9: Oceansat-3 image of severe cyclonic storm Dana during 23rd October 2024

Satellite based Land Surface temperature product is currently generated on a pilot mode for Delhi-NCR region. The region-specific land surface temperature values from INSAT 3D and 3DR are generated for improved understanding of the urban hotspots over the city. This module is also planned for other smart cities in near future. An example is presented is fig 1.10.

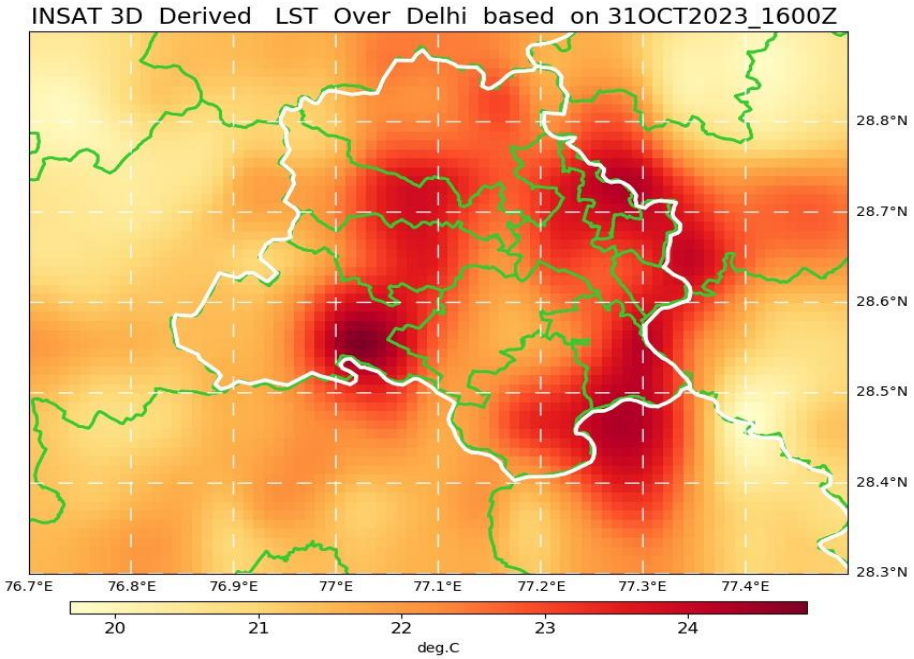


Fig.1.10: Satellite based land surface temperature

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 3DS 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-3DS and INSAT 3DR products & imageries are archived. Spectral Band images and product images are archived online for last 6 months. The generation of around ten new products has been put in operational chain of MMDRPS to meet the NWP, Forecaster and Agromet services requirement.

INSAT-3DR Imager payload is used to conduct rapid scans during active cyclones following a standard operating procedure. Each Rapid scan cover 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).

1.3.4.1 Advanced Capabilities of Modern Indian Satellites:

Modern Indian satellites are equipped with sophisticated instruments that provide comprehensive atmospheric observations. These instruments include:

- Multispectral Imagers: These imagers capture images in multiple spectral bands, allowing for detailed analysis of cloud cover, land surface conditions, and ocean features.
- Sounders: Sounders measure the temperature and moisture profiles of the atmosphere, providing crucial information for weather forecasting and climate studies.

The recently launched **INSAT-3DS**, with its improved blackbody calibration and advanced sounder payload, further enhances India's capabilities in satellite meteorology.

By harnessing the power of satellite technology, India has significantly improved its weather forecasting and climate monitoring capabilities, contributing to the safety and well-being of its citizens and the global community.

INSAT-3DS, launched on February 17, 2024, is the latest addition to India's geostationary satellite fleet. It is designed to provide enhanced meteorological observations and monitoring of land and ocean surfaces, significantly improving weather forecasting and disaster warning capabilities.

1.3.4.2 Key Features of INSAT-3DS:

- Advanced Payloads: Similar to INSAT-3D and INSAT-3DR, INSAT-3DS carries a 6-channel imager and a 19-channel sounder.
- Improved Capabilities: The satellite incorporates advancements in radiometric accuracy, black body calibration, thermal management, and imaging throughput.
- Enhanced Data Quality: Provides higher-quality data for more precise weather analysis and forecasting.
- Real-time Monitoring: Contributes to real-time monitoring of weather systems, including cyclones, thunderstorms, and fog.
- Improved Disaster Warning: Helps in early warning systems for extreme weather events like floods, droughts, and heatwaves.

Contribution to Weather Forecasting:

INSAT-3DS, along with INSAT-3DR, plays a crucial role in:

- Accurate Weather Prediction: Provides high-resolution imagery and atmospheric profiles for precise weather forecasting.
- Tropical Cyclone Tracking: Enables real-time monitoring of cyclone formation, intensification, and movement.
- Monsoon Monitoring: Helps in understanding and predicting the Indian monsoon, a vital weather system for the country.
- Extreme Weather Event Monitoring: Detects and tracks extreme weather events like heatwaves, cold waves, and heavy rainfall.
- Climate Studies: Contributes to long-term climate studies and monitoring climate change impacts.

By leveraging the capabilities of these advanced satellites, India is strengthening its capacity to monitor weather patterns, issue timely warnings, and mitigate the impacts of natural disasters

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 300 No. of lightning detectors in the country. The area of lightning during preceding 5 min, 10 min and 15 min are superimposed with satellite and radar imageries. It helps in proper monitoring of thunderstorm and lightning activities and nowcasting of such events.

1.3.6 Operational forecast and warning production

1.3.6.1 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.1.11

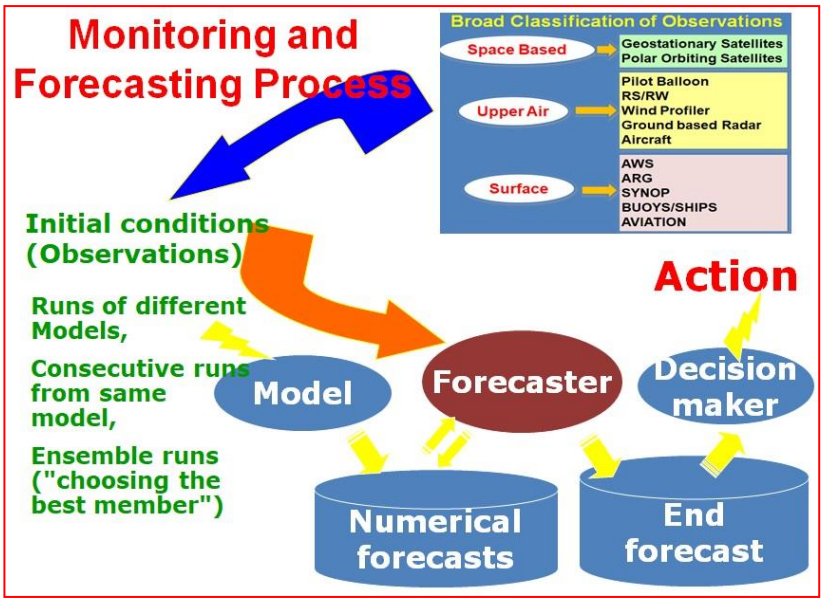


Fig.1.11. Strategy adopted for cyclone analysis and forecasting

The **indigenously developed decision support system has** following facilities.

- Analysis of all synoptic, satellite, radar and NWP model products for genesis, intensity and track monitoring and prediction
- Preparation of past and forecast tracks upto 120 hrs
- Depiction of uncertainty in track forecast
- Preparation of quadrant wind radii forecast upto 120 hrs.

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

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

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

In addition, IMD has developed GIS based decision support indigenously which has the facility to overlay various model products at a single platform. It is utilized by the forecasters to generate probabilistic area of cyclogenesis, multi model based warnings for fishermen, probabilistic area of winds exceeding 25 knots and 34 knots, probabilistic heavy rainfall warning maps etc.

1.3.7 Performance of operational NWP models during 2024

1.3.7.1. Global Forecast System

The Global Forecast System (GFS), adopted from National Centre for Environmental Prediction (NCEP) USA is operationally run at India Meteorological Department (IMD), New Delhi on Cray XC40 based High Power Computing Systems (HPCS). The IMD-GFS (T1534/L64) global model is run with ~12 km horizontal resolution and 64 hybrid sigma-pressure layers with Ensemble Kalman Filter (ENKF) based Grid Point Statistical

Interpolation (GSI) scheme as the global data assimilation to generate 10 days forecast. The model is run four times in a day (00, 06, 12 and 18 UTC). The real-time outputs are made available to the national web site of IMD (https://mausam.imd.gov.in/ under Short to Medium Range Model Guidance).

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

1.3.7.2. Regional Forecast System

IMD operationally runs regional models Weather Research Forecast Advance Research for Weather Forecasting (WRFARW) (v3.9) with regional GSI based data assimilation, and Atmosphere-Ocean coupled Hurricane Weather Research and Forecast (HWRF) modelling system for short-range prediction during cyclone.

1.3.7.2.1. Mesoscale modeling system WRF-ARW with regional GSI based Data Assimilation system

The mesoscale Weather Research and Forecast WRF (version 3.9.1) with 3DVAR data assimilation is being operated daily twice to generate mesoscale analysis at 8 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 3 km and 45 Eta levels in the vertical 4 times a day at 06 hourly interval.

The model domain covers the area between lat. 5ºS to 40ºN long 50ºE to 102ºE covering India and neighbouring south Asian countries. The model runs with its own regional data assimilation (Com GSI V3.7_EnKF1.3).

1.3.7.2.2. Hurricane WRF Model (HWRF)

Since 2011, time to time the HWRF modelling system is developed and customized atmospheric and ocean models with other associated pre-processing and post-processing components are implemented in IMD under the framework of MoU between Ministry of Earth Sciences (MoES) India and National Oceanic and Atmospheric Administration (NOAA) USA. The HWRF version H217 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^{o}, 24°x24^{o} and 7°x7^{o} respectively. The special feature modified for tropical cyclone forecasting includes vortex initialization and correction, GSI based regional data assimilation, coupler for two-way coupling between atmosphere and ocean components and fine-tuned physical parameterization schemes. This model is customized specifically to forecast the track, intensity and structure of tropical cyclones. The HWRF modelling system uses the dynamics and infrastructure from the Non-Hydrostatic Mesoscale Model (NMM) WRF modelling system. It uses physics that are proven to be better for the tropics. Also, at this time, it is an Ocean coupled model system with a Moving two-way interactive nest, and advanced data assimilation. IMD is operationally running ocean coupled HWRF models during Tropical Cyclone (TC) events with two ocean models viz. Princeton Ocean Model (POM-TC) and Hybrid Coordinate Ocean Model (HYCOM). HYCOM initial conditions are provided through

Indian National Centre for Ocean Information Services (INCOIS) whereas POM-TC is initialized based on climatology.

It is run 4 times a day in cyclic mode with GSI based (hybrid-Ensemble Variation (EnVar)) assimilation (80 members) with 6 hourly cycles in cycling mode with full physics configuration. The Unified Post-Processor (UPP) coverts raw model outputs from all three domains into standard GRIB1/2 format. Moreover, Global Fluid Dynamics Laboratory (GFDL) tracker generates track and intensity information in a standard Automated Tropical Cyclone Forecasting System (ATCF) format processing all GRIB files with a specified time interval (3 or 6 hours) as per requirement.

The modeling system was fully operational and predicted all cyclones during the years. Whenever any low-pressure system intensified and became depression over both sub-basins of North Indian Ocean, the cyclic run of the modelling system had been initiated. The model utilized ocean initial state from the INCOIS Tendral Ocean Prediction System – Indian Ocean Model (ITOPSI) during each cycle to initialize the HYCOM ocean component. All available observed data including conventional and satellite observations were assimilated into the regional GSI system to improve further the initial condition after the vortex initialization of the atmospheric first guess state of the model forecast from previous cycle (except first cycle).

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 Real-Time Ocean Forecast System (RTOF) 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 coupled HWRF system with both ocean models viz, POM-TC and HYCOM was operational simultaneously and model guidance products were provided from both the configurations. The coupled HWRF model uses TC Vital parameters generated by RSMC, New Delhi every six hour from Deep depression state till landfall of TC

1.3.7.2.3. High Resolution Rapid Refresh Modeling System (HRRR)

The High Resolution Rapid Refresh (HRRR) system based on Weather Research and Forecast (WRF-ARW) model with WRFDA (3DVAR-FGAT) data assimilation is operationalized in IMD in collaboration with Space Application Center (ISRO) from beginning of 2021. The HRRR is hourly updated atmospheric model with horizontal resolution of 2km. The model uses forecast of IMD-GFS (T1534L64) model as first guess and forecast as boundary during cold start and is then cycled providing hourly updates based on Radar Data

assimilation. Using analysis and updated boundary conditions from the WRFDA, the HRRR is run to produce forecasts up to 12 hours and forecasts are made available after every two hours on NWP website of IMD.

The model is run in three different domains covering Indian mainland. The three domains are North-West domain, East & North-East domain and South-Peninsular domain. HRRR with hourly updates provide frequent and updated precipitation and reflectivity forecasts with respect to the TCs which could be very useful in planning effective and immediate disaster mitigation strategies in very short range.

1.3.7.2.4. Dynamical statistical models

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) 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 relative 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 (T 3.0) 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. 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 2022-2023 affirm its usefulness as a predictive signal (4-5 days in advance) for cyclogenesis over the North Indian Ocean.

b) 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.

With the latest version of different models & EPS as well as different tracker used for tracking the centre of TC in models, the IMD has developed another MME for track, intensity & landfall forecasts since 2021. It performs better than the individual models.

c) 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.

The MME based all available NWP models on EPS is also developed by IMD since 2021 for intensity prediction.

d) Rapid Intensification (RI) Index

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

e) Decay of Intensity after the landfall

Tropical cyclones (TCs) are well known for their destructive potential and impact on human activities. The Super cyclone Odisha (1999) illustrated the need for the accurate prediction of inland effects of tropical cyclones. The super cyclone of Odisha 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

The THORPEX Interactive Grand Global Ensemble (TIGGE, Philippe Bougeault et al. 2010) is an implementation of ensemble forecasting for global weather forecasting and is part of THORPEX, an international research programme established in 2003 by the World Meteorological Organization (WMO) to accelerate improvements in the utility and accuracy of weather forecasts up to two weeks ahead. 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 since 2018. The EPS involves the generation of multiple forecasts using slightly varying initial conditions. The forecast products from these two prediction systems are available at the following links (http://nwp.imd.gov.in/gefspro.php) and http://www.ncmrwf.gov.in/ product_main.php). The frameworks of the new EPSs are among the best weather prediction systems in the world at present. Very few forecasting centres in the world use this high resolution for short-medium range probabilistic weather forecasts.

1.5.5.1. The Ensemble Mean and Spread

The ensemble spread is a measure of the difference between the members and is represented by the standard deviation (SD) with respect to the ensemble mean (EM). On average, small (high) spread indicates a high (low) forecast accuracy.

- The ensemble spread is flow-dependent and varies for different parameters.
- It usually increases with the forecast range, but there can be cases when the spread is larger at shorter forecast ranges than at longer ranges. This might happen when the initial days are characterized by strong synoptic systems with complex structures but are followed by large-scale "fair weather" high pressure systems.

1.5.6. Models run at NCMRWF

Two global models are also run at NCMRWF, NGFS adapted from NCEP GFS and NCUM unified model adapted from UK Met Office. The observations assimilated at NCMRWF include various in-situ and remote sensing observations. In-situ observations includes measurements come from land weather stations, aircraft, radiosondes, ships and buoys. Satellite observation includes Infrared and microwave radiance measurements from Low Earth Orbiting (LEO) and Geostationary (GEO) satellites, Atmospheric Motion Vectors from LEO and GEO, ocean surface winds from scatterometers, GPS Radio Occultation measurements etc. Indian Doppler Weather Radar (DWR) observations are also assimilated in the NCMRWF NWP systems. NCUM-G (N1024/L70) model features a horizontal resolution of 12km and 70 vertical levels reaching upto an altitude of 80 km. It uses “ENDGame” dynamical core, which provides improved accuracy of the solution of primitive model equations and reduced damping. This was upgraded in June 2018 from the earlier model with a horizontal resolution of 17km. NCUM is a grid point model which has a Non-hydrostatic dynamics with a deep atmosphere suitable for all scales. It has semi-implicit time integration with 3D semi-Lagrangian advection, terrain following height coordinates and high order advection. It features mass-flux for shallow convection with convective momentum

transport, non-local mixing and entrainment for boundary layer. The new version of the NCUM has the model physics configuration of GA6.0 (Global Atmosphere version 6.0) and a land surface model configuration of GL 6.0 which is based on JULES land surface scheme (Walters et al., 2017). This helps in producing finer details in the simulations of synoptic scale systems such as cyclones, fronts, troughs and jet stream winds. ENDGame also increases variability in the tropics, which leads to an improved representation of tropical cyclones and other tropical phenomena (Walters et al., 2017). Hybrid 4D-Var data assimilation system prepares initial condition for NCUM. The advantage of the Hybrid 4D-Var is that it uses a blended background error, blend of "climatological" error and day-to-day varying flow dependent background error derived from the 22–member ensemble forecasts at NCMRWF. The hybrid approach is scientifically attractive because it elegantly combines the benefits of ensemble data assimilation with the known benefits of 4D-Var within a single data assimilation system.

NCUM-R is a regional model having a horizontal grid resolution of ~4km with 80 vertical levels reaching up to 38.5 km height. NCUM-R uses the high-resolution analysis prepared by regional 4D-Var system. In addition to most of the in-situ and satellite observation types used in the global NCUM, Indian DWR observations of radial wind and rainfall intensity estimates are also used in the regional NCUM DA system. The model domain of NCUM-R spans entire south Asia covering Bay of Bengal and part of Arabian Sea (5 N-40 N, 65-100 E).

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 ~12km. 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 are 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 Coupled Ocean Atmosphere Model at NCMRWF (CNCUM) uses the Nucleus European Modelling of Ocean (NEMO) based global ocean analysis and forecast system at 0.25x0.25degree resolution is used to compute the upper ocean heat content up to 26°C isotherm depth called as Tropical Cyclone Heat Potential (TCHP). It is important oceanic parameter which affects the intensity of the TCs. At NCMRWF, it is produced in real time using the global ocean forecast system up to 10 days using the ocean only model and up to 15 days using the coupled atmosphere-ocean model for monitoring the upper ocean and also for research purpose mainly for Tropical Cyclone (TC) study. Further, the NEMO based temperature and salinity forecast from the Extended Range Prediction (ERP) is also used to compute the TCHP up to 4 week periods.

1.5.7. Models run at IITM Pune

Since 2018, Global Ensemble Forecast System (GEFS) T1534 (~12 km) is used for operational short-range probabilistic weather forecast system including cyclone prediction at IITM. It is based on Global Forecast System (GFS v14.1) which is a part of the 'Operational

Model' developed at NCEP, USA in 2018. This is a spectral model with semi lagrangian dynamics and semi implicit time scheme. It has a horizontal resolution of 12.5 km. The total number of 21 Ensembles (20 perturbed forecasts + 1 control forecast) constitutes the ensemble system. These 20 ensembles analysis are generated by Ensemble Kalman Filter (EnKF) method from the forecast perturbation of the previous cycles four times a day (00, 06, 12 and 18 UTC) at all 64 model vertical levels. These analysis perturbations are added to the reconfigured analysis obtained from the hybrid four-dimensional Ensemble variational data assimilation system (GDAS-Hybrid4DEnsVar) as part of the suite. The 243 hour forecast of GEFS is routinely generated based on 00UTC and 12UTC initial conditions which include a control forecast starting from GDAS assimilation and 20 (20 perturbations) ensemble members with each perturbed initial conditions.

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. The ERF is generated based on consensus approach utilizing the forecast guidance from different deterministic and probabilistic NWP models, ERF models and the large scale processes like convectively coupled equatorial waves such as Maden Julian Oscillation (MJO), Equatorial Rossby waves, Kelvin waves, low background waves. For details kindly refer SOP of cyclone warning services in India available on RSMC website at https://rsmcnewdelhi.imd.gov.in/report.php?internal_menu=NjE=).

1.6.2 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, Moderate and High probability corresponding to expected probability of occurrence of 00, 01 – 33, 34 – 67 and 68 – 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.

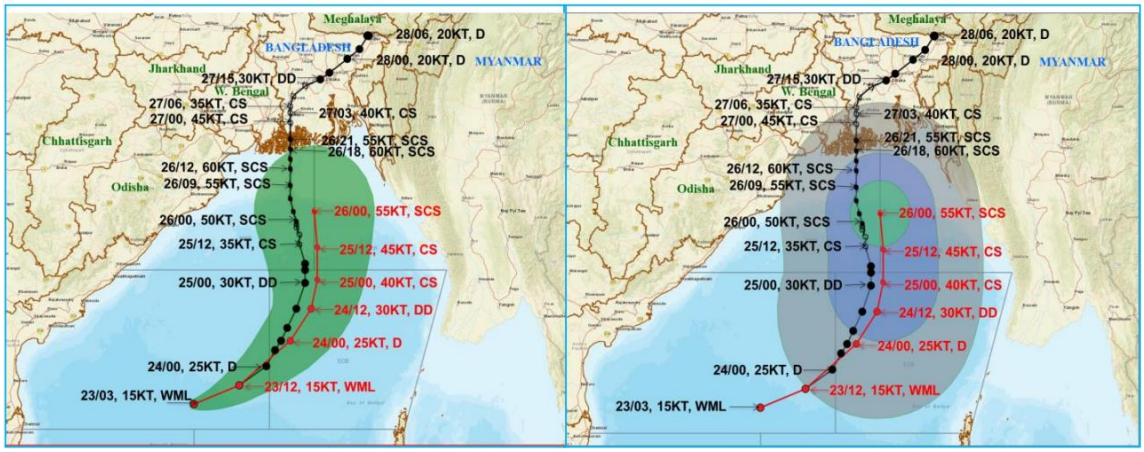
The outlook is generated based on consensus approach utilizing the forecast guidance from different deterministic and probabilistic NWP models, the large scale processes like convectively coupled equatorial waves such as Maden Julian Oscillation (MJO), Equatorial Rossby waves, Kelvin waves, low background waves and the guidance on genesis potential

parameters. For details kindly refer SOP of cyclone warning services in India available on RSMC website at https://rsmcnewdelhi.imd.gov.in/report.php?internal_menu=NjE=.

1.6.3 Pre-Genesis Forecast:

India Meteorological Department has commenced pre-genesis forecast of probable date, time and location of expected cyclogenesis (formation of depression) over the NIO along with 12 hourly forecast of track, intensity and structure upto next 72 hours, once daily from the stage of low pressure area on 17th March, 2022. Typical example of pre-genesis forecast issued during Severe cyclonic storm "REMAL" is presented in Fig. 1.12

Fig. 1.12: Pre-genesis forecast issued at the stage of well marked low pressure area



on 23rd May, 2024 (3 and 1/2 days prior to landfall on 26th May over Bangladesh) demonstrating accuracy in track and intensity forecast

The pre-genesis forecast is generated based on consensus approach utilizing the forecast guidance from different deterministic and probabilistic NWP models, and the large scale processes like convectively coupled equatorial waves such as Maden Julian Oscillation (MJO), Equatorial Rossby waves, Kelvin waves, low background waves and regional scale process as well as genesis potential parameters. For details kindly refer SOP of cyclone warning services in India.

1.6.4. 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 and www.rsmcnewdelhi.imd.gov.in**. RSMC, New Delhi can also be contacted through e-mail (**cwdhq2008@gmail.com and cyclonewarningdivision@gmail.com**) for any real time information on cyclonic disturbances over NIO.

1.6.5 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** and **www.rsmcnewdelhi.imd.gov.in**.

1.6.6 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. Recently INCOIS Hyderabad has developed an ADvanced CIRCulation (ADCIRC) Storm Surge and Coastal Inundation model which is running experimentally since 2013. In future it will be used as an input for providing storm surge guidance to member countries. RSMC New Delhi also commenced probabilistic storm surge guidance from Severe Cyclonic Storm "Remal" in May 2024. Typical guidance product is placed at Fig. 1.13.

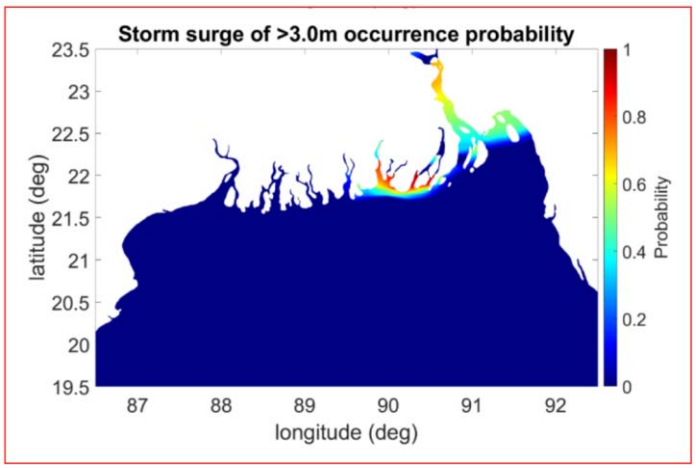


Fig. 1.13: Probabilistic Storm Surge during SCS REMAL

1.6.7 Marine weather 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, sea area bulletin, coastal weather 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.

The fishermen warnings for next 5 days based on multi-model ensemble and probability of exceedance of winds ≥ 45 kmph and 35 knots are available at www.rsmcnewdelhi.imd.gov.in.

IMD has also commenced preparation of marine weather bulletins in graphical format using QGIS tool and these graphical products are also available over GIS platform since January, 2021 based on multi model ensemble guidance. Sample fishermen graphics is placed at Fig. 1.14. During the cyclonic disturbance period the frequency of these bulletins increase. Kindly refer SOP for detailed information available on RSMC website at https://rsmcnewdelhi.imd.gov.in/report.php?internal_menu=NjE=.

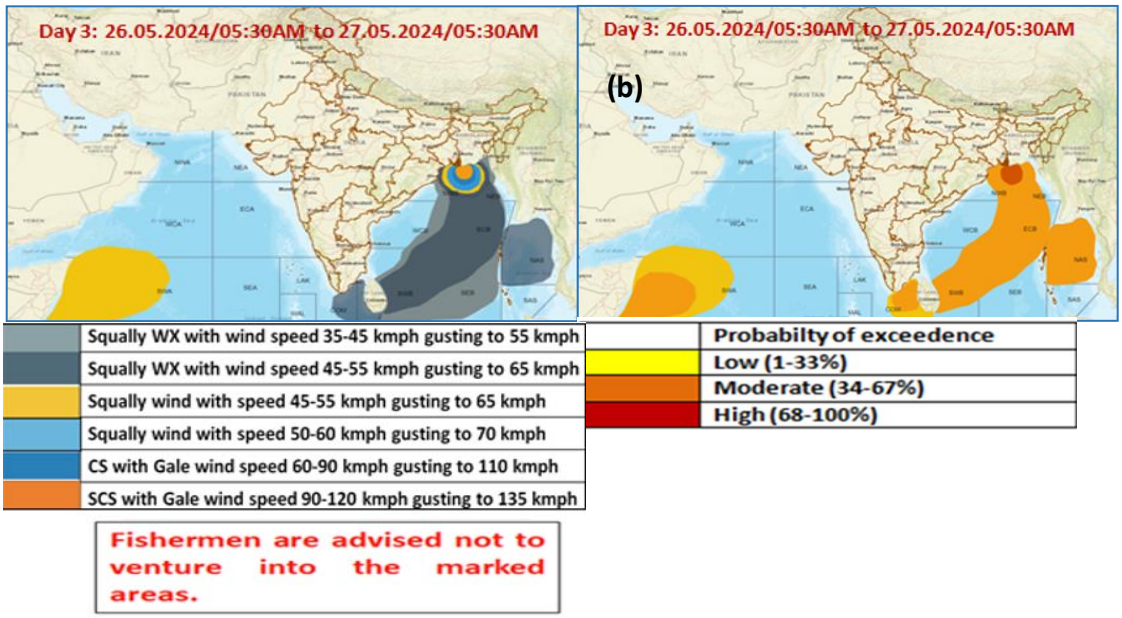


Fig. 1.14: Typical (a) fishermen warning graphics and probabilistic map for wind exceeding 45 kmph issued on 24th May 2024

1.6.8. Tropical Cyclone Advisories for Aviation

Tropical Cyclone Advisories for aviation are issued for international aviation as soon as any disturbance over the NIO attains or likely to attain the intensity of cyclonic storm (maximum sustained surface wind speed ≥ 34 knots) within next six hours. These bulletins are issued at six hourly intervals based on 00, 06, 12, 18 UTC synoptic charts and the time of issue is HH+03 hrs. These bulletins contain present location of cyclone in lat./long., maximum sustained surface wind (in knots), direction of past movement and estimated central pressure, change in intensity, forecast position as Lat./Long (in degree & minutes), and forecast winds in knots valid at HH+6, HH+12, HH+18 and HH+24 hrs. The tropical

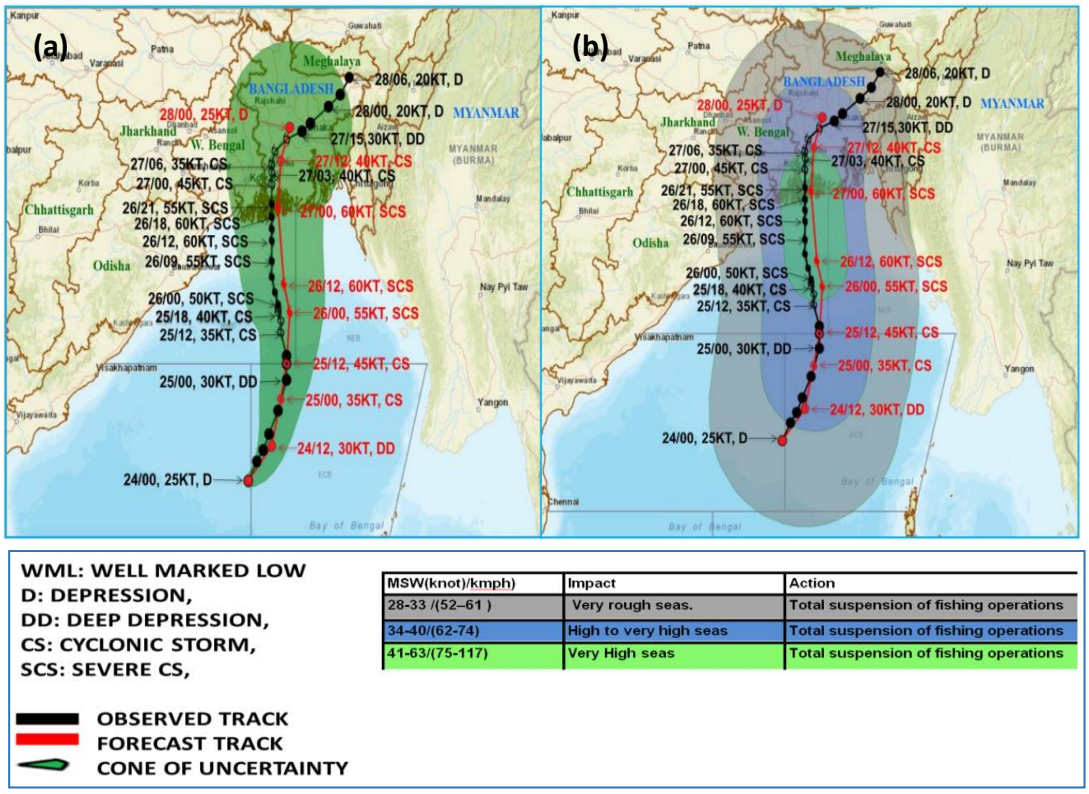
cyclone advisories are transmitted on real time basis through GTS & AFTN channels to designated International Airports of the region prescribed by ICAO and ftp to ADRR, Hong Kong (WMO's Aviation Disaster Risk Reduction) in coded form. It is also sent in graphics form in PNG format through GTS. The text and graphical bulletins are also uploaded on www.rsmcnewdelhi.imd.gov.in

1.6.9. National bulletin

These bulletins are issued from the stage of low pressure area as a "Special Message", once daily. In case of cyclones, IMD follows a 4 stage warning system with issue of (a) pre-cyclone watch at least 72 hours, (b) cyclone alert at least 48 hours, (c) cyclone warning at least 24 hours and (d) post landfall outlook for the interior districts issued 12 hours ahead of commencement of adverse weather over the coast. During the stage of depression/deep depression; it is issued 5 times daily based on 00, 03, 06, 12, and 18 UTC observations. When the system intensifies into a cyclonic storm over NIO, these bulletins are issued every three hourly based on 00, 03, 06, 09, 12, 15, 18 and 21 UTC (every three hourly interval) at +03HH. This bulletin contains present status of the system i.e. the location, intensity; past movement and forecast track & intensity for next 120 hours or till the system weakens 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 these bulletins. This bulletin is completely meant for national users and these are disseminated through various modes of communication including Email, Telephone/FAX, All India Radio, Doordarshan (National TV), SMS and Print & electronic media. It is also posted on cyclone page of IMD website and RSMC website. These are also posted on social networking sites like facebook, tweeter and whatsapp.

1.6.10. Cone of uncertainty forecast

The Cone of uncertainty (COU) represents the uncertainty in forecast centre of a CD/TC's 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 Severe Cyclonic Storm "REMAL" is presented in Fig. 1.14 (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 platform at www.rsmcnewdelhi.imd.gov.in



WML: WELL MARKED LOW
D: DEPRESSION,
DD: DEEP DEPRESSION,
CS: CYCLONIC STORM,
SCS: SEVERE CS,

OBSERVED TRACK
FORECAST TRACK
CONE OF UNCERTAINTY

MSW(knot)/kmph)	Impact	Action
28-33 /(52–61)	Very rough seas.	Total suspension of fishing operations
34-40/(62-74)	High to very high seas	Total suspension of fishing operations
41-63/(75-117)	Very High seas	Total suspension of fishing operations

Fig.1.14: Observed and Forecast track alongwith (a) cone of uncertainty and (b) w issued at 0915 hrs IST/0345 UTC of 24th May demonstrating accuracy in track and intensity forecast about 62 hours ahead of landfall.

1.6.11. Wind forecast for different quadrants

The forecast of the radius of maximum sustained wind in four quadrants of a cyclone commenced with effect from the cyclone, GIRI during October 2010. In this forecast, the radius of 28, 34, 50 and 64 knot winds are given for various forecast periods like +06, +12, +18, +24, +36, +48, +60, … 120 hrs. A typical graphical presentation of this forecast is shown in Fig.2.12 (b). 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.

1.6.12 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.

1.6.13 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 Impact Based Forecast and Risk Based Warning for heavy rainfall over cities and districts

India Meteorological Department introduced impact based forecasts (IBF) & warnings for cyclonic Storms since long. Recently, since 2014, IMD introduced colour coded IBF for other severe weather events as per WMO guidelines. However, since 2019, IMD started issuing IBF & suggested actions for severe weather events at District level. It was further enhanced for all severe weather events at city & District level in 2020. It is a four stage warning system which includes advisories, alert and warnings in a pre-defined colour coded format. It has also provision of 3-hourly updates of the bulletin during the warning stage that includes a record of realised rainfall, probable impacts and action suggested. It has been made mandatory to provide 3-hourly observations and warnings information to disaster authorities and other state users through WhatsApp group, website, E-mail and all other possible means of communication.

- Stage - 1 comprises of Heavy rainfall advisory (Watch) issued with a lead time of often 3-4 days, with 12 hourly updates and is disseminated mainly to the disaster managers of the City.
- Stage -2 is the Heavy rainfall Alert, issued nearly 48 hours prior to the occurrence of the event with 12 hourly updates. Alert will be disseminated via E-Mail, website, Social media, WhatsApp etc.
- Stage -3 will contain the Heavy rainfall warning issued 24 hours prior to the commencement of the event with frequent updates (06 hourly or as the situation demands). This bulletin will be disseminated to all user communities including local media using web page, e-mails, various social media, WhatsApp, etc.
- Stage-4 warning bulletins are issued 12 hours prior to the occurrence of the maximum rainfall spell. In this, warnings and all accompanying information including situation reports are updated to the users on a 3 hourly or hourly basis depending on the situation. This will also contain more specific information like which part of the city is likely to have intense rain spells in the ensuing three hours etc.

1.7.1 Web Based Dynamic Composite Risk Atlas (Web-DCRA) & DSS Tool

Web-DCRA&DSS Tool for Cyclone impacts forecasting for the area falling within 10 m elevation above mean sea level in 13 Coastal States/UTs of the Country has been developed under National Cyclone Risk Mitigation Project (NCRMP) Phase II and is installed/hosted at IMD, HQ, New Delhi. The responsibility for operating the DSS Tool at central level has been entrusted to IMD, being Nodal Agency for cyclone warning, while outputs of Web-DCRA & DSS Tool is being accessed by States through State specific credentials and utilized by Disaster Management Authorities in all 13 coastal States/UTs for

mitigation planning and decision making during cyclonic event. The Web-DCRA & DSS Tool has been operationalized during the cyclone 'Biparjoy' in 2023.

The outputs of Web-DCRA & DSS Tool are probabilistic and real-time hazard layer of cyclonic wind, storm surge and cyclone induced rainfall flooding, which can be used by Disaster Management Authorities of the 13 cyclone-prone States and Union Territories (UTs) of India in advance mitigation planning as well as dynamic response during a real time cyclonic event. Using this Tool, dynamic and impact-based cyclone warnings will be release by IMD aiming to minimize economic losses and damage to property due to the intense weather system. The Offline version of Web-DCRA has been installed in State Disaster Management Authority (SDMA) for routine updation of exposure database by the coastal States.

1.8. 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 NAVIK systems. IMD has also established new cyclone warning centre at Thiruvananthapuram w.e.f. October, 2018 to improve dissemination of warnings and advisories for the states of Kerala, Karnataka and Lakshadweep Islands.

Since 2019, IMD is also notifying cyclone warnings on mobile apps Umang and Meghdoot Apps. IMD has also started the dissemination of weather information through common alerting protocol. The URL of RSS feed is https://cap-sources.s3.amazonaws.com/in-imd-en/rss.xml. Since Super Cyclone Amphan, 2020, cyclone warnings were transmitted through CAP.

IMD has also commenced sharing of cyclone bulletins through whatsapp with 13 WMO/ESCAP panel member countries in 2023. Application Programming Interface (API) has been developed for various products like heavy rainfall, cyclones, rainfall, thunder storms, heat wave etc in 2021. It is used by various stake holders within the country and outside including Global Multi-hazard Alert System (GMAS) of WMO, Google, Apple, windy etc. and various state governments.

Public can also report their observations (textual and PNG format) along with their location and time of the events through Crowd source web interface launched in 2021. This feature is available in the “Public Observation” section of Mausam website of IMD (https://city.imd.gov.in/citywx/crowd/enter_th_datag.php). User can.

1.9. Tropical Cyclone Forecasting Programme (TCFP) 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 30th November every year. The demonstration project has been renamed as Tropical Cyclone Forecasting Programme (TCFP) in 2022. During the year 2023, the TCFP campaign commenced on 15th October and was extended upto 10th December 2023. Like previous years (2008-2021), several national institutions participated for joint observational, communicational & NWP activities. There was an improved observational campaign with the observation from Buoys, Scatterometer based satellite and microwave imageries products. 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 various coastal states of India along the east & west coasts and for Oman, Yemen & Bangladesh in association with depressions/deep depressions and tropical cyclone. 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 TCFP are available at RSMC, New Delhi website.

CHAPTER-II

CYCLONIC ACTIVITIES OVER NORTH INDIAN OCEAN DURING 2024

The salient features of the cyclonic disturbances (CDs) over the North Indian Ocean (NIO) during the year 2024 are presented below:

2.1. Salient features of CDs over the NIO

Following CDs developed over the NIO during 2024:

1. *Severe Cyclonic Storm Remal over Bay of Bengal (24-28 May, 2024)*
2. *Depression over Bay of Bengal (19-20 July, 2024)*
3. *Deep Depression over North Jharkhand & neighbourhood (02-06 August, 2024)*
4. *Cyclonic Storm Asna over Arabian Sea (25 August-02 September, 2024)*
5. *Depression over Westcentral Bay of Bengal (31 August-02 September, 2024)*
6. *Deep Depression over Westcentral and adjoining Northwest Bay of Bengal (08-10 September, 2024)*
7. *Depression over Northeast Madhya Pradesh (11-13 September, 2024)*
8. *Deep Depression over Northeast Bay of Bengal and adjoining Bangladesh (13-17 September, 2024)*
9. *Depression over central Arabian Sea (13-15 October, 2024)*
10. *Depression over southwest Bay of Bengal during (15-16 October, 2024)*
11. *Severe Cyclonic Storm Dana over Eastcentral Bay of Bengal (22-26 October, 2024)*
12. *Cyclonic Storm Fengal over Southwest Bay of Bengal (25 November – 01 December, 2024)*
13. *Depression over westcentral Bay of Bengal (20-21 December, 2024)*

Observed tracks of the CDs during 2024 are presented in **Fig. 2.1.1.**

- Annual Frequency of CDs: During 2024, 13 cyclonic disturbances (CDs) (maximum sustained wind speed (MSW) ≥ 17 knots) developed over the North Indian Ocean (NIO) against the normal of 11.2 per year during 1965-2023. Thus, annual activity of formation of CDs was above normal.
- Frequency of different categories of CDs: There were 6 depressions and 3 deep depressions (MSW: 17-33 knots) (Normal: 6.5 per year) (Above Normal), 2 cyclonic storms (MSW: 34-47 knots) (Normal: 1.8 per year) (Above Normal), 2 severe cyclonic storms (MSW: 48-63 knots) and 0 Extremely Severe Cyclonic Storms (Normal: 2.9 per year) (Less than Normal).
- Frequency of CDs over Bay of Bengal and Arabian Sea: There were 2 CDs over Arabian Sea (Normal: 2.3 per year) (Less than Normal), 9 over Bay of Bengal (Normal: 7.8 per year) (Above Normal).
- Frequency of cyclones over Bay of Bengal (BoB) and Arabian Sea (AS): There was 1 CD over Arabian Sea (Normal: 2.3 per year) (Below Normal), 3 over Bay of Bengal (Normal:7.8 per year) (Below Normal). Overall activity was below normal over Bay of Bengal and Arabian Sea.
- Frequency of CDs in different seasons: There was no CD during Winter Season (Normal: 0.2 per year), 1 CD during pre-monsoon season (Normal:1.4 per year), 7 CDs during monsoon season (Normal: 4.9 per year) which was above normal, 5 CDs during post-monsoon season (Normal: 4.8 per year). Overall activity was above normal during monsoon season. Also, the

total number of Low-pressure systems (Low Pressure Area + CDs) was 16 against the normal of 13.5 during monsoon season. It led to above normal rainfall over India (10% of long period average) during the season.

- Landfall: Out of the 4 cyclones, 3 (Remal, Dana and Fengal) crossed the coast as cyclones (Normal: 3.2 per year) and Asna emerged into northeast Arabian Sea from land, then intensified into a cyclone and weakened over Sea.
- Tracks (Straight/recurving): All 4 cyclones had recurving tracks.

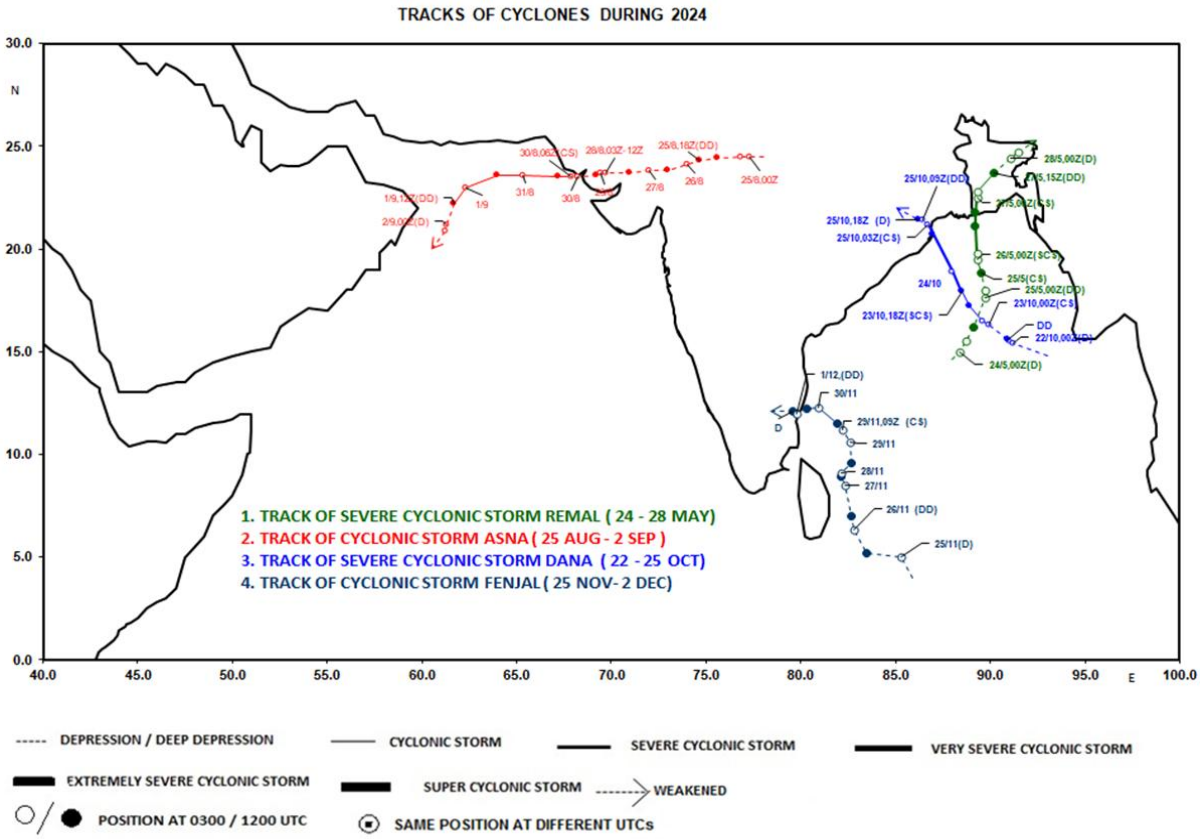


Fig 2.1.1: Observed Tracks of all cyclonic disturbances during 2024

Table 2.1.1 Some Characteristic features of cyclonic disturbances formed over north Indian Ocean and adjoining region during 2024

S N.	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.	Severe Cyclonic Storm REMAL over westcentral & adjoining south Bay of Bengal	0000 UTC of 24th May, 2024 over westcentral& adjoining south Bay of Bengal (15.0/88.4)	Crossed the Bangladesh & adjoining West Bengal coasts between Sagar islands and Khepupara close to southwest of	978hpa at 1200 UTC of 26th May, 2024. (21.1/89.2)	60kt at 1200 UTC of 26th May, 2024. (21.1/89.2)	3.5

	(24-28 May, 2024)		Mongla near latitude 21.75°N and longitude 89.20°E between 2230 hours IST/1700 UTC of 26 th and 0030 hours IST/1900 UTC of 27th May 2024.			
2.	Depression over Bay of Bengal (19-20 July, 2024)	0300 UTC of 19th July, 2024 over Bay of Bengal (19.2/86.2)	Weakened into a Well-Marked Low-Pressure Area over Coastal Odisha.	990hpa at 1200 UC of 19th July, 2024 (19.4/85.7)	25 kts at 0300 UTC of 19th July, 2024 (19.2/86.2)	1.5
3.	Deep Depression over North Jharkhand &neighbourhood(02-06 August, 2024)	1200 UTC of 02nd August, 2024 over North Jharkhand (24.2/85.2)	Weakened into a Well-Marked Low-Pressure area over central parts of Pakistan and adjoining northwest Rajasthan.	988 hpa at 1200 UTC of 3rd August, 2024 (24.8/83.0)	30 kts at 0300 UTC of 3rd August, 2024 (24.4/84.4)	-
4.	Cyclonic Storm Asna over Arabian Sea (25 August-02 September, 2024)	0000 UTC of 25th August, 2024 over Northwest MP (24.5/77.3)	Weakened into a well-marked low-pressure area over Northwest Arabian Sea.	990 hpa at 0000 UTC of 31st August, 2024 (23.6/65.8)	40 kts at 0000 UTC of 31st August, 2024 (23.6/65.8)	2.5
5.	Depression over Westcentral Bay of Bengal (31 August-02 September, 2024)	0000 UTC of 31st August, 2024 over Westcentral Bay of Bengal (17.5/84.6)	Weakened into a well-marked low-pressure area over central parts of Vidarbha and neighbourhood .	996 hpa at 1200 UC of 31st August, 2024 (18.1/84.0)	25 kts at 0000 UTC of 31st August, 2024 (17.5/84.6)	1.5
6.	Deep Depression over Westcentral and adjoining Northwest Bay of Bengal	0000 UTC of 08th Sept, 2024 over Westcentral and adjoining Northwest Bay of Bengal (17.9/87.0)	Crossed Odisha coast close to Puri between 0500 to 0600 UTC of 9th September (1030 to 1130 hrs IST of 9th September) as	991 hpa at 0000 UTC of 09th Sept, 2024 (19.3/86.2)	30 kts at 1800 UTC of 08th Sept, 2024 (18.9/86.3)	1.5

	(08-10 September, 2024)		a deep depression with wind speed of 55-65 gusting to 75 kmph			
7.	Depression over Northeast Madhya Pradesh (11-13 Sept, 2024)	0300 UTC of 11th Sept, 2024 over Northeast MP (24.0/80.0)	Weakened into a well-marked low-pressure area over northwest Uttar Pradesh & neighborhood.	993 hpa at 0000 UTC of 12th Sept, 2024 (26.7/78.3)	20 kts at 0300 UTC of 11th Sept, 2024. (24.0/80.0)	-
8.	Deep Depression over Northeast Bay of Bengal and adjoining Bangladesh (13-17 September, 2024)	1200 UTC of 13th September, 2024 over Northeast Bay of Bengal and adjoining Bangladesh (22.0/90.8)	Crossed Bangladesh coast close to Patuakhali (Bangladesh) between 1700 to 1800 UTC of 13th September (2230 to 2330 hrs IST of 13th September) as a depression with wind speed of 45-55 gusting to 65 kmph	989 hpa at 1200 UTc of 14th Sept, 2024 (22.4/88.5)	30 kts at 0000 UTC of 14th Sept, 2024 (22.8/89.2)	1.5
9.	Depression over central Arabian Sea (13-15 October, 2024)	1200 UTC of 13th Sept, 2024 over central Arabian Sea. (15.6/65.0)	Crossed North Oman coast close to Duqm (41291, Oman) between 1700 to 1800 UTC of 15th October (2230 to 2330 hrs IST of 15th October) as a depression with wind speed of 40-50 gusting to 60 kmph	1004 hpa at 1200 UTC of 13th Sept 2024 (15.6/65.0)	30 kts at 1200 UTC of 13th Sept, 2024 (15.6/65.0)	1.5
10	Depression over southwest Bay of Bengal during (15-16 October, 2024)	1200 UTC of 15thOctober, 2024 over southwest Bay of Bengal (11.4/84.4)	Crossed north Tamil Nadu – south Andhra Pradesh coast between Puducherry and Nellore, close to north of Chennai	1002 hpa at 1200 UTC on 15th October, 2024. (11.4/84.4)	25 knots at 1200 UTC on 15th October, 2024. (11.4/84.4)	T 1.5

			around 2300 UTC of 16th October			
11	Severe Cyclonic Storm "DANA" over Eastcentral Bay of Bengal (22-26 October, 2024)	0000 UTC of 22nd October, 2024 over eastcentralBay of Bengal (15.4/91.6)	Crossed North Odisha coast close to Habalikhati Nature Camp (Bhitarkanika) &Dhamara between 2000 to 2200 UTC of 24th October as a Severe Cyclonic Storm	986 hpa at 0900 UTC on 24th October, 2024. (19.4/87.6)	60 knots at 0900 UTC on 24th October, 2024. (19.4/87.6)	T 3.5
12	Cyclonic Storm "Fengal" over Southwest Bay of Bengal (25 November – 01 December, 2024)	0300 UTC of 25th November, 2024 over southwest Bay of Bengal (5.0/85.3)	Crossed North Tamil Nadu and Puducherry coast near lat. 12.05N and long 79.9E close to Puducherry between 1700-1800 UTC of 30th November 2024.	992 hpa at 0900 UTC on 30th November, 2024. (12.3/80.5)	45 knots at 0000 UTC on 30th November, 2024. (12.2/81.2)	T 3.0
13	Depression over westcentral Bay of Bengal (20-21 December, 2024)	1200 UTC of 20thDecember, 2024 Over westcentralBay of Bengal (13.7/83.5)	Weakened into a well-marked low-pressure area over westcentral Bay of Bengal.	1002 hpa at 1200 UTC on 20th December, 2024 (13.7/83.5)	25 knots at 1200 UTC on 20th December, 2024 (13.7/83.5)	T 1.5

Table 2.1.2 Statistical data relating to cyclonic disturbances over the north Indian Ocean during 2024

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

↔ Peak intensity of the system, LD: Land Depression

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

6.	ESCS												
7	SuCS												

B) Life time of cyclonic disturbances during 2024 at different stages of intensity

i. For NIO Region

S.No.	Type	Life Time in (Days)
1	D	18 days12 hours
2.	DD	15 days 18hours
3.	CS	6 days 6 hours
4.	SCS	2 days 9 hours
	Total Life Time in(Days)	42 days 21 hours

ii. For Bay of Bengal Region

S.No.	Type	Life Time in (Days)
1	D	11 days 15 hours
2.	DD	8 days 21 hours
3.	CS	4 days 0 hours
4.	SCS	2 days 9 hours
	Total Life Time in(Days)	26 days 21 hours

iii. For Arabian Sea Region

S.No.	Type	Life Time in (Days)
1	D	3 days6 hours
2.	DD	5 days 0 hours
3.	CS	2 days 6 hours
	Total Life Time in (Days)	10 days 12 hours

iv. For Land Region

S.No.	Type	Life Time in (Days)
1	D	3 days 15 hours
2	DD	1 days 21 hours
	Total Life Time in(Days)	5 days 12 hours

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

CI No (≥)	**≥1.5**	**.≥2.0**	**.≥2.5**	**.≥3.0**	**.≥3.5**	**.≥4.0**	**.≥4.5**	**.≥5.0**	**≥5.5**	**≥6.0**
No of Disturbances	11	4	4	3	2	0	0	0	0	0

D) Basin-wise distribution of cyclonic distribution

Basin	**Number of cyclonic disturbances**
Bay of Bengal	2
Arabian Sea	9
Land depression	2

Table 2.1.3. Cyclonic disturbances formed over the north Indian Ocean and land areas of India during 1997-2024

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**			
2021	BOB	3	1	2	0	1	0	0	**7**
	ARB	1	0	0	1	0	1	0	**3**
	Land	0	0	0	0	0	0	0	**0**
	Total					**10**			
2022	BOB	4	3	1	2	0	0	0	**10**
	ARB	2	1	0	0	0	0	0	**3**
	Land	2	0	0	0	0	0	0	**2**
	Total					**15**			
2023	BOB	1	1	1	1	1	1	0	**6**
	ARB	1	0	0	0	0	2	0	**3**
	Land	0	0	0	0	0	0	0	**0**
	Total					**9**			
2024	BOB	4	2	1	2	0	0	0	**9**
	ARB	1	0	1	0	0	0	0	**2**
	Land	1	1	0	0	0	0	0	**2**
	Total					**13**			

Table 2.1.4 Average translational speed of Tropical cyclones over the NIO during 2024

TC Name	Basin	Period	Average Translational Speed (kmph)		
			6 Hr	12 Hr	24 Hr
REMAL	BoB	24-28 May, 2024	12.2	18.3	11.8
ASNA	AS	25 August-02 September, 2024	9.3	9.3	9.2
DANA	BoB	22-26 October, 2024	10.8	11.5	11.5
FENGAL	BoB	25 November – 01 December, 2024	7.7	7.6	7.6

Table 2.1.5 Velocity Flux of Tropical cyclones over the NIO during 2024

TC Name	Velocity Flux (10^2 kt)	Accumulated Cyclone Energy (10^4 kt^2)	Power Dissipation Index (10^6 kt^3)
REMAL	4.1	1.95	0.97
ASNA	5.1	1.78	0.63
DANA	4.8	2.36	1.21
FENGAL	2.8	1.09	0.44

2.2 Severe Cyclonic Storm "REMAL" over the Bay of Bengal during 24th- 28th May, 2024

2.2.1 Life History of "REMAL":

- An upper air cyclonic circulation developed in lower tropospheric levels over the southwest Bay of Bengal (BoB) in the early morning (0530 hours IST/0000 UTC) of 21st May, 2024, ahead of the advancing phase of southwest monsoon over the BoB.
- Under its influence, a low pressure area (L) formed over southwest and adjoining westcentral BoB in the early morning (0530 hours IST/0000 UTC) of 22nd May, 2024.
- It lay as a well-marked low pressure area (WML) over westcentral & adjoining south BoB in the morning (0830 hours IST/ 0300 UTC) of the 23rd May.
- It concentrated into a depression (D) over central BoB in the early morning (0530 hours IST/ 0000 UTC) of the 24th May.
- It moved nearly northwards and intensified into a deep depression (DD) over the same region in the early morning (0530 hours IST/ 0000 UTC) of 25th May.
- It intensified into a cyclonic storm (CS) "REMAL" {pronounced as RE-MAL} over the north and adjoining eastcentral BoB in the same evening (1730 hours IST/ 1200 UTC of 25th May).
- Continuing to move nearly northwards, it intensified further into a severe cyclonic storm(SCS) over the North BoB in the early morning (0530 hours IST/ 0000 UTC) of 26th May.
- Moving in the same direction, it crossed Bangladesh and adjoining West Bengal coasts between Sagar Islands and Khepupara close to southwest of Mongla near latitude 21.75°N and longitude 89.2°E between 2230 hrs IST (1700 UTC) of 26th May and 0030 hrs IST of 27th May 2024 (1900 UTC of 26th May) as an SCS with wind speed of 110 to 120 kmph gusting to 135 kmph.
- Continuing to move northwards after landfall, it weakened into a CS over coastal Bangladesh and adjoining coastal West Bengal in the early morning (0530 hours IST/ 0000 UTC) of 27th May, 2024.
- It continued to move nearly northwards till the afternoon (1430 hours IST/ 0900 UTC) of 27th May and thereafter gradually recurved northeastwards. It weakened into a DD during the night (2030 hours IST/ 1500 UTC) of 27th May over central Bangladesh.
- Continuing to move further northeastwards, it weakened into a D over northeast Bangladesh in the early morning (0530 hours IST/ 0000 UTC) and into a WML over south Assam and neighbourhood in the evening (1730 hours IST/ 1200 UTC) of 28th May, 2024
- The observed track of the system is presented in **Fig. 2.2.1**. The best track parameters associated with the system are presented in Table 2.2.1.

Table 2.2.1: Best track positions and other parameters of the SCS "REMAL" over BoB during 24th -28th May, 2024

Date	Time (UTC)	Lat.	Long.	C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
24.05.24	0000	15.0	88.4	1.5	996	25	3	D
	0300	15.5	88.7	1.5	996	25	3	D
	0600	15.8	88.9	1.5	996	25	3	D
	1200	16.2	89.1	1.5	995	25	3	D
	1800	16.8	89.4	1.5	995	25	3	D
25.05.24	0000	17.6	89.7	2.0	993	30	4	DD
	0300	18.0	89.7	2.0	992	30	5	DD
	0600	18.2	89.7	2.0	991	30	5	DD
	1200	18.8	89.5	2.5	989	35	7	CS
	1500	19.1	89.5	2.5	989	35	7	CS
	1800	19.3	89.4	2.5	988	40	8	CS
	2100	19.4	89.4	2.5	986	45	10	CS
26.05.24	0000	19.5	89.4	3.0	984	50	12	SCS
	0300	19.8	89.3	3.0	984	50	12	SCS
	0600	20.2	89.2	3.0	983	50	13	SCS
	0900	20.6	89.2	3.5	981	55	15	SCS
	1200	21.1	89.2	3.5	978	60	18	SCS
	1500	21.4	89.2	3.5	978	60	18	SCS
	1800	21.7	89.2	3.5	978	60	18	SCS
		Crossed the Bangladesh & adjoining West Bengal coasts between Sagar islands and Khepupara close to southwest of Mongla near latitude 21.75°N and longitude 89.20°E between 2330 hours IST of 26th and 0030 hours IST of 27th May (1800 – 1900 UTC of 26th May)						
	2100	22.0	89.2	-	980	55	16	SCS
27.05.24	0000	22.5	89.2	-	982	45	12	CS
	0300	22.8	89.2	-	984	40	10	CS
	0600	23.0	89.2	-	985	35	9	CS
	0900	23.3	89.4	-	986	35	8	CS
	1200	23.6	89.7	-	987	35	7	CS
	1500	23.8	90.2	-	988	30	6	DD
	1800	24.0	90.5	-	990	30	5	DD
28.05.24	0000	24.4	91.1	-	991	20	4	D
	0300	24.7	91.5	-	992	20	3	D
	0600	25.1	91.8	-	993	20	3	D
	1200	Weakened into a well-marked low pressure area (WML) over Northeast Assam and neighbourhood						

Maximum sustained surface wind speed (MSW) in knots (kt), 1 kt = 1.86 kmph, D: Depression, DD: Deep depression, CS: Cyclonic storm, SCS: Severe Cyclonic Storm, ECP: Estimated Central Pressure, C.I. No.: Current Intensity No., ∆P: Pressure drop at center

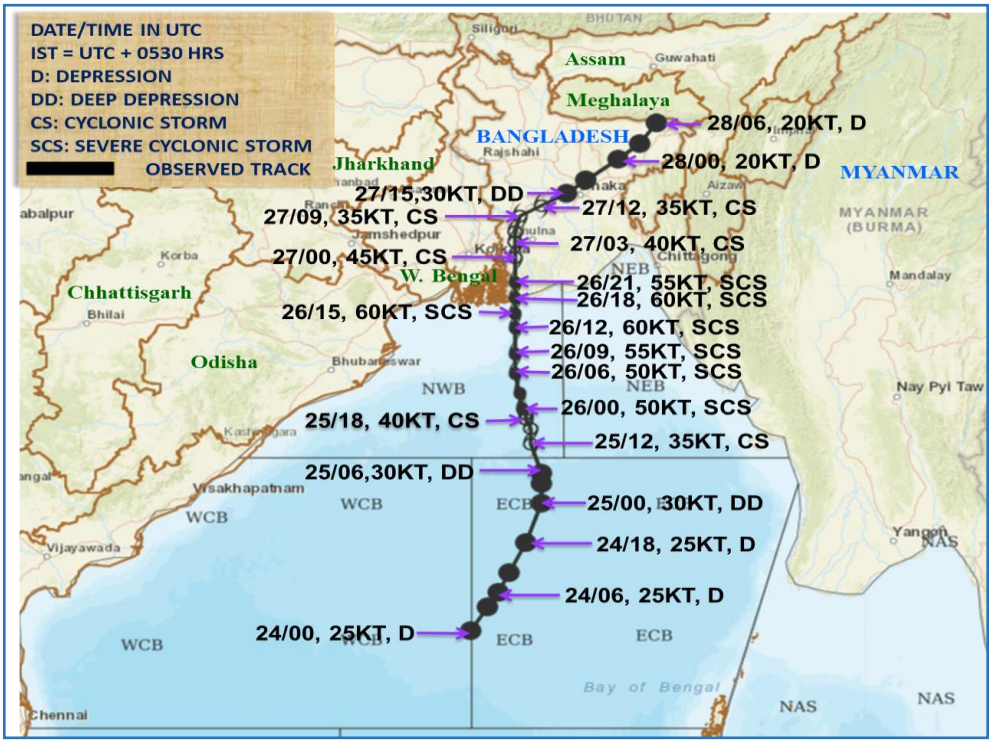


Fig. 2.2.1: Observed track of severe cyclonic storm 'REMAL" over Bay of Bengal during 15th – 18th November, 2024.

2.2.2 Salient Features

(i) Salient features compared to climatology:

It was the first cyclonic disturbance (CD) over the North Indian Ocean during 2024. During the last 62 years (1961-2023), about 38 cyclones (MSW ≥ 34 knots) developed over the BoB in the month of May. Out of these 18 crossed Bangladesh, 9 crossed Myanmar, 3 crossed West Bengal, 2 crossed Odisha, 5 crossed Andhra Pradesh and 1 crossed Tamil Nadu coast. Further out of 38 cyclones developing over BoB in the month of May, 28 intensified into SCS & above category (MSW ≥ 48 knots) with 10 crossed Bangladesh, 6 Myanmar, 3 West Bengal, 2 Odisha & 3 Andhra Pradesh as an SCS and remaining 4 crossed coasts as CS (**Fig. 2.2.2**). Considering the development in the grid (13-18N/86-90E) within ± 2.5^0 of point of genesis of SCS, REMAL, a total of 6 cyclones developed over the region in the month of May and out of these 4 crossed Bangladesh coasts and 1 each crossed West Bengal and Andhra Pradesh coasts (**Fig. 2.2.3a**). The analogous tracks are presented in **Fig. 2.2.3b**. Thus climatologically, there was 67% probability for the SCS REMAL to cross Bangladesh coast and 83% probability for the SCS REMAL to cross Bangladesh and adjoining West Bengal coasts.

(ii) Movement:

The six hourly average translational speed of "REMAL" was 12.2 kmph against the normal speed of 15 kmph for SCS category over the BoB during the pre-monsoon season (March-June) (**Fig.2.2.4 a)**. It initially moved north-northeastwards till morning (0000 UTC of 25th May) and then nearly northwards till noon of 27th May and thereafter it gradually recurved northeastwards from 27th evening (1200 UTC) towards the northeastern states of India. It weakened into a WML over northeast Assam and neighbourhood in the evening (1200 UTC) of 28th May.

(ii) Maximum sustained wind speed (MSW) and estimated central pressure (ECP):
No rapid intensification was observed during the life cycle of REMAL. The system reached it's peak intensity of MSW of 60 knots gusting to 70 knots (110-120 kmph gusting to 135 kmph) at 1200 UTC (1730 IST) of 26th May with estimated central pressure (ECP) of 978 hPa and pressure drop of about 18 hPa. It was moving in a favourable environment with high sea surface temperature, high low level positive relative vorticity, low to moderate anticyclonic vertical wind shear (5-15 knots), enhanced warm moist air incursion into the core region of the system from southeast, favourable Madden Julian Oscillation and convectively coupled equatorial waves (**Fig. 2.2.3b**).

(iii) Landfall and dissipation characteristics:
It maintained its intensity of SCS and crossed Bangladesh & adjoining West Bengal coasts between Sagar islands and Khepupara close to southwest of Mongla around 1800 UTC (2330 IST) of 26th May 2024 with MSW of 60 knots gusting to 70 knots (110-120 gusting to 135 kmph). It maintained the intensity of CS for next 18 hours after landfall as the system was getting moist air from the BoB. However, there was rapid weakening during 1800 UTC (2330 IST) of 26th to 1800 UTC (2330 IST) of 27th with system experiencing a fall in MSW by 30 knots (55 kmph) in 24 hours due to decrease in moisture supply and interaction with orography over northern part of Bangladesh and Northeastern states of India.

(iv) Track length:
The total track length of "REMAL" was 1294 km against average track length of 1032 km for all CDs developed over the BoB during pre-monsoon season based on data of 1990-2020.

(v) Life Period:
The total life period (D to D) of "REMAL" was 4 days & 12 hours against the normal of 3 days & 8 hours for SCS category developed over the BoB in pre-monsoon season based on the data of 1990-2013.

(vi) Accumulated Cyclone Energy and Power Dissipation Index:
The Velocity Flux, Accumulated Cyclone Energy (a measure of damage potential) and Power Dissipation Index (a measure of loss) were 4.1×10^2 knots, 1.95×10^4 knots^2 and 0.97×10^6 knots^3 respectively against normal of 4.12×10^2 knots, 1.96×10^4 knots^2 and 0.96×10^6 knots^3 for SCS category over the BoB developed in pre-monsoon season based on data of 1990-2020.

(vii) Adverse weather: The cyclone "REMAL" caused, torrential rains (heavy to extremely heavy rainfall) and gale-force winds over coastal districts of Bangladesh and West Bengal on 26th and 27th May. While moving northeastwards, outer rainbands reached the northeastern states and caused squally wind and heavy to very heavy rainfall activity over Assam, Meghalaya, Nagaland, Manipur, Mizoram and Tripura on 27th and 28th May. Some of the states like Assam, Meghalaya, Mizoram and Tripura reported extremely heavy rainfall leading to floods and landslides, especially over Mizoram, Tripura and South Assam and also in Bangladesh. Extremely heavy rainfall of 66 cm was reported at Mawsynram & Cherrapunji in 24 hours ending at 0830 hrs IST of 30th May & 59 cm was reported at Sohra (Meghalaya) in 24 hours ending at 0830 hrs IST 28th May and 30 cm over West Bengal in 24 hours ending at 0830 IST of 27th May. It caused maximum storm surge of 3.8 meters over Bangladesh and about one metre over south and north 24 Parganas districts of Bangladesh during the landfall.

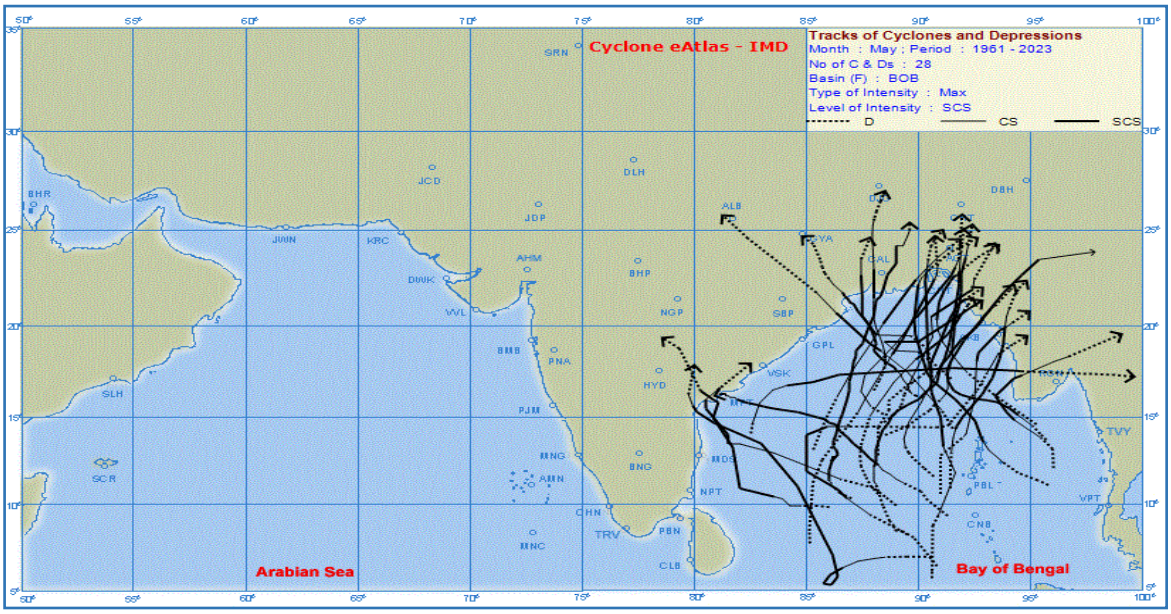


Fig. 2.2.2: Tracks of SCS over the BoB in the month of May during 1961-2023

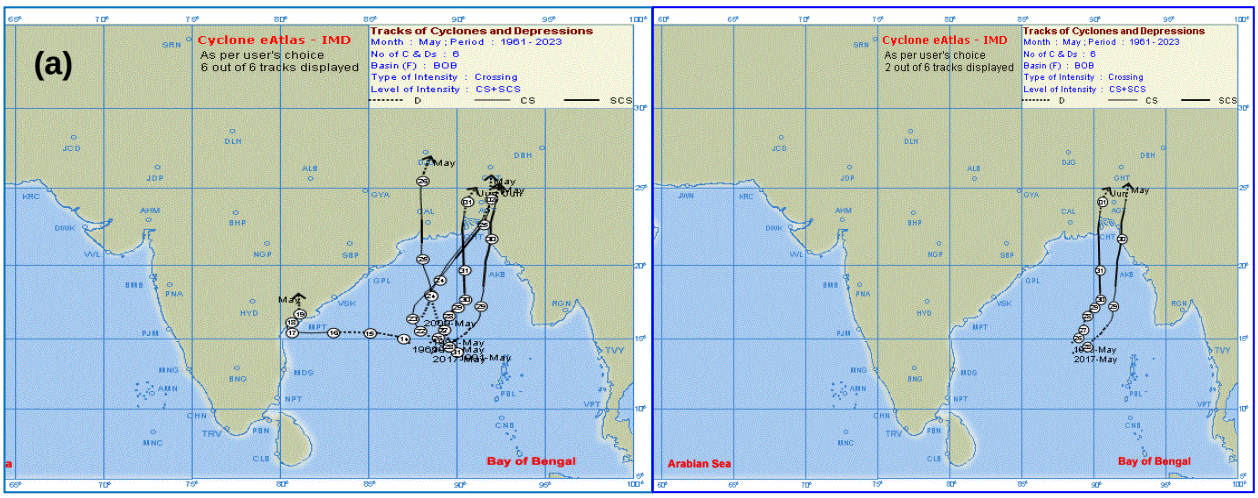


Fig. 2.2.3: Tracks of cyclones in the grid box (13-18N/86-90E) within ± 2.5^0 of point of genesis and (b) analogous tracks in the month of May during 1961-2023

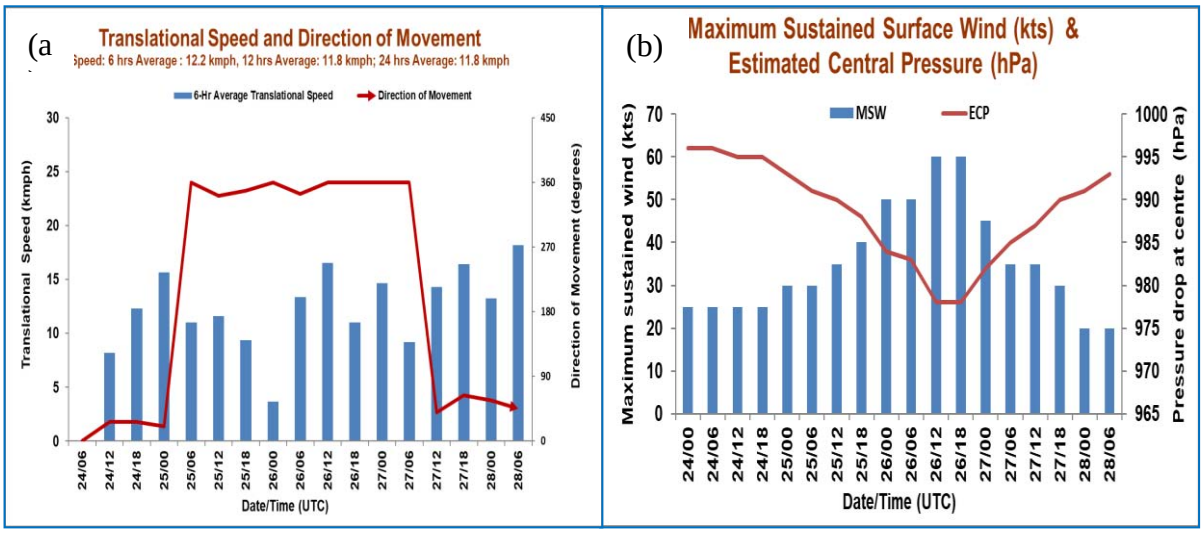


Fig. 2.2.4: (a) 6 hourly average translational speed and (b) maximum sustained wind speed & estimated central pressure during life cycle of REMAL

2.2.3. Brief life history - Genesis Intensification and movement

2.2.3.1. Genesis

An upper air cyclonic circulation developed in lower tropospheric levels over the southwest BoB in the early morning (0530 hours IST/0000 UTC) of 21st May, 2024, ahead of the advancing phase of southwest monsoon over the BoB. Under its influence, a low pressure area (L) formed over southwest and adjoining westcentral BoB in the early morning (0530 hours IST/0000 UTC) of 22nd May, 2024. At 0300 UTC of 22nd May, 2024, The Madden Julian Index (MJO) lay in phase 4 with amplitude more than 1. It continued in same phase for next 7 days. Thus, MJO phase & amplitude were highly conducive for cyclogenesis and further intensification over the BoB for next 5 days. Strong easterly winds (5-7 mps) prevailed over central BoB for next 2 days & north BoB during subsequent 3-5 days in the lower tropospheric levels. Strong westerly winds (5-7 mps) prevailed over the south BoB and Andaman Sea for next 5 days and over central BoB during 25th to 27th may. In addition, kelvin waves, equatorial Rossby waves prevailed over south BoB & coupled with MJO. These waves provided a conducive environment for cyclogenesis and intensification of system over BoB. The tropical cyclone heat potential (TCHP) was more than 100 KJ/cm2 over major parts of BoB. It indicated slightly decreasing tendency towards north BoB and along the coasts. Sea surface temperature (SST) was around 30-32°C over entire BoB. The sea conditions over BoB were also conducive for cyclogenesis and intensifcation. Considering the environmental conditions, low level relative vorticity was about 50- 60x$10^{-6}s^{-1}$ over southwest & adjoining westcentral BoB to the south of system centre with vertical extension upto 500 hPa levels. Two relative vorticity centered one over southeast & other over southwest BoB were seen at 850 hPa level. Low level convergence increased during past 24 hours and was about 10-15x$10^{-6}s^{-1}$ over south BoB and was east-west oriented. Upper level divergence was 10-20x$10^{-6}s^{-1}$ over south BoB & south Andaman Sea. It was also east-west oriented. The vertical wind shear (VWS) was low to moderate over major parts of BoB. Mid-level wind shear was anticyclonic over south BoB. The VWS thus supported further intensification of system. The upper tropospheric ridge at 200 hPa was located near 12.0^0N in association with an anticyclone over eastcentral BoB. Ridge was located to the south of system centre, indicating northeastwards movement of the system.

Under such favourable conditions continuing on 23rd, it lay as a well-marked low pressure area (WML) over westcentral & adjoining south BoB in the morning (0830 hours IST/ 0300 UTC) of the 23rd May. At 0300 UTC of 23rd May, 2024,

Considering the environmental conditions, low level relative vorticity increased during past 12 hours and was about 150x$10^{-6}s^{-1}$ to the south of system centre over southwest BoB with vertical extension upto 200 hPa levels. Low level convergence increased and was about 20 x 10^{-6} s^{-1} over south BoB and was east-west oriented. Another zone of positive convergence was seen to the southeast of system centre (20x$10^{-6}s^{-1}$). Upper level divergence was the same and was about 20x$10^{-6}s^{-1}$ over south BOB & south Andaman Sea . It was also east-west oriented. The VWS was low to moderate over major parts of BOB. Mid-level wind shear was anticyclonic over south BOB. The system was moving northeastwards under the influence of southwesterly winds associated with advance of southwest monsoon over the south BoB. The upper tropospheric ridge at 200 hPa was located near 15.0^0N. The ridge was likely to shift northwards leading to near northwards movement of the system from 24th May.

WML concentrated into a depression (D) over central BoB in the early morning (0530 hours IST/ 0000 UTC) of the 24th May. At 0000 UTC of 24th May, 2024, The MJO currently lay in phase 4 with amplitude more than 1. Thus, MJO phase & amplitude continued to be highly

conducive for cyclogenesis and further intensification over the BoB for next 5 days. Strong easterly winds (5-7 mps) prevailed over central BoB for next 24 hours & north BoB for subsequent 3-4 days in the lower tropospheric levels. Strong westerly winds (5-7 mps) prevailed over the south BoB and Andaman Sea for next 5 days and over central BoB for 25th to 27th May. In addition, kelvin waves, equatorial Rossby waves prevailed over south BoB & coupled with MJO. These waves provided a conducive environment for cyclogenesis and intensification of system over BoB. The Tropical Cyclone Heat Potential (TCHP) continued to be more than 100 KJ/cm^2 over major parts of BoB. It was indicating slightly decreasing tendency towards north BoB and along the coasts. The SST continued to be around 30-32°C over entire BoB.

Considering the environmental conditions, low level relative vorticity was about 150x10^{-6}s^{-1} to the south of system centre over westcentral & adjoining eastcentral BoB with vertical extension upto 200 hPa levels. Low level convergence increased and was about 30 x 10^{-6} s^{-1} to the south of the system centre. Upper level divergence had two patches with east-west orientation and it was about 30x10^{-6}s^{-1} to southwest of the system center and it was about 40x10^{-6}s^{-1} to southeast of the system center. The VWS was low to moderate over near the system center and along the forecast track. Mid-level wind shear was anticyclonic over central and northwest BoB. The VWS thus supported further intensification of system. The system moved northeastwards under the influence of southwesterly steering winds associated with advance of southwest monsoon over the south BoB. The upper tropospheric ridge at 200 hPa was located near 17.5^{0}N.

2.2.3.2 Intensification

The D moved nearly northwards and intensified into a deep depression (DD) over the same region in the early morning (0530 hours IST/ 0000 UTC) of 25th May. At 0000 UTC of 25th May, 2024, The MJO lay in phase 4 with amplitude more than 1. Strong easterly winds (5-7 mps) prevailed over central BoB for next 24 hours & north BoB Strong westerly winds (5-7 mps) prevailed over the south BoB and Andaman Sea and over central BoB for 25th to 27th May. In addition, kelvin waves, equatorial Rossby waves prevailed over south BoB & coupled with MJO. These waves provided a conducive environment for intensification of system over BoB. The similar sea conditions over BoB prevailed like previous day which were also conducive for intensification.

Considering the environmental conditions, low level relative vorticity increased and was about 150-200x10^{-6}s^{-1} to the east of system centre over eastcentral & adjoining westcentral BoB with vertical extension upto 200 hPa level. Low level convergence was about 20 x 10^{-6} s^{-1} to the east-northeast of the system center. Upper level divergence was about 20x10^{-6}s^{-1} and 30x10^{-6}s^{-1} to southeast and southwest of the system center, respectively. Vertical wind shear (VWS) was low to moderate (15-20 m/s) oriented the east-west of the system centre and along the forecast track. It was high to the southwest of the system centre. The high wind shear to the southwest was helping the system to segregate itself from the Comorian area convection. Mid-level wind shear was anticyclonic over central and northwest BoB. VWS thus supported further intensification of system. The system moved northeastwards under the influence of southwesterly winds. The upper tropospheric ridge at 200 hPa was located near 18.7^{0}N.

DD intensified into a cyclonic storm (CS) “REMAL” {pronounced as RE-MAL} over the north and adjoining eastcentral BoB in the same evening (1730 hours IST/ 1200 UTC of 25th May). At 1200 UTC of 25th May, 2024, The MJO lay in phase 4 with amplitude more than 1.. Strong easterly winds (5-7 mps) prevailed over north BoB for 3 days in the lower tropospheric levels.

Strong westerly winds (5-7 mps) prevailed over the south & central BoB and Andaman Sea for next 3 days. In addition, kelvin waves, equatorial Rossby waves were also prevailing over south BoB & coupled with MJO. The sea conditions over BoB were also conducive for further intensification of system. Considering the environmental conditions, low level vorticity has increased and was about $200x10^{-6}s^{-1}$ to the south of system centre over eastcentral BoB with vertical extension upto 200 hPa level. Low level convergence was about $20x10^{-6}s^{-1}$ to the southeast of the system center. Strong equator ward outflow was seen. Upper level was about $30x10^{-6}s^{-1}$ to the southeast of system centre. Vertical wind shear (VWS) was moderate (around 20 kt) along the forecast track. Mid-level wind shear was anticyclonic over the system area which supported further intensification of the system. The system moved nearly northwards along the periphery of the upper tropospheric ridge at 200 hPa located near 18.0^0N.

Continuing to move nearly northwards CS intensified further into anSCS over the North BoB in the early morning (0530 hours IST/ 0000 UTC) of 26th May. At 0000 UTC of 26th May, 2024, The MJO lay in phase 4 with amplitude more than 1. Strong easterly winds (5-7 mps) prevailed over north BoB in the lower tropospheric levels. Strong westerly winds (5-7 mps) prevailed over the south & central BoBand Andaman Sea for next 3 days. In addition, kelvin waves, equatorial Rossby waves were also prevailing over south BoB These waves provided a conducive environment for further intensification into SCS. The sea conditions over BoB were also conducive for further intensification of system. Considering the environmental conditions, low level relative vorticity was about $250x10^{-6}s^{-1}$ to the over eastcentral and north BoB with vertical extension upto 200 hPa level. Low level convergence was about $30x10^{-6}s^{-1}$ to the west of the system center. Strong equator ward outflow was seen. Upper level divergence was about $20x10^{-6}s^{-1}$ around the southwest of the system centre. VWS was moderate (around 15-20 kt) along the forecast track. Mid-level VWS was anticyclonic over the system area which would supported further intensification of the system.The system moved nearly northwards along the periphery of the upper tropospheric ridge at 200 hPa located near 18.0^0N.

Thereafter, the system moved slowly from 1430 IST, as its centre lay close to ridge.

2.2.3.3 Weakening

Continuing to move slowly northwards crossed Bangladesh and adjoining West Bengal coasts between Sagar Islands and Khepupara close to southwest of Mongla near latitude 21.75°N and longitude 89.2°E between 2230 hrs IST (1700 UTC) of 26th May and 0030 hrs IST of 27th May 2024 (1900 UTC of 26th May) as an SCS with wind speed of 110 to 120 kmph gusting to 135 kmph Continuing to move northwards, it weakened into a CS over coastal Bangladesh and adjoining coastal West Bengal in the early morning (0530 hours IST/ 0000 UTC) of 27th May, 2024. It continued to move nearly northwards till the afternoon (1430 hours IST/ 0900 UTC) of 27th May and thereafter gradually recurved northeastwards.
At 0000 UTC of 27th May, 2024, low level relative vorticity was about $300x10^{-6}s^{-1}$ over North BoB with vertical extension upto 200 hPa level. Low level convergence was about $30x10^{-6}s^{-1}$ to the south of the system center. Strong equator ward outflow was seen. Upper level divergence was about $10x10^{-6}s^{-1}$ to the southwest of the system centre. The VWS was anticyclonic and low (05-10 kt) along the forecast track. After landfall due to land interaction and friction intensity of the system decreased gradually. The system moved slowly and remains in the close vicinity of Bangladesh and West Bengal coast. The total precipitable water vapour (TPWV) map suggested abundance of moisture in the mid atmosphere which was helping the system to maintain it intensity of cyclonic storm for some time.

CS weakened into a DD during the night (2030 hours IST/ 1500 UTC) of 27th May over central Bangladesh. At 1500 TC of 27th November, The environmental conditions indicated that system was still in a favorable environment, leading to slow weakening of the system. Low level relative vorticity was about 100-150x$10^{-6}s^{-1}$ over North BoB& adjoining coastal Bangladesh to the south of system centre, with vertical extension upto 200 hPa level. Low level convergence was about 50x$10^{-6}s^{-1}$ to the south of the system centre. Upper-level divergence was about 30x$10^{-6}s^{-1}$ near system centre. The VWS was low (05-10 kt) along the forecast track. The system was moving away from the ridge at around 21.5^{0}N and hence moved northeastwards. As it moved further northeastwards, the moist air advection into the core decreased and the system weakened gradually into a D over northeast Bangladesh in the early morning (0530 hours IST/ 0000 UTC) of 28th May, 2024. At 0000 UTC of 28th May, 2024, The low level relative vorticity was about 50x$10^{-6}s^{-1}$ over North BoB & adjoining coastal Bangladesh to the south of system centre, with vertical extension up to 500 hPa level. Low level convergence was about 30x$10^{-6}s^{-1}$ to the south of the system centre. Upper-level divergence was about 40x$10^{-6}s^{-1}$ near system centre. The VWS was low (05-10 kt) along the forecast track. The system was lying far away from the ridge around 21.5^{0}N. As it moves further northeastwards, the moist air advection into the core decreased and the system weakened gradually into a WML over south Assam and neighbourhood in the evening (1730 hours IST/ 1200 UTC) of 28th May, 2024.

2.2.3.4 Characteristics features wrt Maximum Sustained Surface Wind speed and estimated central pressure and translational speed

(a) Maximum Sustained Surface Wind speed and estimated central pressure

The system reached its peak intensity of 60 knots at 1200 UTC of 26th May and maintained its peak intensity till landfall at 1900 UTC of 26th May. The lowest ECP of 978 hPa with pressure drop of about 18 hPa was observed during the period of 1200 UTC of 26th May to landfall time. The six hourly MSW and ECP during the life cycle of REMAL are presented in **Fig. 2.2.5(a).**

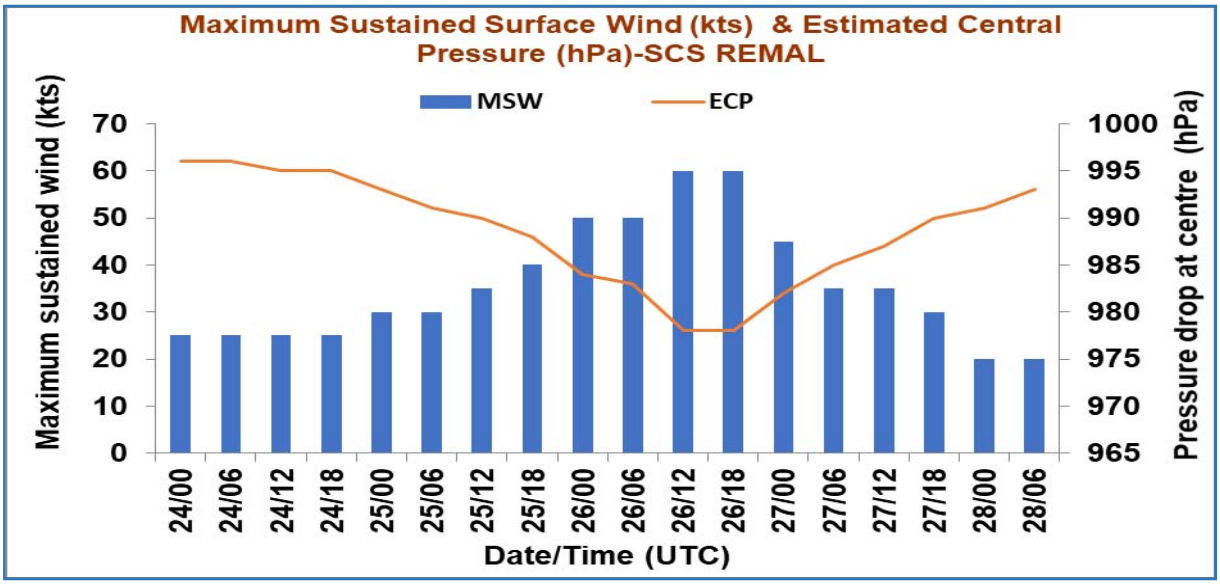


Fig.2.2.5. (a) six hourly Maximum sustained surface winds (kts) & Estimated Central Pressure

b. Translational speed & direction of movement

Remal exhibited six hourly average translational speed of 12.2 kmph against normal of 11.4 kmph for SCS over the BoB in the pre-monsoon season based on data of 1990-2013 (**Fig.2.2.5(b**)).

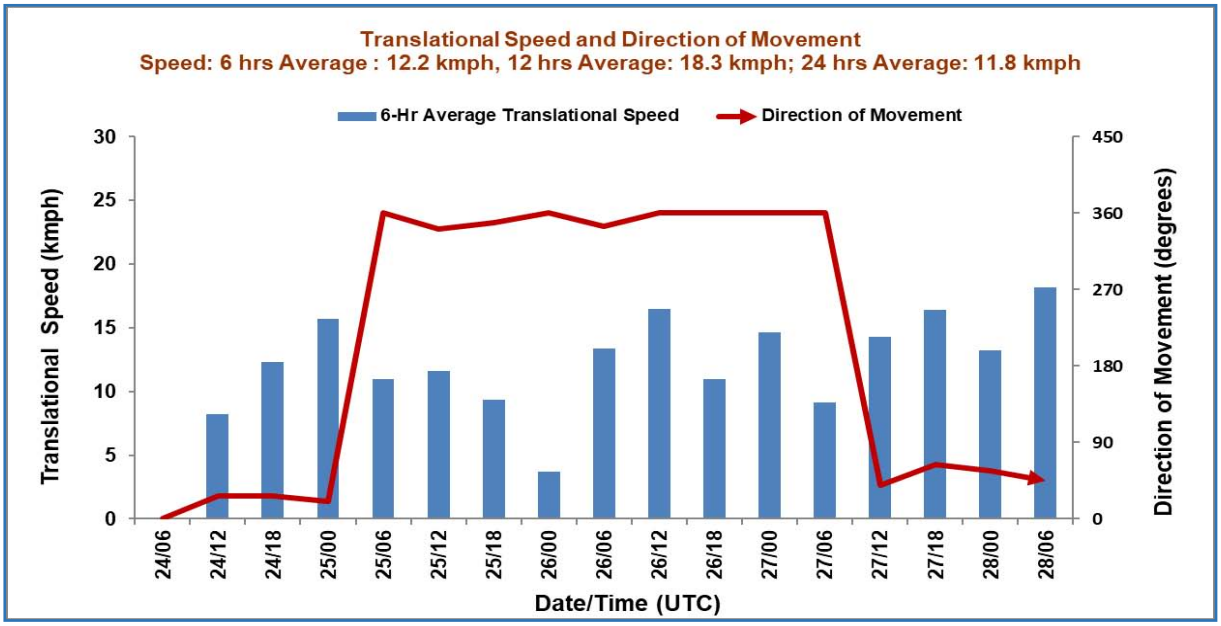


Fig.2.2.5. (b) Past six hourly average translational speed ending at date/time mentioned in the X-axis and direction of movement of cyclonic storm 'REMAL

2.2.4 Monitoring of CS, "REMAL"

India Meteorological Department (IMD) maintained round the clock watch over the north Indian Ocean and the cyclone was monitored since 9th May, about 15 days prior to formation of depression on 24th May and 18 days prior to the landfall of system over Bangladesh-West Bengal coasts. The information about the system was first released in the weekly extended range outlook issued by IMD on 9th May [**Fig. 2.2.6(a**)], indicating formation of depression over central parts of south BoB around 23rd May during the week 2 (17-23 May). Further, the extended range outlook issued on 16th May [**Fig. 2.2.6(b**)], indicated formation of a depression over central BoB during the beginning of the week (24-30 November) with moderate confidence (34-67%) (about 8 days ahead of formation of depression on 24th May). Further, the extended range outlook issued on 23rd May [**Fig. 2.2.6(c**)] indicated with high confidence

The cyclone was monitored with the help of available satellite observations from INSAT 3D and 3DR, SCAT SAT, ASCAT, microwave imageries and available ships, buoy observations, Doppler Weather Radar Kolkata (India) & Khepupara (Bangladesh) and coastal observations in the region. Various global models and dynamical-statistical models run by Ministry of Earth Sciences (MoES) institutions including IMD, NCMRWF, IITM & INCOIS and guidance from models from various international agencies under bilateral arrangement and cyclone specific Hurricane Weather Research Forecast (HWRF) model were utilized to predict the genesis, track, landfall and intensity of the cyclone as well as associated severe weather. The forecasts were mainly based on multi-model ensemble technique developed by IMD further modulated by observations and experience, expertise & analysis by the forecasters at IMD. An indigenously developed digitized forecasting system of IMD was utilized for analysis and comparison of various observations and numerical weather prediction models guidance, decision making process and warning products generation.

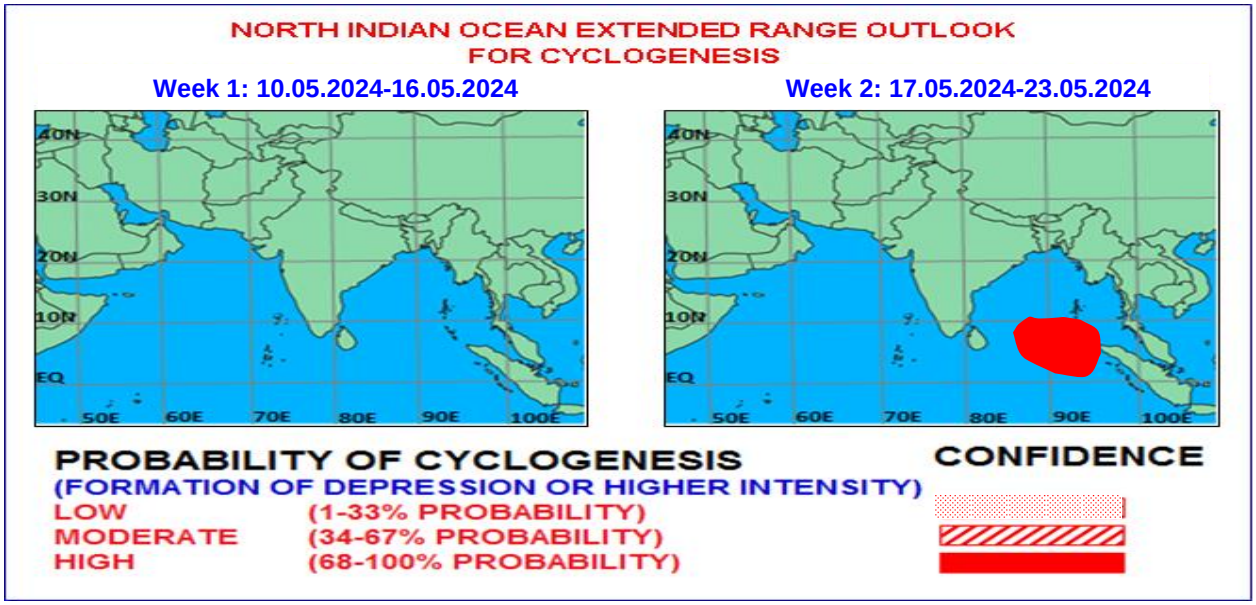


Fig. 2.2.6 (a): Weekly extended range outlook issued by IMD on 9th May, 2024, (15 days prior to formation of depression on 24th May) indicating area of cyclogenesis over southeast & adjoining southwest BoB during the week 2 (actually on 23rd the system lay as a well-marked low pressure area over eastcentral BoB)

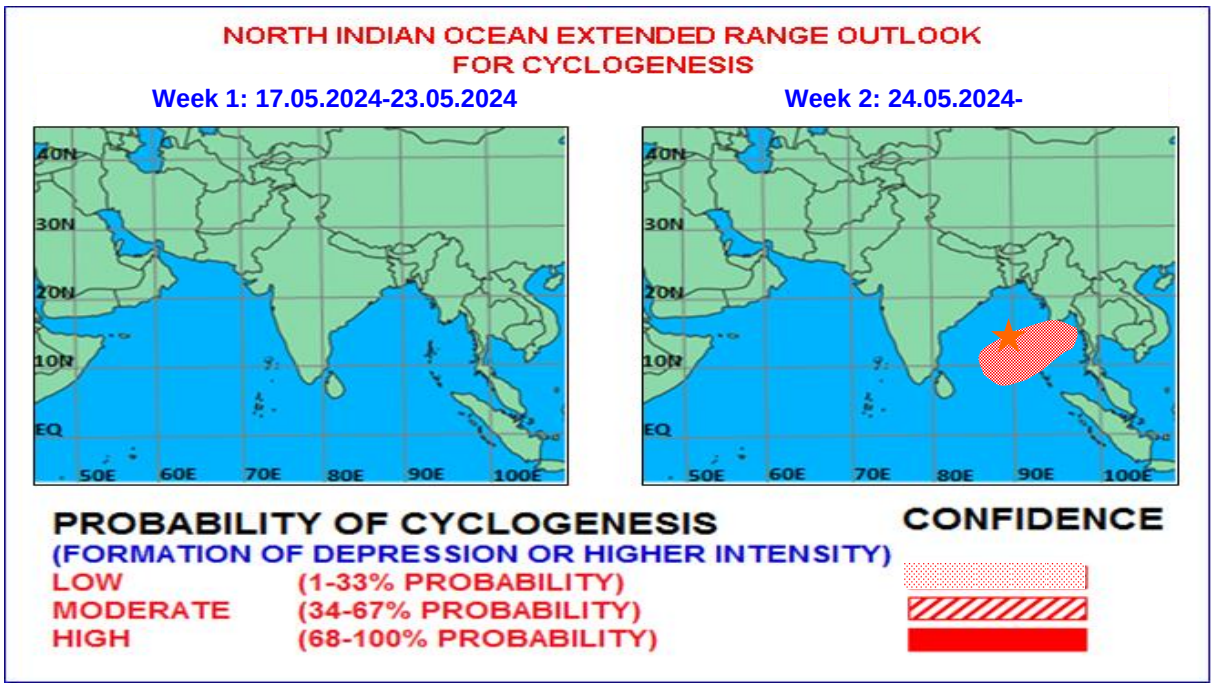


Fig. 2.2.6 (b): Weekly extended range outlook issued by IMD on 16th May, 2024, (8 days prior to formation of depression on 24th May) indicating area of cyclogenesis over central BoB during the week 2 (actually on 24th the system lay as a depression over central BoB)

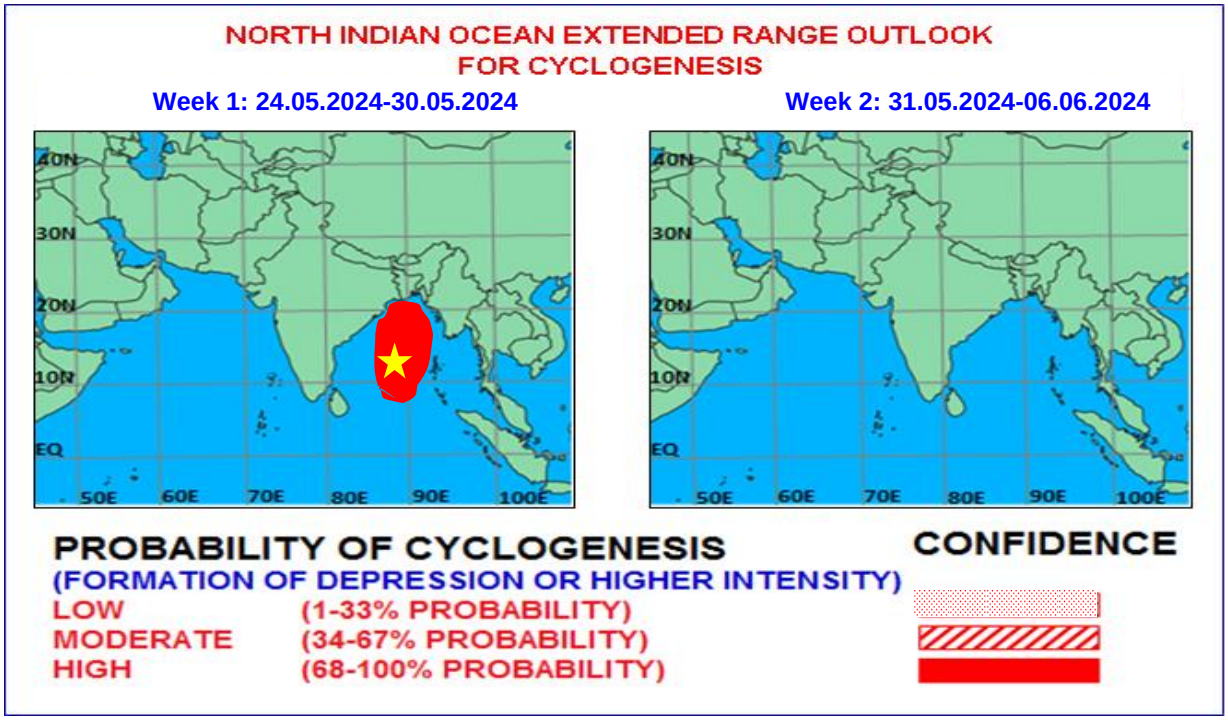


Fig. 2.2.6 (c): Weekly extended range outlook issued by IMD on 23rd May, 2024 indicating area of genesis and movement towards Bangladesh coast with high confidence. (Actually on 24th the system lay as a depression over central BoB)

2.2.4.1 Features observed through satellite and radar

The cyclone was monitored with the help of available satellite observations from INSAT 3D and 3DR, SCAT SAT, ASCAT, microwave imageries Typical INSAT-3D visible/IR imageries, enhanced colored imageries and cloud top brightness temperature imageries are presented in Fig.2.2.7 (a) to (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.

At 0300 UTC of 22nd May, 2024, a low level circulation lay over southwest & adjoining westcentral BoB off north Tamil Nadu – south Andhra Pradesh coasts. Associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over south & central BoB & north coastal Tamil Nadu (minimum cloud top temperature (CTT) -93^{0}C). The water vapour imagery was indicating high humidity in mid tropospheric levels.

At 0300 UTC of 23rd May, the convection had further organized. Intensity of the system was **CI 1.0**. Associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over south & central BoB Andaman Sea (minimum CTT -93^{0}C). As per multi-satellite winds, stronger winds were seen in southern sector.

At 0000 UTC of 24th May, the convection had further organized. Intensity of the system was characterised as **CI 1.5**. Associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over central & south BoB and north Andaman sea (minimum CTT -93^{0}C). As per multi-satellite winds, stronger winds were seen in southern sector. The total precipitable water imagery indicated warm moist air incursion into the core of the system.

At 0000 UTC of 25th May, the convection had further organised. Intensity of the system was characterized as **CI 2.0** centered at 17.6^{0}N latitude and 89.5^{0}E longitude. Associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over central & south BoB and Andaman sea, Gulf of Martaban & Tenasserim coast (minimum CTT -93^{0}C). Scattered low and medium clouds with embedded moderate to intense convection over North BoB. As per multisatellite winds, stronger winds were seen in southern eastern sector. The total precipitable water imagery indicated warm moist air incursion into the core of the system.

At 1200 UTC of 25th May, the convection had intensified. Clouds were organised in curved band pattern. Intensity of the system was characterised as **CI 2.5**. Associated broken low and medium clouds with embedded intense to very intense convection lay over central and adjoining south BoBand north Andaman Sea (minimum CTT -93^{0}C). As per multi-satellite winds, stronger winds were seen in southern eastern sector. The total precipitable water imagery indicated warm moist air incursion into the core of the system. The multi-satellite winds indicated stronger winds in eastern sector.

At 0000 UTC of 26th May, clouds were organised in curved band pattern. Intensity of the system was characterised as **CI 3.0**. Associated broken low and medium clouds with embedded intense to very intense convection lay over north and adjoining central BoB & north Andaman sea (minimum CTT -93^{0}C). As per multi-satellite winds, stronger winds were seen in southern eastern sector. The total precipitable water imagery indicated warm moist air incursion into the core of the system. The multi-satellite winds indicate stronger winds in eastern sector.

At 0900 UTC of 26th May, clouds were organised in curved band pattern. Intensity of the system was characterised as **CI 3.5**. Associated broken low and medium clouds with embedded intense to very intense convection lay over north and adjoining central BoB, east Odisha, south Jharkhand, south Gangetic West Bengal, Mizoram, Tripura and south Bangladesh (minimum CTT -93^{0}C). As per multi-satellite winds, stronger winds were seen in eastern sector and northwest sector. The total precipitable water imagery indicated warm moist air incursion into the core of the system.

At 0000 UTC of 27th May, clouds were organised in curved band pattern. Associated broken low and medium clouds with embedded intense to very intense convection lay over north BoB south Gangetic West Bengal, south Manipur, Mizoram, Tripura adjoining Assam and Bangladesh (minimum CTT -93^{0}C). As per multi-satellite winds, stronger winds were seen in southeast sector. The total precipitable water imagery indicated warm moist air incursion from North West sector into the core of the system.

At 1500 UTC of 27th May, satellite imagery indicated that convection got disorganized and reduced in terms of size & depth. However, intense convection was seen in southern sector. Also, there was no cold air advection into the core of the system. Associated scattered to broken low/medium clouds with embedded intense to very intense convection over north BoB, eastern parts of Gangetic West Bengal, South Bangladesh, (CTT -85 to -93^{0}C) and moderate to intense convection over East Odisha, Tripura, Gangetic West Bengal, East Jharkhand, East Bihar, Sub Himalayan West Bengal, Sikkim, (CTT -55 to -65^{0}C). Scattered low/medium clouds with embedded moderate to intense convection over Central BoB, North Andaman Sea & Gulf of Martaban and isolated weak to moderate convection over south BoB.

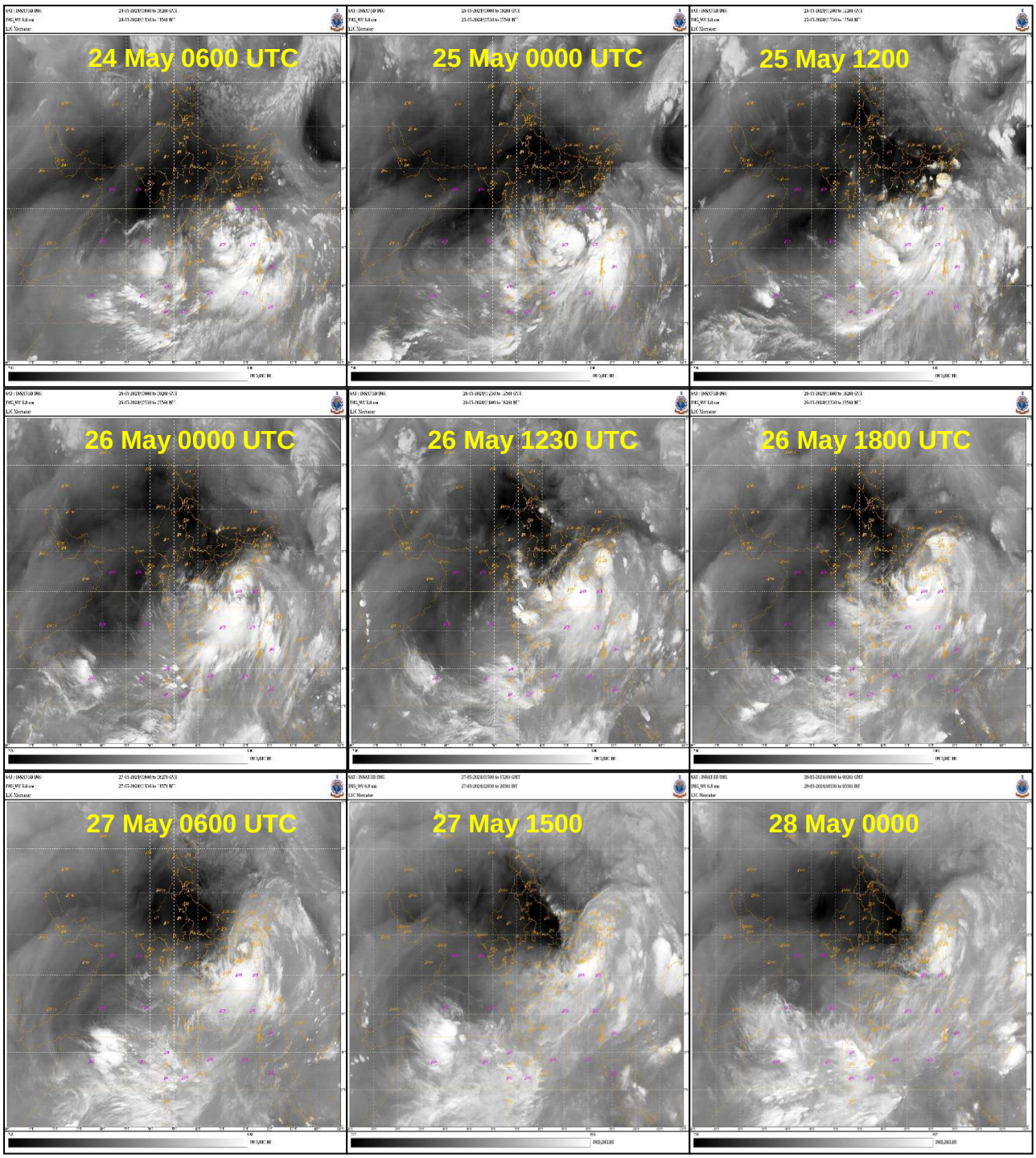


Fig. 2.2.7(a): INSAT-3D Water Vapour imageries during life cycle of SCS REMAL (24-28 May, 2024)

At 0000 UTC of 28th May, satellite imagery indicated that the vortex lay over north-east Bangladesh & neighbourhood centered within half a degree of 24.4^{0}N / 91.1^{0}E overland. Center was not well defined in satellite imagery. Associated scattered to broken low/medium clouds with embedded intense to very intense convection over north BoB, south eastern parts of Assam, Manipur, Mizoram, east Bangladesh, (CTT -85 to -93^{0}C) and moderate to intense convection over east Gangetic West Bengal, north eastern states of India (CTT -55 to -65^{0}C). Scattered low/medium clouds with embedded moderate to intense convection over central BoB, north Andaman Sea & Gulf of Martaban and isolated weak to moderate convection over south BoB.

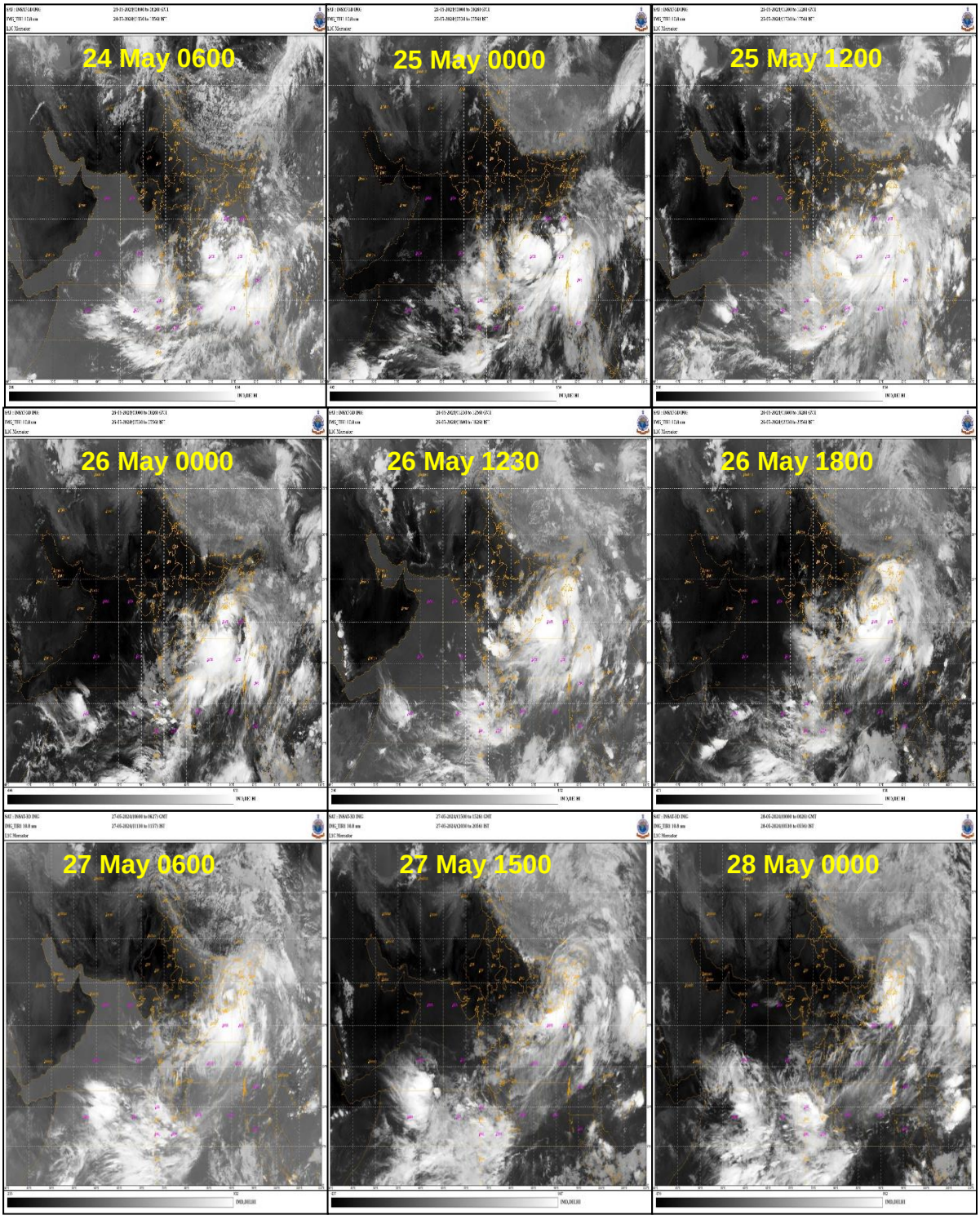


Fig. 2.2.7(b): INSAT-3D IR imageries during life cycle of SCS REMAL (24-28 May, 2024)

At 1200 UTC of 28th May, satellite imagery indicated that the vortex lay over east Meghalaya and adjoining Assam. Associated scattered to broken low/medium clouds with embedded moderate to intense convection over east Assam, Manipur, Nagaland, Mizoram, Nagaland, Manipur, Tripura, rest northeast states (CTT -65 to -70^{0}C).

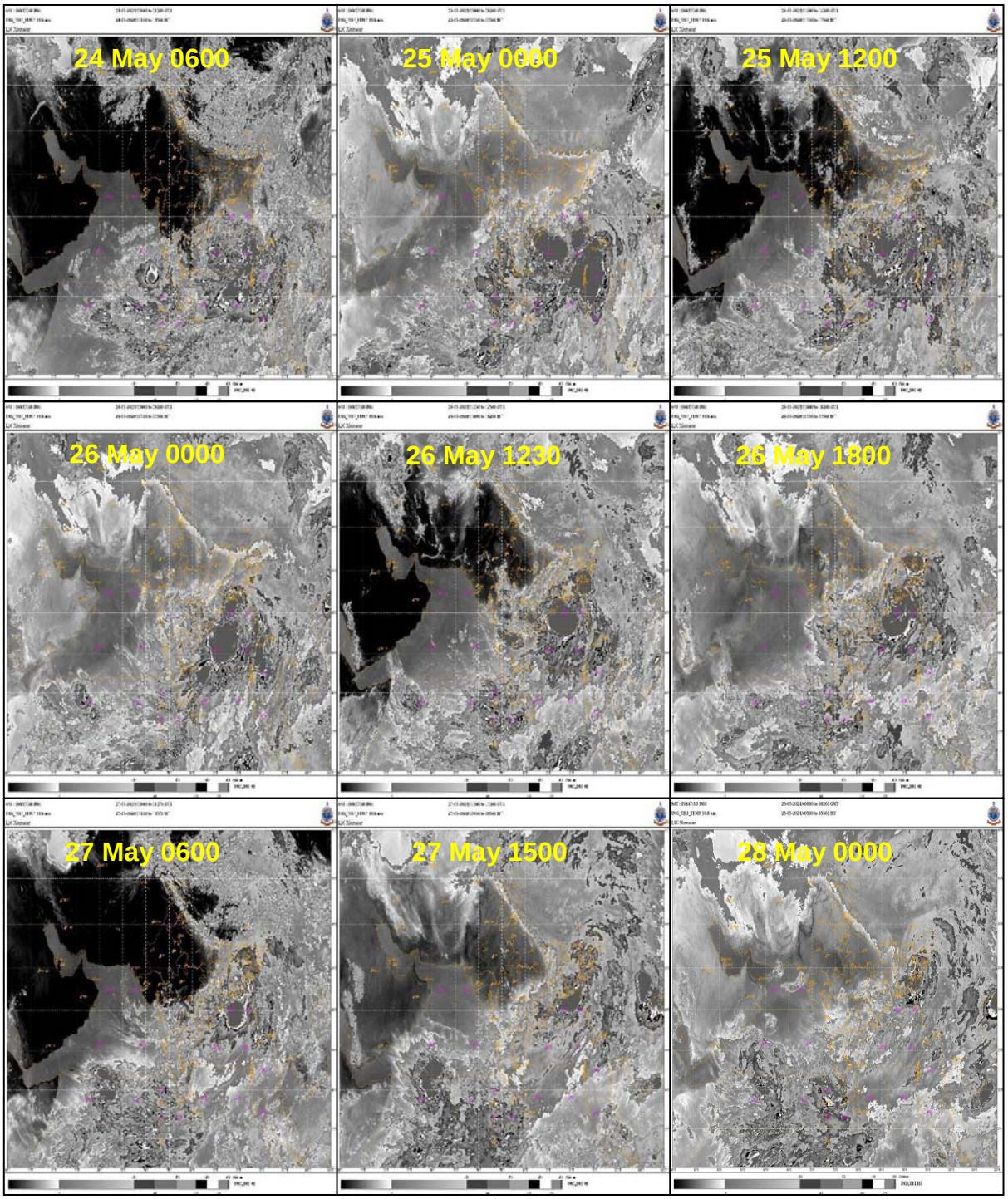


Fig. 2.2.7(c): INSAT-3D IR BD imageries during life cycle of SCS REMAL (24-28 May, 2024)

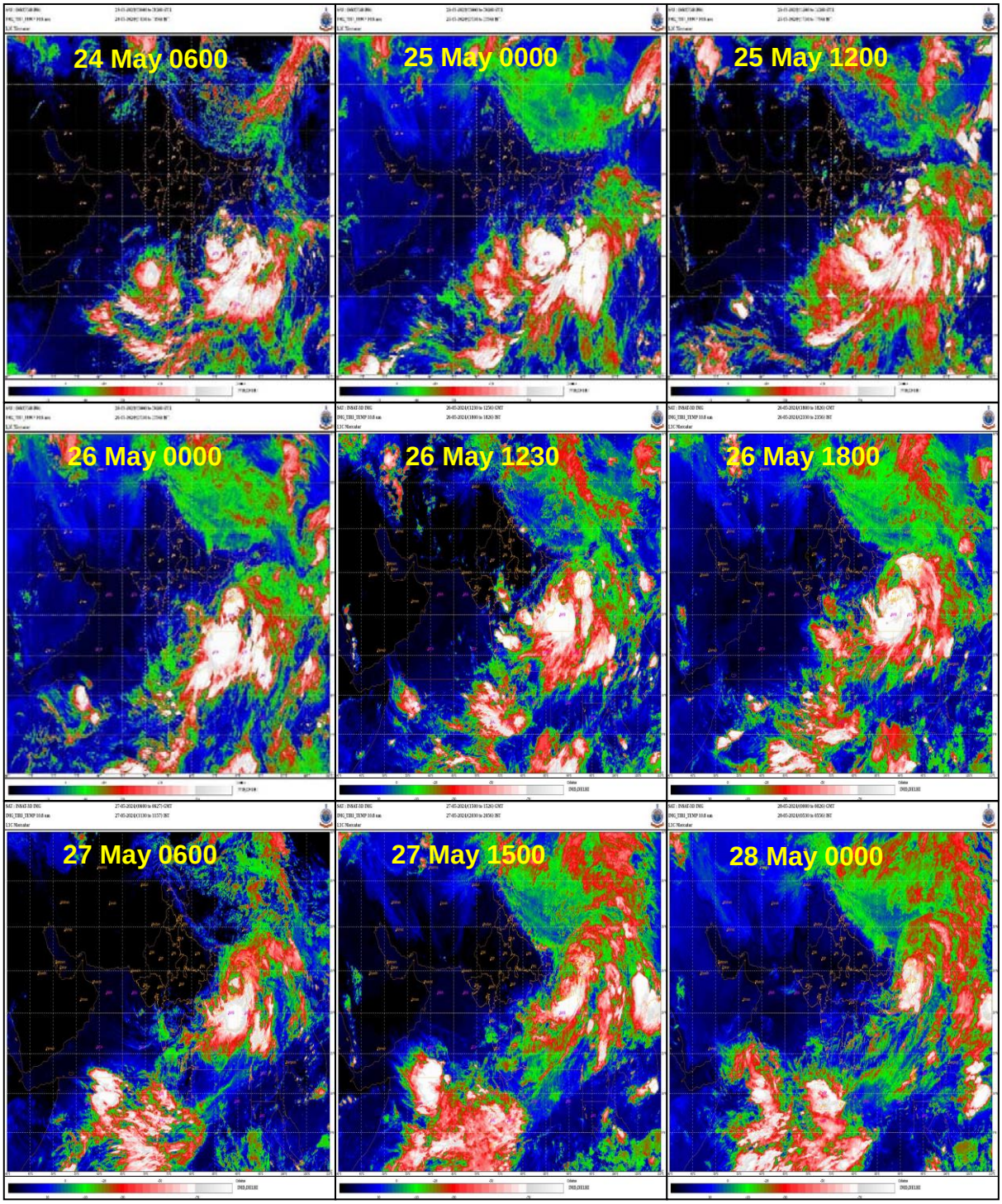


Fig. 2.2.7(d): INSAT-3D NHC imageries during life cycle of SCS REMAL (24-28 May, 2024)

The Fig. 2.2.7(e) is representing the reflectivity plots in terms of Maximum dbZ at different times sequentially during the period on 26th to 27th May, 2024. The plots in the figure capture the structural evolution of the severe cyclonic storm Remal as observed by the Doppler Weather Radar (DWR) at Kolkata, while it was making landfall over Bangladesh and West Bengal coasts.

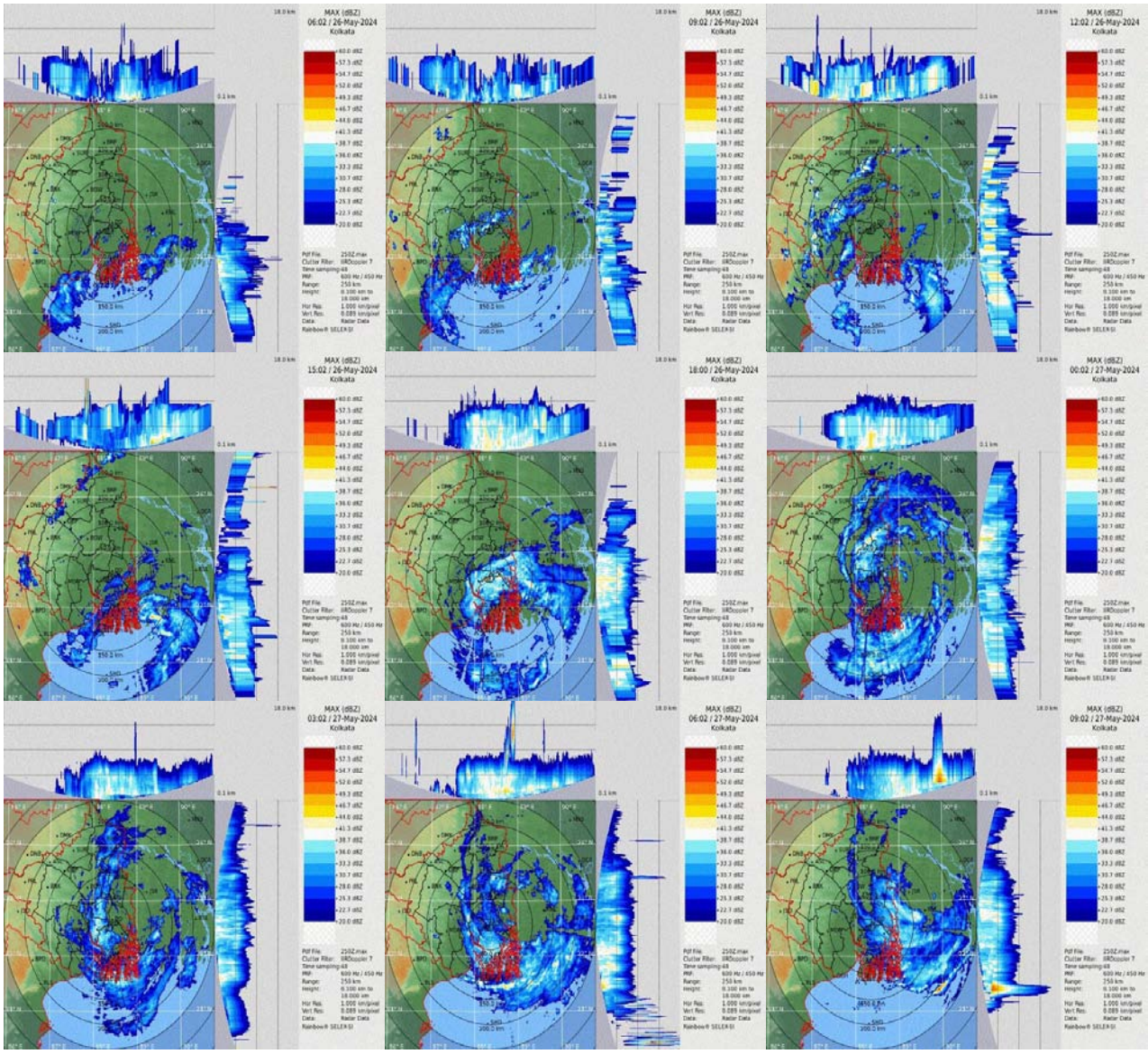


Fig. 2.2.7(e): Reflectivity (Max dbZ) imageries of SCS REMAL captured by DWR Kolkata during (26-27 May, 2024).

2.2.5 Dynamical features

IMD GFS (T1534) analyses of mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels during 21st October - 24th October are presented in **Fig. 2.2.8.1 – 2.2.8.7** respectively. All the figures are optimally estimated representation of the three-dimensional evolution of the system by the model analysis from the surface to upper-air with time in terms of surface pressure and wind characteristics along with vertical structures.

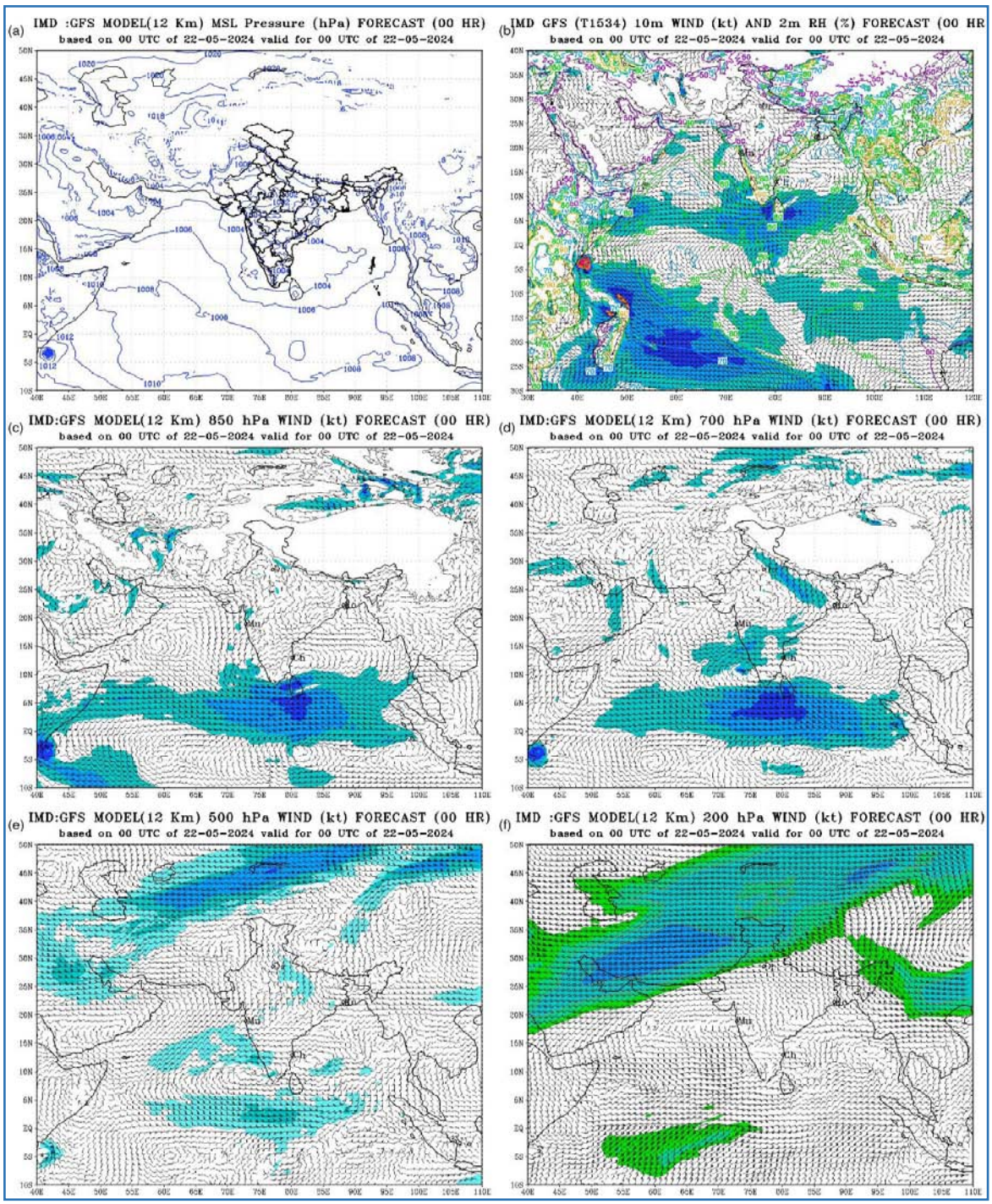


Fig.2.2.8.1: IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 22nd May, 2024

The figure 2.2.8.1 is atmospheric status of the atmosphere at 0000 UTC of 22nd May, 2024. The surface pressure isobaric analysis in the figure [Fig. 2.2.8.1(a)] did not depict the storm as there was not a single closed isobar over BoB. However, there is a feeble cyclonic circulation embedded within an east-west trough in the wind field [Fig. 2.2.8.1(b)] at the surface (10m) over westcentral BoB. The cyclonic circulation in the upper level at 850 hPa [Fig.2.2.8.1(c)] and 700 hPa [Fig. 2.2.8.1(d)] pressure levels is more distinct over the same region.

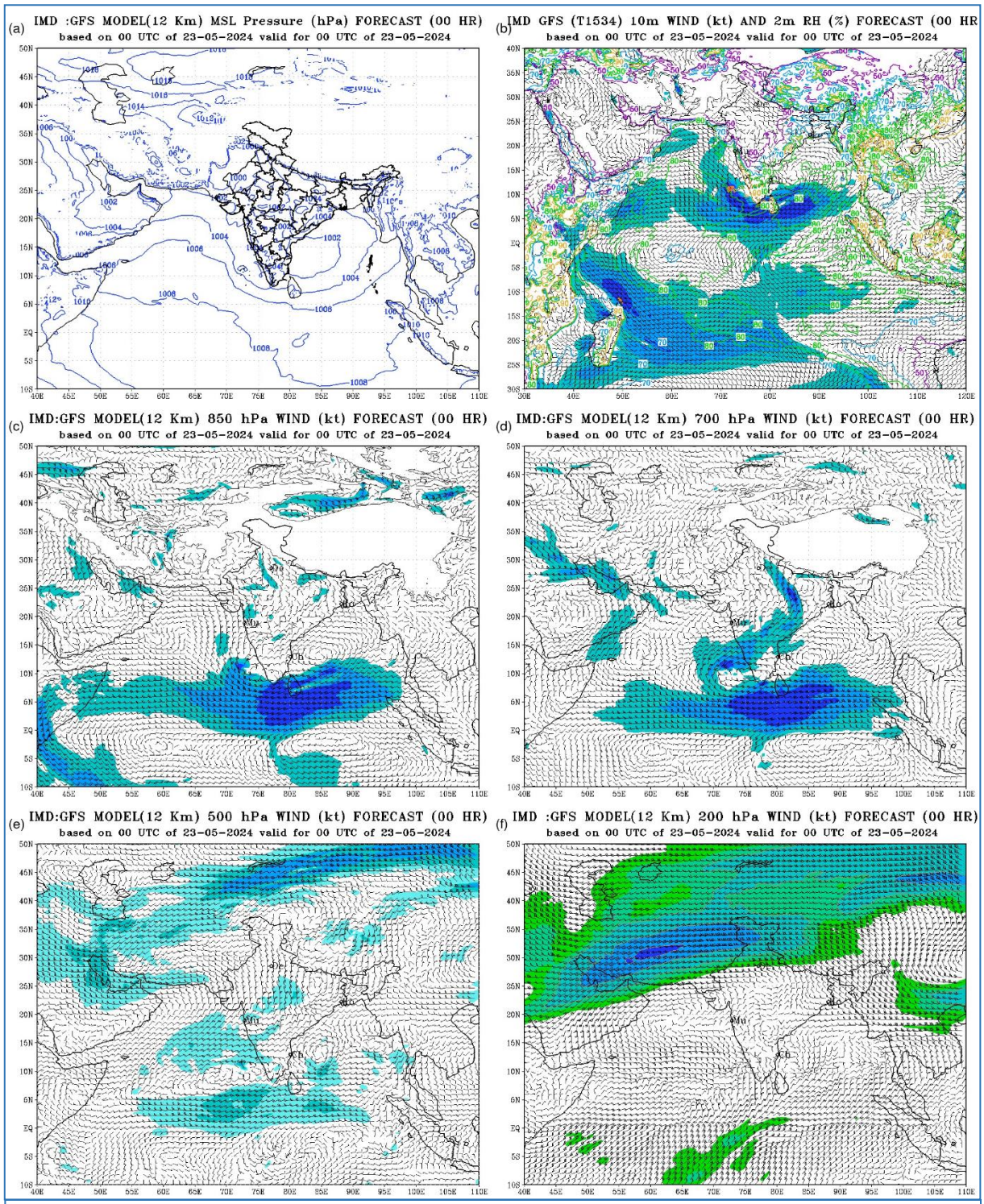


Fig.2.2.8.2: IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 23nd May, 2024

Although, the cyclonic circulation in the lower levels was very much integrated inside the large-scale equatorial trough of northern hemisphere and not independent one, became a detached weather element in the middle atmosphere at 500 hPa pressure level [Fig.2.2.8.1(e)].

In the figure [Fig. 2.2.8.1(f)], the upper level with showed a ridge line in the wind circulation along 15-16°N with westerly is prominent over northern side. However, the core of the strongest westerly was situated north of 28°N. No trough in westerly was seen in both 500 hPa and 200 hPa pressure levels.

In the Fig. 2.2.8.2(a), the MSLP analysis at 0000 UTC of 23rd May did not indicate a low pressure area with marked centre with a closed isobar. But a feeble low pressure area was visible over westcentral BoB. The system was not very clearly represented in MSLP field. However, the cyclonic circulation is indicated in the 10 m wind field. The cyclonic circulation was more obvious at lower-middle levels from 850 hPa level extending up to 500 hPa. The westerly winds at southern sectors of the system being embedded with largescale westerly winds, was stronger than the other sectors. The strength of westerly winds decreases gradually with height [Fig. 2.2.8.2(c) to (e)] and the system became more detached to the northern hemispheric equatorial trough region. The mid-latitude westerly in the upper level at 500 hPa and 200 hPa showed weakening tendency from 22nd May, though the position of the ridge line showed no shifting from the previous day keeping system south of the ridge.

The analyses of the GFS model valid at 0000 UTC of 24th May i.e., MSLP at the surface and wind fields at other upper-tropospheric levels are shown in Fig 2.2.8.3. The MSLP field with two closed isobars indicated that the low pressure area concentrated into a depression with its centre over eastcentral BoB. The associated cyclonic circulation is extended up to 500 hPa over the same region. The strong large-scale westerly winds were seen to influence the southern sectors of the system. This feature was persistent and visible even up to middle tropospheric levels [Fig. 2.2.8.3 (b) to (e)]. The upper air southeasterly flow at 200 hPa indicated a steering over the system towards west-northwest direction. The ridge at 200 hPa was shifted a little northward but however placing the system south of the ridgeline. The upper-level mid-latitude westerlies were visible and reach up to 26°N over northern India with a strong core along 30°N. At this point of time, the system had very little interaction with the upper-level westerlies.

The model analyses for the 0000 UTC of next day, the 25th May are shown in the panels of Fig. 2.2.8.4. It is now clearly observed that the system started to move northwards and organize over the westcentral BoB. It was visible through obvious two closed isobars in MSLP at the surface as well as in the cyclonic circulation in the 10 m wind field over the same region. As the system intensified to a stage of depression and above, the strong surface winds prevailed around the system center. However, the strong westerly components were still pre-dominant in southern sectors of the storm. The associated cyclonic circulation extended crossing middle tropospheric level of 500 hPa [Fig. 2.2.8.4(e)]. Along with the intensification of the system the lower tropospheric westerlies of the environmental flow at 850 and 700 hPa also became stronger over south BoB with a maximum zonal wind far away from the system center. Due to the additional background wind the stronger values of MSW were visible in the southeast sector which makes the storm spatially asymmetric. This asymmetry was even visible throughout the atmospheric column. The upper-level strong westerly extended from mid-latitude over western Himalayan region

and some parts of northwest India. However, the ridgeline was passing along 18-19°N and the system was being close to the ridge and hence experienced weak northerly steering at this stage. The wind circulation features at 200 hPa indicated that the system started to develop a prominent poleward outflow guided by the upper-level westerlies compared to the equatorward outflow.

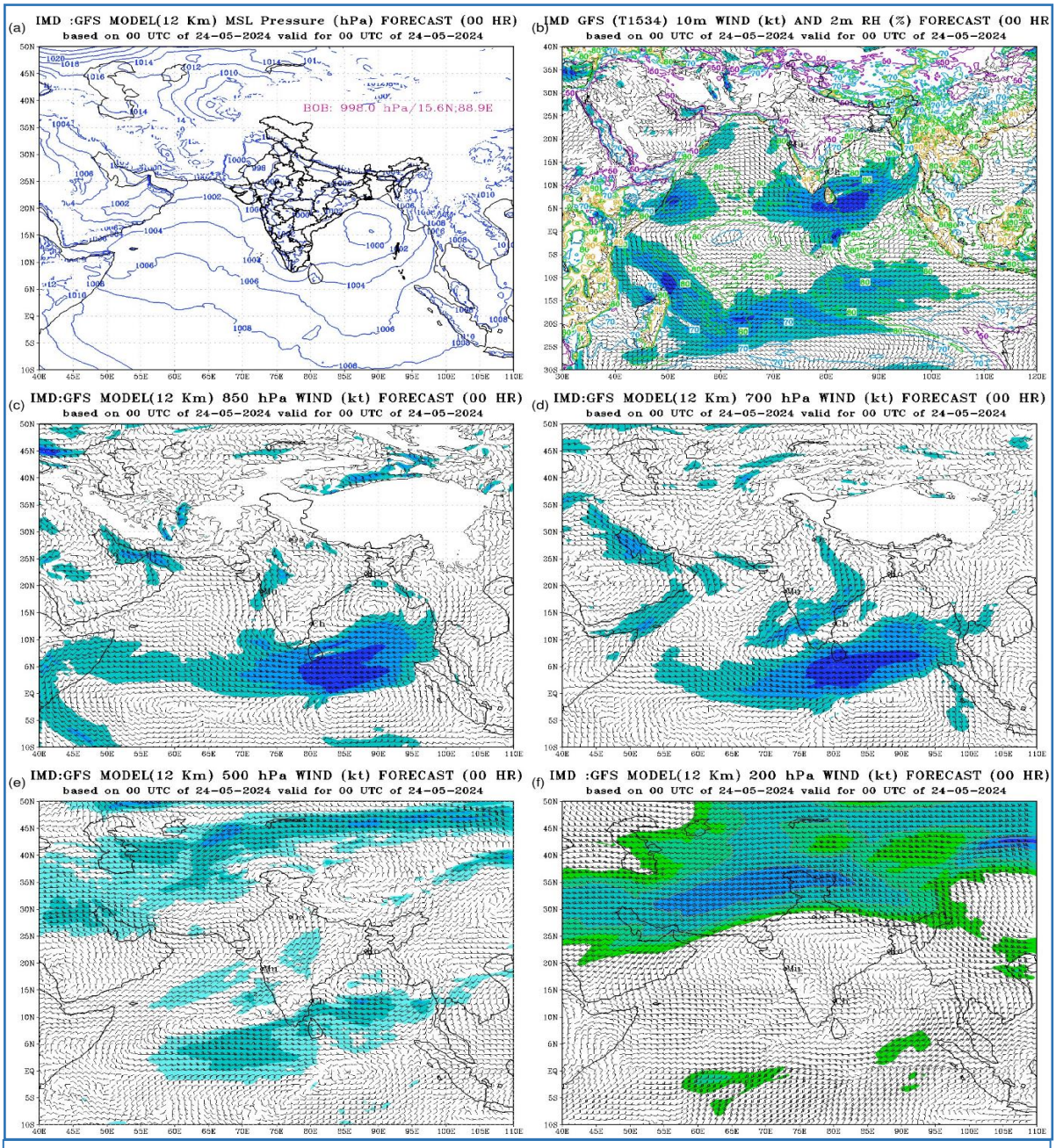


Fig.2.2.8.3: IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 24th May, 2024

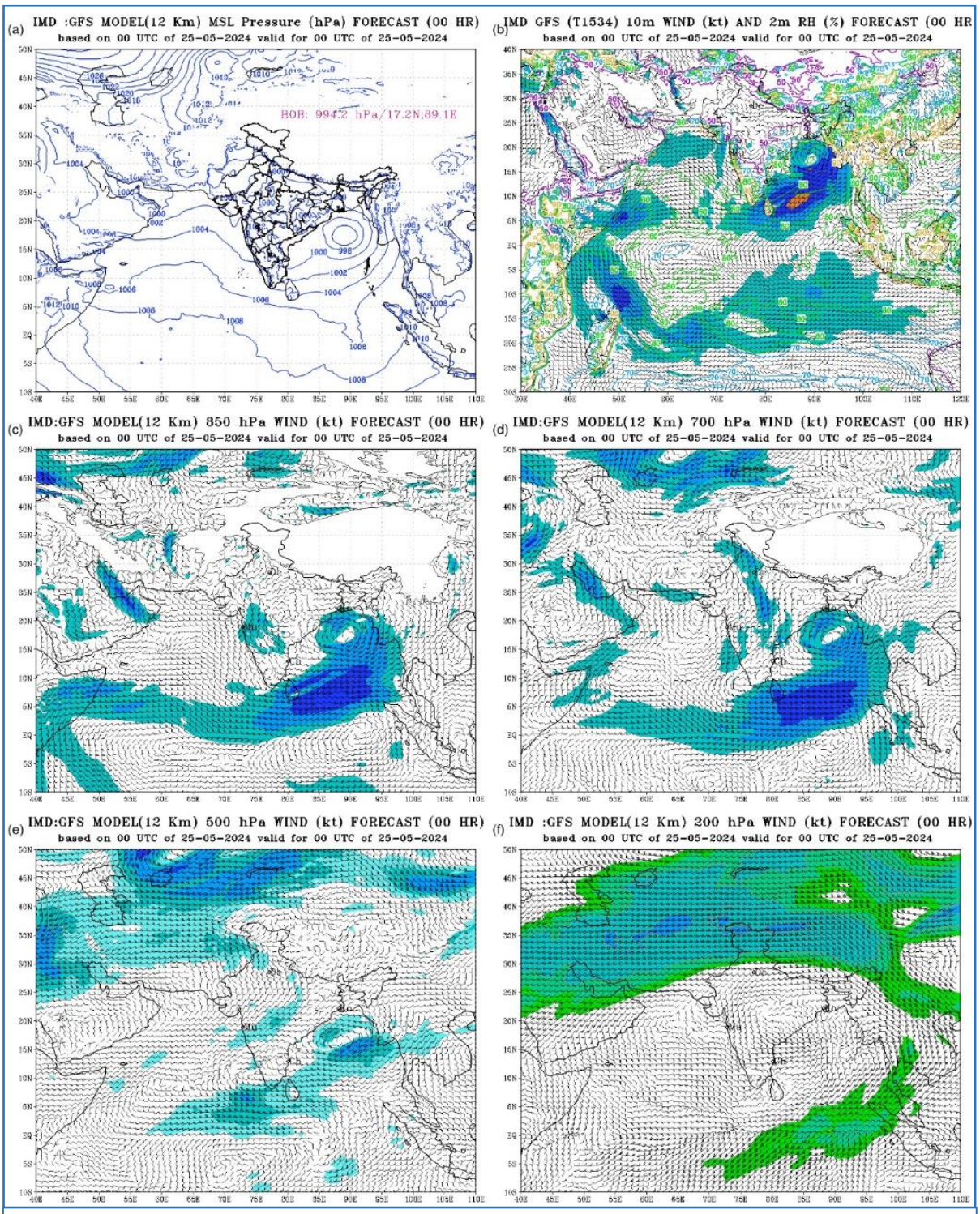


Fig.2.2.8.4: IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 25th May, 2024

The Fig. 2.2.8.5 depicts the atmospheric states at 0000 UTC of 26th May, 2024 represented by the GFS model analyses, in terms of MSLP and wind distributions at various pressure levels. The increased number of the closed isobars [in Fig. 2.2.8.5(a)] clearly demonstrated the intensification of the system to the stage of SCS. The movement of the system further

northward was also illustrated by the spatial pattern of the MSLP and 10 m wind circulation [in Fig. 2.2.8.5(b)].

Associated cyclonic circulation extending up to middle tropospheric levels was seen in by the wind maps in Fig. 2.2.8.5(c) to (e).

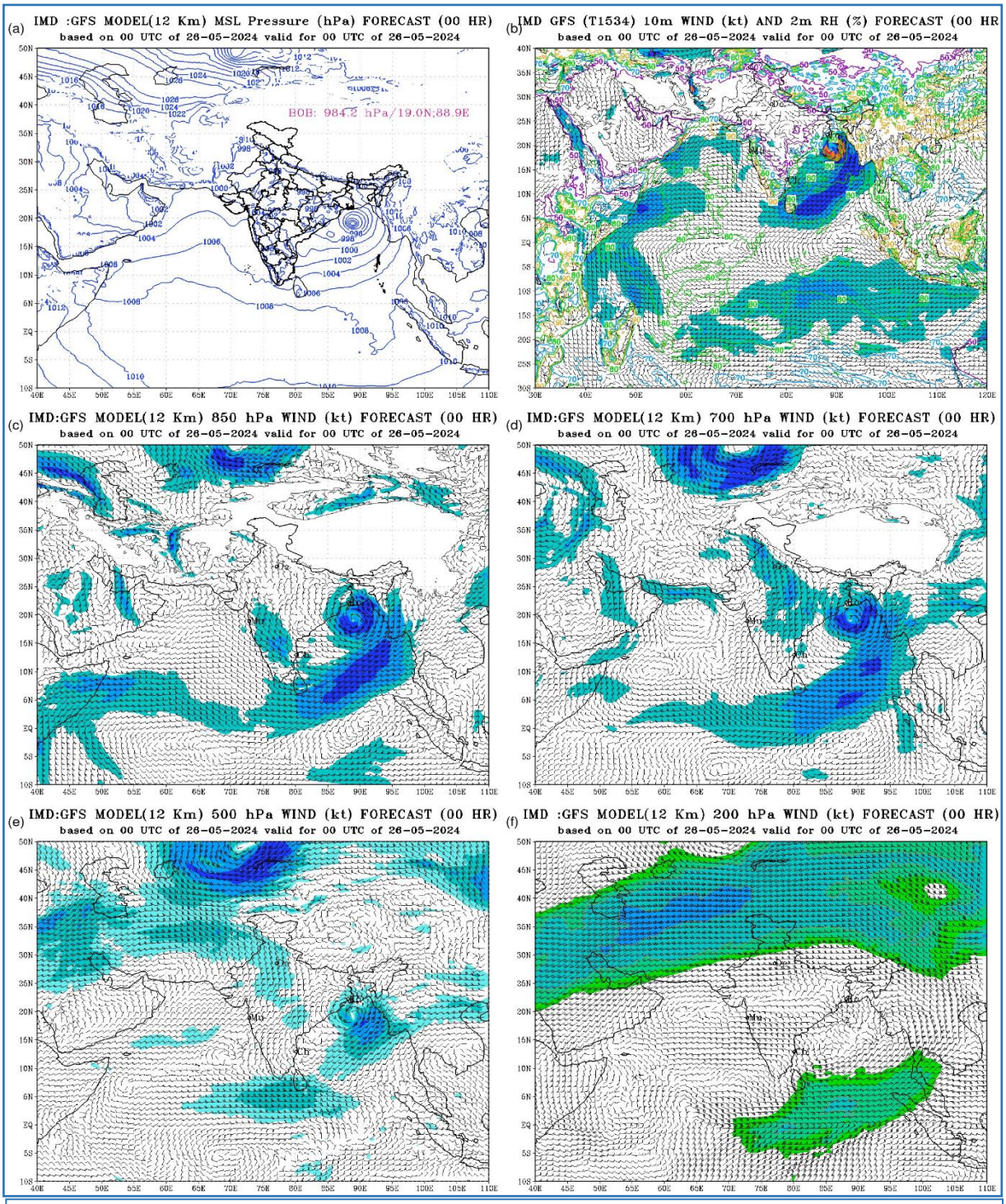


Fig.2.2.8.5: IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 26th May, 2024

Although the intensity of the system increased, still an asymmetric structure was maintained from the surface extending up to the mid-tropospheric levels. The spatial distribution of 10 m wind revealed that the MSW was forming a semi-circular ring around system starting from southwest sector covering up to northeast sector. Similar wind structure was continued to be seen at 850 hPa and 700 hPa level as well. But with height, the maximum winds were found to be prevailing mostly at the southern sectors of the system. The winds at upper tropospheric level at 200 hPa were showing an anticyclonic outflow from the center of the system. As the system moved northwards with time, it became close to the strong upper-level westerlies and poleward outflow was seen to be controlled by the same.

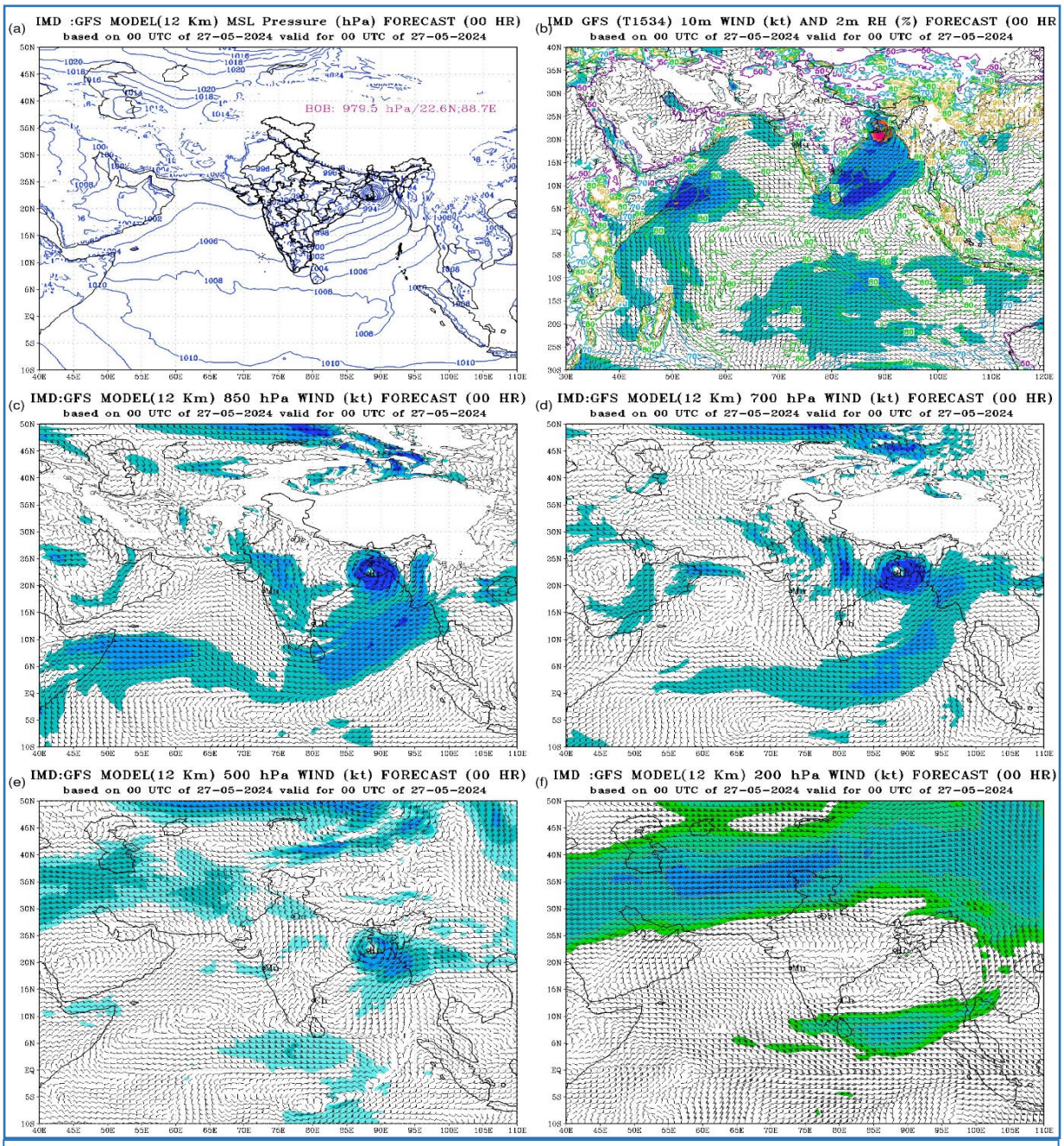


Fig.2.2.8.6: IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 27th May, 2024

In the Fig. 2.2.8.6, all the panels represent MSLP and wind analyses of IMD GFS model valid at 0000 UTC of 27th May, 2024. The isobars depicted the centre of the system lying over the land as the system made landfall during 1700 to 1900 UTC of 26th May, 2025. The intensity of the storm was seen to be maintained even after the landfall as indicated in the 10 m wind distribution as well. Due to the landfall of the system the lower level strong westerly flow prevailing at the south of the system helped to nudge the monsoonal southwesterly wind to reach up to Myanmar and northeastern states. Reaching over land, the asymmetric structure of the system became more symmetric as MSW differences amongst various sectors of the storm are decreased. However, the asymmetric structure is maintained at 500 hPa in the mid-tropospheric level with higher wind speed is seen over southern sectors.

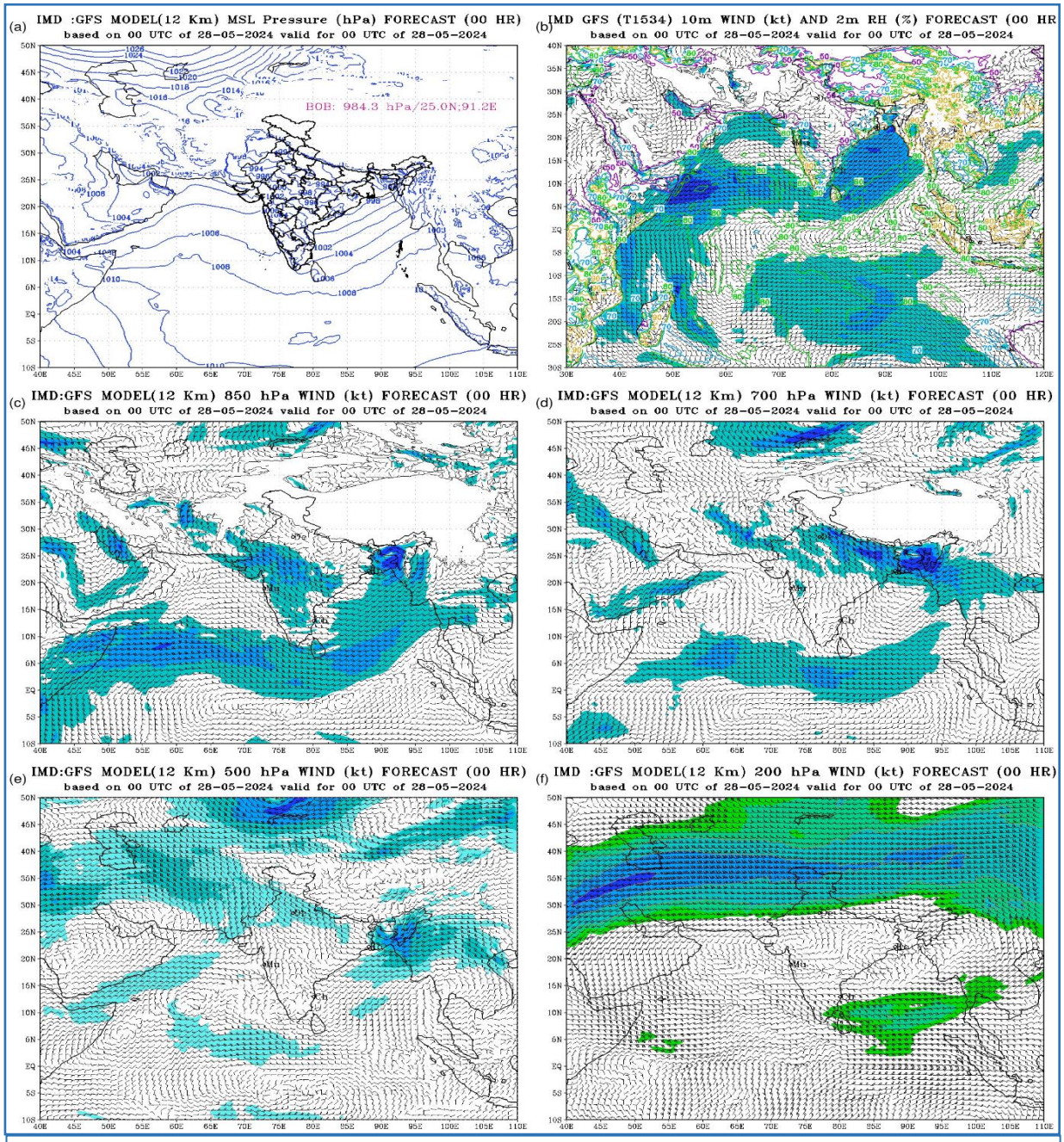


Fig.2.2.8.7: IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 28th May, 2024

The wind at 200 hPa level showed the direct influence of upper level westerly winds over the outflow from the system. Accordingly, the stronger deep wind shear was leading to weakening of the system.

The Fig. 2.2.8.7 shows the model analyses at 0000 UTC of 28th May, 2024. Nearly 30 hours after the landfall, the MSLP [Fig.2.2.8.7(a)] showed a low over south Assam and adjoining area. The wind strength and circulation feature as prescribed by the 10 m wind indicated clearly a very weak system. However, associated upper-level cyclonic circulations were sustained extending up to 500 hPa pressure level. The extension of monsoonal southwesterly winds reaching up to the center of the system could be seen at 850 hPa and 700 hPa pressure levels [Fig. 2.2.8.7(c) and (d)]. A weak outflow at 200 hPa was seen in association with the system merged with the upper-level westerlies.

Therefore, the IMD GFS model analyses represented the location, intensity and structure of the system in general at various stages of the cyclonic storm. The interaction of the system with environmental flow at various pressure levels was also depicted well. However, the steering force on the system could not be explained with analyses of the parameters as plotted in the Figures 2.2.8.1 to 2.2.8.7.

2.2.6 Realized Weather

2.2.6.1. Realized rainfall

The system caused heavy to extremely heavy rainfall activity over West Bengal, Bangladesh and Northeastern states of India including Assam, Meghalaya, Nagaland, Manipur, Mizoram and Tripura. NCMRWF IMD satellite gauge merged data plot showing 24 hours accumulated rainfall ending at 0300 UTC of dates during 23rd – 29th May is presented in **Fig. 2.2.9**.

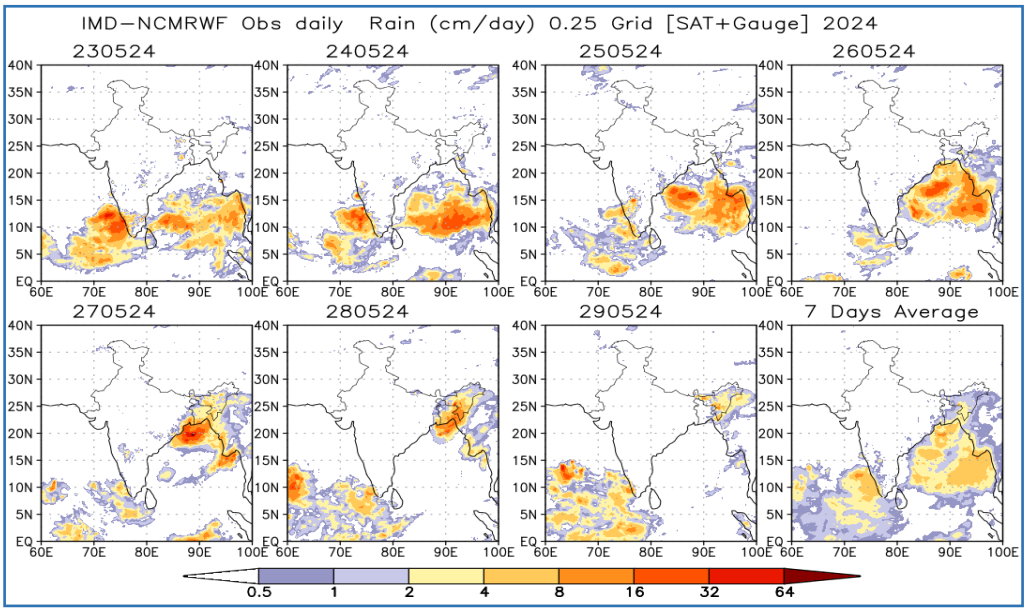


Fig. 2.2.9: NCMRWF-IMD satellite gauge merged data plots of 24 hours accumulated realized rainfall during 23rd May to 29th May, 2024

24 hours accumulated realized heavy rainfall (≥7cm) ending at 0830 hours IST of date are given below:

2.2.6.2. Realised wind

Khepupara and Patuakhali stations in Bangladesh reported 111 kmph during landfall. In West Bengal highest wind speed of 91 kmph was reported at Dum Dum followed by 78 kmph at Canning. Realised wind reported at different stations of Bangladesh and West Bengal is presented in **Table 2.2.2 and 2.2.3 respectively.** Estimated maximum sustained wind speed realised during cyclone “REMAL” is presented in **Fig.2.2.10**.

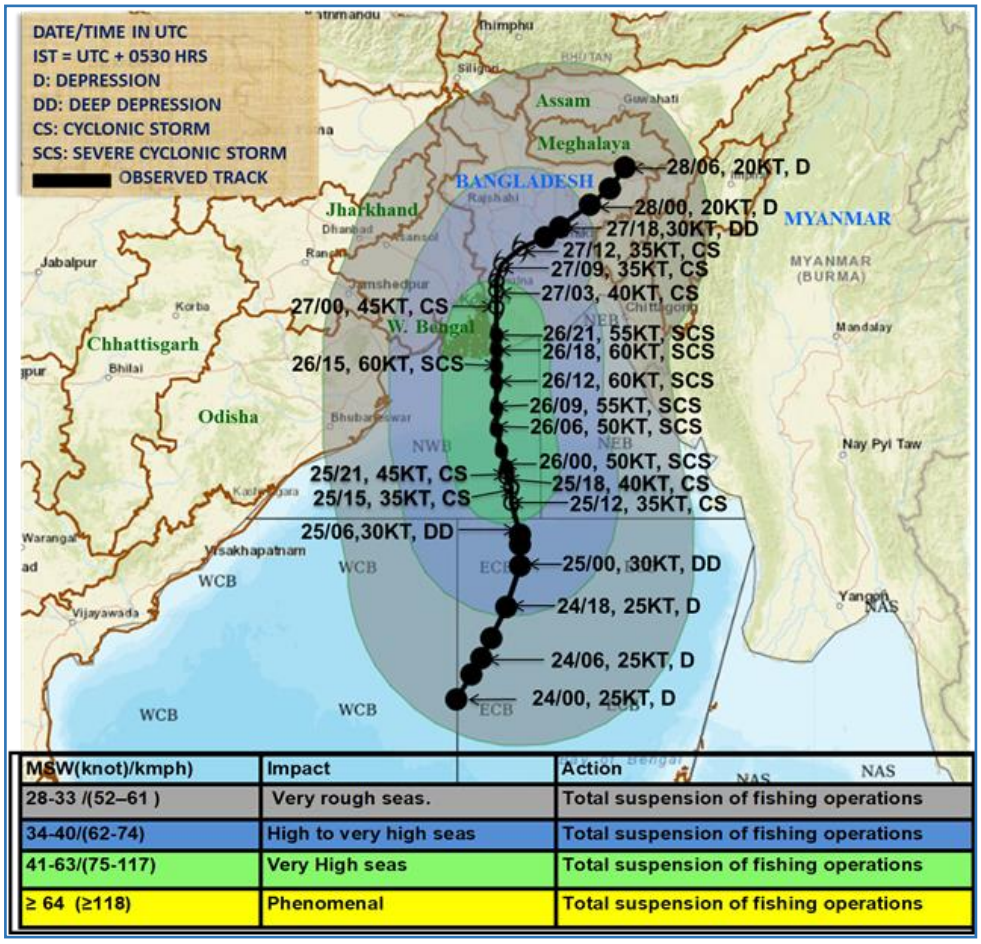


Fig. 2.2.10: Estimated maximum sustained wind during the life cycle of SCS REMAL

Table 2.2.2: Realised wind (kmph) in Bangladesh

Name	Date	TIME	Wind (Kmph)
Khepupara	27-05-2024	01:30-02:00 AM	111
Khepupara	26-05-2024	11:30-11:59 PM	91
Patuakhali	27-05-2024	01:30-02:00 AM	111
Patuakhali	26-05-2024	11:30-11:59 PM	102
Patuakhali	26-05-2024	2:30 PM	89
Satkhira	26-05-2024	11:30-11:59 PM	70
Mongla	27-05-2024	12:30 PM	80
Mongla	27-05-2024	3:00 AM	79
Khulna	27-05-2024	11:30-11:59 PM	72
Dhaka	27-05-2024	6:20 AM	59
Chandpur	27-05-2024	3:30 AM	65
Patenga	27-05-2024	6:05 AM	74
Patenga	27-05-2024	11:45 AM	92

Table 2.2.3: Realised wind over West Bengal during landfall

Station	Highest Wind Speed (kmph)
Kolkata	74
Dum Dum	91
Diamond Harbour	69
Canning	78
RKM College	78
Uluberia	73
Baruipur	69
Ramsaday College	67
Kzi Airport	65
Kalyani	65
Howrah	65
Sagar Deep	63

2.2.6.3. Realised storm surge

Storm surge of about 3.8 m height inside the creeks of Balaswar river close to Sapleja, Bangladesh occurred during landfall (**Fig. 2.2.11**). The inundation details are given below:

- ❖ Inland inundation of about 1 - 2 km along the banks of Balaswar river between 'Gabbaria' & 'Haringhata' of Bangladesh.
- ❖ Inland inundation of about 1.5 to 2 km along the banks of Tetula river close to Rangabali & about 3.5 km around Burirchar, Bangladesh.
- ❖ Inland inundation of about 4 km near Aicha, Bangladesh.
- ❖ Inland inundation of about 2 - 5 km along the parts of Meghana river banks.

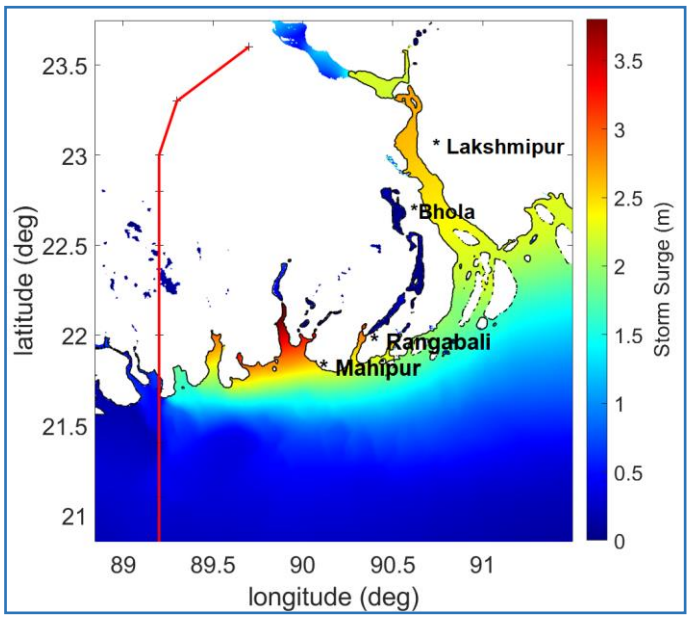


Fig. 2.2.11: Estimated storm surge based on best track parameters of SCS REMAL

2.2.7 Damage report

In West Bengal, the cyclone caused significant structural damages and loss of lives. 7 fatalities were recorded, including deaths from collapsing roofs, electrocution, and accidents caused by falling electric wires. Bangladesh faced a similar fate, with Cyclone Remal claiming at least 10 lives and destroying over 30,000 homes.

Fig. 2.2.12 (a) Storm surge and associated damage due to Cyclone Remal in coastal Bangladesh (ddindia.co.in, 27th May, 2024), (b) Flooding in Bangladesh on May 26, 2024 (edition.cnn.com, 26th May, 2024), (c) Damage in Bangladesh's coastal districts by SCS Remal (asinews.it, 28th May, 2024), (d) Damage in West Bengal by Cyclone Remal (economictimes.indiatimes.com, 27th May, 2024), (e) Damage in West Bengal (ET 28 May, 2024) and (f) Rescue team clearing fallen trees in West Bengal (Air News Alerts, 28 May 2024)

In Northeast India, Mizoram bore the brunt of the cyclone's wrath, with 30 fatalities reported mainly due to landslides. Landslides, collapsed quarries, and disrupted connectivity caused widespread destruction. Assam, Nagaland, Meghalaya, Tripura, and Manipur also suffered casualties, injuries, and infrastructure damage. Floods, landslides, and road blockages hampered rescue and relief efforts, displacing thousands and damaging homes, bridges, and roads. The cyclone disrupted normal life, with power outages, disrupted communication networks, and extensive agricultural losses. The damage photographs received from different sources are presented in **Fig. 2.2.12 to 2.2.14.**

Fig. 2.2.13: (a) Uprooting of electric pole due to SCS Remal, (b) Landslides in Mizoram (eastmojo.com, 28th May, 2024) (c) A car damaged after a shed fell on it after the landfall of Cyclone Remal in Guwahati on Tuesday (indianexpress.com,28th May,2024), (d) A house damaged by the severe cyclonic storm, Remal (indiatvnews.com, 27th May, 2024)

Fig. 2.2.14: Damage over Northeastern states of India (a)-(c) Tree fell on a school bus killing students (Source: All India Media Asociation, 28 May)

2.3. Depression over Northwest and adjoining Westcentral Bay of Bengal off Odisha and adjoining North Andhra Pradesh coasts during 19th July-20th July 2024

2.3.1. Introduction

- A low-pressure area formed over central and adjoining north Bay of Bengal (BoB) with associated cyclonic circulation extending upto mid-tropospheric levels tilting southwestwards with height in the morning (0830 hours IST) of 18th July, 2024.
- It lay as a well marked low pressure area over central and adjoining north BoB in the evening (1730 hours IST/1200 UTC) of 18th July, 2024.
- It moved northwestwards and concentrated into a depression over northwest and adjoining westcentral BoB off Odisha and adjoining north Andhra Pradesh coasts in the morning (0830 hours IST) of 19th July, 2024. Continuing to move further northwestwards, it lay centered at 1130 hours IST of 19th July, 2024 over the same region near latitude 19.3°N and longitude 86.1°E, about 60 km south-southeast of Puri (Odisha), 130 km East of Gopalpur (Odisha), 130 km south-southwest of Paradip (Odisha) and 230 km east-northeast of Kalingapatnam (Andhra Pradesh).
- Depression further moved west-northwestwards and lay centered at 0830 hours IST of 20th July, 2024 over the same region at latitude 19.6°N and longitude 85.4°E, about 40 km south-southwest of Puri (Odisha) and 70 km East-Northeast of Gopalpur (Odisha). It moved northwestwards, crossed Odisha coast near Chilika during 0830-0930 IST and weakened into a well-marked low pressure area over coastal Odisha in the same evening (1730 hours IST/1200 UTC of 20th July, 2024). It further moved northwestwards and lay over Odisha and adjoining Chhattisgarh in the morning (0830 hours IST/0300 UTC) of 21st July 2024.
- The observed track of the system is presented in **Fig. 2.3.1.** The best track parameters of the system are presented in Table 2.3.1.

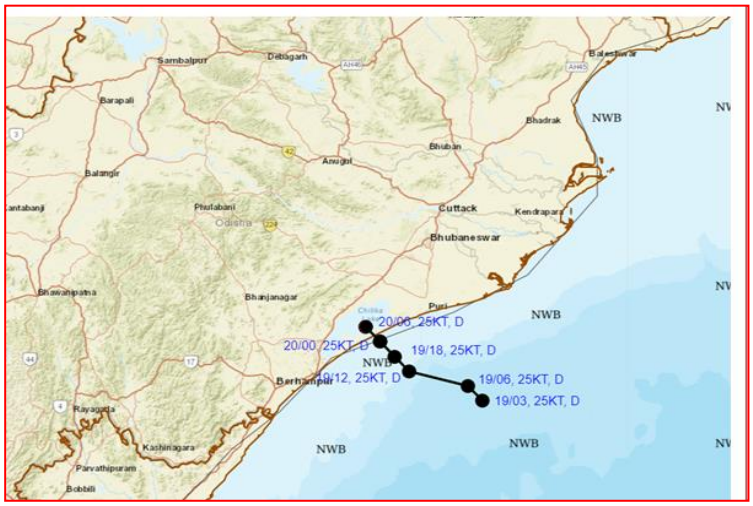


Fig. 2.3.1: Observed track of Depression over Northwest and adjoining Westcentral Bay of Bengal during 19th July-20th July 2024

Table 2.3.1: Best track positions and other parameters of the Depression over Northwest and adjoining Westcentral Bay of Bengal during 19th July-20th July 2024

Date	Time (UTC)	lat	lon	CI No	ECP (hPa)	ΔP (hPa)	MSW (kt)	Category
19.07.24	0300	19.1	86.2	1.5	992	3	25	D
	0600	19.2	86.0	1.5	992	3	25	D
	1200	19.4	85.7	1.5	990	4	25	D
	1800	19.5	85.6	1.5	990	4	25	D
20.07.24	0000	19.6	85.5	1.5	991	4	25	D
	0300	19.6	85.5	1.5	992	3	25	D
			Crossed Odisha coast near Chilika during 0830-0930 IST					
	0600	19.7	85.4	1.5	992	3	25	D
	1200		Depression weakened into a Well Marked Low Pressure Area over Coastal Odisha					

KT: Knots (nautical mile per hour), 1 KT=1.85 kmph, D: Depression, DD: Deep Depression

2.3.2. Salient features of the system

- The life period of the system was 1 day and 9 hours which is below normal for depressions over BoB during monsoon season.
- First depression of monsoon season
- Climatologically about two depressions form over the BoB in July

2.3.3. Brief life history - Genesis Intensification and movement

2.3.3.1 Genesis

A low-pressure area formed over central and adjoining north Bay of Bengal (BoB) with associated cyclonic circulation extending upto mid-tropospheric levels tilting southwestwards in the morning (0830 hours IST/0300 UTC) of 18th July, 2024.
It lay as a well-marked low pressure area over central and adjoining north Bay of Bengal in the evening (1730 hours IST) of 18th July, 2024.
It moved northwestwards and concentrated into a depression over northwest and adjoining westcentral BoB off Odisha and adjoining north Andhra Pradesh coasts in the morning (0830 hours IST/0300 UTC) of 19th July, 2024.

The Madden Julian Oscillation (MJO) index was located in phase 5 with amplitude more than 1 and remained in same phase for next 2 days. Thus, MJO phase and its amplitude were favourable for enhancement of convective activity over the north BoB. The NCICS based forecasts for zonal winds indicate strong easterly winds (~ 3 to 7 mps) over north BoB and adjoining central India and strong westerly winds (~ 3 to 7 mps) over the southern and adjoining eastcentral part of BoB. Additionally, there existed an Equatorial Rossby Wave (ERW). Thus, zonal winds and equatorial waves contributed to formation of depression over north BoB on 19th July. Low level vorticity was about $120 \times 10^{-6} S^{-1}$ around the system centre over westcentral & adjoining northeastcentral BoB with vertical extension upto 700 hpa

levels. Low level convergence was east-west oriented and was about 10-15x$10^{-6}S^{-1}$ to the west of the system center. Upper level divergence is also east-west oriented and is about 10-20x$10^{-6}S^{-1}$ around the system center. Vertical wind shear (VWS) was low to moderate (10-15 kt) near the system center.

2.3.3.2 Intensification and movement

At 0300 UTC of 20th July, the depression has moved northwestwards lay over the same region.

The low-level vorticity has decreased approximately to 75x$10^{-6}S^{-1}$ over the northwest and adjoining west central Bay of Bengal, and over the east of the system center. The vertical extension was up to 200 hPa level, the low-level convergence is circular, measuring about 20 x$10^{-6}S^{-1}$ around the system center. Moreover, upper-level divergence was about 10x$10^{-6}s^{-1}$ to the southwest of the system center. It's has to be noted that the VWS was very high, ranging from 40-50 KT over the area. Under these circumstances, it did not intensified further and crossed coast as a depression.

2.3.4. Monitoring

India Meteorological Department (IMD) maintained round the clock watch over the north Indian Ocean (NIO) and the system was monitored well in advance since 15th July. The system was monitored with the help of available satellite observations from INSAT 3D and 3DR, polar orbiting satellites, available ships & buoy observations in the region and coastal observations on the day of landfall. 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 system. A digitized forecasting system of IMD was utilized for analysis and comparison of various models' guidance, decision making process and warning products generation.

2.3.4.1. Features observed through satellite

Satellite monitoring of the system was mainly done by using half hourly INSAT-3D and 3DR imageries. Satellite imageries of other international geostationary satellites, high resolution polar orbiting satellites and scatterometer imageries from ASCAT were also considered for monitoring of the system. Typical INSAT-3D enhanced colored imageries, visible/ IR, brightness temperature and water vapour imageries are presented in **Fig. 2.3.2 (a) to (d)**. During the entire life cycle, the clouds were organized in shear pattern. The detailed features from the satellite pictures are discussed in this section.

At 0300 UTC of 19th July, based on INSAT-3D imagery, the convection has organized, and the intensity of the system was **C.I**.1.5. There were scattered to broken low and medium clouds with embedded intense to very intense convection over the northwest and adjoining west central Bay of Bengal, as well as the north coastal Andhra Pradesh and south Odisha. The minimum cloud top temperature is -93.0°C.

At 1200 UTC of 19th July, based on INSAT-3D imagery, the convection has further organized. The intensity of the system was **C.I**.1.5. Scattered to broken low and medium clouds with embedded intense to very intense convection were observed over northwest and adjoining west-central Bay of Bengal, as well as north coastal Andhra Pradesh and Odisha. The minimum cloud top temperature is -93.0°C.

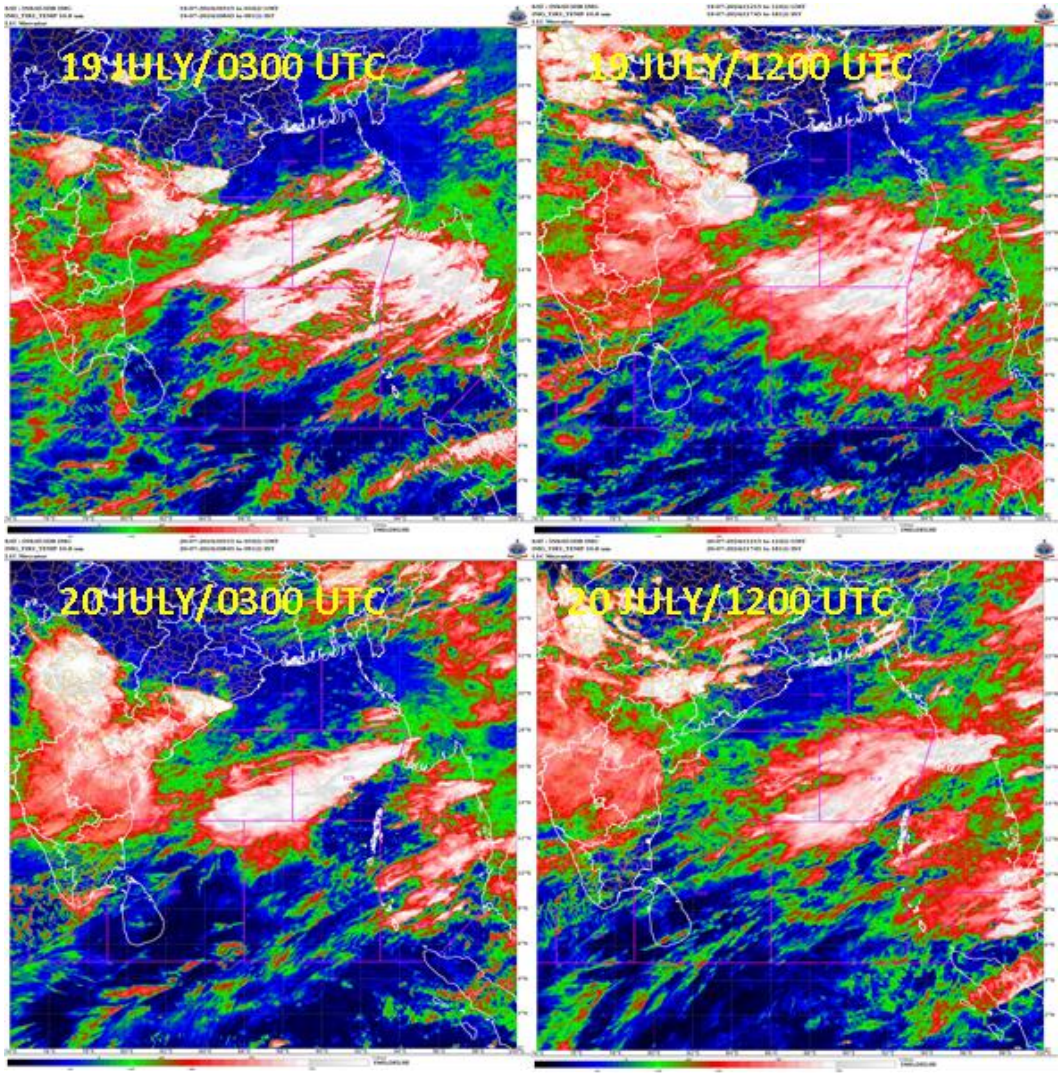


Fig.2.3.2(a): INSAT-3D enhanced colored imageries during life cycle of Depression over Northwest and adjoining Westcentral Bay of Bengal during 19th July-20th July 2024

At 0300 UTC of 20th July, based on INSAT-3D visible imagery, the system's intensity was C.I.1.5. Scattered to broken low and medium clouds with embedded intense to very intense convection were observed over west-central and adjoining northwest Bay of Bengal, off south Odisha and adjoining north Andhra Pradesh coasts, as well as south Odisha and north coastal Andhra Pradesh. The minimum cloud top temperature was -93.0°C.

At 1200 UTC of 20th July, based on INSAT-3D imagery, the system was positioned over the south Odisha coast as a vortex. Associated scattered to broken low and medium clouds with embedded intense to very intense convection were observed over south Chhattisgarh and northwest Odisha, with moderate to intense convection over north Chhattisgarh and Jharkhand. The minimum cloud top temperature was -93.0°C.

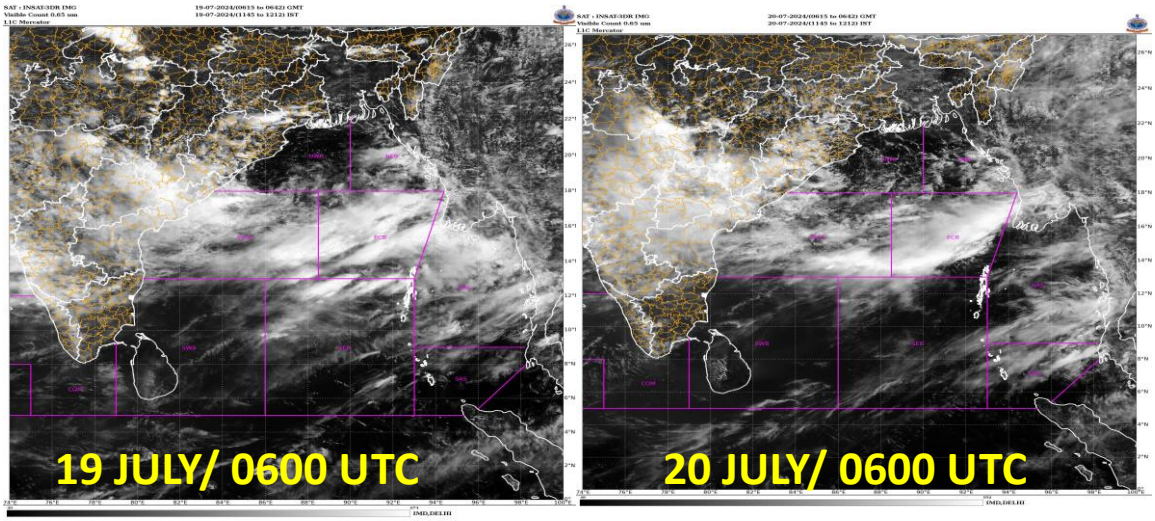


Fig. 2.3.2 (b): INSAT-3D Visible imageries during life cycle of Depression over Northwest and adjoining Westcentral Bay of Bengal during 19th July-20th July 2024

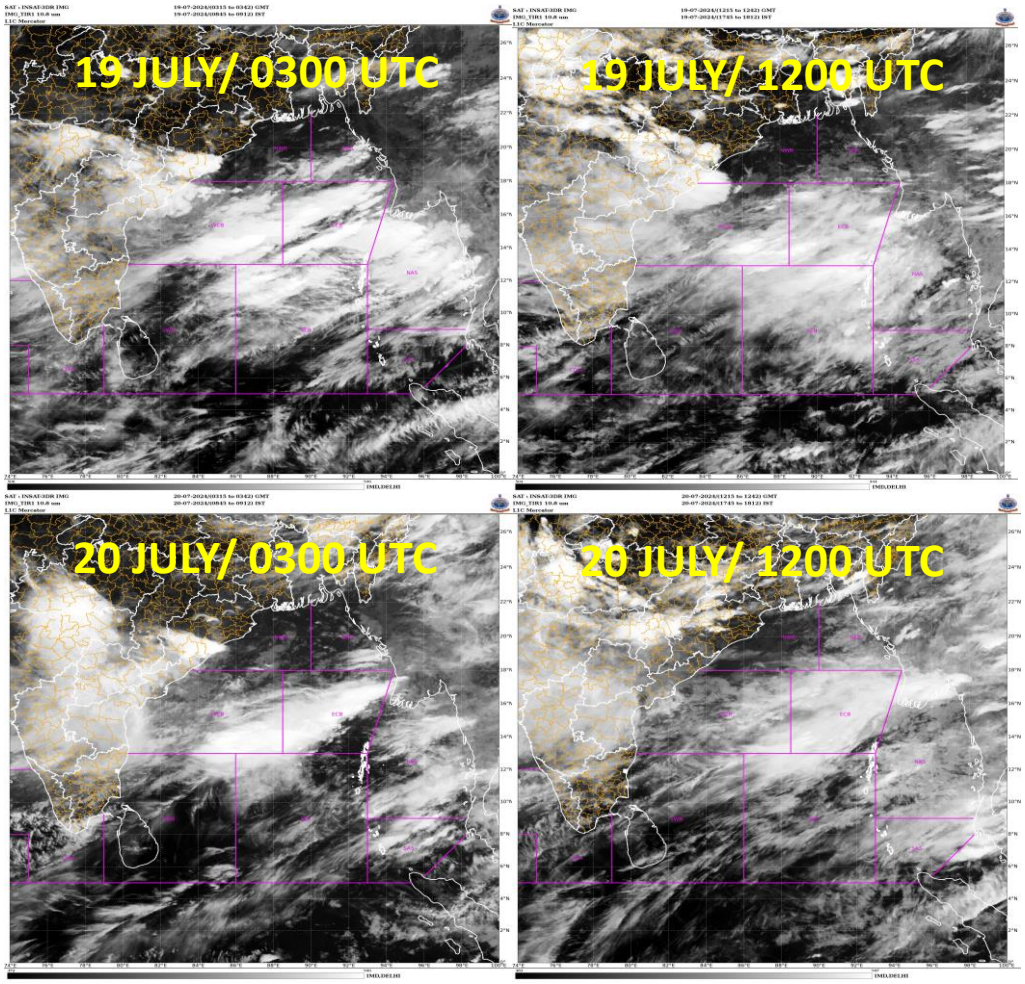


Fig. 2.3.2(c): INSAT-3D IR imageries during life cycle of Depression over Northwest and adjoining Westcentral Bay of Bengal during 19th July-20th July 2024

ASCAT winds in Fig 2.3.3 clearly indicated that the circulation associated with the depression over northwest and adjoining westcentral BoB on 19th and along the Odisha coast on 20th July 2024.

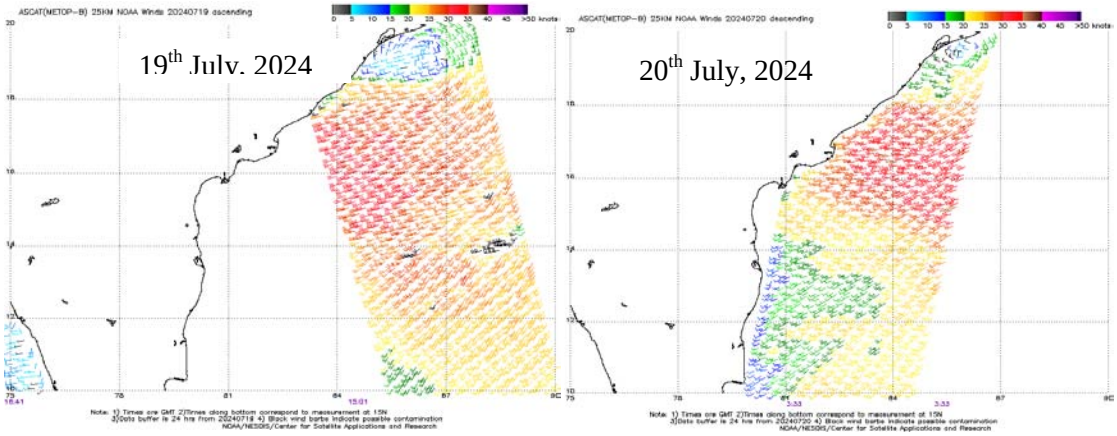


Fig. 2.3.3: ASCAT winds on 19th and 20th July 2024.

2.3.5. Dynamical Features

IMD GFS (T1534) daily analyses at 0000 UTC of mean sea level pressure (MSLP), winds at various pressure levels from 19th July to 20th July are presented in **Fig. 2.3.4(a) to (b)** respectively.

The MSLP analysis field on 19th July indicated that the system was over northwest BoB near 19.5°N/86.0°E. Actually, based on the best track the system was located near 19.1°N/86.2°E at 0300 UTC. Thus, GFS well captured the initial conditions on 19th July.

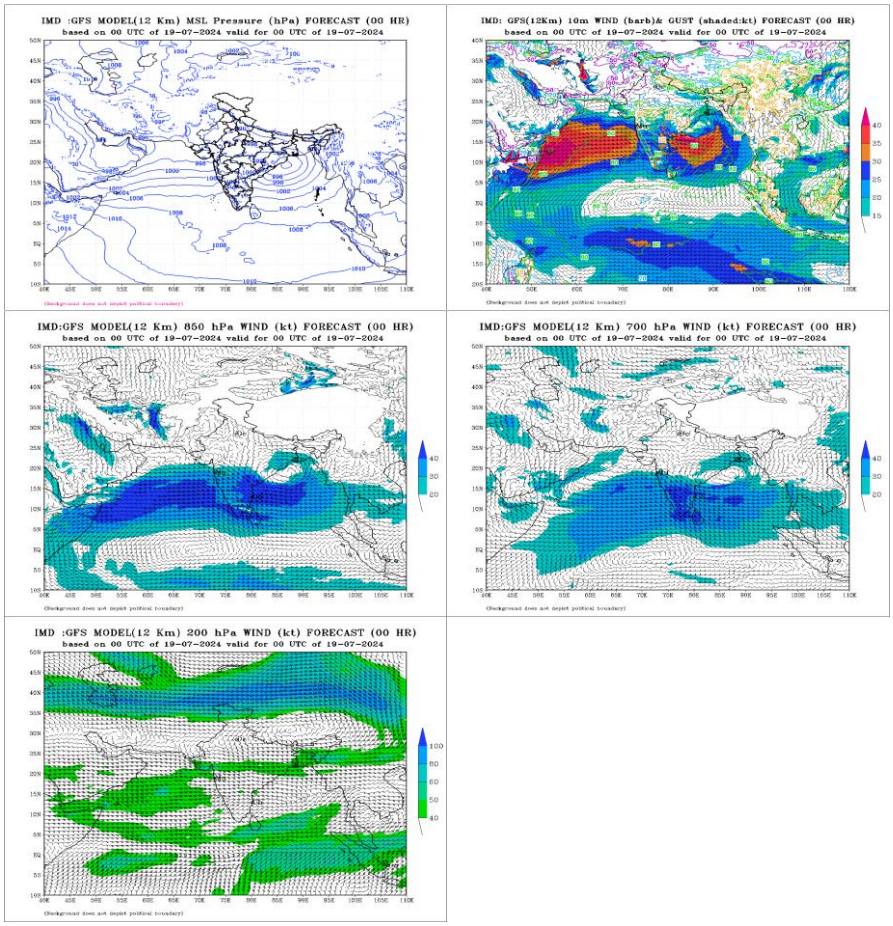


Fig. 2.3.4(a): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 19th July 2024

The MSLP analysis field on 20th July indicated that the system touched the Odisha coast and lay centered at 19.8°N/86.0°E. Actually, based on the best track the system was located at 19.6°N/85.5°E at 0000 UTC of 20th July. Thus, GFS reasonably captured the initial conditions on 19th July. It also indicated that the system vertically extended up to 500 hPa level.

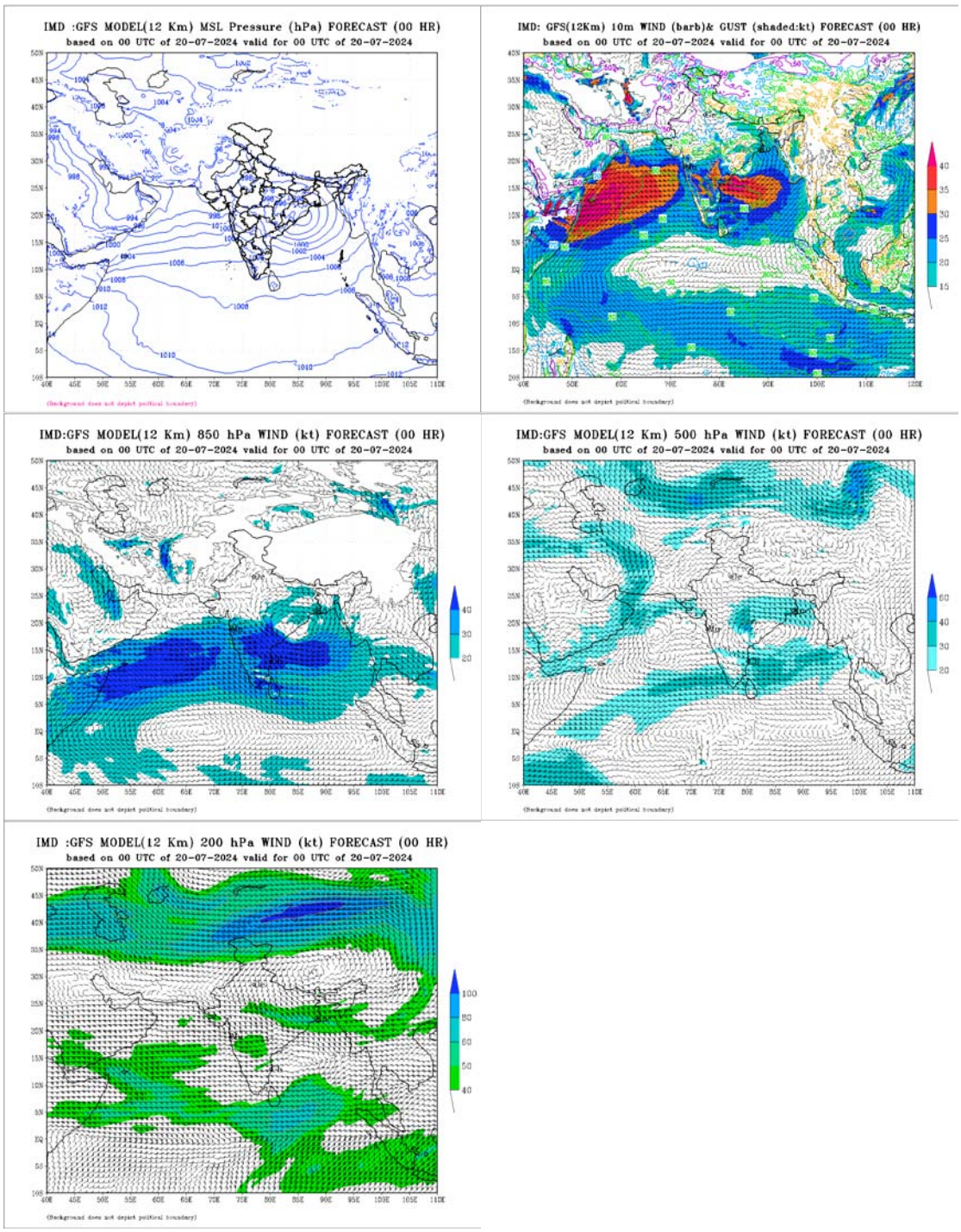


Fig. 2.3.4(b): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 20th July 2024

2.3.6. Realized Weather

Rainfall associated with the deep depression based on IMD-NCMRWF satellite gauge merged data are depicted in Fig 2.3.5. It is seen that heavy to very heavy rainfall occurred at isolated places over coastal Andhra Pradesh and coastal Odisha on 19th July & heavy to very heavy rainfall at isolated places over costal Odisha, costal Andhra Pradesh on 20th July.

Light to moderate rainfall at a few places with heavy to very heavy rainfall at isolated places occurred over Madhya Pradesh, Jharkhand, Chhattisgarh and Odisha on 20th July.

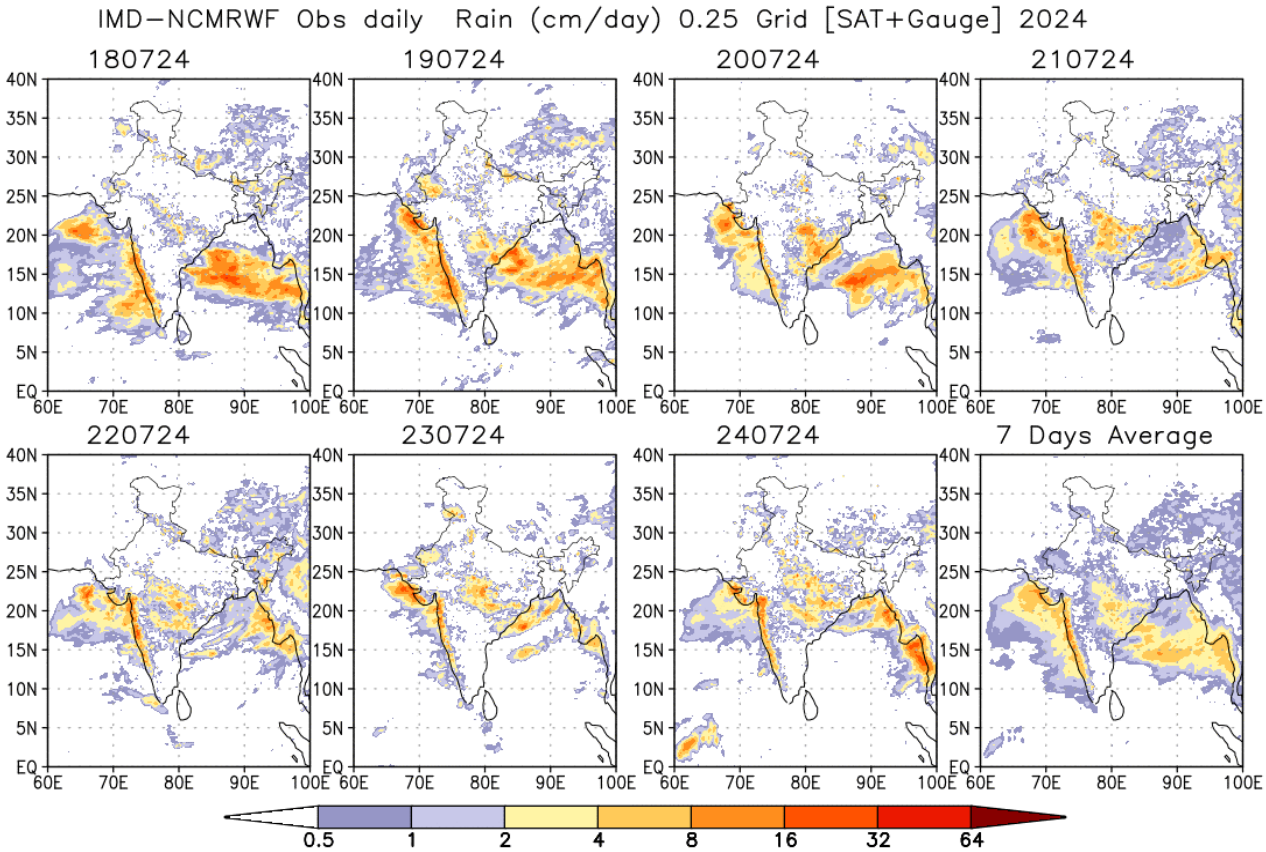


Fig. 2.3.5: NCMRWF-IMD satellite gauge merged data plots of realized 24 hours accumulated rainfall from 18th to 24th July, 2024.

2.3.6.1 Rainfall forecast verification

The forecast for heavy to extremely heavy rainfall episodes in association with the system are verified with the 24 hours accumulated rainfall realized at various stations. The details of the day-wise verification are given in Table -2.

Table 2.3.2: Day wise daily 24 hours cumulative rainfall forecast verification with station observations

Date/Base Time of observation	24 hr Heavy rainfall warning ending at 0300 UTC of next day	Realised 24-hour heavy rainfall (≥ 7 cm) ending at 0300 UTC of date
19.07.2024 / 0830	**Odisha:** ❖ South Odisha: Heavy to very heavy rainfall at a few places is very likely over South Odisha on 19th and 20th July and extremely heavy rainfall at isolated places on 19th July. ❖ North Odisha: Heavy to very heavy rainfall at isolated places on 19th and 20th July. Gangetic West Bengal: Light to moderate rainfall is very likely at most places on 19th and 20th July. Andhra Pradesh: ❖ North Coastal Andhra Pradesh: Heavy to very heavy rainfall at a few places is most likely on 19th & 20th July and extremely heavy rainfall at isolated places on 19th July. ❖ South Coastal Andhra Pradesh: Heavy rainfall at isolated places is likely over South Coastal Andhra Pradesh on 19th and 20th July. Jharkhand: Heavy rainfall at isolated places is very likely on 20th July. Chattisgarh: Heavy to very heavy rainfall at isolated places is very likely on 19th and 20th July and	**Odisha** Chitrakunda K Guma (Malkangiri) & Korukunda (Malkangiri) – 22 each, Malkangiri (Malkangiri) - 18, Mathili (Malkangiri) & Kotpad (Koraput) - 16 each, Padia (Malkangiri) - 13, Nandahandi (Nawarangpur), Tentulikhunti (Nawarangpur) & Papadahandi (Nawarangpur) - 11 each, Aska (Ganjam) & Kosagumda (Nawarangpur) - 10 each, Nawarangpur (Nawarangpur), Nawarangpur Pto (Nawarangpur), Jeypore (Koraput), Nandapur (Koraput) & Th Rampur (Kalahandi) - 9 each, Purushottampur (Ganjam) & Lamataput (Koraput) - 8 each, Berhampur (Ganjam), Similiguda (Koraput), Rangeilunda (Ganjam), Ganjam (Ganjam), Pottangi (Koraput) & Dharakote (Ganjam) - 7 each. **Coastal A.P. & Yanam** Chintur (Alluri Sitharamaraju) - 21, Anakapalle (Anakapalli) - 13, Nuzvid (Eluru) - 10, Paderu (Alluri Sitharamaraju), Vararamachandrapur (Alluri Sitharamaraju) & Narsipatnam (Anakapalli) - 9 each, Araku Valley (Alluri Sitharamaraju) & Kukunoor (Eluru) – 8 each, Visakhapatnam Ap (Vishakhapatnam), Therlam (Vizianagaram), Bondapalle (Vizianagaram), Kurupam(Parvathipuram Manyam), Tekkali(Srikakulam), Kunavaram (Alluri Sitharamaraju) & Chodavaram (Anakapalli) – 7 each

	extremely heavy rainfall at isolated places on 19th July. Telangana & Vidarbha: Heavy to very heavy rainfall at a few places and extremely heavy rainfall at isolated places is very likely on 19th July. Heavy to extremely heavy rainfall at isolated places is very likely on 20th July.	**<u>Rayalaseema</u>** Rudravaram (Nandyal) & Dornipadu (Nandyal) – 7 each, **<u>Telangana</u>** Venkatapuram (Mulugu) – 8, Bayyaram (Mahabubabad), Julurpad (Kothagudem) & Manuguru (B. Kothagudem) – 7 each **<u>Chhattisgarh</u>** Bhairamgarh (Bijapur) - 25, Aundhi (Mohala Manpur Chowki), Durgkondal (Kanker) & Bhanupratappur (Kanker) - 17 each, Konta (Sukma), Sukma (Sukma) & Dornapal (Sukma) – 15 each, Gadiras (Sukma) - 14, Doundi (Balod), Tongpaal (Sukma), Kutaru (Bijapur), Chhindgarh (Sukma), Jagargunda (Sukma) & Nangur (Bastar) - 13 each, Antagarh (Kanker), Narayanpur (Narayanpur), Bijapur (Bijapur) & Lal Bahadur Nagar (Rajnandgaon) - 12 each, Kohkameta (Narayanpur), Gangalur (Bijapur), Bastanar (Bastar), Chhuria (Rajnandgaon) & Katekalyan (Dantewada) - 11 each, Kuakonda (Dantewada), Gidam (Dantewada), Manpur (Mohala Manpur Chowki), Gurur (Balod), Bhanpuri (Bastar) & Pakhanjur (Kanker) - 10 each, Kondagaon (Kondagaon), Darbha (Bastar), Chhotedongar (Narayanpur), Lohandiguda (Bastar), Dantewara (Dantewada), Orcha (Narayanpur), Balod (Balod), Khadgaon (Mohala Manpur Chowki), Bade Bacheli (Dantewada), Jagdalpur (Bastar), Dongargarh (Rajnandgaon) & Ambagarh Chowki (Mohala Manpur Chowki) - 9 each, Charama (Kanker), Usoor (Bijapur), Kukrel (Dhamtari), Baderajpur (Kondagaon), Mohla (Mohala Manpur Chowki), Dhanora (Kondagaon), Pharasgaon (Kondagaon) & Bastar (Bastar) - 8 each, Dongargaon (Rajnandgaon),
20.07.2024 / 0830	**Gangetic West Bengal**: Light to moderate rainfall is very likely at most places on 20th July. **Odisha**: ❖ **South Odisha**: Heavy to very heavy rainfall at a few places is very likely over South Odisha on 20th July ❖ **North Odisha**: Heavy rainfall at isolated places on 20th July. **Chattisgarh:** ❖ South Chattisgarh: Heavy to extremely heavy rainfall at isolated places is very likely on 20th and isolated heavy to very heavy rainfall on 21st July. ❖ North Chattisgarh: Heavy to very heavy rainfall at isolated places is very likely on 20th and isolated heavy rainfall on 21st July. **Andhra Pradesh**: ❖ **North Coastal Andhra Pradesh**: Heavy to very heavy rainfall at isolated places is very likely on 20th July and heavy rainfall at isolated places is likely on 21st July. ❖ **South Coastal Andhra Pradesh**: Heavy rainfall at isolated places is	

	likely over South Coastal Andhra Pradesh on 20th July. **Vidarbha**: Heavy to very heavy rainfall at a few places on 20th & 21st July and extremely heavy rainfall at isolated places on 20th July. **Telangana:** Heavy to very heavy rainfall at isolated places is very likely on 20th July and heavy rainfall at isolated places is likely on 21st July.	Makadi (Kondagaon), Kanker (Kanker), Barsur (Dantewada), Dondilohara (Balod) & Gundardehi (Balod) - 7 each **Vidharbha** Lakhandur (Bhandara) - 24, Pauni (Bhandara) - 20, Bramhapuri (Chandrapur) - 19, Arjuni Morgaon (Gondia) - 15, Desaiganj (Gadchiroli), Bhiwapur (Nagpur) - 14 each, Deori (Gondia), Armori (Gadchiroli), Nagbhir (Chandrapur) & Umrer (Nagpur) - 12 each, Kurkheda (Gadchiroli), Korchi (Gadchiroli), Chimur (Chandrapur) & Bhandara (Bhandara) - 11 each, Kuhi (Nagpur), Sakoli (Bhandara), Sindewahi (Chandrapur), Kamptee (Nagpur), Dhanora (Gadchiroli) & Lakhani (Bhandara) - 10 each, Bhamragad (Gadchiroli), Selu (Wardha), Nagpur Aerodrome (Nagpur), Agriculture College (Nagpur) & Nagpur (Nagpur) - 9 each, Gadchiroli (Gadchiroli), Sadakarjuni (Gondia) & Salekasa (Gondia) - 8 each, Mauda (Nagpur), Wardha (Wardha), Tirora (Gondia), Sakoli (Bhandara), Tiroda(Gondia), Saoli (Chandrapur), Samudrapur (Wardha), Hinganghat (Wardha), Etapalli (Gadchiroli) & Mul (Chandrapur) - 7 each, **21st July:** **Vidarbha:** Nagpur Aerodrome & Gadchiroli-16 each, Gadchiroli-15, Sindewahi & Chandrapr-14 each, Pombhurna, Perseoni, Hingna & Bhamragad-11 each, Bhadravati & Mauda-10 each, Chamorshi, Deoli, Kamptee, Warora, Samudrapur & Ramtek-9 each, Selu, Sironcha, Chimur, Armori, Wani, Saoner, Zarizamni, Tumsar & Wardha-8 each, Amgaon, Hinganghat, Maregaon,

		Umrer, Ralegaon & Kalmeshwar-7 each **Chhattisgarh:** Bijapur-21, Gurur-16, Kutaru & Rajnandgaon-14 each, Marri Bangla Deori, Arjunda, Gangalur & Balod-12 each, Gundardehi-11, Bhopalpatnam-10, Lal Bahadur Nagar, Bhairamgarh, Usoor, Dhamtari & Dongargarh-9 each, Nerharpur & Sarona-8 each, Dongargaon, Gidam, Bade Bacheli & Narayanpur-7 each **Telangana:** Mortad-14, Mallapur, Metpalle & Sarangapurnrl-13 each, Laxmanchanda, Khanpur & Balkonda-12 each, Kammar Palle, Navipet, Bheemgal, Makloor & Nandipet-11 each, Velpur, Ranjal, Armur, Yeda Palle, Jannaram & Nirmal-10 each, Kathlapur, Regonda, Shayampet, Nizamabad, Atmakurwrgl & Jainoor-9 each, Bodhan, Parkal, Aswapuram, Venkatapuram, Asifabad, Chityal, Huzurabad, Gangadhara, Dandepalle & Jaipur-8 each, Sirpuru, Kataram, Manuguru & Dummagudem-7 each **Odisha:** Athmalik-15, Boden-14, Padampur, Padmapur, Sinapali & Dunguripalli-11 each, Nawapara & Bolangir-10 each, Bangamunda-9, Salebhatta, Gania, Patnagarh, Binika, Kantamal, Agalpur & Ullunda-8 each, Tarva, Mathili, Khariar, Boudhgarh, Barpalli, Gaisilet, Chitrakunda K Guma, Khairamal, Jaipatna & Komna-7 each

2.3.7. Damage due to the system

No damage was reported in association with this system.

2.4 Life History of Deep Depression over North Jharkhand during 2nd – 6th August, 2024

2.4.1 Introduction

- An upper air cyclonic circulation lay over Jharkhand & neighbourhood between 3.1 & 7.6 km above mean sea level tilting southwards with height in the morning (0830 hours IST / 0300 UTC) of 30th July, 2024. It lay as an upper air cyclonic circulation over Gangetic West Bengal and neighbourhood in the morning (0830 hours IST / 0300 UTC) of 31st July, 2024. It lay over Gangetic West Bengal and south Bangladesh in the morning (0830 hours IST / 0300 UTC) of 1st August, 2024.
- Under its influence, a low pressure area formed over Gangetic West Bengal and adjoining Jharkhand in the early morning (0530 hours IST / 0000 UTC) of 2nd August, 2024.
- It moved west-northwestwards and concentrated into a depression over North Jharkhand and neighbourhood in the same evening (1730 hours IST / 1200 UTC) of the 2nd August, 2024.
- Continuing to move west-northwestwards, it intensified into a deep depression over Southwest Bihar and adjoining Northwest Jharkhand in the morning (0830 hours IST / 0300 UTC) of 3rd August, 2024.
- Further moving west-northwestwards, it weakened into a depression over Northeast Rajasthan and neighbourhood in the morning (0530 hours IST / 0000 UTC) of 5th August, 2024, into a Well Marked Low Pressure area over Central parts of Pakistan & neighbourhood in the early morning (0530 hours IST / 0000 UTC) of 6th August, 2024 and into a low pressure area over central parts of Pakistan in the morning (0830 hours IST / 0300 UTC) of 6th August, 2024.
- Observed track of Deep Depression during 2nd – 6th August is presented in **Fig. 2.4.1.** The best track parameters of the system are presented in **Table 2.4.1**.

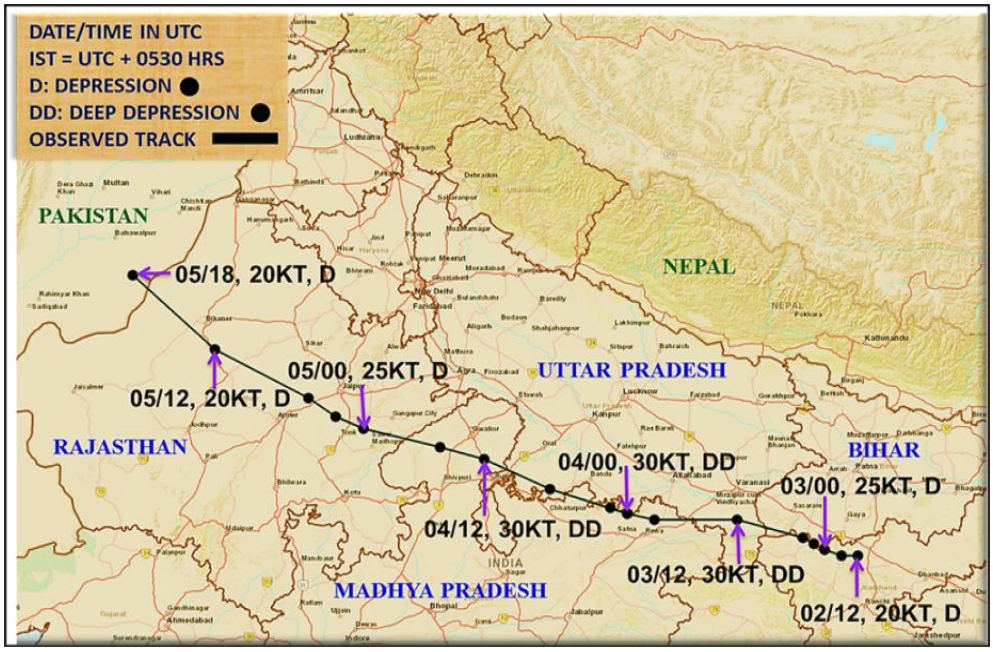


Fig. 2.4.1: Observed track of the Deep Depression over North Jharkhand & neighbourhood during 02nd – 06th August, 2024

Table 2.4.1: Best track positions and other parameters of the Deep Depression over North Jharkhand and neighbourhood during 02nd – 06th August, 2024

Date	Time (UTC)	Lat. (°N)	Long. (°E)	CI No.	ECP (hPa)	MSW (kt)	∆P (hPa)	Category
02.08.24	1200	24.2	85.2	-	992	20	3	D
	1800	24.2	84.9	-	992	20	3	D
03.08.24	0000	24.3	84.6	-	991	25	4	D
	0300	24.4	84.4	-	990	30	5	DD
	0600	24.5	84.2	-	988	30	6	DD
	1200	24.8	83.0	-	988	30	6	DD
	1800	24.8	81.5	-	990	30	6	DD
04.08.24	0000	24.9	81.0	-	990	30	6	DD
	0300	25.0	80.7	-	991	30	5	DD
	0600	25.3	79.6	-	992	30	5	DD
	1200	25.8	78.4	-	992	30	5	DD
	1800	26.0	77.6	-	992	30	5	DD
05.08.24	0000	26.3	76.2	-	993	25	4	D
	0300	26.5	75.6	-	993	25	4	D
	0600	26.8	75.2	-	994	25	3	D
	1200	27.6	73.5	-	994	20	3	D
	1800	28.8	72.0	-	996	20	3	D
06.08.24	0000	Weakened into a Well-Marked Low-Pressure area over central parts of Pakistan and adjoining northwest Rajasthan.						

KT: Knots (nautical mile per hour), 1 KT=1.85 kmph, D: Depression, DD: Deep Depression, ECP: Estimated Central Pressure (hPa), MSW: Estimated Maximum Sustained Surface Wind (kt), ∆P: Estimated Pressure drop at the Centre (hPa)

2.4.2 Monitoring

India Meteorological Department (IMD) maintained round the clock watch over the north Indian Ocean (NIO) and the system was monitored well in advance since 31st July. The system was monitored with the help of available satellite observations from INSAT 3D and 3DR, polar orbiting satellites, available ships & buoy observations in the region and coastal observations on the day of landfall. 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 system. A digitized forecasting system of IMD was utilized for analysis and comparison of various models' guidance, decision making process and warning products generation.

2.4.2.1 Features observed through satellite

Satellite monitoring of the system was mainly done by using half hourly INSAT-3D and 3DR imageries. Satellite imageries of other international geostationary satellites, high resolution polar orbiting satellites and scatterometer imageries from ASCAT were also considered for monitoring of the system. Typical INSAT-3DR enhanced colored imageries, visible/ IR, brightness temperature and water vapour imageries are presented in **Fig.2.4.2 (a) to 2.4.2 (c)**. During the entire life cycle, the clouds were organised in shear pattern.

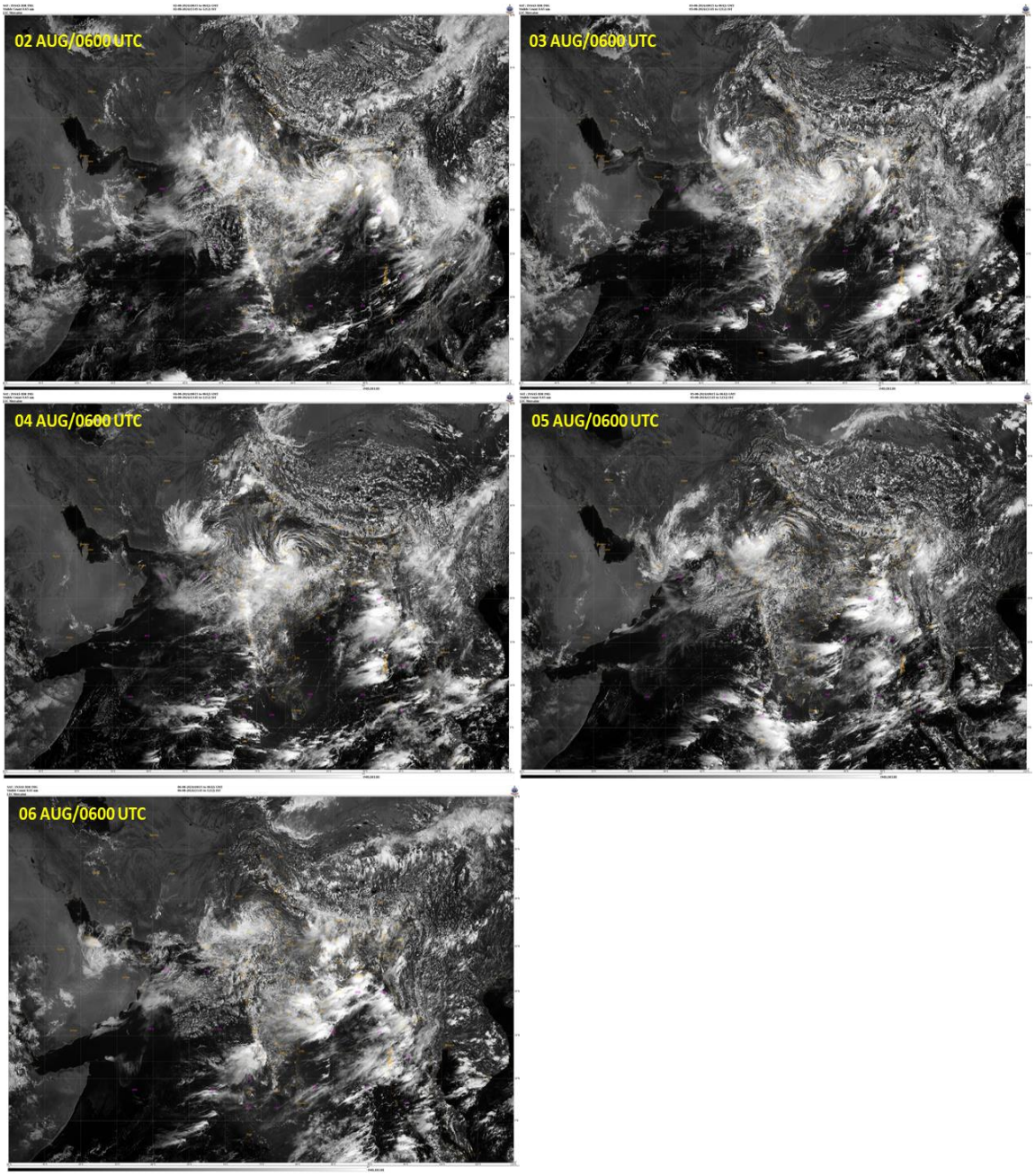


Fig.2.4.2 (a): INSAT-3DR IR imageries during life cycle of Deep Depression over North Jharkhand and neighbourhood during 2nd Aug - 6th Aug, 2024

At 1200 UTC of 2nd August, According to INSAT 3DR imagery at 1200 UTC, low level cloud over Jharkhand adjoining Gangetic west Bengal & neighbourhood intensified into a vortex

and lay over Jharkhand & neighbourhood. Associated broken low & medium clouds with embedded intense to very intense convection lay over Jharkhand adjoining North Orissa, North Chhattisgarh, and South Bihar, Gangetic west Bengal. Minimum cloud top temperature (CTT) minus 93 degree Celsius.

At 0300 UTC of 3rd August, According to INSAT 3DR imagery at 0300 UTC, Vortex lay over northwest Jharkhand & neighbourhood. Associated broken low & medium clouds with embedded intense to very intense convection lay over Jharkhand, southwest Bihar adjoining Southeast Uttar Pradesh, Chhattisgarh, East Madhya Pradesh and Northwest Orissa. Minimum CTT minus 93 degree Celsius.

At 1200 UTC of 3rd August, According to INSAT 3DR imagery at 1200 UTC, Vortex lay over Southeast Uttar Pradesh adjoining Northeast Madhya Pradesh, Chhattisgarh & neighbourhood. Associated scattered to broken low & medium clouds with embedded intense to very intense convection lay over South Uttar Pradesh, East Madhya Pradesh and Chhattisgarh (Minimum CTT minus 93 degree Celsius) & moderate to intense convection lay over West Bihar, West Jharkhand, West Orissa and South Chhattisgarh.

At 0300 UTC of 4th August, According to INSAT 3DR imagery at 0300 UTC, Vortex lay over Northeast Madhya Pradesh & neighbourhood. Associated scattered to broken low & medium clouds with embedded intense to very intense convection lay over Southeast Rajasthan, Madhya Pradesh and Maharashtra(Minimum CTT minus 80-93 degree Celsius) & moderate to intense convection lay over South Uttar Pradesh and Chhattisgarh.

At 1200 UTC of 4th August, According to INSAT 3DR imagery at 1200 UTC, Vortex lay over North Madhya Pradesh adjoining South Uttar Pradesh. Associated scattered to broken low & medium clouds with embedded intense to very intense convection lay over Southeast Rajasthan, Madhya Pradesh, East Gujarat (Minimum CTT minus 80-90 degree Celsius) & moderate to intense convection lay over South Uttar Pradesh and Maharashtra.

At 0300 UTC of 5th August, According to INSAT 3DR imagery at 0300 UTC, Vortex lay over Northeast Rajasthan adjoining Northwest Madhya Pradesh & neighbourhood. Associated low & medium clouds with embedded intense to very intense convection lay over Rajasthan adjoining North Gujarat, West Madhya Pradesh (Minimum CTT minus 80-93 degree Celsius.

At 1200 UTC of 5th August, According to INSAT 3DR imagery at 1200 UTC, Vortex lay over North-Central Rajasthan & neighbourhood. Associated broken low & medium clouds with embedded intense to very intense convection lay over Southwest Rajasthan (Minimum CTT minus 80-93 degree Celsius) and Moderate to intense convection lay over North Gujarat (Minimum cloud top temperature minus 50-60 degree Celsius).

At 0300 UTC of 6th August, According to INSAT 3DR imagery at 0300 UTC, Vortex lay over Pakistan adjoining Northwest Rajasthan. Associated scattered low & medium clouds with embedded moderate to intense convection lay over Southwest Rajasthan & South Pakistan (Minimum CTT minus 70 degree Celsius.

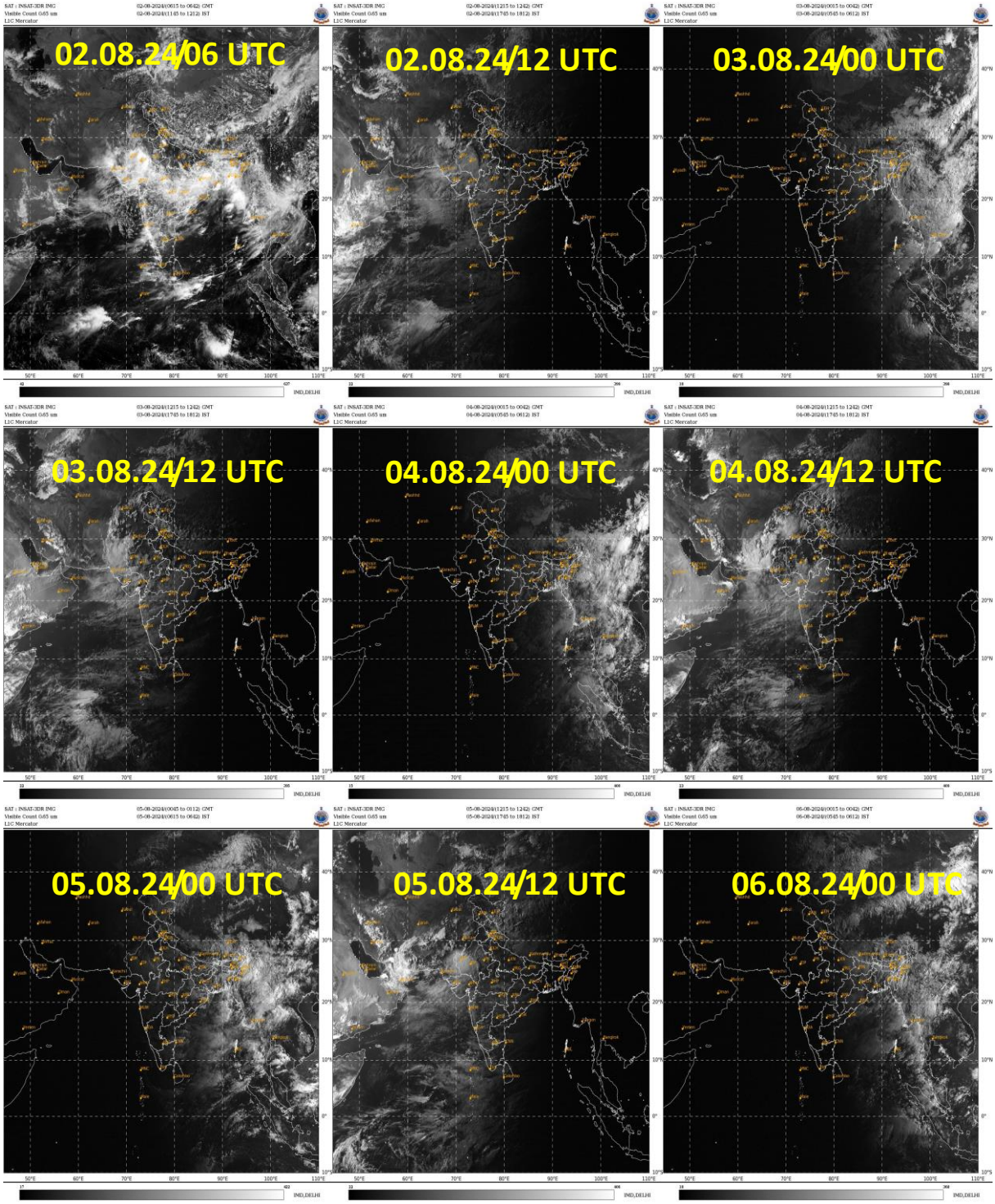


Fig.2.4.2 (b): INSAT-3DR Visible imageries during life cycle of Deep Depression over North Jharkhand and neighbourhood during 2nd Aug-6th Aug, 2024

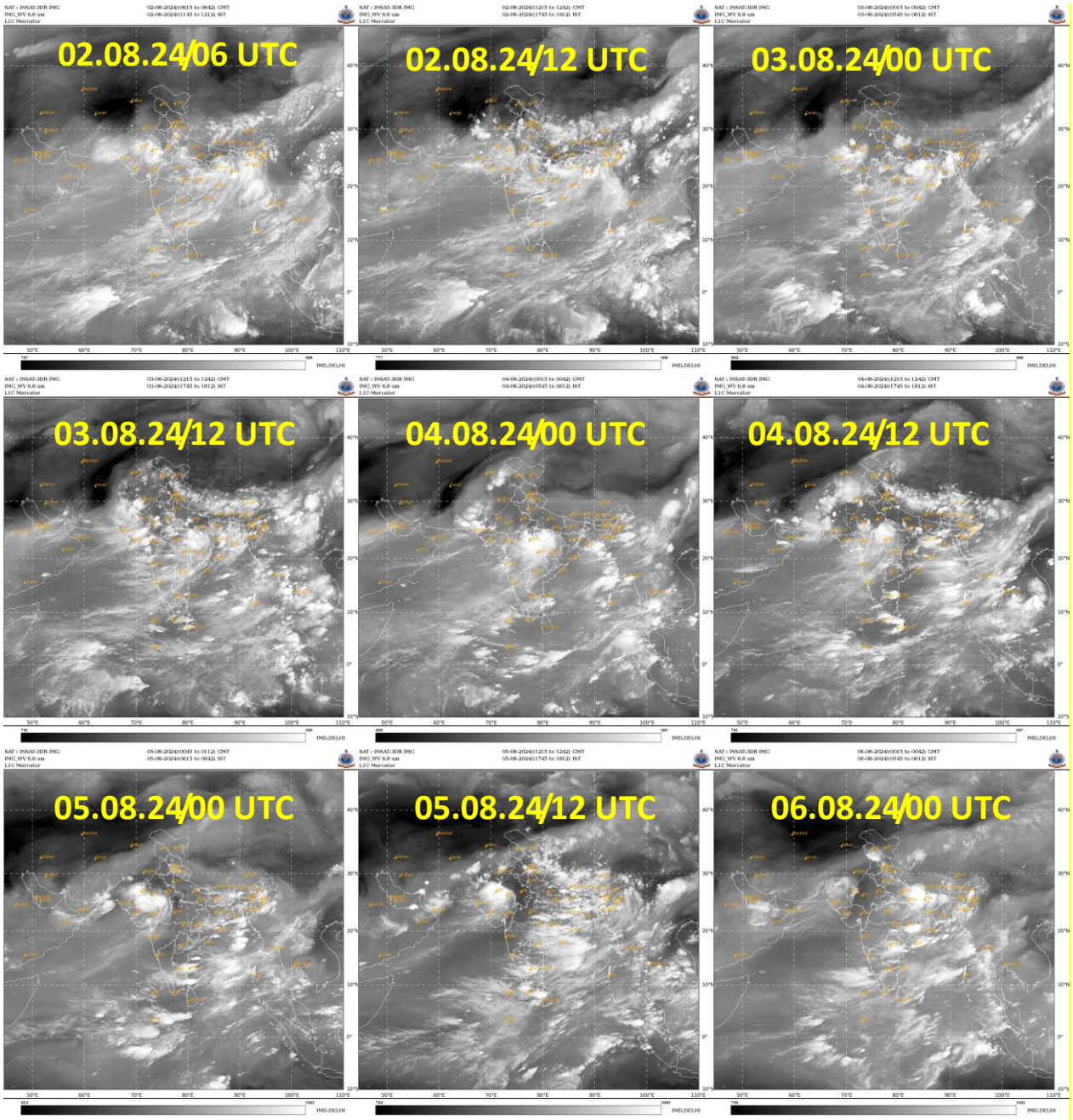


Fig.2.4.2 (c): INSAT-3DR water vapour imageries during life cycle of Deep Depression over North Jharkhand and neighbourhood during 2nd Aug-6th Aug, 2024

2.4.3 Dynamical Features

IMD GFS (T1534) daily analyses of mean sea level pressure (MSLP), winds at 10 m, 850, 500 and 200 hPa levels valid at 0000 UTC of everyday from 2nd August to 6th August are presented in **Fig. 2.4.3(a) to 2.4.3(e)** respectively. The figures are representing the evolution of the low pressure system in terms of location, size, intensity, horizontal and vertical structure of the system with time. The figures are also illustrating the circulation features of the large-scale environment associated with the system and also its role it the movement of the system with time.

The MSLP analysis field in the top-left panel of Fig. 2.4.3(a) indicated a well-marked low pressure area over Gangetic West Bengal and neighbourhood with only one closed isobar at 0000 UTC of 2nd August. Therefore, the intensity of the system was underestimated in the model MSLP field. The associated cyclonic circulations were visible in every starting from 10 m above surface extending up to 500 hPa pressure level [other panels of Fig. 2.4.3(a)]. As the model could not capture the intensity, comparatively weaker spatial winds around the system center were noticed. The upper level outflow at the top was embedded within northeasterly monsoon winds.

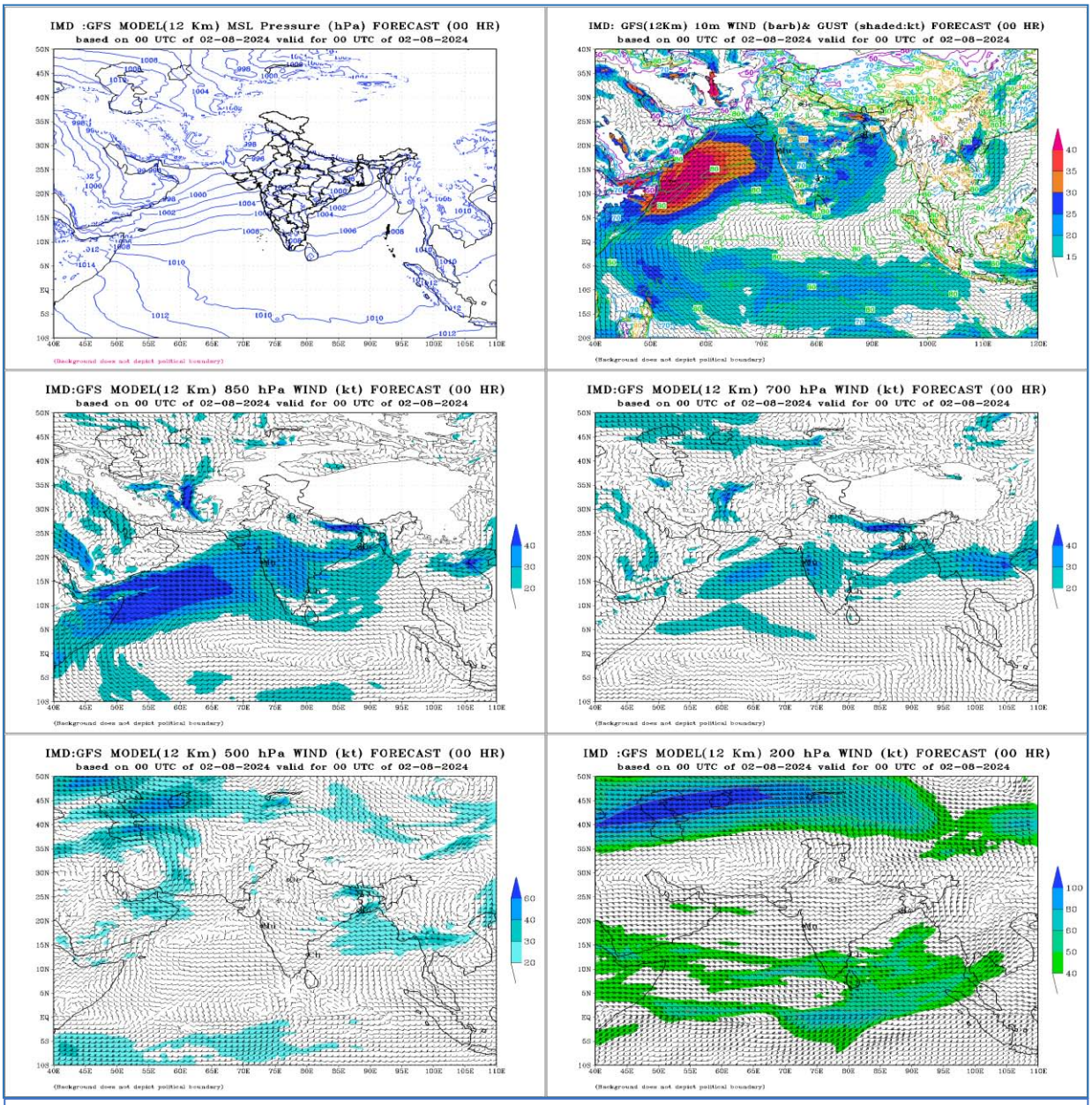


Fig.2.4.3(a): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850,500&200 hPa levels based on 0000 UTC of 2nd August, 2024

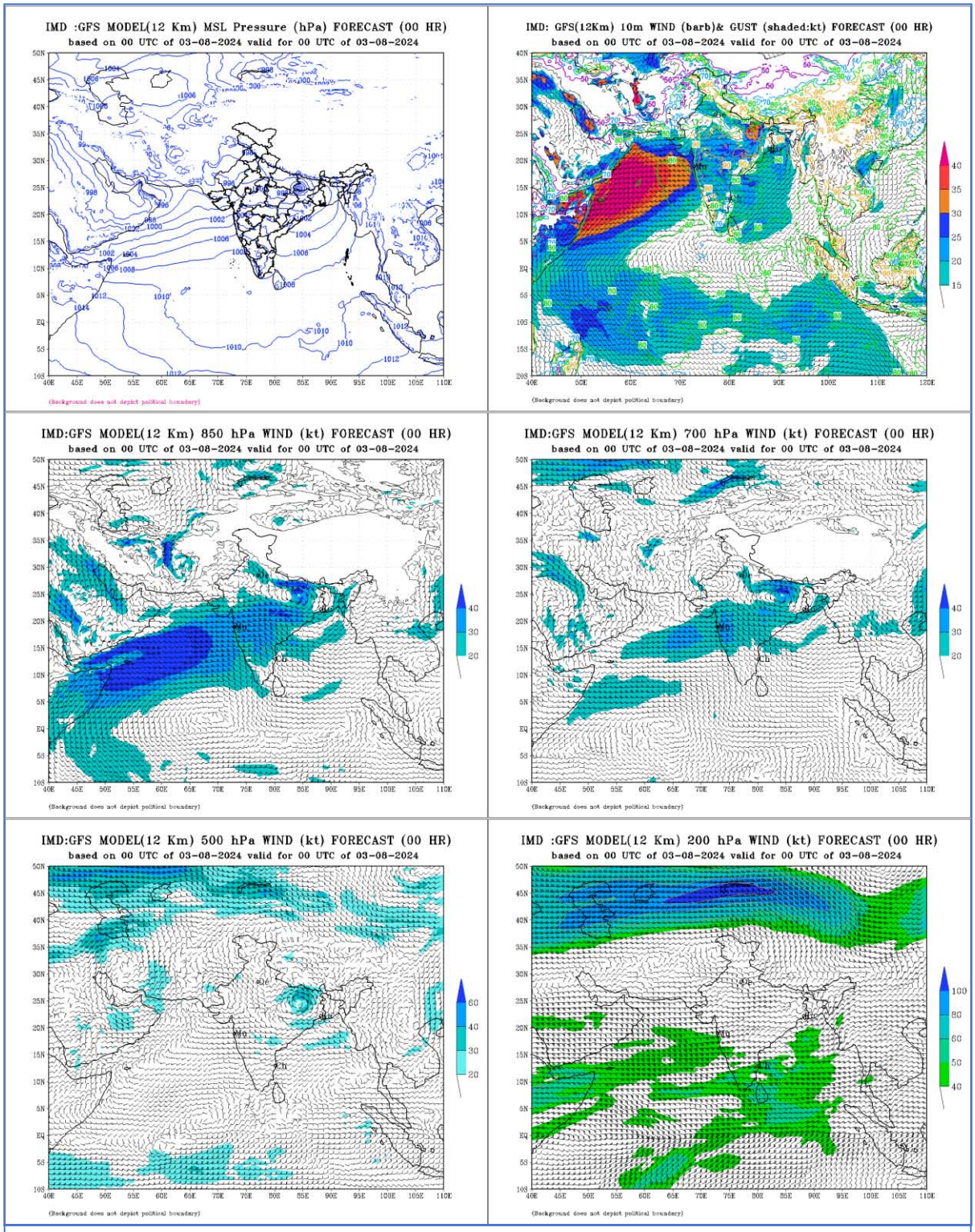


Fig. 2.4.3(b): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 3rd August, 2024

In the Fig. 2.4.3(b), the MSLP analysis field at 0000 UTC of 3rd August, indicated a system with more than 3 closed isobars representing an intensity stronger than a deep depression over Gangetic West Bengal and adjoining areas. The 10 m winds also indicated strong surface winds near the system center. Accordingly, the intensity of the system was well captured at this stage. Associated cyclonic circulations were well-established at every pressure level of the atmosphere extending up to 500 hPa. The spatial structure of the

system was fairly symmetric with a little modulation by the orientation of the monsoon trough. The outflow of the system was merged with the upper-level east-northeasterly winds of monsoon at 200 hPa. However, the wind exactly near the system center was easterly which regulated the westward movement.

The MSLP and 10 m wind analyses in the top two panels of the Fig. 2.4.3(c) defined the location of the system at a location near the border area of east Madhya Pradesh and Uttar Pradesh at 0000 UTC of 4th August, 2024.

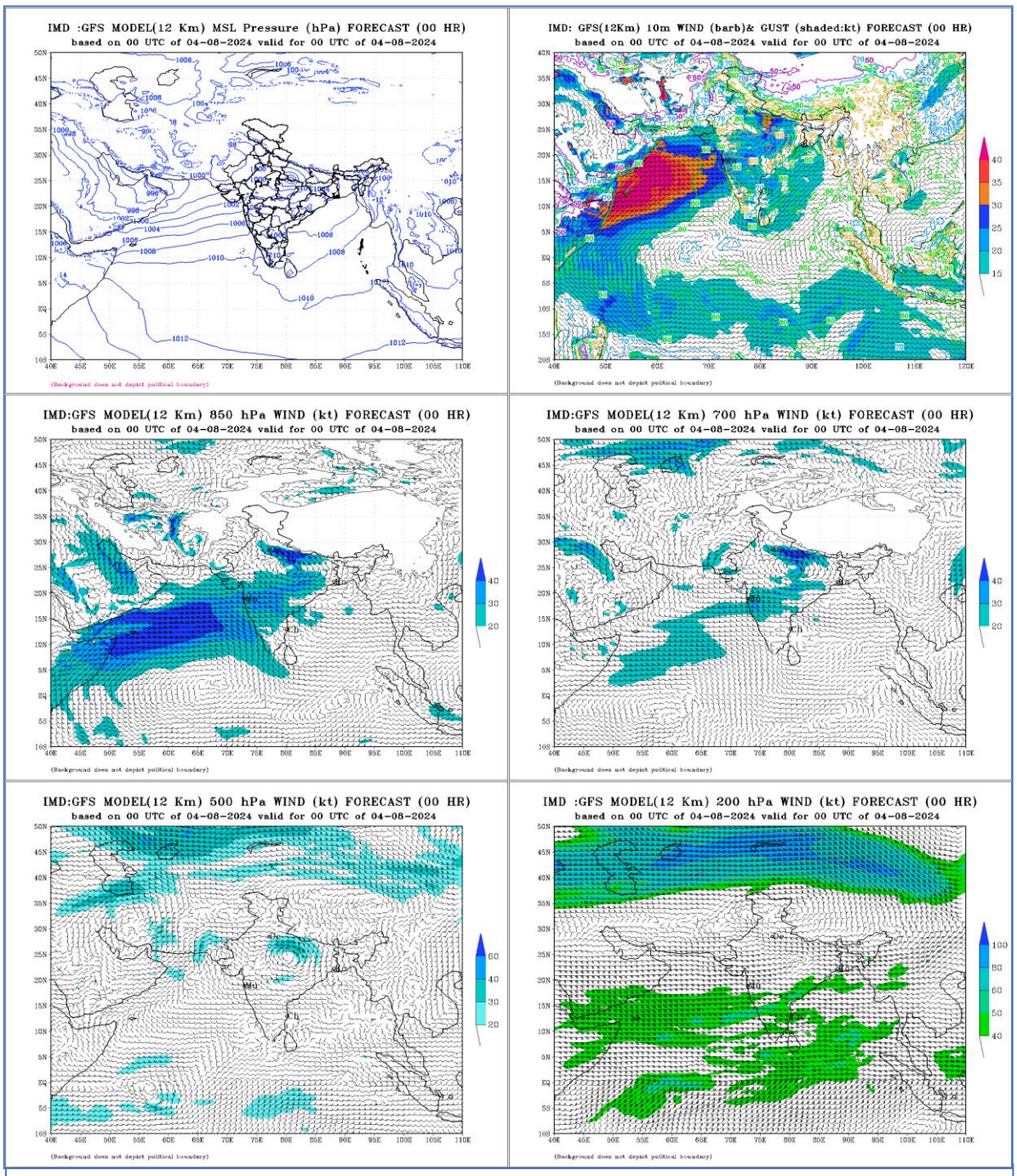


Fig. 2.4.3(c): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 4th August, 2024

The intensity of the deep depression was also captured well by the surface analyses. Although the upper-level cyclonic circulations at every level had two distinct regions of strong

winds situated at both north and south sectors, the winds of the northern sectors were comparatively stronger than other. The uppe-level winds structure at 200 hPa shifted the location of outflow along with the system but still with easterlies at the top.

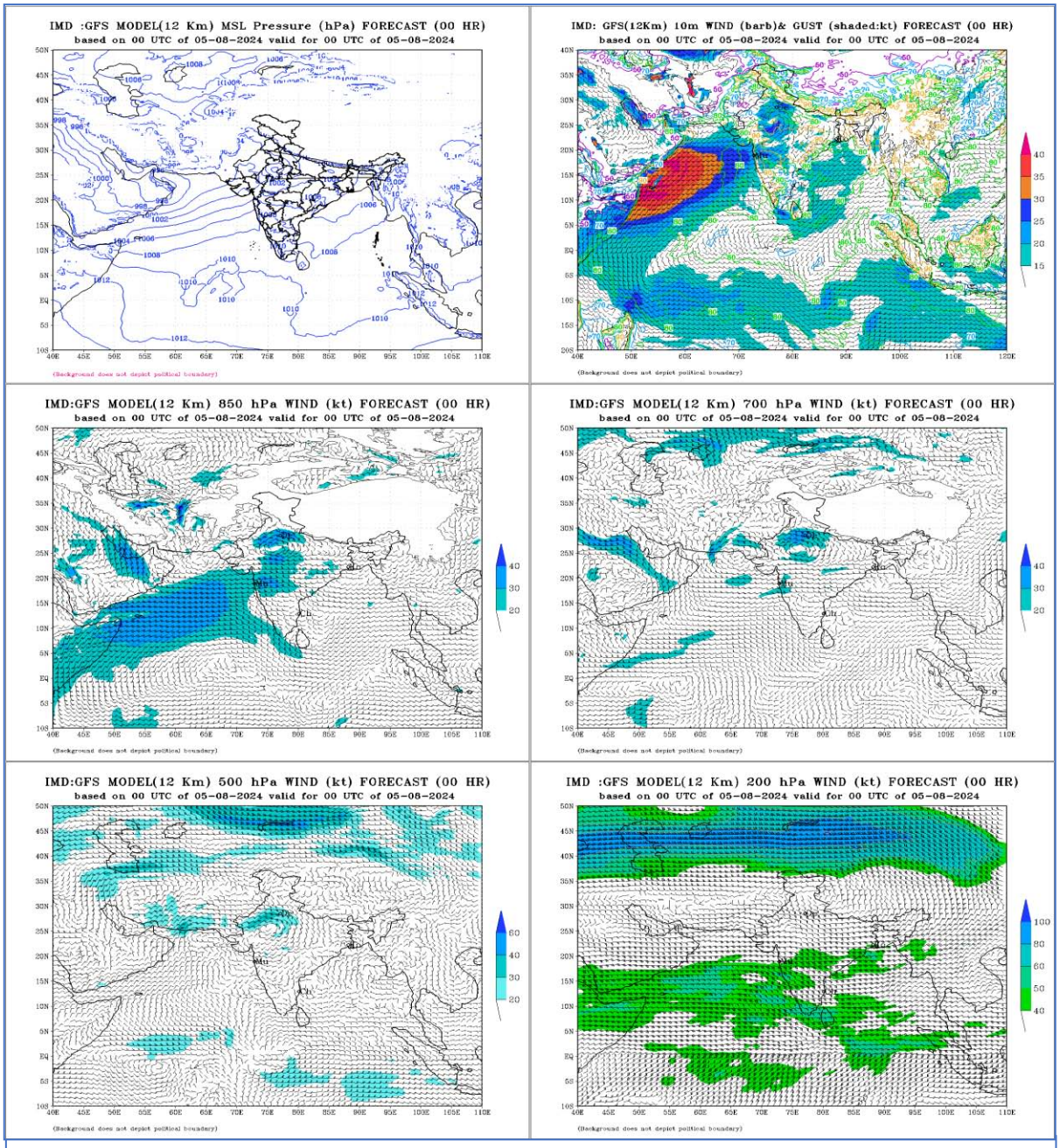


Fig. 2.4.3(d): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 5th August, 2024

In the Fig. 2.4.3(d), the surface MSLP and 10 m wind analyses indicated westward movement of the system along with a marginal weakening with a reduced number (2) of closed isobars. The system was located over east Rajasthan as a depression at 0000 UTC of 5th August. The weakening was also produced well by the model analyses. Eventually associated cyclonic circulations from the surface extending vertically up to 500 hPa pressure level represented the reducing area of strong winds. But the horizontal structure still portrayed an east-west elongation along the monsoon trough. A prominent reduction in the

upper-level outflow was noticed at 200 hPa as it was completely unnoticeable over environmental easterlies.

The Fig. 2.4.3(e) indicated model analyses at 0000 UTC of 6th August, 2024. The MSLP and 10 m winds indicated further weakening of the system. It moved westward located over northwest Rajasthan without any closed isobar. However, upper-level associated cyclonic circulations at different pressure levels could be distinguished with clear vertical extension up to 500 hPa with a southward tilt with height. In the upper-tropospheric level at 200 hPa, the system could not be marked.

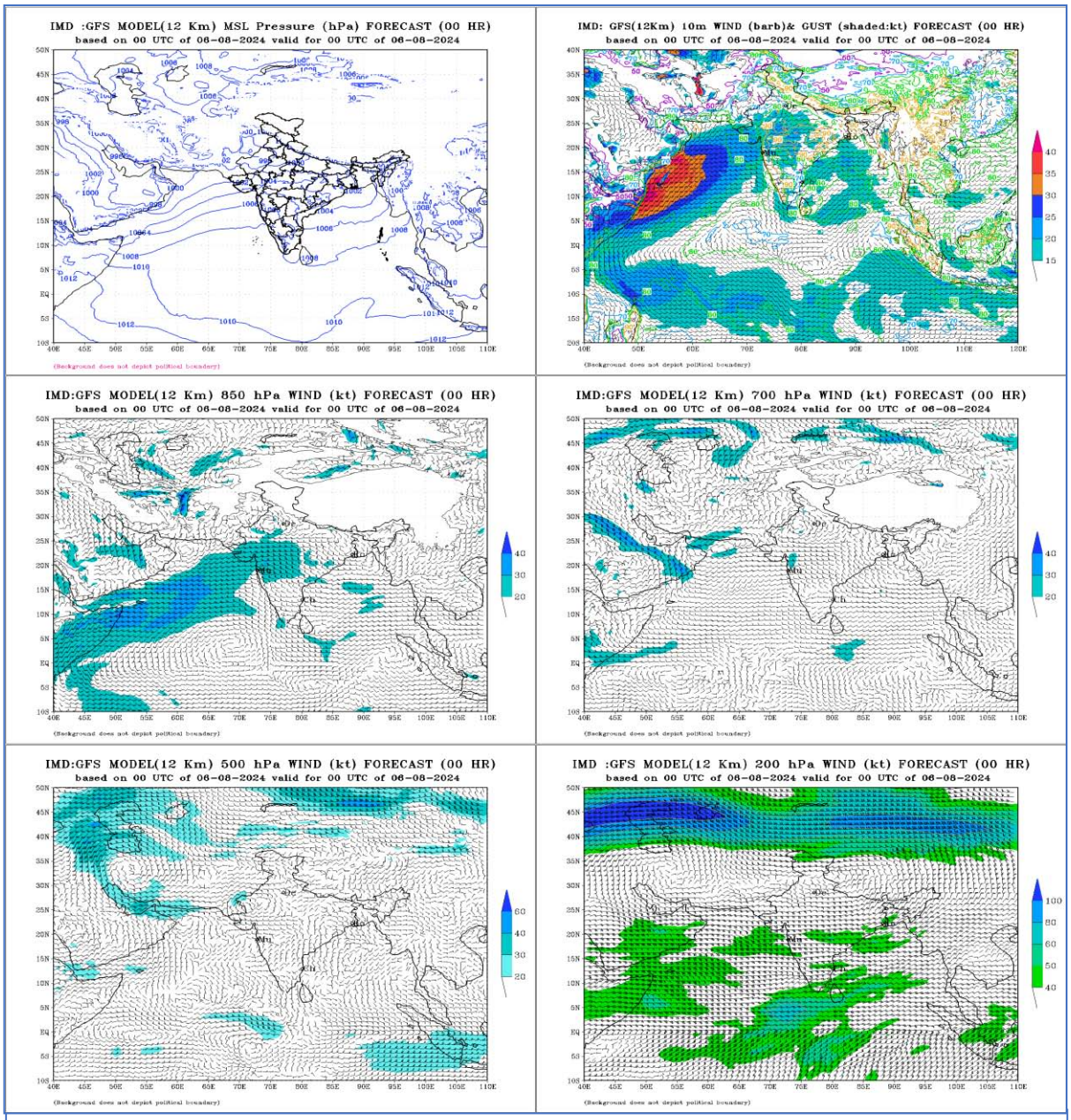


Fig. 2.4.3(e): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 6th August, 2024

2.4.4 Realized Weather

Rainfall associated with the deep depression based on IMD-NCMRWF satellite gauge merged data are depicted in Fig 2.4.4. It is seen that light to moderate rainfall occurred at

many places over Jharkhand, Chattisgarh; at a few places over Gangetic West Bengal, Madhya Pradesh on 2nd August. Light to moderate rainfall occurred at most places with extremely heavy rainfall at isolated places over Jharkhand with heavy to very heavy rainfall at isolated places over East Rajasthan and Chattisgarh with heavy rainfall at isolated places over Gangetic West Bengal, Bihar, Sub Himalayan West Bengal and Madhya Pradesh on 2nd August.

Light to moderate rainfall occurred at most places with extremely heavy rainfall at isolated places over Madhya Pradesh, Konkan & Goa, Madhya Maharashtra and Chhattisgarh with heavy to very heavy rainfall at isolated places over Gujarat region and heavy rainfall at isolated places over Rajasthan, Jharkhand, Bihar and East Uttar Pradesh on 3rd August.

Light to moderate rainfall occurred at most places with extremely heavy rainfall at isolated places over Rajasthan, Gujarat region with heavy to very heavy rainfall at isolated places over Madhya Maharashtra Madhya Pradesh, Konkan & Goa on 4rd August.

Light to moderate rainfall occurred at many places with extremely heavy rainfall at isolated places over West Rajasthan with heavy to very heavy rainfall at isolated places over East Rajasthan & heavy rainfall at isolated places over Madhya Maharashtra on 5th August.

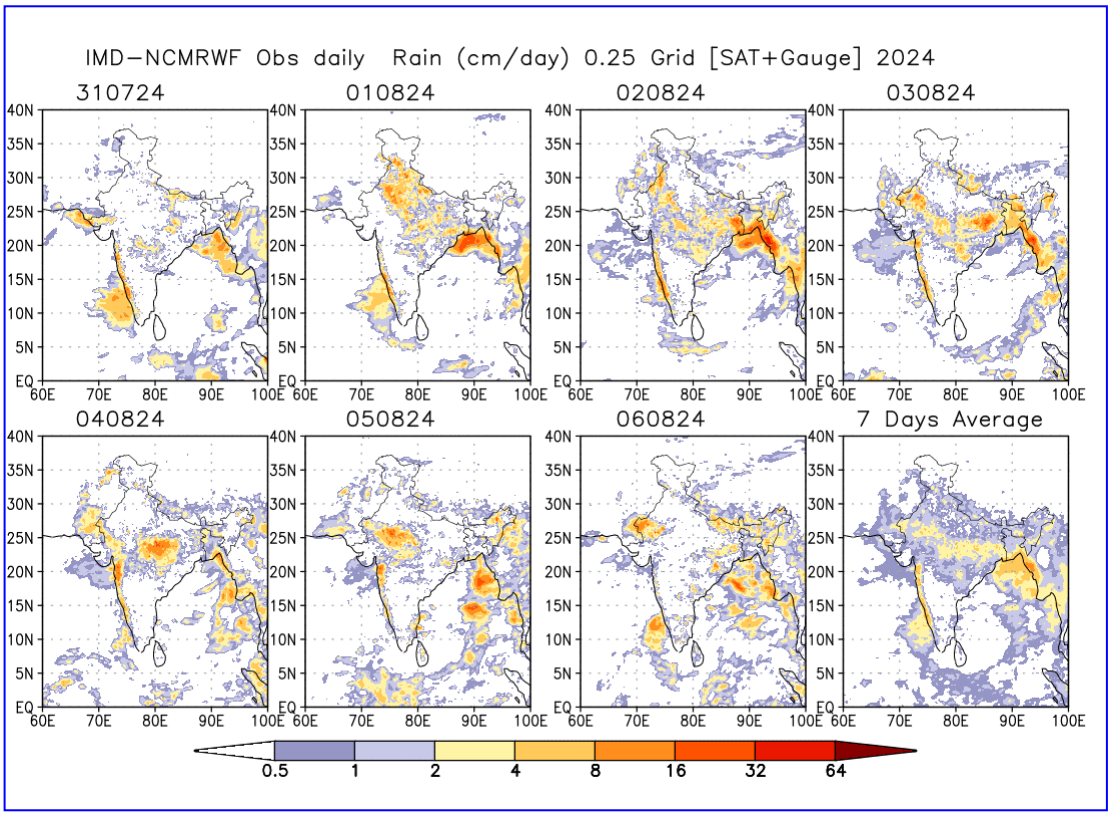


Fig. 2.4.4: NCMRWF-IMD satellite gauge merged data plots of realized 24 hours accumulated rainfall from 31st July to 06th August, 2024. **(cm/day)**

2.4.5 Rainfall forecast verification

The forecast for heavy to extremely heavy rainfall episodes in association with the system are verified with the 24 hours accumulated rainfall realized at various stations. The details of the day-wise verification are given in Table -2.4.2.

Table 2.4.2: Day wise daily 24 hours cumulative rainfall forecast verification with station observations

Date/Base time of observation	24 hours Heavy rainfall warning ending at 0300 UTC of date	Realized 24 hour heavy rainfall (≥7 cm) ending at 0300 UTC of date
02.08.2024/ 0300	**West Bengal**: Heavy to extremely heavy rainfall at isolated places over Sub-Himalayan West Bengal during 3rd to 6th; heavy to very heavy rainfall at isolated places over Gangetic West Bengal on 2nd August. **Jharkhand:** Heavy to extremely heavy rainfall at isolated places on 2nd ; heavy rainfall at isolated places on 3rd August. **Bihar:** Heavy to extremely heavy rainfall at isolated places on 2nd; heavy to very heavy rainfall at isolated during 3rd to 6th August. **Chhattisgarh:** Heavy to extremely heavy rainfall at isolated places on 2nd; heavy to very heavy rainfall at isolated places on 3rd August. **East Madhya Pradesh:** Heavy to very heavy rainfall at isolated places during 2nd -4th and extremely heavy rainfall at isolated on 2nd and 3rd August. **West Madhya Pradesh:** Heavy to very heavy rainfall at isolated places during 2nd -5th and extremely heavy rainfall at isolated on 3rd and 4th August. **East Uttar Pradesh:** Heavy rainfall at isolated places during 2nd -6th August. **East Rajasthan**: Heavy rainfall at isolated places during 2nd -6th; very heavy rainfall at isolated places on 2nd and 3rd and extremely heavy rainfall on 4th August.	**02.08.2024** **Gangetic West Bengal** Dum Dum 10, Mo Saltlake, Diamond Harbour, Burnpur & Asansol– 8 each, Rajnagar 7 **Sub Himalayan West Bengal** Buxaduar 7 **Bihar** Puraini 11, Sherghati 9, Dobhi & Imamganj 8, Udai Kishanganj, Kumarkhand, Barachatti, Banka, Rajauli , Chausa & Deo – 7 each **Jharkhand** Mandu & Ramgarh 27, Bau Kanke 26, Purvi Tundi 24, Hendigir 21, Koner 19, Bokaro Thermal, Ranchi Aero & Ormanjhi – 17 each, Papunki & Ramgarh – 16 each, Icar Namkum 15, Rajdhanwar & Balumath – 14 each, Putki , Barkisuriya , Bhurkunda , Tenughat , Maithon & Mandu Dvc – 13 each, Gobindpur , Tilaiya , Giridih , Bandgaon (West Singbhum), Sisai & Jamtara Fmo – 12 each, Kuru , Dumri , Panchet , Tundi, Diyakel Khunti , Chandwa & Raidih – 11 each, Dhurki , Daltonganj & Rajmahal – 10 each, Murhu , Lesliganj , Markachou , Torpa , Maharo , Latehar , Palamu Dtg , Bharno , Koderma , Latehar Balumat & Patratu – 9 each, Ramgarh(bdo) , Rania , Messenjor , Nawa Bazar , Arki , Nandadih , Mohanpur & Garu – 8 each, Barkagaon , Gola , Simdega & Amrapara – 7 each **East Rajasthan** Masuda Sr 18, Nayanagar/beawar & Pisagan Sr – 17 each, Mangliawas Sr &

		Bhim – 15 each, Tatgarh Sr 13, Deogarh 10, Mounntabu Tehsil Sr & Begu – 9 each, Pushkar 8, Raipur , Hurda , Mounnt Abu & Sangod – 7 each **Chhattisgarh** Shankarh 21, Kusmi 18, Rajpur 16, Odagi 13, Ramanujganj , Pratappur , Samari & Chando – 12 each, Raghunath Nagar 11, Bhanupratappur , Balrampur , Wandrafnagar & Doura Kochali – 10 each, Bhatgaon , Kelhari , Janakpur Bharatpur & Chalgali – 9 each, Durg , Biharpur , Kutaru , Bhairamgarh , Sonhat & Durgkondal – 8 each, Kotadol , Manora , Latori , Bhaiyathan , Pakhanjur , Kunkuri & Lundra – 7 each **East Madhya Pradesh** Amarpatan, Ramnagar & Matiyari – 9 each, Jaisingh Nagar 8, Barhi , Khurai , Venkatnagar , Sarai , Nagode & Jaitpur – 7 each **West Madhya Pradesh** Biaora 12, Sultanpur & Harda – 11 each, Raisen 9, Gairatgang & Bareli – 8 each, Sehore- , Udaipura , Badi , Shamshabad , Berasia & Ganjbasoda – 7 each
03.08.2024/ 0300	**Jharkhand:** Heavy to very heavy rainfall at a few places is very likely on 3rd and isolated extremely heavy rainfall is also very likely over Northwest Jharkhand on 3rd ; heavy rainfall at isolated places on 4th August. **Bihar:** Light to moderate rainfall at most places with heavy to very heavy rainfall at isolated places over Bihar on 3rd and 6th, heavy rainfall at isolated places on 4th & 5th August. **Chhattisgarh:** Heavy to very heavy rainfall at a few places and extremely heavy rainfall at isolated places also over north Chhattisgarh is very likely	**03.08.2024** **Madhya Pradesh**:-Katni -24, Badwara 20, Garhakota 19, Ramnagar & Sihora 19 each, Vijayraghavgarh, Majholi, Singodi & Jaisinagar 18 each, Devsar & Tendukheda 17 each, Maihar, Barhi , Bilharli, Deemarkheda, Umariyapan, Beohari & Bichhiya 16 each, Mada, Patan & Shahpura – 15 each **Konkan & Goa**: Matheran 29, Thane 15, Karjat & Talasari 13 each, Murbad & Ulhasnagar 12 each, Khalapur, Kalyan & Bhiwandi 11 each, Mokheda,

	on 3rd August. **East Madhya Pradesh**: Heavy to very heavy rainfall at isolated places is very likely on 3rd & 4th and extremely heavy rainfall at isolated places is also very likely on 3rd August. **West Madhya Pradesh**: Heavy to very heavy rainfall at isolated places is very likely during 3rd to 5th and extremely heavy rainfall at isolated places is also very likely on 3rd and 4th August. **East Uttar Pradesh**: Heavy to very heavy rainfall at a few places and extremely heavy rainfall at isolated places over southeast Uttar Pradesh is very likely on 3rd and 4th August. **West Uttar Pradesh**: Heavy to very heavy rainfall at isolated places is very likely on 3rd and isolated heavy on 4th. **East Rajasthan**: Heavy rainfall at isolated places is very likely during 3rd to 6th; very heavy rainfall at isolated places on 3rd and extremely heavy rainfall is very likely on 4th August. **West Rajasthan**: Heavy to very heavy rainfall at isolated places is very likely during 3rd, 5th and 6th and heavy rainfall at isolated places on 4th August. **Gujarat region**: Heavy to very heavy rainfall at isolated on 3rdand 4th and extremely heavy rainfall at isolated places on 3rd. Saurashtra & Kutch. Heavy to very heavy rainfall at isolated on 3rd and heavy rainfall on 4th |August. **West Bengal**: Heavy to very heavy rainfall at isolated places is very likely over Sub-Himalayan West Bengal during 3rd to 6th August. Heavy rainfall is very likely over Gangetic West Bengal on 3rd August.	Jawhar, Panvel_agri & Santacruz Imd Obsy 10 each, Wada, Poladpur & TbiaImd Part Time 9 each, Ambernath, Vikramgad, Shahapur & Canacona 8 each, Mangaon, Mahad, Quepem, Pen & Uran 7 each **Madhya Maharashtra**: Igatpuri & Lonavala_agri 24 each, Surgana 17, Trimbakshwar 16, Mahabaleshwar- 14, Akole & Ozharkheda 13 each, Harsul 12, Velhe & Peth 11 each, Nashik Imd Obsy, Chandgad , Shahuwadi & Vani 7 each. **Chhattisgarh**: Janakpur Bharatpur 23, Wandrafnagar 17, Doura Kochali 15, Ramanujganj & Biharpur 13 each, Kotadol & Bhatgaon 11 each, Kukdur 10, Balrampur, Raghunath Nagar, Ramchandrapur & Rajpur 8 each, Odagi, Chalgali, Belgahna & Ramanujnagar 7 each. **Gujarat Region**: Vansda 18, Waghai 16, Nanipalson 14,Dharampur 14, Kaprada 14, Dolvan & Dang 13 each, Silvassa, Khergam & Vapi 12 each, Khanvel, Dholka, Songadh & Valsad 11 each, Chikhli, Umerpada, Subir & Madhbun 10 each, Mahuva, Valod , Godra, Godhra & Gandevi 9 each, Padra & Vyara 8 each, Pardi, Vijaynagar, Sagbara & Dhanera 7 each **East Rajasthan**: Arai 10, Kekri 9, Nithuwa & MounntAbu 7 each; **West Rajasthan**: Gudamalani 9, Sum 8, Raniwada, Ramsar & Bagoda 7 each **Jharkhand:** Messenjor 9, Daltonganj & Dhurki 7 each **Bihar**: Mansahi & Amdabad 9 each, Katihar 7 **East Uttar Pradesh**: Dudhi 6,

		Prayagraj & Churk 5 each,
04.08.2024/ 0300	**East Madhya Pradesh**: Heavy to very heavy rainfall at a few places during 4th-6th August. **West Madhya Pradesh**: Heavy to very heavy rainfall at a few places during 4th-6th August with extremely heavy rainfall at isolated places is very likely on 4th August. **East Uttar Pradesh**: Heavy to very heavy rainfall at isolated places over East Uttar Pradesh on 4th August and isolated heavy rainfall is likely during 5th-6th August. **West Uttar Pradesh**: Heavy rainfall at isolated places over West Uttar Pradesh during 4th-5th August and very heavy rainfall at isolated places over Southwest Uttar Pradesh on 4th August. **East Rajasthan**: Heavy to very heavy & extremely heavy rainfall at isolated places on 4th August. Light to moderate rainfall at most places with isolated heavy rainfall is very likely at isolated places on 5th August. **West Rajasthan**: Heavy to very heavy rainfall at isolated places very likely during 4th - 6th August. **Gujarat region**: Heavy to very heavy rainfall at isolated places on 4th and 5th August and heavy rainfall at isolated places on 6th August. **Saurashtra & Kutch**: Heavy rainfall at isolated places on 4th and 5th August. **Madhya Maharashtra**: Heavy rainfall at a few places during 4th to 6th August, very heavy rainfall at isolated places on 5th August and extremely heavy rainfall at isolated places on 4th August. **Konkan & Goa**: Heavy rainfall at a few places is very likely during 4th to 6th August and extremely heavy rainfall at isolated places on 4th	**04.08.2024** **East Rajasthan**: Nagrarfort 32, Hindoli 22, Jahazpur 21, Bundi 19, Sarwar & Kekri 18 each, Sawar, Geola & Deoli 17 each, Kishanganj 16, Mangliawas & Mangrol 15 each, Bakani & Pisagan 13 each, Uniara / Aligarh & Deogarh 12 each, Bhinay, Badesar, Shahpura, Baran, Malpura, Patan, Mandalgarh, Nayanagar/beawar, Todaraisingh & Talera 11 each, Bhainsroadgarh, Nainwa, Tatgarh, Pratapgarh, Tonk Tehsil, Atru ed & Nimbahera 10 each, Masuda, Pachpahar, Pushkar, Jhalarapatan, Piplu & Nasirabad 9 each, Bijoliya, Kotri, Pirawa, Shahabad, Ladpura, Indergarh, Gangdhar & Aklera 8 each, Chothkabarwara, Degod, Kota, Mavli, Anta, Ramganjmandi , Arai, Railmagra, Chittorgarh, Begu, Jhalawar, Rashmi & Dug 7 each, **West Rajasthan**: Sojat 26, Degana 10, Raipur & Bilara 9 each, Jaitran 6, **Gujarat Region:** Khergam 23, Dharampur 18, Kaprada 17, Dangs 16, Chikhli 15, Vansda, Waghai & Valsad 14 each, Dang, Pardi 7 & Daman 13 each, Subir, Dolvan & Valsad 11 each, **Madhya Maharashtra**: Surgana 20, Lonavala 15, Igatpuri 14, Peth, Mahabaleshwar 12 each, Ozharkheda & Yaval 11 each, Trimbakshwar 10, Harsul 9, Paud Mulshi 7, Velhe & Dindori 6 each; **East Madhya Pradesh:** Buxwaha & Orchha 15 each, Hatta 14, Patera, Bina 12 each, Shahgarh 11, Malthone 11 each, Mohangarh, Amarkantak &

	August. **Vidarbha**: Heavy rainfall at isolated places on 4th August.	Panagar 9 each, Khargapur & Junnardeo 8 each, Prithvipur, Badagaon Dhasan, Palera & Niwari 7 each, **West Madhya Pradesh**: Malhargarh 15, Karhal 14, Jawad & Pohri 13 each, Kolaras 12, Sheopur-aws & Karera 11 each, Pichhore & Bamori 10 each, Zirapur , Narwar, Badoda, Manasa, Shivpuri & Kayampur 9 each, Raghogarh, Dhundhadaka, Biaora, Khirkiya-arg & Barod 8 each, Bhanpura, Bhimpur, Nepanagar, Susner, Bairad, Neemuch, Shamgarh, Badarwas, Sitamau & Pachore 7 each, **Konkan & Goa:** Vikramgad 15, Jawhar 15, Mokheda & Talasari 9 each, Khalapur & Pen 8 each, Palghar & Matheran 7 each,
05.08.2024/ 0300	**East Rajasthan**: Heavy to very heavy rainfall at isolated places on 5th and heavy rainfall at isolated places on 6th August. **West Rajasthan**: Heavy to extremely heavy rainfall at isolated places on 5th and heavy to very heavy rainfall at isolated places on 6th August. **Gujarat region**: Heavy to very heavy rainfall at a few places on 5th and heavy rainfall at isolated places on 6th August. **Saurashtra & Kutch**: Heavy rainfall at isolated places on 5th August. **West Madhya Pradesh**: Heavy rainfall at isolated places on 05th August. **Madhya Maharashtra**: Heavy to very heavy rainfall at a few places on 5th and heavy rainfall at isolated places on 6th August. **Konkan & Goa**: Heavy rainfall at a few places is very likely on 5th & 6th August.	**05.08.2024** **East Rajasthan**: Nasirabad 17, Srinagar 14, Pisagan 13, Ajmer & Ajmer Tehsil 11 each, Mangliawas 10, Pushkar & Deogarh 9 each, Nayanagar/beawar & Tatgarh 8 each, **West Rajasthan**: Pali 26, Pokhran 19, Marwar Junction 17, Ahore 16, Jalore 15, Rohat & Nachna / Lathi 13 each, Fatehgarh 12, Phalodi 11, Sojat, Phalodi Tehsil, Gida & Nokh 10 each, Jaisalmer 9, Luni 8 **Madhya Maharashtra**: Gaganbawada & Lonavala 7 each

2.5 Cyclonic Storm "ASNA" over the Arabian Sea during 25th August - 2nd September, 2024

2.5.1 Life History of "ASNA":

- A **Low-pressure area** formed over northwest Bay of Bengal (BoB) and adjoining areas of West Bengal and Bangladesh in the morning (0530 hrs IST/0000 UTC) of 16th August 2024. It lay over South Bangladesh during 17th to 19th August, over Central Bangladesh on 20th and over North Bangladesh on 21st and 22nd August. Thereafter it moved westwards and lay over West Bengal & adjoining Northeast Jharkhand on 23rd August.
- While moving westwards, it concentrated into a well-marked low-pressure area over Southeast Uttar Pradesh (UP) & adjoining areas of northeast Madhya Pradesh (MP) in the morning of 24th August.
- Continuing to move further westwards, it intensified into a **Depression** over Northwest MP in the morning (0530 hours IST/0000 UTC) of 25th August.
- It then moved west-south-westwards and intensified into a **Deep Depression** over East Rajasthan & adjoining West MP in the same midnight (2330 hours IST/1800 UTC) of 25th August. The deep depression continued to move west-south-westwards and lay centred over North Gujarat region by evening (1730 hours IST/1200 UTC) of 26th August.
- It then moved westwards across Gujarat state during 27th -29th August. It emerged into the Northeast Arabian Sea off Kachchh and the adjoining Pakistan coast on 30th August morning (0830 hrs IST/0300 UTC).
- It intensified into a **cyclonic storm (CS) "ASNA"** over northeast Arabian Sea off Kachchh and adjoining Pakistan coast around noon (1130 hours IST/0600 UTC) of 30th August. It then moved nearly westwards, intensified slightly and lay cantered over Northeast Arabian Sea in the morning (0530 hours IST/0000 UTC) of 31st August.
- It then gradually moved south-south-westwards and weakened into a **Deep Depression** in the evening (1730 hours IST/1200 UTC) of the 1st September, 2024 over northwest Arabian Sea.
- Continuing to move further south-south-westwards, it weakened into a **Depression** in the morning (0530 hours IST/0000 UTC) of the 2nd September, 2024 over the northwest Arabian Sea and into a **well-marked low-pressure area** over the same region in the afternoon (1130 hours IST/0600 UTC) of 2nd September, 2024.
- It further weakened into a **low-pressure area** over westcentral & adjoining northwest Arabian Sea in the morning (0830 hours IST/0300 UTC) of 3rd September, 2024.
- The observed track of the cyclonic storm "ASNA" since its inception from a low-pressure area over Northwest Bay of Bengal on 16th August is presented in **Fig. 2.5.1a** and from the stage of depression on 25th August to weakening into a depression on 2nd September is presented in **Fig. 2.5.1b** and table 2.5.1.

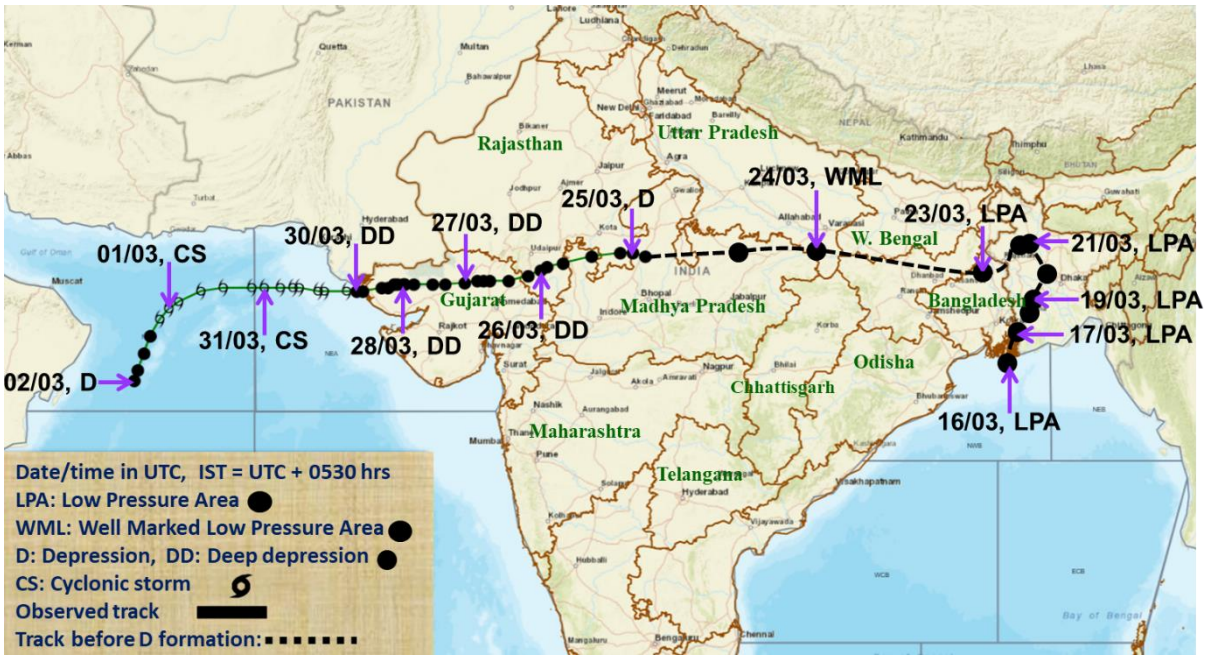


Fig. 2.5.1a: Track of Cyclonic Storm "ASNA" during 16th August-02nd September from the stage of low-pressure area

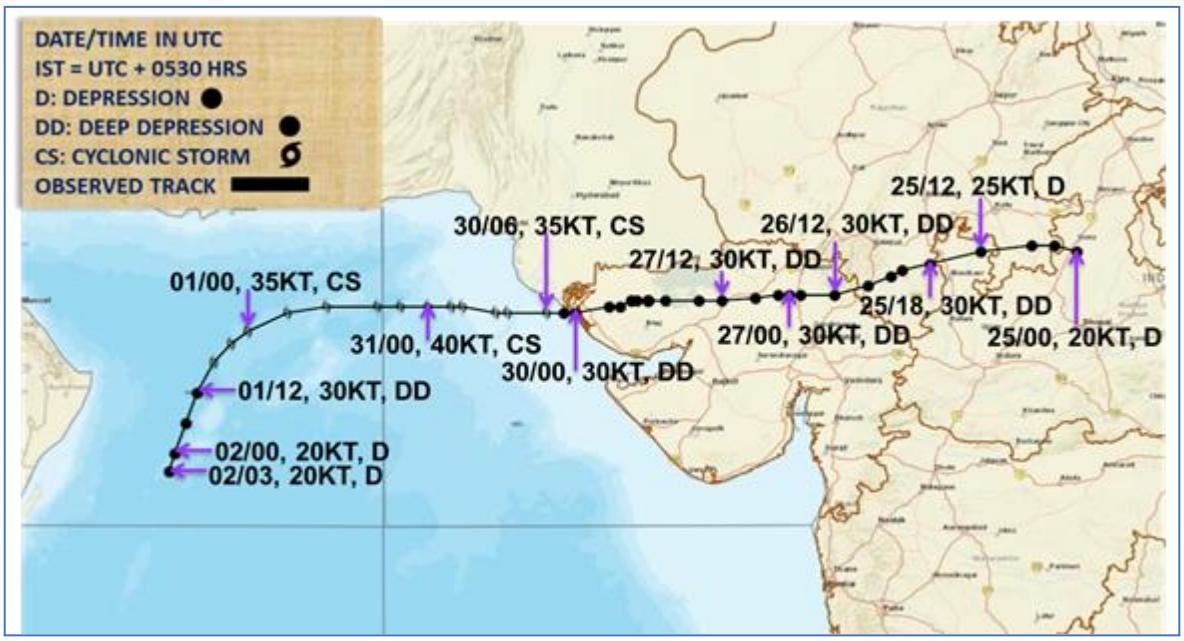


Fig. 2.5.1b: Observed track of cyclonic storm "ASNA" over the land/Arabian Sea during 25th August– 2nd September, 2024

2.5.2 Salient Features

(i) Salient features compared to climatology:

The development of cyclonic storms in August over the Arabian Sea is a rare activity. However, during 1891-2023, 3 cyclonic storms developed over the Arabian Sea in the years 1944, 1964 and 1976. Out of these 3, 2 developed from low pressure area over North Bay

of Bengal and neighbourhood and 1 developed over the Arabian Sea. All three dissipated over the sea **(Fig. 2.5.2).** Details of these cyclonic storms are given below:

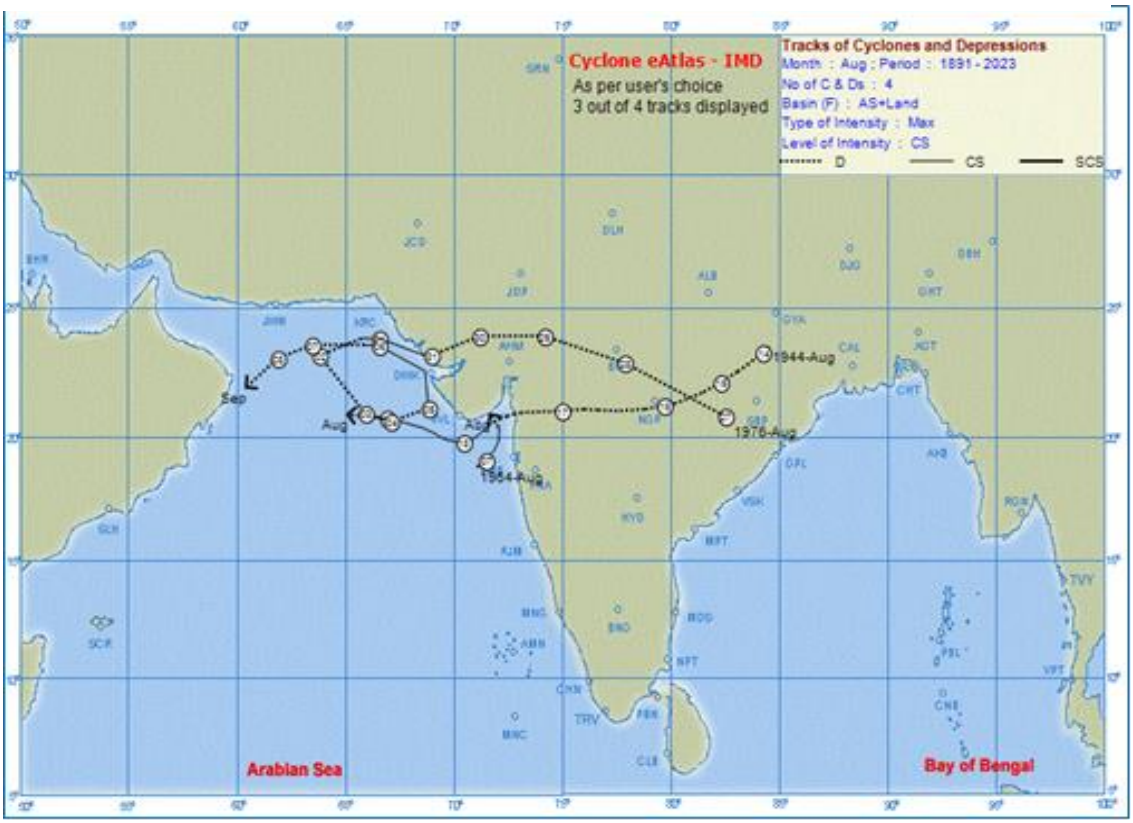


Fig. 2.5.2: Tracks of cyclonic storms (≥ 34 knots or 63 kmph) in the month of August during 1891-2023 over the Arabian Sea

- **1944**: A depression formed over Jharkhand on 14th August. It moved west-south westwards across central parts of the country and emerged into the Northeast Arabian Sea off the South Gujarat coast. Thereafter, it moved southwestwards and intensified into a cyclonic storm over eastcentral & adjoining northeast Arabian Sea near South Gujarat coast around 18th August. Thereafter, it moved west-northwestwards as a cyclonic storm, away from the Indian coast and weakened over Northeast Arabian on 19th August.
- **1964**: A depression formed over Eastcentral Arabian Sea off North Maharashtra coast on 7th August. It moved initially north-northeastwards, intensified into a cyclonic storm for a brief period and gradually recurved north-northwestwards and weakened into a low-pressure area near the South Gujarat coast in the same evening.
- **1976**: A depression formed over Odisha on 27th August. It moved across northern parts of the country across Chhattisgarh, East Rajasthan, North Gujarat region and intensified into a cyclonic storm near Saurashtra and Kutch coast on 31st August. Thereafter, it made a loop over the northeast Arabian Sea and weakened near Oman coast on 8th September.

(ii) Movement:

The six hourly average translational speed of "ASNA" was 12.3 kmph against the normal speed of 14.7 kmph for the CS category **(Fig. 2.5.3.a)** over the Arabian Sea during the monsoon season (June-September). The translational speed initially decreased till 29th

midnight (1800 UTC/2330 hrs IST) and increased thereafter becoming maximum around the early morning of 1st September (during the cyclone intensity period). The translational speed decreased thereafter with almost southwards movement and a decrease in the intensity of the system. The decrease in translational speed of the system during the period from 24th to 29th September can be attributed to the presence of a trough in westerly winds in middle tropospheric levels that restricted the westward movement of the system. The increased translational speed on 30th and 31st is attributed to the steering anticyclone over the Arabian Peninsula and adjoining northwest Arabian Sea. It initially moved west-southwestwards till early morning (0000 UTC) of 30th August and then nearly westwards till evening (1200 UTC) of 31st August. Thereafter, it gradually recurved south-southwestwards and weakened into a well-marked low-pressure area over the Northwest Arabian Sea at noon (0600 UTC) on 2nd September.

(ii) Maximum sustained wind speed (MSW) and estimated central pressure (ECP):
No rapid intensification was observed during the life cycle of ASNA. The system reached its peak intensity of maximum sustained wind speed of 40 knots gusting to 50 knots (70-80 kmph gusting to 90 kmph) at 0000 UTC (0530 IST) 31st August with estimated central pressure (ECP) of 990 hPa and pressure drop of about 8 hPa over Northeast Arabian Sea. It was moving in a favourable environment with high sea surface temperature (SST), high positive vorticity at lower levels, low to moderate anticyclonic vertical wind shear (5-15 knots), enhanced warm moist air incursion into the core region of the system from southeast Arabian Sea, favourable Madden Julian Oscillation and convectively coupled equatorial waves (**Fig. 3b**). After, entering northwest Arabian Sea, it encountered colder sea conditions and started weakening gradually from 1st September Morning (0300 UTC).

(iii) Landfall characteristics:
Cyclonic Storm ASNA didn't make any landfall. It rather emerged into sea after moving slowly across Northwest Madhya Pradesh, South Rajasthan and North Gujarat State as a depression/deep depression for 5 days during 25th morning (0530 hours IST/0000 UTC) to 30th morning (0530 hours IST/0000 UTC). Cyclone/Deep depressions/low pressure systems generally weaken during their movement over land. However, this system intensified during its movement over land during west-south-westward movement of the depression. Due to west-south-westward movement over Rajasthan and Gujarat, it got continuous moisture supply from the Arabian Sea and hence intensified into a deep depression and maintained its intensity over land. Further moisture supply and other environmental conditions became favourable over north Arabian Sea for its intensification into cyclonic storm around 30th August noon (1130 hrs IST/0600 UTC)

(iv) Track length:
The total track length of cyclonic storm "ASNA" was 1780 km against average track length of 1032 km.

(v) Life Period:
The total life period (depression to depression) of "ASNA" was 8 days & 6 hours against the normal of 3 days & 18 hours for cyclonic storm category over the NIO in monsoon season based on the data of 1990-2013.

(vi) Accumulated Cyclone Energy and Power Dissipation Index:
The Velocity Flux, Accumulated Cyclone Energy (a measure of damage potential) and Power Dissipation Index (a measure of loss) were 5.1×10^2 knots, 1.78×10^4 knots^2 and 0.63×10^6 knots^3 respectively.

(vii) Dissipation over the sea: "ASNA" dissipated over the sea like the earlier CS in August during the period 1891-2023 indicating the climatological pattern. All models and the observational diagnostics also suggested the weakening of the system over the sea well in advance.

(viii) Adverse weather:
During its different stages of development, i.e. during low pressure area to deep depression stage, while moving over land it affected almost all the states over the eastern and western parts of the country from Tripura, Meghalaya, Gangetic West Bengal, Odisha, Jharkhand, Chhattisgarh, Madhya Pradesh, Rajasthan & Gujarat State and also Bangladesh leading to extensive flooding and massive damage to life and property. Some of the highest amount of 24 hourly accumulated rainfall during the life period of this system are:

At the stage of low pressure area over northwest Bay of Bengal during 16-22 August, it caused extremely heavy rainfall over Tripura, Meghalaya and Bangladesh leading to massive flooding over these regions. Cherrapunji (Meghalaya) reported 34 cm, Mawsynram (Meghalaya) 25 cm, Bagafa (Tripura) 38 cm & Belonia (Tripura) 32 cm on 19th August; Mawsynram (Meghalaya) reported 34 cm & Agartala (Meghalaya) reported 20 cm on 20th August and Bagafa (Tripura) reported 49 cm on 21st August. Bangladesh also reported heavy to very heavy rainfall over southeast Bangladesh during 17th – 20th August.

Vapi (Gujarat) reported 36 cm & Kathiawada (Madhya Pradesh) 21 cm on 24th August, Khergam (Gujarat) reported 35 cm, Pipalkhunt (East Rajasthan) 26 cm, Rajkot (Saurashtra & Kachchh) 23 cm on 25th August, Tankara (Saurashtra & Kachchh) 36 cm, Morva Hadaf 34 cm (Gujarat region) & Bagidora (East Rajasthan) 20 cm on 26th August; Khambhalia (Saurashtra & Kachchh) reported 43 cm on 27th August, Naliya Saurashtra & Kachchh) 30 cm on 28th August and Mandvi 39 cm on 29th August. Details are discussed in Realised Weather Section. No adverse situations due to strong winds and storm surges were experienced in association with this system.

(ix) Forecast performance:
The genesis, track and intensity, emergence into Arabian Sea, its further intensification into Cyclonic storm and then weakening over Sea was well predicted 3-4 days in advance. The track (intensity) forecast errors were 56 kms (3.2 kts), 110 kms (5.0 kts), 174 kms (1.7 kts) for 24, 48 and 72 hours lead periods respectively. Similarly, the occurrence of heavy to extremely heavy rainfall along its path from Tripura to Gujarat was also predicted well in advance (3-4 days) along with expected damage and suggested actions. Details are given in section 2.5.4.

Table 2.5.1: Best track positions and other parameters of the Cyclonic Storm ASNA over Land/Arabian Sea from 25th August – 02nd September, 2024

Date	Time (UTC)	Lat.	Long.	C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (KT)	Estimated Pressure drop at the Centre (hPa)	Grade
25.08.24	0000	24.5	77.3	-	997	20	3	D
	0300	24.6	76.9	-	997	20	3	D
	0600	24.6	76.5	-	996	20	4	D
	1200	24.4	75.6	-	996	25	4	D
	1800	24.3	74.7	-	995	30	5	DD
26.08.24	0000	24.2	74.2	-	995	30	5	DD
	0300	24.1	74.0	-	995	30	5	DD
	0600	23.8	73.6	-	995	30	5	DD
	1200	23.8	73.0	-	995	30	5	DD
	1800	23.8	72.4	-	995	30	5	DD
27.08.24	0000	23.8	72.2	-	995	30	5	DD
	0300	23.8	72.0	-	995	30	5	DD
	0600	23.7	71.7	-	995	30	5	DD
	1200	23.7	71.0	-	995	30	5	DD
	1800	23.7	70.6	-	995	30	5	DD
28.08.24	0000	23.7	70.0	-	995	30	5	DD
	0300	23.7	69.7	-	995	30	5	DD
	0600	23.7	69.7	-	994	30	6	DD
	1200	23.7	69.7	-	994	30	6	DD
	1800	23.7	69.7	-	994	30	6	DD
29.08.24	0000	23.7	69.5	-	994	30	6	DD
	0300	23.7	69.4	-	994	30	6	DD
	0600	23.7	69.4	-	994	30	6	DD
	1200	23.6	69.2	-	994	30	6	DD
	1800	23.6	69.0	-	994	30	6	DD
30.08.24	0000	23.5	68.4	-	994	30	6	DD
	0300	23.5	68.2	2.0	994	30	6	DD
	0600	23.5	67.9	2.5	993	35	7	CS
	0900	23.5	67.5	2.5	993	35	7	CS
	1200	23.5	67.2	2.5	993	35	7	CS
	1500	23.5	67.0	2.5	992	35	7	CS
	1800	23.6	66.4	2.5	992	35	7	CS
	2100	23.6	66.2	25	992	35	7	CS
31.08.24	0000	23.6	65.8	2.5	991	40	8	CS
	0300	23.6	65.3	2.5	991	40	8	CS
	0600	23.6	64.9	2.5	991	40	8	CS

	0900	23.6	64.4	2.5	991	40	8	CS
	1200	23.6	64.4	2.5	990	40	8	CS
	1500	23.6	63.7	2.5	990	40	8	CS
	1800	23.5	63.7	2.5	990	40	8	CS
	2100	23.4	63.0	2.5	990	40	8	CS
01.09.24	0000	23.2	62.6	2.5	990	40	8	CS
	0300	23.0	62.3	2.5	992	35	7	CS
	0600	22.7	62.0	2.5	993	35	7	CS
	0900	22.5	61.8	2.5	993	35	7	CS
	1200	22.2	61.7	2.0	996	30	6	DD
	1800	21.7	61.5	2.0	998	30	5	DD
02.09.24	0000	21.2	61.3	1.5	999	20	4	D
	0300	20.9	61.2	1.5	1000	20	3	D
	0600	Weakened into a well-marked low-pressure area over Northwest Arabian Sea.						

Maximum sustained surface wind speed (MSW) in knots (kt), 1 kt = 1.86 kmph, D: Depression, DD: Deep depression, CS: Cyclonic storm, SCS: Severe Cyclonic Storm, ECP: Estimated Central Pressure, C.I. No.: Current Intensity No., ∆P: Pressure drop at centre.

2.5.3 Genesis, intensification and movement

2.5.3.1 Genesis

At 0000 UTC on 15th August 2024, a cyclonic circulation had formed over South Bangladesh and adjoining Gangetic West Bengal. Under its influence, a Low-Pressure Area was established over the northwest Bay of Bengal and adjoining areas of West Bengal and Bangladesh at 0000 UTC on 16th August 2024 (Fig. 1a). It lay as a Well-Marked Low-Pressure Area over southeast Uttar Pradesh and adjoining northeast Madhya Pradesh at 0300 UTC on 24th August 2024. Moving nearly westward under favourable conditions, it concentrated into a Depression over northeast Madhya Pradesh and its neighbourhood at 0000 UTC on 25th August 2024. Most numerical weather prediction models (IMD GFS, NCEP GFS, GEFS, ECMWF, and NCUM) had shown consensus, indicating that the existing Depression over Madhya Pradesh would move nearly west-south-westwards and intensify into a Deep Depression over South Rajasthan and adjoining North Gujarat around 27th August. The Madden-Julian Oscillation (MJO) index was in phase 3 with amplitude greater than 1. It moved eastwards across phases 3 and 4, with its amplitude remaining close to 1 during the last week of August and the initial 2 to 3 days of September. Consequently, the MJO index enhanced the convective activity over the eastern parts of the Arabian Sea (AS) during this period. Weak westerly winds (1–3 mps) prevailed over southern and adjoining central parts of AS and BoB during both weeks. Also, the Eastward-moving Kelvin waves (KW) were observed over the northern parts of AS and the southern BoB during this period. Zonal winds and equatorial waves supported the convective activities associated with the Depression over Central India and the expected Low-Pressure Area over Bangladesh and its neighbourhood. East-north-easterly winds in the middle levels steered the Depression west-south-westwards over central and west

India. The approaching trough in the westerlies favoured the system's intensification and slowed its westerly movement.

2.5.3.2 Intensification

Depression over northeast Madhya Pradesh and Neighborhood at 0000 UTC of 25th August 2024, moved west-south-westwards and intensified into a **Deep Depression** over East Rajasthan & adjoining West MP at midnight of 25th August (2330 hours IST/1800 UTC) of 25th August. The Deep Depression continued to move west-south-westwards and lay centred over North Gujarat region by evening (1730 hours IST/1200 UTC) of 26th August. It then moved westwards across Gujarat state during 27th -29th August. It emerged into the Northeast Arabian Sea off Kachchh and the adjoining Pakistan coast on 30th August morning (0830 hrs IST/0300 UTC). It intensified into a **cyclonic storm (CS) "ASNA" over** northeast Arabian Sea off Kachchh and adjoining Pakistan coast around noon (1130 hours IST/0600 UTC) of 30th August. It then moved nearly westwards, intensified slightly and lay cantered over Northeast Arabian Sea in the morning (0530 hours IST/0000 UTC) of 31st August with a maximum sustained wind speed of 40 KTS.

At 0000 UTC of 26th August 2024, the Madden-Julian Oscillation (MJO) index was in phase 3 with amplitude greater than 1. It moved eastwards across phases 3 and 4, with the amplitude remaining close to 1 during the subsequent five days. The presence of convectively coupled equatorial Rossby waves (ERW) propagating westwards, starting from the South China Sea and Bay of Bengal (BoB) to the southeast and east-central regions during this period. Weak westerly winds (1–3 mps) prevailed over southern and adjoining central parts of the Arabian Sea and Bay of Bengal. Eastward-moving Kelvin waves (KW) were observed over the northern parts of the Arabian Sea and the southern Bay of Bengal. Low-level convergence had increased to around $20\times10^{-6}s^{-1}$ southwest of the system centre. Upper-level divergence was approximately $30\times10^{-6}s^{-1}$ to the southwest of the system centre, extending up to the east-central Arabian Sea. The wind shear was moderate over the system area. Vorticity at the 850 hPa level was around $100\times10^{-6}s^{-1}$ near the system area, extending up to 200 hPa. Thus, a favourable MJO, the presence of equatorial waves, moisture feedback from the Arabian Sea, and moderate wind shear contributed to the conditions.

At 0000 UTC of 27th August 2024, the Madden-Julian Oscillation (MJO) index was in phase 4 with an amplitude greater than 1. It moved across phases 4 and 5, with the amplitude remaining above 1 during the subsequent five days. There was also a significant presence of convectively coupled equatorial Rossby waves (ERW) propagating westwards from the Bay of Bengal (BoB), central India, and the central Arabian Sea during that period. Westerly winds (5–7 mps) were observed over the same region, while strong easterlies (5–7 mps) prevailed over the northwestern parts of India and the northeast Arabian Sea during the same time frame. Eastward-moving Kelvin waves (KW) were also present over the southeast Arabian Sea. These features supported the enhancement of convective activity over the Arabian Sea and the Bay of Bengal. Vorticity at the 850 hPa level was around 250×10^{-6} s^{-1} near the system area, extending up to 200 hPa. Shear tendency was increasing over the system area and decreasing toward southern Pakistan. Low-level convergence was approximately $20\times10^{-6}s^{-1}$ around the system area, while upper-level divergence was also about $20\times10^{-6}s^{-1}$, extending into the east-central Arabian Sea. The wind shear was moderate (15–25 knots) over the system area.

At 0000 UTC of 28th August 2024, the Madden-Julian Oscillation (MJO) index lay in phase 4 with amplitude greater than 1. It moved across phases 4 and 5, with the amplitude remaining above 1 during the subsequent five days. A significant presence of convectively coupled equatorial Rossby waves (ERW) propagating westwards from the Bay of Bengal, central India, and the central Arabian Sea during the period was also noticed. Westerly winds (5–7 mps) prevailed over the same region, while strong easterlies (5–7 mps) were observed over the north-western parts of India and the northeast Arabian Sea during the same period. Eastward-moving Kelvin waves (KW) were also present over the southeast Arabian Sea. These features favoured the enhancement of convective activity over the Arabian Sea and the Bay of Bengal. Vorticity at the 850 hPa level was around $250\times10^{-6}s^{-1}$ near the system area, extending up to 200 hPa. Shear tendency had increased over the system area and decreased toward southern Pakistan. Low-level convergence was approximately $20\times10^{-6}s^{-1}$ southwest of the system area. Upper-level divergence was about 20×10^{-6} s^{-1} southwest of the system area, extending into the northeast Arabian Sea. The wind shear was moderate (15–20 knots) over the system area.

At 0000 UTC of 29th August 2024, The Madden-Julian Oscillation (MJO) index lay in phase 4 with amplitude greater than 1. It moved across phases 4 and 5, with the amplitude remaining above 1 during the subsequent five days. It also indicated a significant presence of convectively coupled equatorial Rossby waves (ERW) propagating westwards from the Bay of Bengal, central India, and the central Arabian Sea during that period. Westerly winds (5–7 mps) prevailed over the same region, while strong easterlies (5–7 mps) were observed over the northwestern parts of India and the northeast Arabian Sea. Eastward-moving Kelvin waves (KW) were also present over the southeast Arabian Sea. These features enhanced convective activity over the Arabian Sea and the Bay of Bengal. Vorticity at the 850 hPa level was around 150×10^{-6} s^{-1} near the system area, extending up to 200 hPa. Shear tendency increased over the system area and decreased toward southern Pakistan. Low-level convergence was approximately $20\times10^{-6}s^{-1}$ to the west of the system area, while upper-level divergence was about $30\times10^{-6}s^{-1}$, extending into the northeast Arabian Sea. The wind shear remained moderate (15–20 knots) over the system area.

At 0000 UTC of 30th August 2024, The Madden-Julian Oscillation (MJO) index was in phase 4 and moved to phase 5 from 30th August with an amplitude greater than 1. Sea surface temperatures (SST) over the Bay of Bengal (BoB) ranged between 28–30°C, while those over the Arabian Sea (AS) were around 27–28°C. Cooler temperatures (<26°C) prevailed over the west-central AS, with very warm conditions (>32°C) over the Gulf of Aden. The Tropical Cyclone Heat Potential (TCHP) was high (>100 kJ/cm²) over the central BoB but lower (<50 kJ/cm²) over the north and adjoining central AS. Sea conditions indicated that the deep depression over the Kachchh coast, adjoining areas of Pakistan, and the northeast Arabian Sea encountered colder sea conditions in the AS, limiting significant intensification. Low-level vorticity was around 250×10^{-6} s^{-1} near the system area over the Saurashtra and Kachchh region. Low-level convergence was approximately $10\times10^{-6}s^{-1}$ near the system centre, while upper-level divergence was about $20\times10^{-6}s^{-1}$, extending into the west-central AS. Wind shear was low to moderate over Saurashtra, Kachchh, and adjoining northeast AS. These conditions supported a favourable environment for intensification, making the strengthening of the deep depression over the Kachchh coast and adjoining regions of Pakistan and northeast AS highly likely. An upper

tropospheric ridge lay near 27°N, associated with an anticyclonic circulation over coastal Iran.

At 0000 UTC of 31st August 2024, the Madden-Julian Oscillation (MJO) index was currently in phase 4 and moved to phase 5 from 31st August with an amplitude greater than 1. The sea surface temperature (SST) over the Bay of Bengal (BoB) and Arabian Sea ranged between 28–29°C. It was cooler (<26°C) over the west-central Arabian Sea (AS) and very warm (>32°C) over the Gulf of Aden. The Tropical Cyclone Heat Potential (TCHP) was high (>100 kJ/cm²) over the central BoB and lower (<50 kJ/cm²) over the northern and adjoining central AS. The cyclone Asna over the northeast Arabian Sea and adjoining areas of the Pakistan coast encountered colder sea conditions in the AS, potentially hindering significant intensification. The low-level vorticity near the system area over the northeast Arabian Sea was around $200\times10^{-6}s^{-1}$. Low-level convergence was approximately 10×10^{-6} s^{-1} to the south of the system centre, while upper-level divergence was also about 10×10^{-6} s^{-1} southwest of the system centre, extending up to the west-central Arabian Sea. Wind shear was low to moderate over the northeast AS, indicating a favourable environment for maintaining its intensification. An upper tropospheric ridge was situated near 30°N. A westerly trough was approaching the Indian region, extending up to 28°N along 62^0E. The system was tracking westwards under the influence of easterlies prevailing to the ridge's south.

At 0000 UTC of 01st September, the Madden-Julian Oscillation (MJO) index was in phase 5 with an amplitude greater than 1. The sea surface temperature (SST) over the Bay of Bengal (BoB) and Arabian Sea (AS) ranged between 28–29°C. It was cooler (<26°C) over the west-central AS and very warm (>32°C) over the Gulf of Aden. The Tropical Cyclone Heat Potential (TCHP) was high (>100 kJ/cm²) over the central BoB and lower (<50 kJ/cm²) over the northern and adjoining central AS. Sea conditions indicated that Cyclone Asna over the northeast and adjoining northwest Arabian Sea had entered an area with TCHP less than 50 kJ/cm², reducing the likelihood of significant intensification. The low-level vorticity was approximately $150\times10^{-6}s^{-1}$ to the south of the system area. Low-level convergence was about $15\times10^{-6}s^{-1}$ to the south of the system center, and upper-level divergence was approximately $20\times10^{-6}s^{-1}$ to the southwest of the system center. Wind shear was low to moderate (15–20 knots) over the central part of the north AS. These features suggested that Cyclonic Storm Asna over the northeast Arabian Sea and adjoining areas of the Pakistan coast had likely maintained its intensity as a cyclonic storm for the next 24 hours. The system tracked westwards under the influence of easterlies prevailing to the south of the ridge.

2.5.3.3 Weakening:

The **cyclonic storm (CS) "ASNA" over** northeast Arabian Sea off Kachchh and adjoining Pakistan coast gradually moved south-south-westwards and weakened into a **Deep Depression** in the evening (1730 hours IST/1200 UTC) of the 1st September, 2024 over northwest Arabian Sea. Continuing to move further south-south-westwards, it weakened into a **Depression** in the morning (0530 hours IST/0000 UTC) of the 2nd September, 2024 over the northwest Arabian Sea and into a **well-marked low-pressure area** over the same region in the afternoon (1130 hours IST/0600 UTC) of 2nd September, 2024. It further weakened into a **low-pressure area** over west central & adjoining northwest Arabian Sea in the morning (0830 hours IST/0300 UTC) of 3rd September, 2024.

At 0000 UTC of 2nd September, the sea surface temperature (SST) over the west-central Arabian Sea ranged between 28–29°C and was expected to decrease along the forecast path of the system. The Tropical Cyclone Heat Potential (TCHP) was less than 50 KJ/cm² over the northwest Arabian Sea. The low-level vorticity was around $100\times10^{-6}s^{-1}$ to the south of the system area. Low-level convergence was approximately $5\times10^{-6}s^{-1}$ to the south of the system centre, while upper-level divergence was also around $5\times10^{-6}s^{-1}$ to the northwest of the system centre. Wind shear was very high (40–50 knots) over the system area. North-easterly winds in the upper levels over the system area steered the system south-westward.

2.5.3.4 Characteristics features w.r.t. Maximum Sustained Surface Wind speed and estimated central pressure and translational speed:

(a) Maximum Sustained Surface Wind speed and estimated central pressure:

No rapid intensification was observed during the life cycle of ASNA. The system reached its peak intensity of maximum sustained wind speed of 40 knots gusting to 50 knots (70-80 kmph gusting to 90 kmph) at 0000 UTC (0530 IST) of 31st August **(Fig. 2.5.1b)** with estimated central pressure (ECP) of 990 hPa and pressure drop of about 8 hPa over Northeast Arabian Sea **(Fig. 2.5.3b)**. It was moving in a favourable environment with high SST, high positive vorticity at lower levels, low to moderate anticyclonic vertical wind shear (5-15 knots), enhanced warm moist air incursion into the core region of the system from southeast Arabian Sea, favourable Madden Julian Oscillation and convectively coupled equatorial waves. After, entering northwest Arabian Sea, it encountered colder sea conditions and started weakening gradually from 1st September Morning (0300 UTC).

b. Translational speed & direction of movement:

"**ASNA"** exhibited six hourly average translational speeds of 12.3 kmph against normal of 14.7 kmph for cyclonic storms over the AS in the monsoon season during 1990-2013 (**Fig.2.5.3a**).

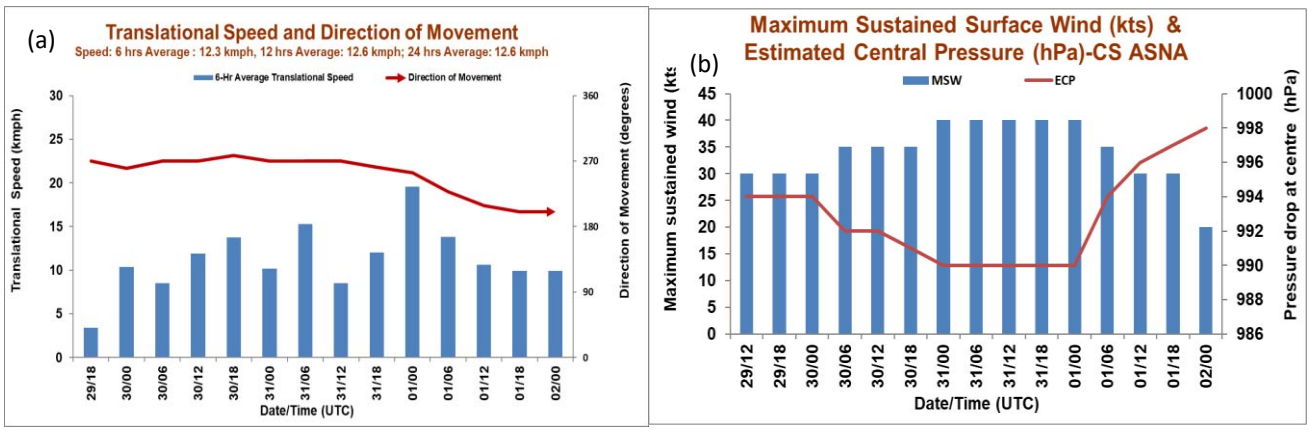


Fig. 2.5.3: (a) 6 hourly average translational speed and (b) maximum sustained wind speed & estimated central pressure during life cycle of ASNA

2.5.4 Monitoring of CS, "ASNA"

India Meteorological Department (IMD) maintained round-the-clock watch over the north Indian Ocean and the cyclone was monitored since 15th August, about 10 days before the formation of the depression on 25th August. The information about the system was first released in the weekly extended range outlook issued by IMD on 15th August, indicating the formation of low-pressure areas with moderate confidence (34-67%) to intensify further into Depression **[Fig. 2.5.4(a)]**. Further, the updated extended range outlook issued on 24th August, indicated the formation of a depression over Northwest Madhya Pradesh during the beginning of the week (24-29 August) with high confidence (68-100%). Actually, a depression formed over Northwest Madhya Pradesh on 25th August **[Fig. 2.5.4(b)]**. In the subsequent week the extended range outlook issued on 29 August indicated high probability of cyclogenesis (68-100%) over the Arabian Sea in week 1 (30 August to 5th September) coinciding with the period of cyclone "ASNA" over the Arabian Sea **[Fig. 2.5.4(c)]**.

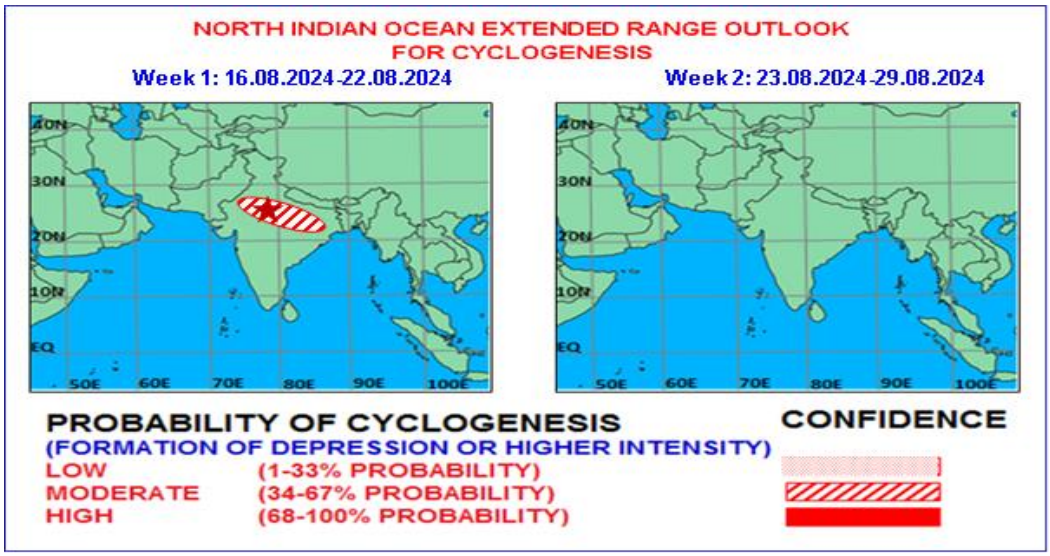


Fig. 2.5.4 (a): Weekly extended range outlook issued by IMD on 15th August, 2024 indicating area of cyclogenesis over Northwest MP during the week 1 (Actually genesis occurred on 25th August over Northwest MP)

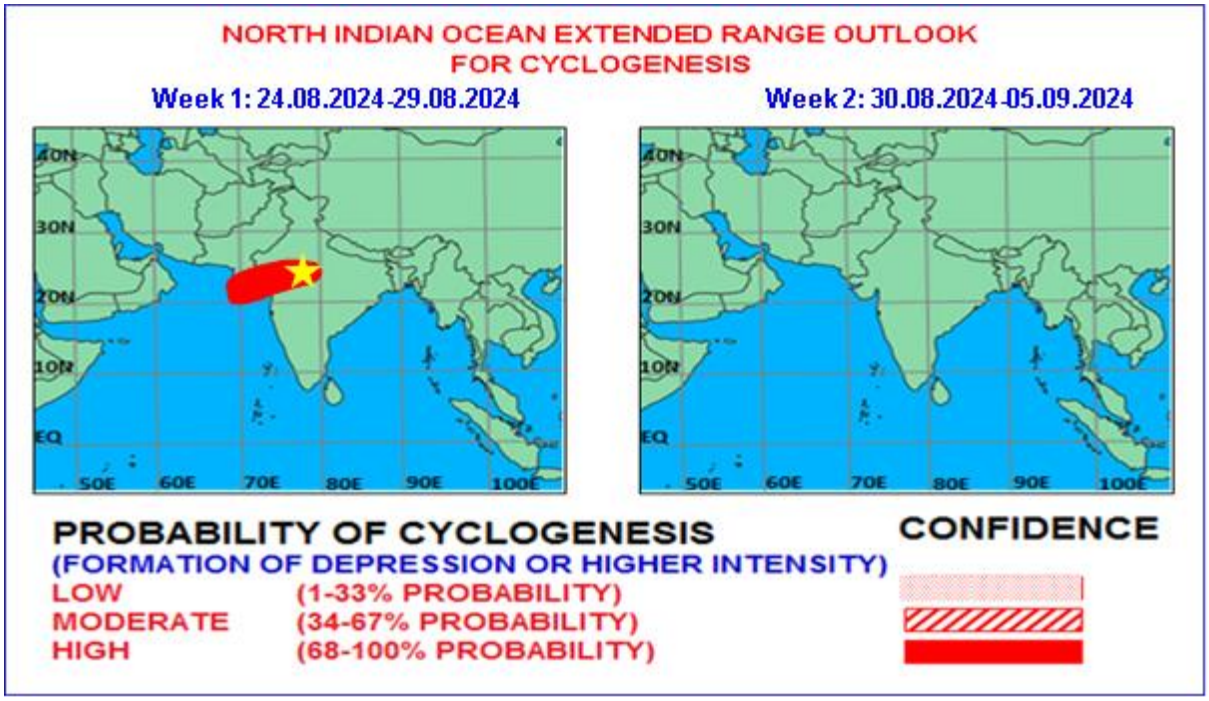


Fig. 2.5.4 (b): Weekly updated extended range outlook issued by IMD on 23rd August, 2024 indicating likely emergence of the system into Arabian Sea during week 1 with High Confidence about 6 days prior to its emergence into Northeast Arabian Sea (actually it emerged into Arabian Sea on 30th August)

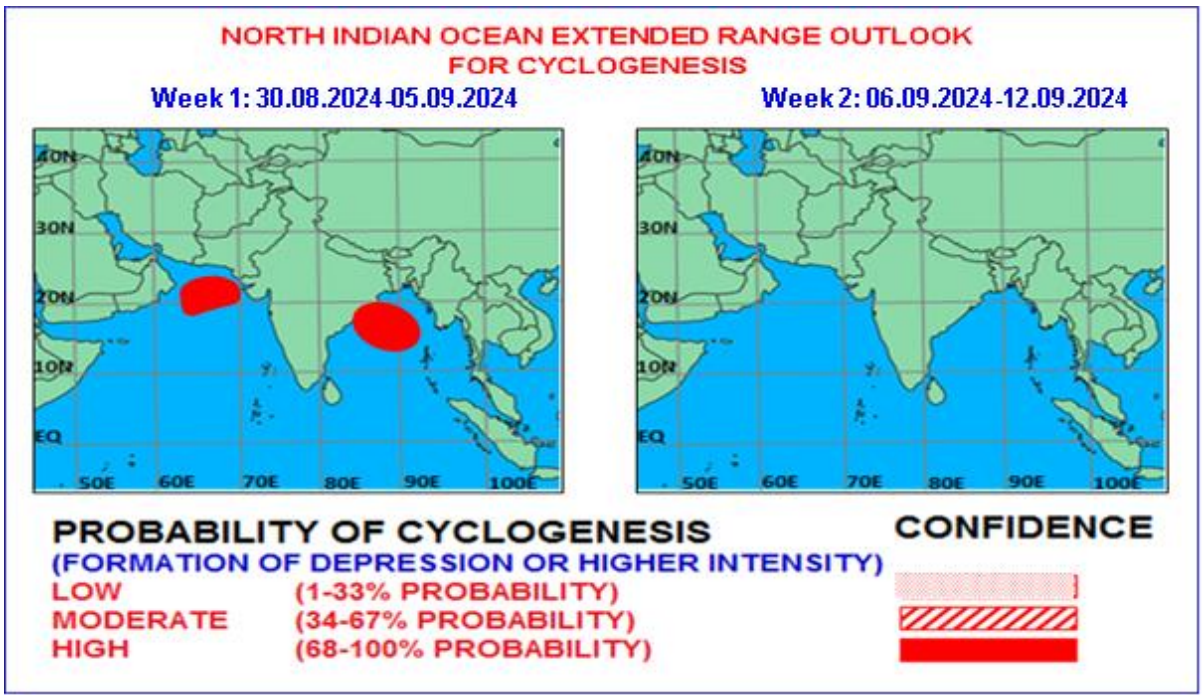


Fig. 2.5.4 (c): Weekly extended range outlook issued by IMD on 29th August, 2024 indicating likely westwards movement of ASNA over Northeast Arabian Sea and gradual south-westwards curvature (Actually it moved nearly westwards over Northeast Arabian Sea and gradually recurved south-south-westwards from 1st September/0000 UTC onwards).

2.5.4.1 Features observed through satellite:

The cyclone was monitored with the help of available satellite observations from INSAT 3D and 3DR, SCAT SAT, ASCAT, microwave imageries and available ships, buoy observations and coastal observations in the region. Various global models and dynamical-statistical models run by Ministry of Earth Sciences (MoES) institutions including IMD, NCMRWF, IITM & INCOIS and guidance from models from various international agencies under bilateral arrangement were utilized to predict the genesis, track and intensity of the cyclone as well as associated severe weather. The forecasts were mainly based on multi-model ensemble technique developed by IMD further modulated by observations and forecasters intervention at IMD. An indigenously developed digitized forecasting system of IMD was utilized for analysis and comparison of various observations and numerical weather prediction model's guidance, decision making process and warning products generation. Typical satellite-based products utilised for monitoring the system are presented in **Fig. 2.5.5**. The satellite imagery during the stage of cyclone suggested organisation of clouds in curved band pattern during intensification phase (30th to 31st August) and shear pattern during weakening phase (1st - 2nd September) are presented in Fig. 2.5.5.

On day to day basis during the life cycle of the system "ASNA" (24 August-02 September) the convective activity that prevailed based on INSAT 3DR Visible images, IR images, Brightness temperature and enhanced coloured images are shown in **Fig.2.5.6(a)-(d)** respectively.

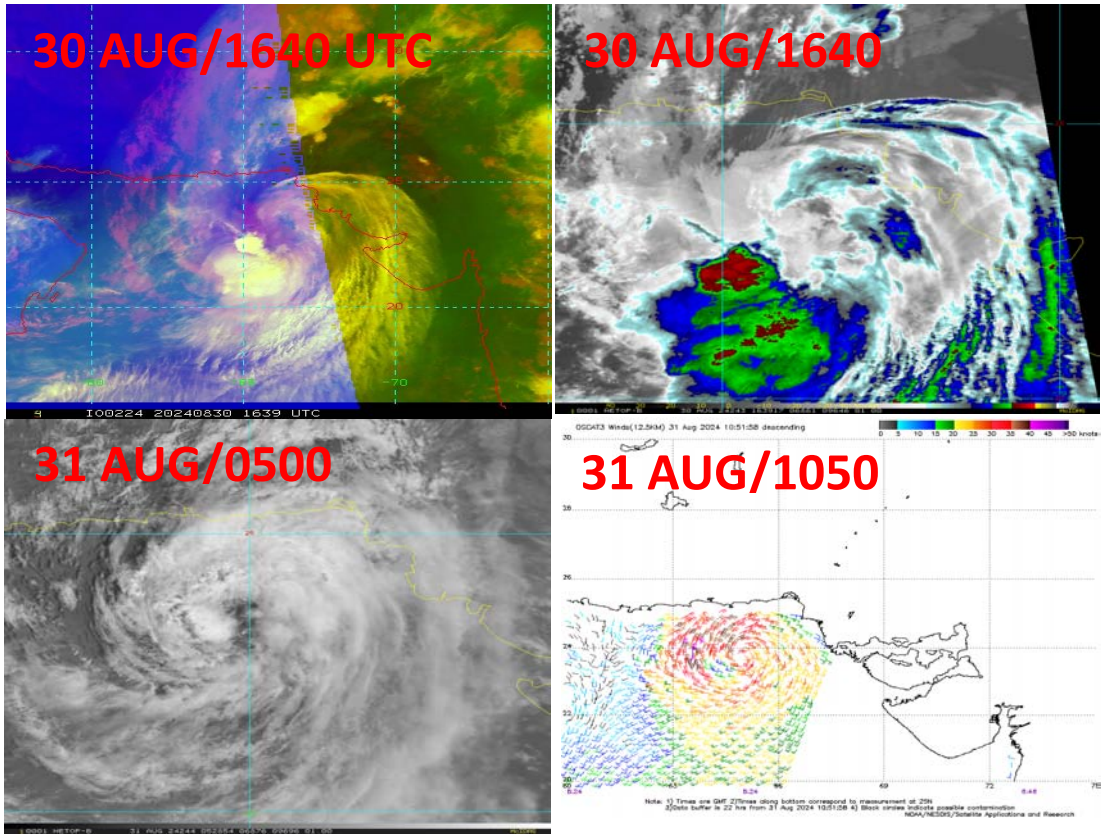


Fig. 2.5.5: Typical (a) INSAT 3D(R) at 2245 hrs IST/ 1715 UTC of 30th August and (b) Oceansat Imagery at 2345 hrs IST/1815 UTC of 31st August, 2024 in connection with cyclonic storm "ASNA"

At 0000 UTC of 24th August 2024, scattered to broken low and medium clouds, with embedded intense to very intense convection, were observed over east Madhya Pradesh, where the minimum cloud top temperature (CTT) reached minus 80°C. Moderate to intense convection was noted over north Chhattisgarh, adjoining southeast Uttar Pradesh, and northwest Jharkhand, with a minimum CTT of minus 50 to 60°C.

At 0000 UTC of 25th August 2024, clouds associated with the depression over northwest Madhya Pradesh and its neighbourhood included scattered to broken low and medium clouds. Embedded intense to very intense convection was observed over Madhya Pradesh, adjoining southwest Uttar Pradesh, east Rajasthan, Gujarat, and Maharashtra, with a minimum cloud top temperature (CTT) of minus 93°C. Moderate to intense convection was noted over Chhattisgarh, where the minimum CTT ranged between minus 50°C and minus 60°C.

At 0000 UTC of 26th August 2024, scattered to broken low and medium clouds with embedded intense to very intense convection was observed over south Rajasthan, southwest Madhya Pradesh, north Madhya Maharashtra, and adjoining north Konkan, with a minimum cloud top temperature (CTT) of minus 93°C. Moderate to intense convection was noted over northeast Rajasthan, northwest Madhya Pradesh, south Madhya Maharashtra, and Konkan & Goa, where the minimum CTT ranged between minus 50°C and minus 60°C.

At 0000 UTC of 27th August 2024, scattered to broken low and medium clouds with embedded intense to very intense convection was observed over Gujarat, adjoining south Rajasthan, southwest Madhya Pradesh, north Madhya Maharashtra, the Gulf of Kutch, the Gulf of Cambay, northeast Arabian Sea, and adjoining south Pakistan, with a minimum cloud top temperature (CTT) of minus 93°C. Moderate to intense convection was noted over south Rajasthan and north Konkan.

At 0000 UTC of 28th August 2024, scattered to broken low and medium clouds with embedded intense to very intense convection was observed over Kutch, Saurashtra, northeast Arabian Sea, and the Gulf of Kutch, with a minimum cloud top temperature (CTT) of minus 93°C. Moderate to intense convection was noted over south Pakistan, southwest Rajasthan, the east Gujarat region, and the Gulf of Cambay.

At 0000 UTC of 29th August 2024, scattered to broken low and medium clouds with embedded intense to very intense convection was observed over Kachchh, Saurashtra, south Pakistan, northeast Arabian Sea, and the Gulf of Kachchh, with a minimum cloud top temperature (CTT) of minus 93°C. Moderate to intense convection was noted over west Rajasthan.

At 0000 UTC of 30th August 2024, scattered to broken low and medium clouds with embedded intense to very intense convection was observed over south Pakistan, the northeast Arabian Sea, and the Gulf of Kachchh, with a minimum cloud top temperature (CTT) of minus 93°C.

At 0600 UTC of 30th August 2024, the Intensity of the system was characterized as **T 2.5**. Scattered to broken low and medium clouds with embedded intense to very intense

convection was observed over the northeast Arabian Sea, Kutch, and Gulf of Kutch, with a minimum cloud top temperature of minus 90°C. Moderate to intense convection was also present over south Pakistan and Saurashtra.

At 0000 UTC of 31st August 2024, the intensity of the system was characterized as **T 2.5.** Scattered to broken low and medium clouds with embedded intense to very intense convection were observed over the north and adjoining central Arabian Sea, with a minimum cloud top temperature of minus 90°C. Moderate to intense convection was noted over the western part of Kachchh and adjoining south Pakistan.

At 2100 UTC on 31st August 2024, the intensity of the system was characterized as **T 2.5**. Scattered to broken low and medium clouds with embedded intense to very intense convection were observed over the northwest Arabian Sea, with a minimum cloud top temperature of minus 90°C. Moderate to intense convection was noted over Oman, the northeast Arabian Sea, south Pakistan, and adjoining Iran.

At 0000 UTC on 1st September 2024, the intensity of the system was characterized as **T 2.5.** Scattered to broken low and medium clouds with embedded intense to very intense convection was observed over the northwest Arabian Sea, with a minimum cloud top temperature of minus 90°C. Moderate to intense convection was noted over Oman, southeast Iran, and adjoining Pakistan.

At 1200 UTC on 1st September 2024, Intensity of the system was characterized as **T 2.0/C.I. 2.5.** The cloud mass showed further disorganisation. Scattered to broken low and medium clouds with embedded intense convection were observed over northwest and southeast Arabian Sea, with a minimum cloud top temperature of minus 70°C. Moderate to intense convection was present over southeast Iran, adjoining south Pakistan, the Gulf of Oman, and northern Oman.

At 0000 UTC on 2nd September 2024, the intensity of the system was characterized as **T 1.5.** Weak convection was observed over the northwest and adjoining west-central Arabian Sea, the Gulf of Oman, and northern Oman, with a minimum cloud top temperature of minus 20°C.

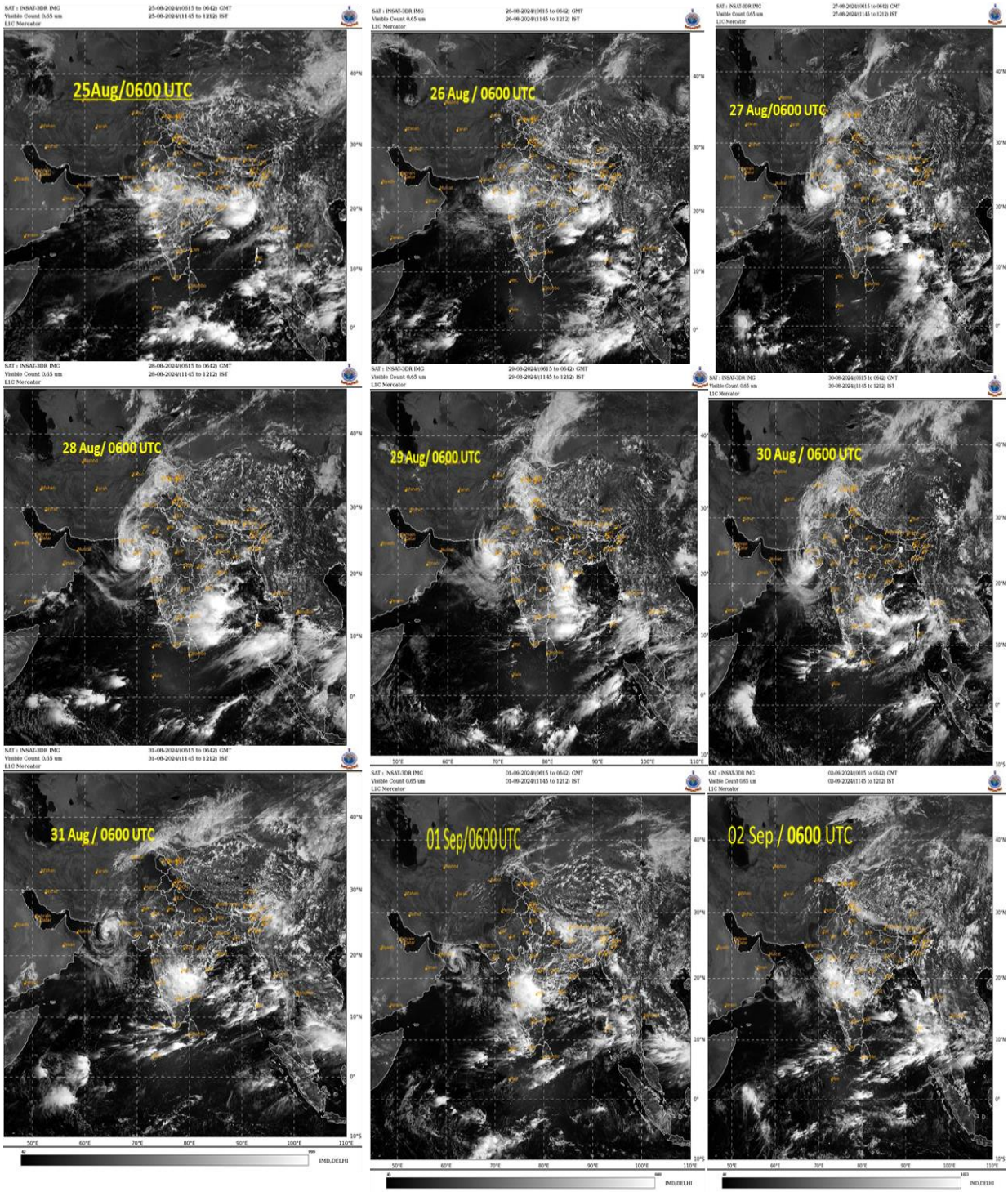


Fig. 2.5.6(a): INSAT 3D(R) Visible imageries in connection with cyclonic storm "ASNA" during 24 Aug - 02 Sep, 2024.

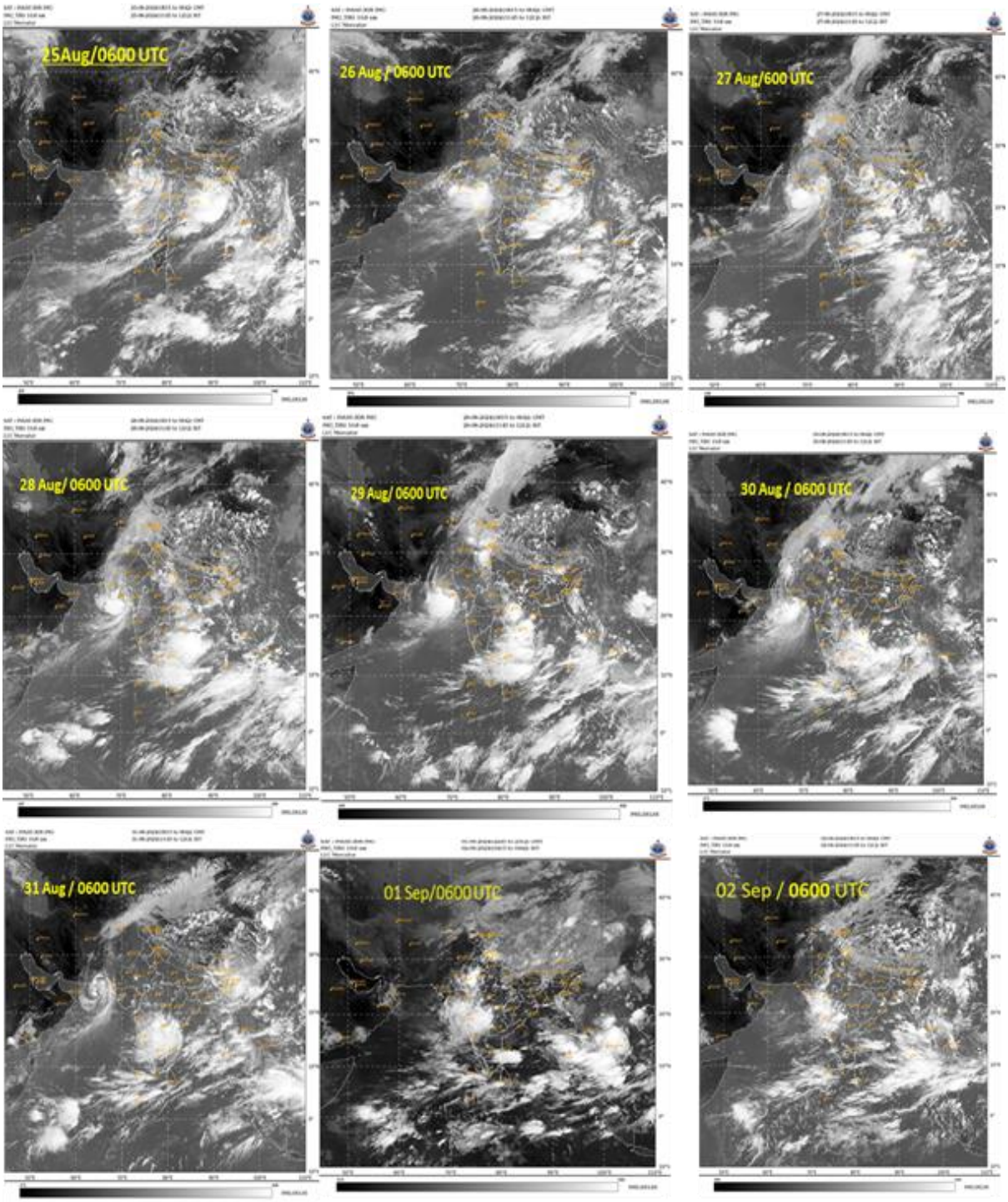


Fig. 2.5.6(b): INSAT 3D(R) IR imageries in connection with cyclonic storm "ASNA" during 24 Aug - 02 Sep, 2024.

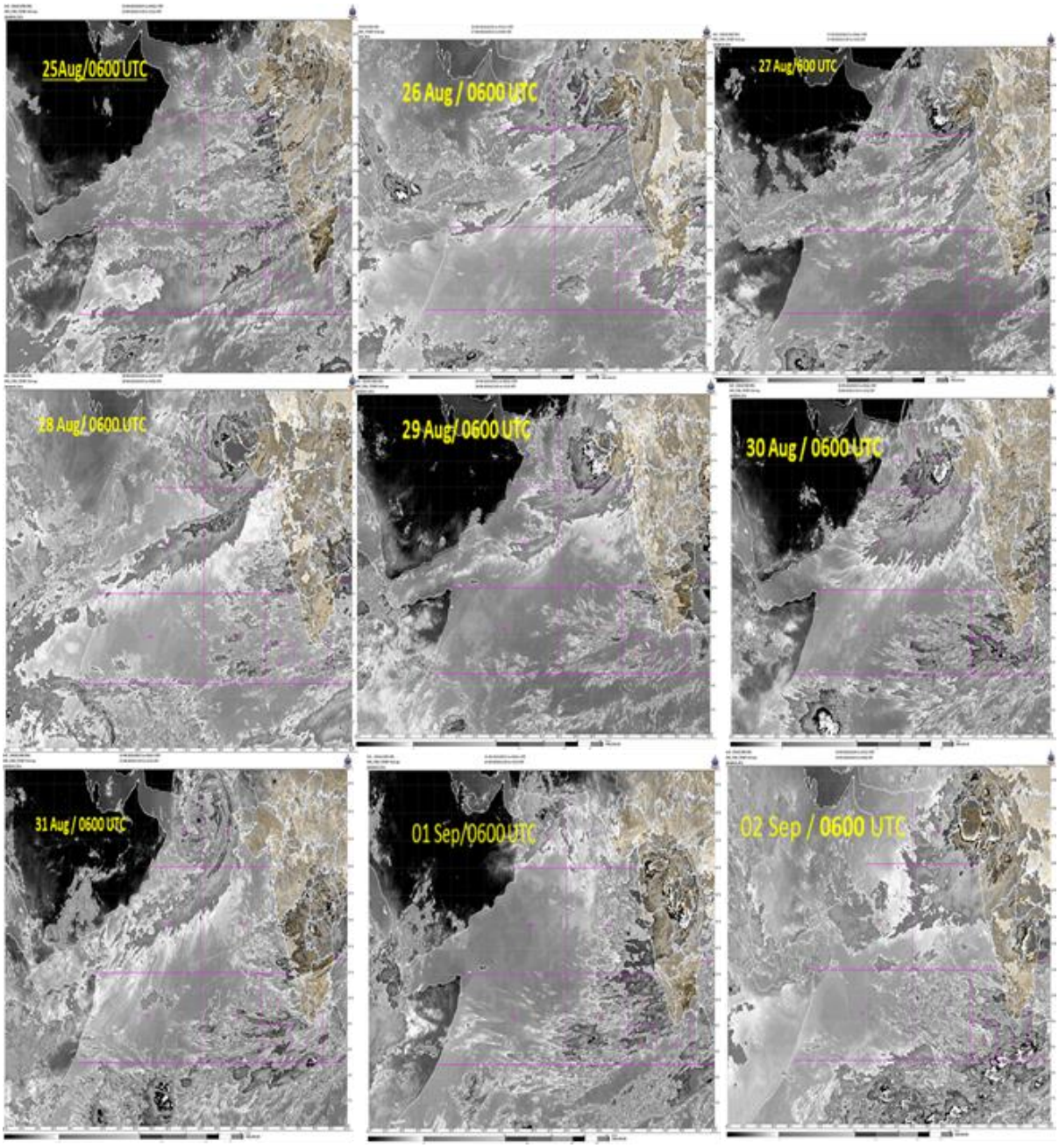


Fig. 2.5.6(c): INSAT 3D(R) IR enhanced imageries in connection with cyclonic storm "ASNA" during 24 Aug - 02 Sep, 2024.

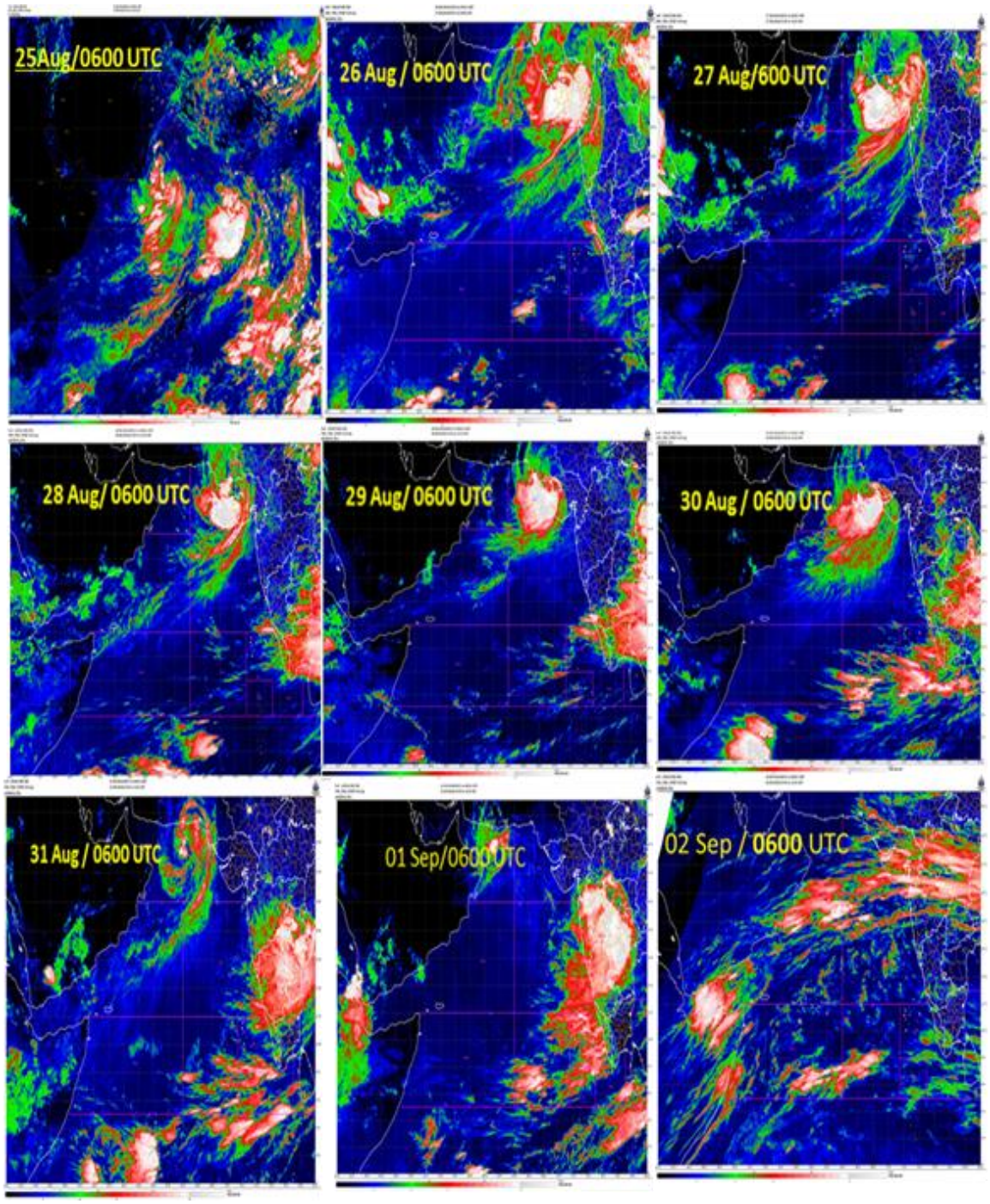


Fig. 2.5.6(d): INSAT 3D(R) enhanced coloured imageries in connection with cyclonic storm "ASNA" during 24 Aug - 02 Sep, 2024.

2.5.5 Dynamical features

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels during 25th August- 2nd September, 2024 are presented in **Fig. 2.5.7.(a) – (i).**

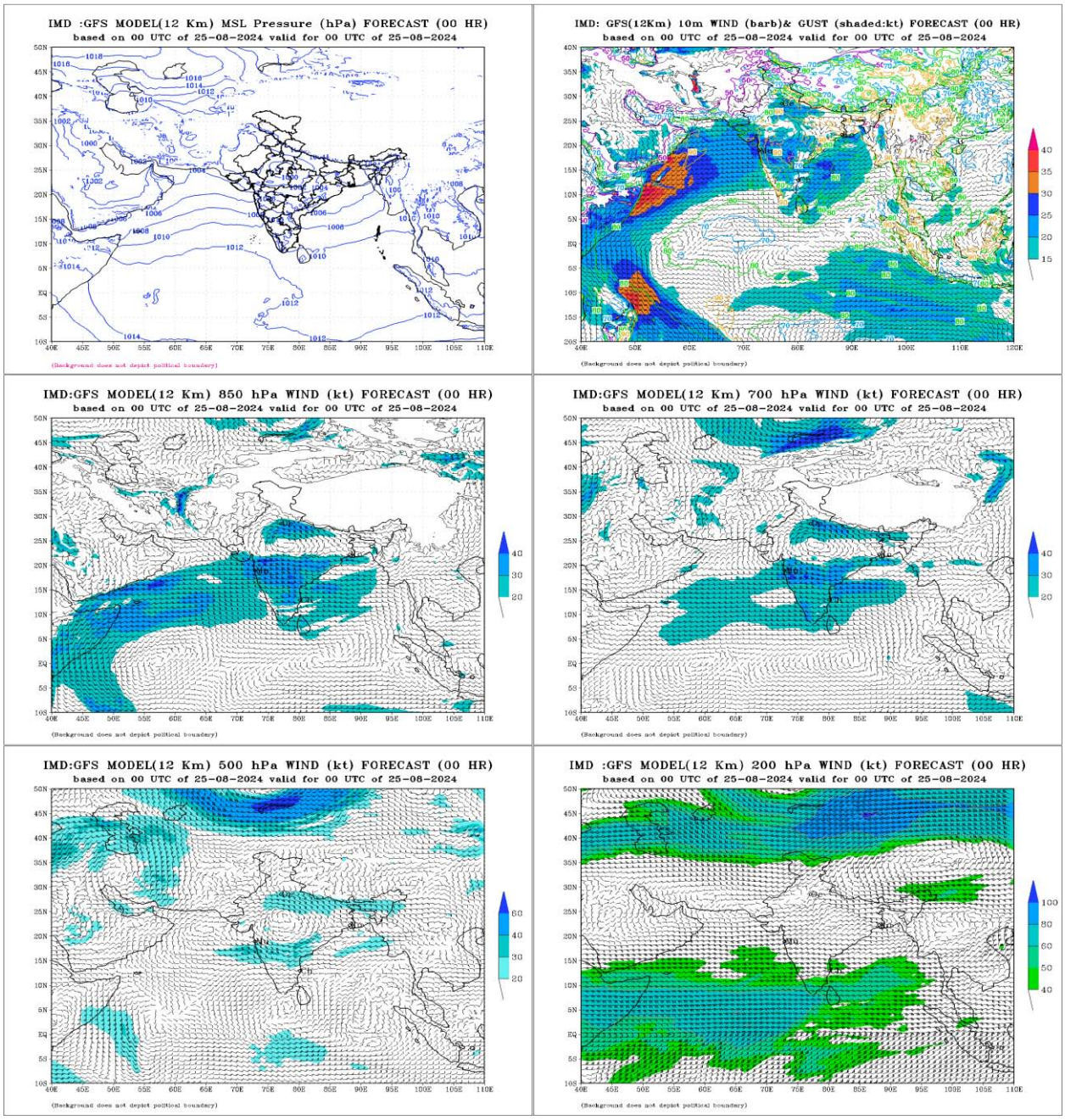


Fig. 2.5.7. (a): IMD GFS mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 25th August, 2024

The large-scale analysis from GFS on 25th August 0000 UTC **Fig. 2.5.7.(a)** indicated two close isobars (with one slightly extended one) in the MSLP analysis over Northwest Madhya Pradesh with associated cyclonic circulation extending upto 500 hPa level. The upper level ridge line was to the north of the system centre associated with easterly/northeasterly wind over the region. It is further observed that the low-level southwest monsoon current was favourable for the moisture incursion from the Arabian Sea at lower level and likely further intensification of the system from the current stage of Depression.

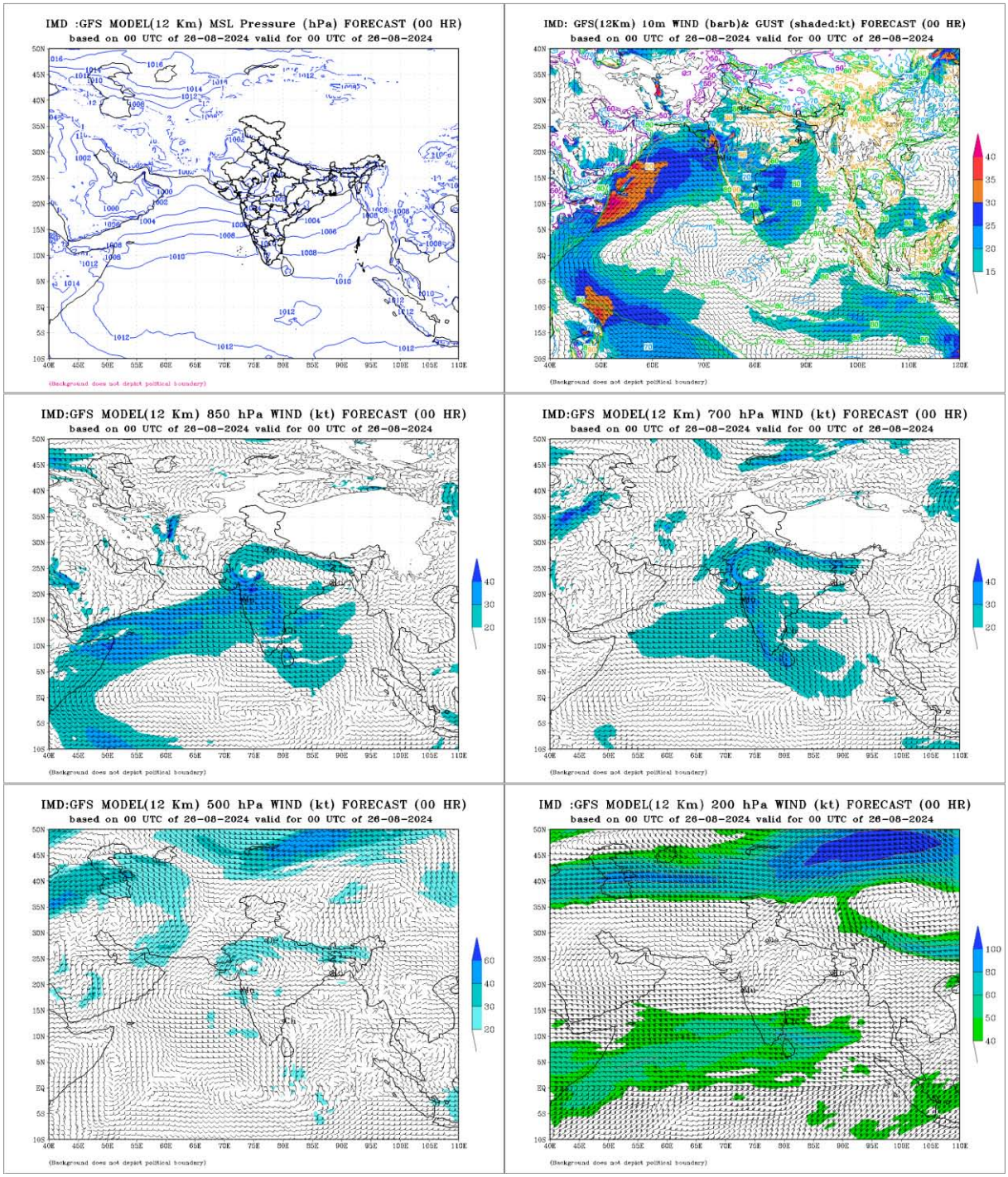


Fig. 2.5.7.(b): IMD GFS mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 26th August, 2024

The analysis from GFS model **Fig.2.5.7 (b)** indicated two closed isobars with centre over NW Madhya Pradesh and adjoining east Rajasthan with a movement of west-southwest direction in past one day with associated cyclonic circulation extending up to 500 hPa level. The upper level ridge line was slightly to the north of the system centre and it is associated with easterly/northeasterly wind over the region.

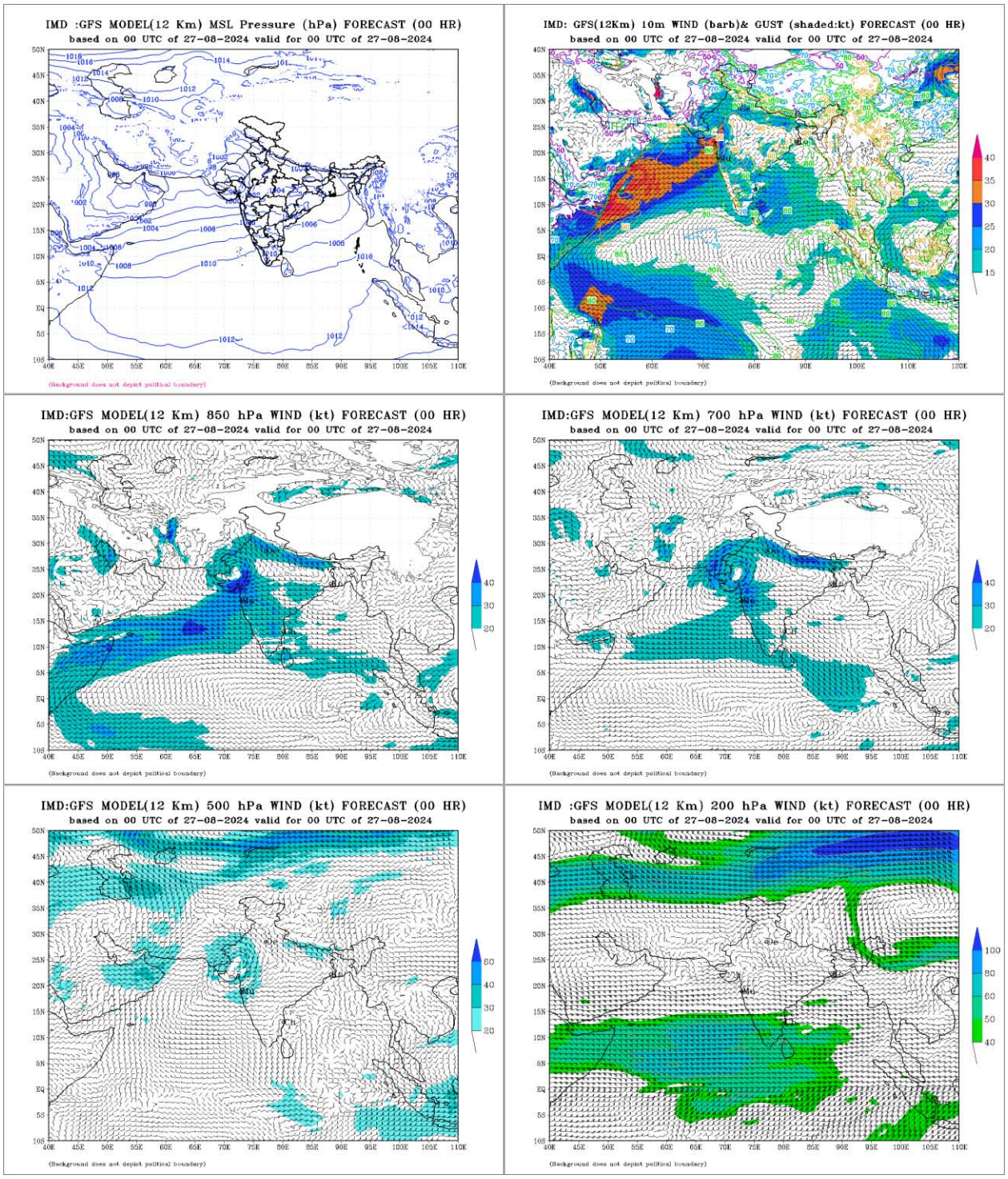


Fig. 2.5.7 (c): IMD GFS mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 27th August, 2024

The analyses from GFS model during the period from 27-29 August **Figs. 2.5.7 (c) to (e)** indicated westward/west-southwestward movement of the system across Gujarat state with 3 clear closed isobars in the MSLP analysis and associated cyclonic circulation extending upto 500 hPa level. The upper level ridge line was slightly to the north of the system centre and it is associated with easterly/northeasterly wind over the region.

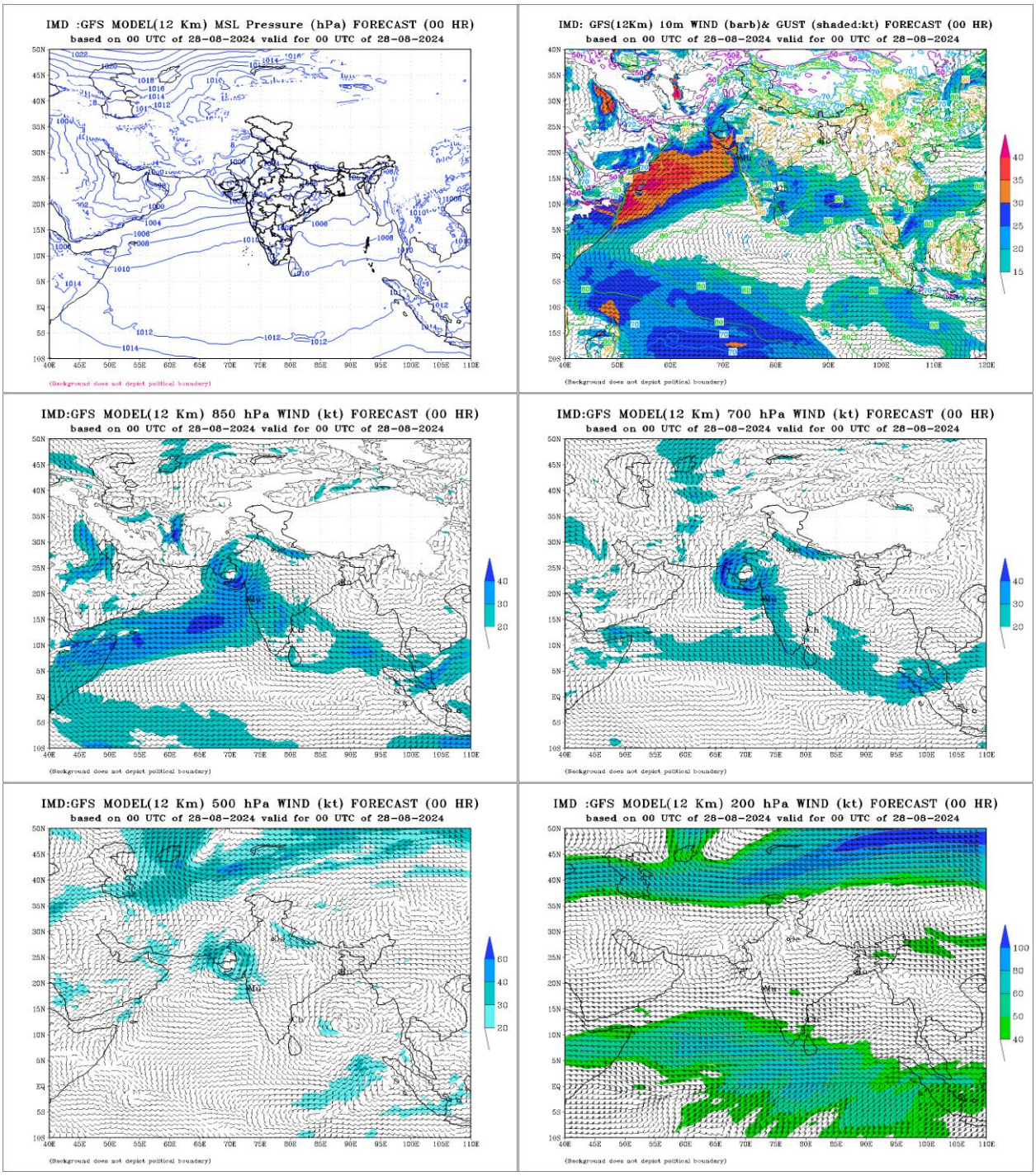


Fig. 2.5.7 (d): IMD GFS mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 28th August, 2024

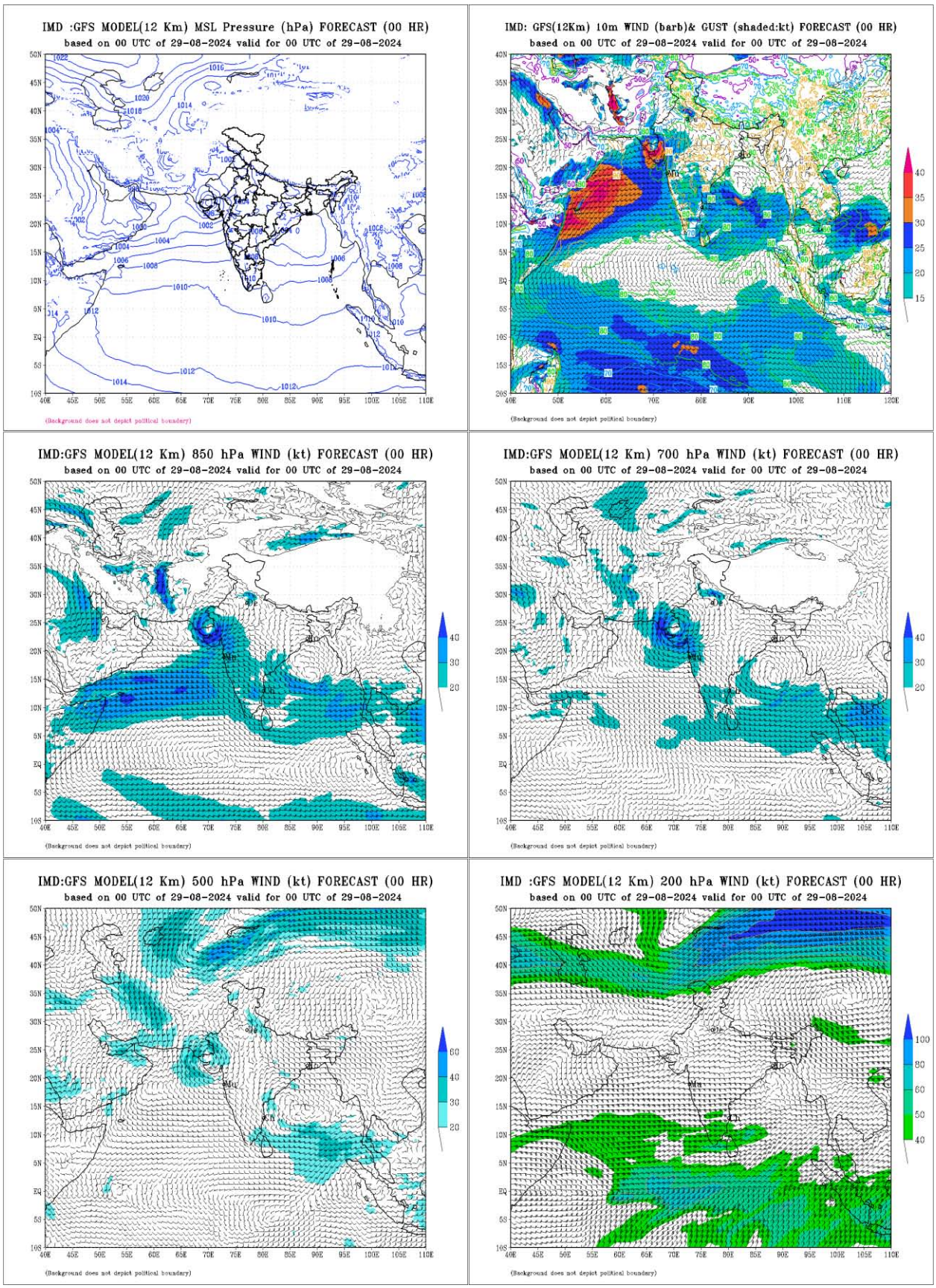


Fig. 2.5.7(e): IMD GFS mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 29th August, 2024

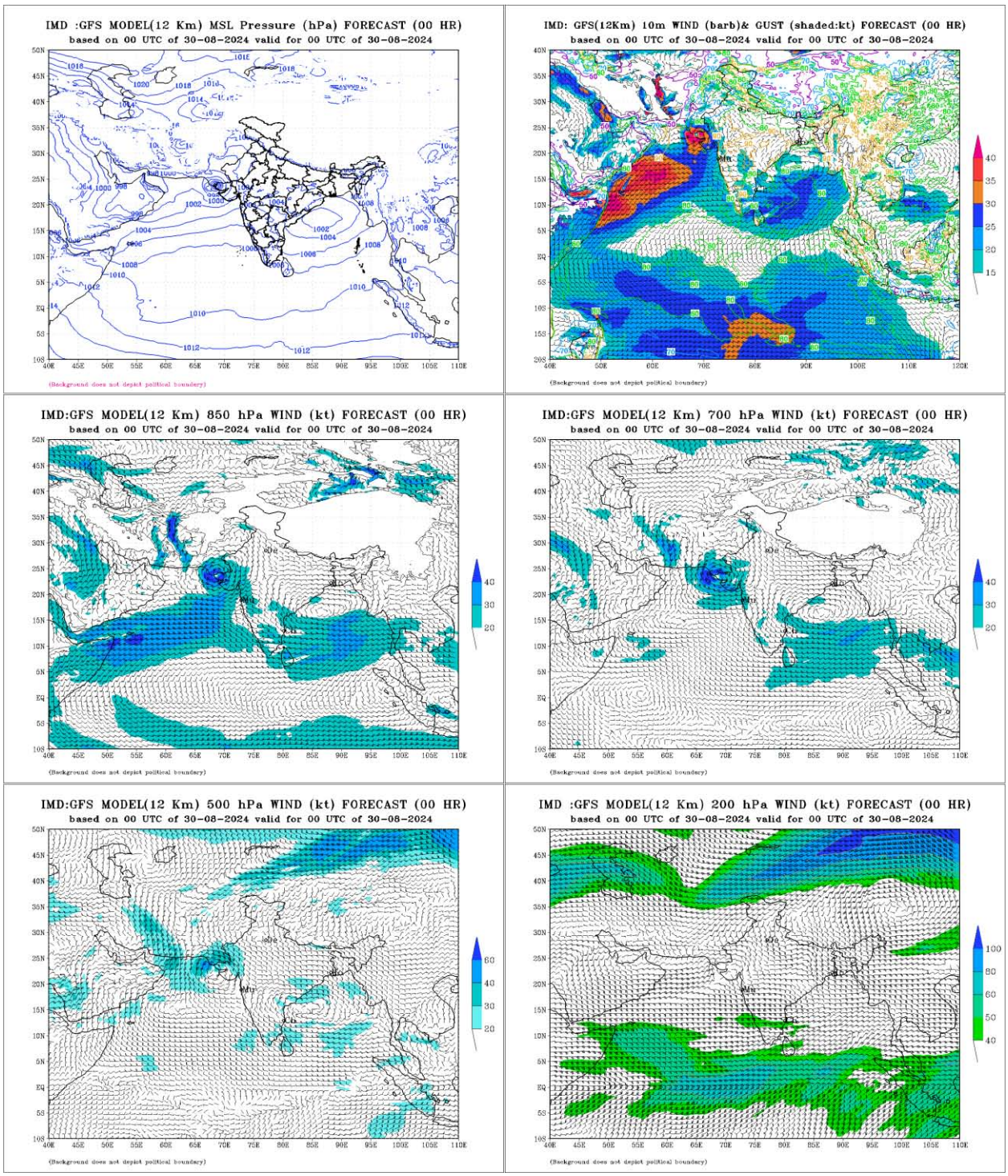


Fig. 2.5.7 (f): IMD GFS mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 30th August, 2024

The GFS model analysis for 30th August **Fig. 2.5.7 (f)** indicated the system over the Northeast Arabian Sea off Kachchh and the adjoining Pakistan coast with 4 or more closed isobars, indicating further intensification of the system with associated cyclonic circulation extending up to 500 hPa level. The 200 hPa level wind indicated a northeast-southwest oriented trough passing close to the system's centre. It may be mentioned here that the system intensified into a cyclonic storm at 0600 UTC of 30th August.

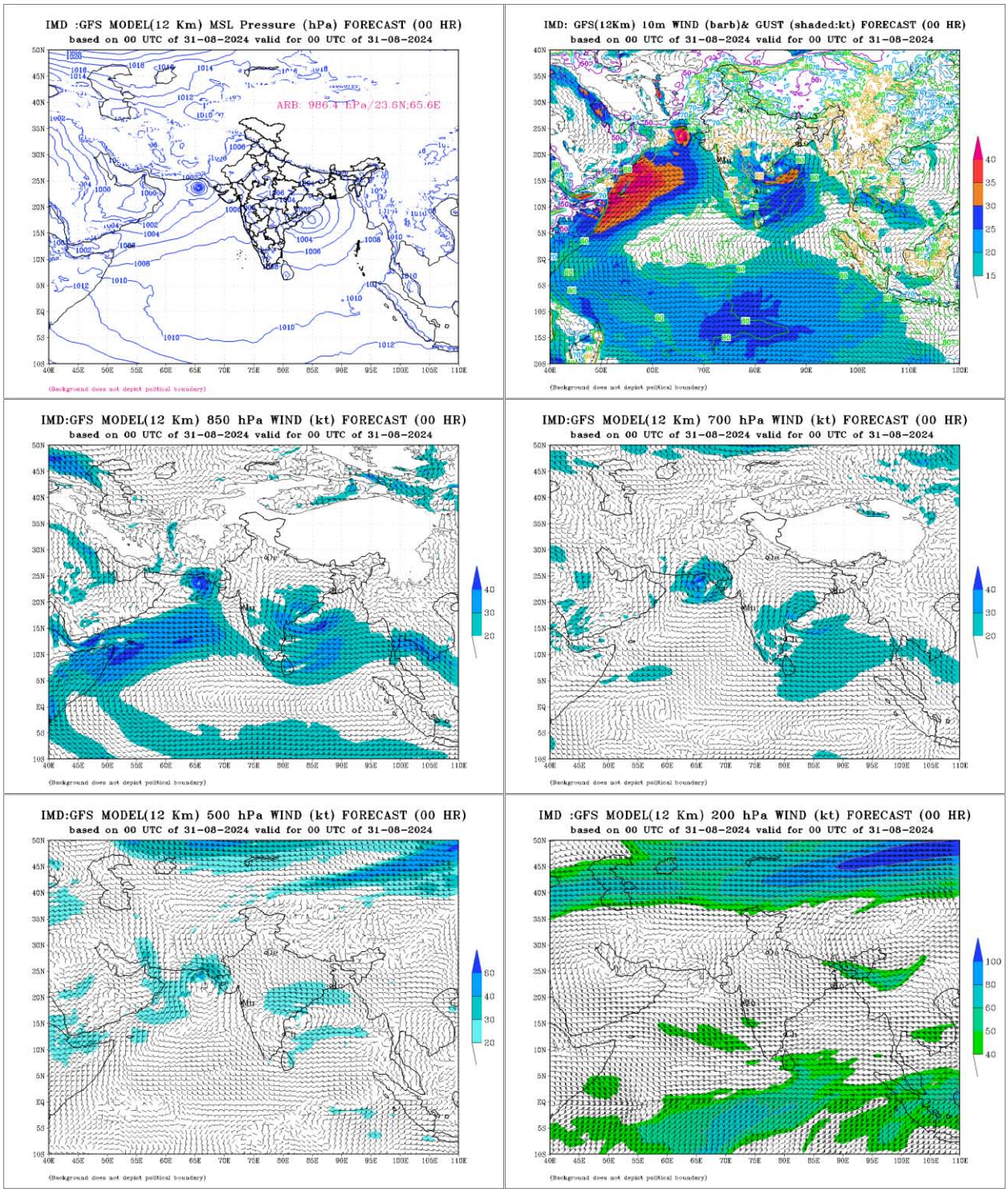


Fig.2.5.7 (g).: IMD GFS mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 31st August, 2024

The GFS model analysis for 31st August **Fig. 2.5.7 (g)** indicated the system over the Northeast Arabian Sea with more than 4 closed isobars, indicating further intensification of the system with associated cyclonic circulation extending up to 500 hPa level. The 200 hPa level wind indicated feeble cyclonic centre indicating intensification of the system with increasing its vertical extension. It may be mentioned here that the system reached its peak intensity of 40 kts at 0000 UTC of 31st August.

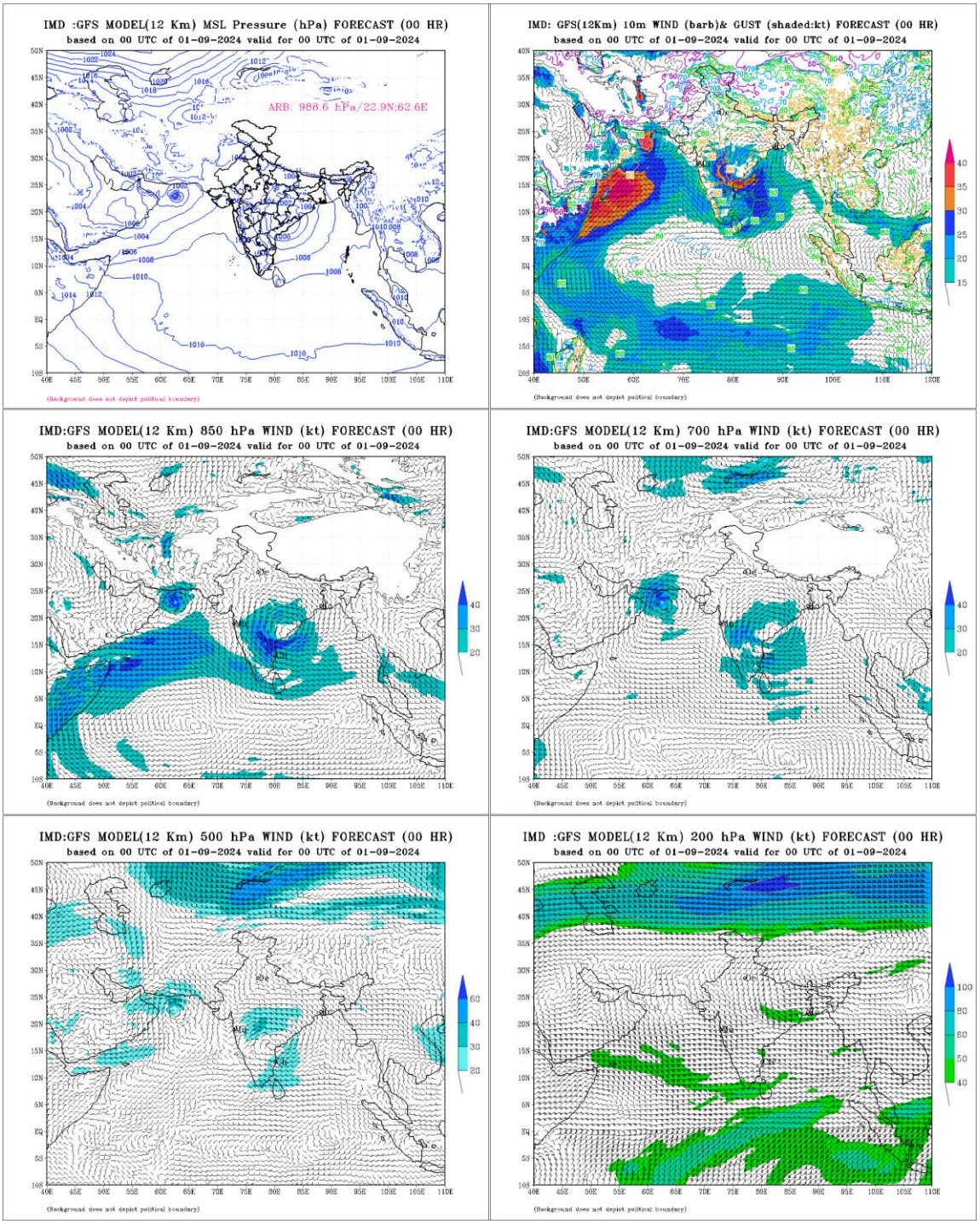


Fig 2.5.7.(h): IMD GFS mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 1st September, 2024

The GFS model analysis for 1st September 0000 UTC **Fig. 2.5.7.(h)** indicated the system over the Northwest Arabian Sea maintaining its intensity of tropical cyclone with 4 closed isobars and associated cyclonic circulation extending up to 500 hPa level.

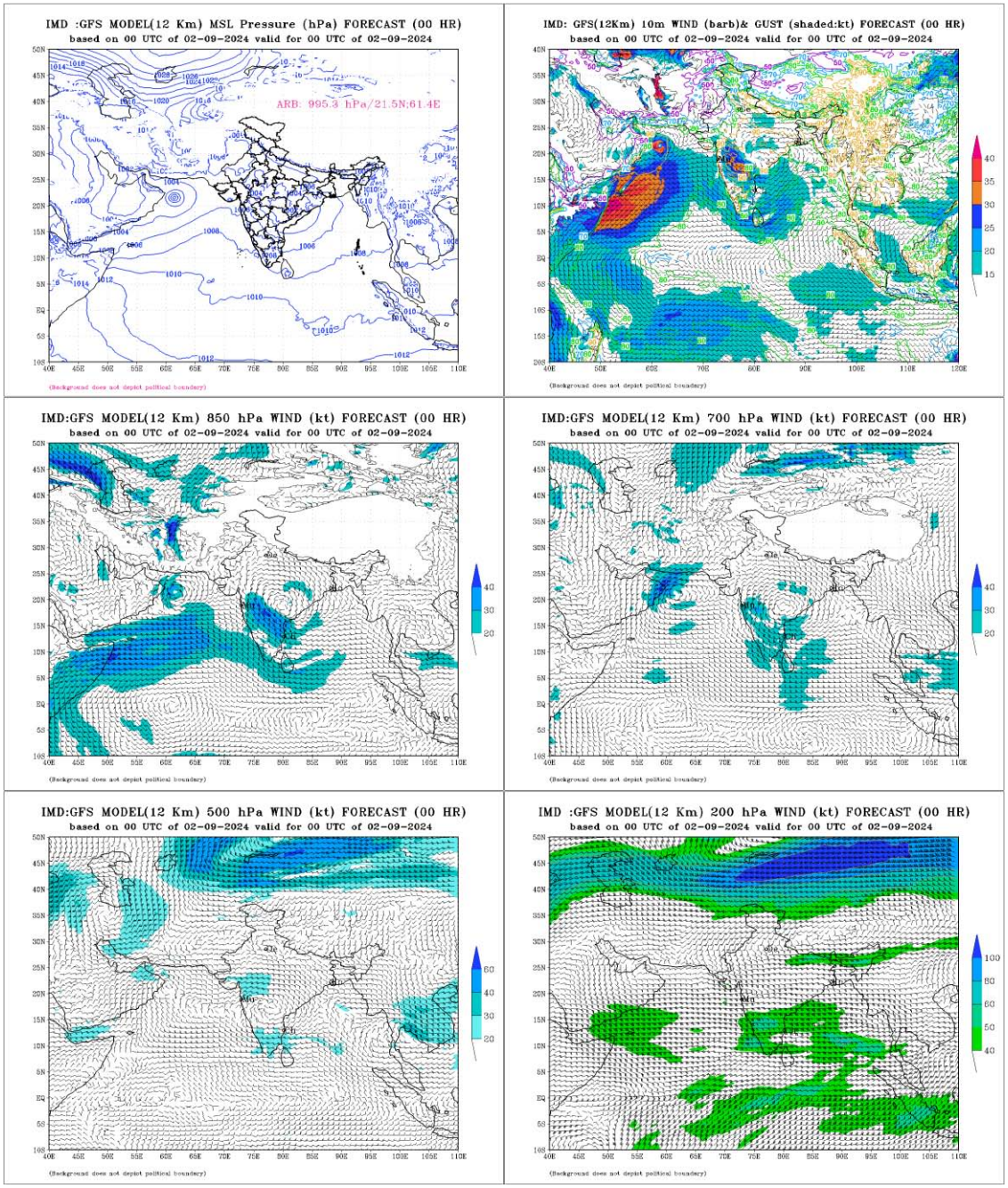


Fig.2.5.7 (i): IMD GFS mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 2nd September, 2024

The GFS model analysis of 2nd September **(Fig. 2.5.7.9)** indicated a weakening of the system over the northwest Arabian Sea with reduced size and number of closed isobars remaining 2 to 3 only. The associated cyclonic circulation at 500 hPa is very feeble. It may be mentioned here that the system had weakened into a Depression on 2nd morning over the northwest Arabian Sea and on the same day it weakened into a low-pressure area in the afternoon.

2.5.6. Realized rainfall

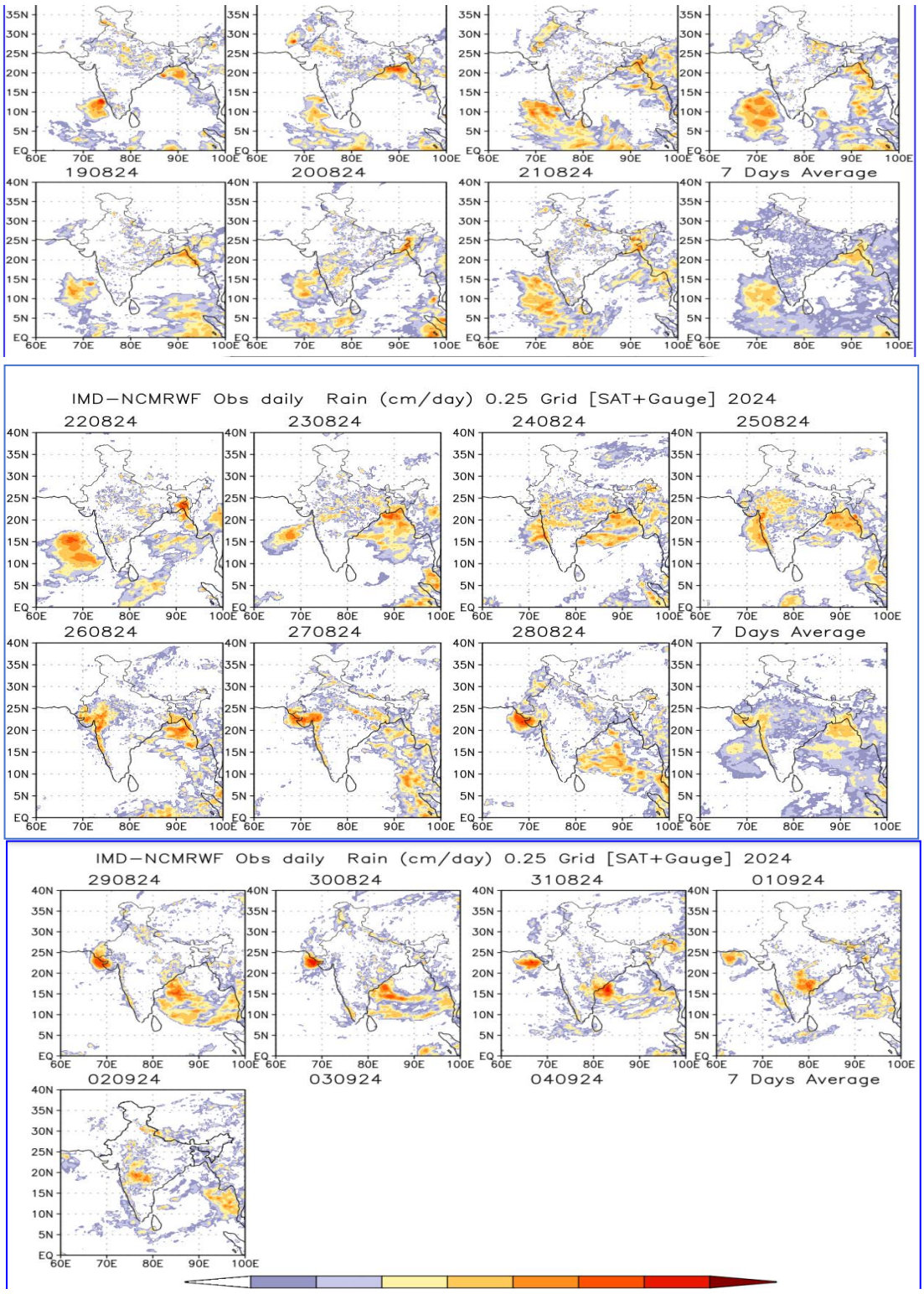
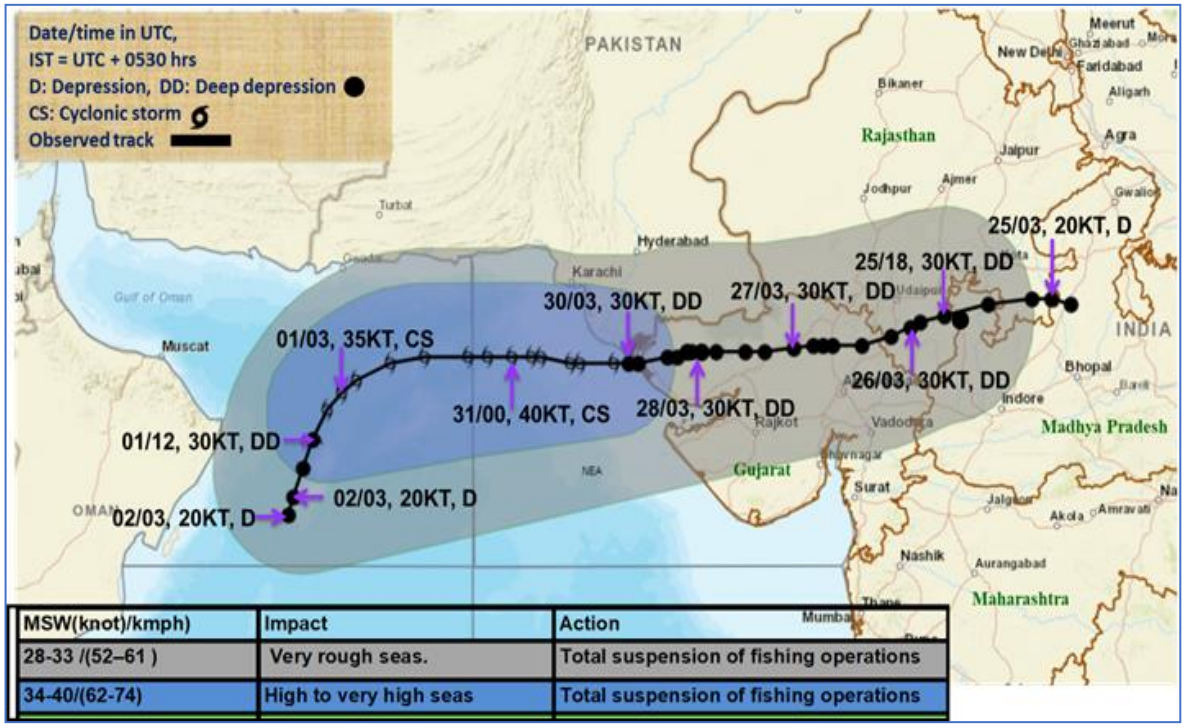


Fig. 2.5.8: NCMRWF-IMD satellite gauge merged data plots of 24 hours accumulated realized rainfall ending at 0830 IST of 15th August to 2nd September, 2024

As seen in **Fig. 2.5.8** the rainfall over north BoB and the adjoining coastal region of Odisha on 23rd August. The belt gradually moved westward along with the movement of the system over central and western parts of India covering Chhattisgarh, Madhya Pradesh, Maharashtra, Rajasthan and Gujarat.

Maximum sustained wind speed (MSW)



MSW(knot)/kmph)	Impact	Action
28-33 /(52–61)	Very rough seas.	Total suspension of fishing operations
34-40/(62-74)	High to very high seas	Total suspension of fishing operations

Fig. 2.5.9: Estimated maximum sustained wind during the life cycle of CS ASNA.

The system reached its peak intensity of maximum sustained wind speed of 40 knots gusting to 50 knots (70-80 kmph gusting to 90 kmph) at 0000 UTC (0530 IST) 31st August with estimated central pressure (ECP) of 990 hPa and pressure drop of about 8 hPa over Northeast Arabian Sea **(Fig. 2.5.9).**

2.5.7 Damage due to CS ASNA

As per media reports, flooding in Gujarat killed 49 people between 25 and 31 August. The flooding also resulted in the death of 2,618 livestock. Crops were destroyed in several districts in Kutch and Saurashtra regions. In Vadodara and elsewhere, there was extensive damage to houses, shops and businesses. 4,173 km of roads were damaged. Total 6,931 villages and 17 cities were affected by the loss of electricity. Total 88 substations were shut down during the flooding. An old bridge between Bodeli and Chhota Udepur on the national highway collapsed. An initial survey reported that the Government of Gujarat suffered damages worth more than ₹250 crore (US$29 million) to government properties and public infrastructure. **Fig. 2.5.10.**

Fig. 2.5.10: (a) A Flooded Area at Kothara village in Kutch District, Image: Ahmedabad Mirror, (b): A flooded area at Kothara village in Kutch district, Image: DNA, (c): Image: PTI

2.6. Depression over Westcentral and adjoining Northwest Bay of Bengal during 31st August-02nd September 2024

2.6.1 Introduction

- Under the influence of the cyclonic circulation over eastcentral Bay of Bengal (BoB) & neighbourhood, a low pressure area formed over central and adjoining north BoB in the morning (0830 hours IST/0300 UTC) of the 29th August, 2024.
- It lay as well marked low pressure area over westcentral & adjoining northwest BoB off north Andhra Pradesh & South Odisha coasts in the morning (1130 hours IST/0600 UTC) of 30th August, 2024.
- It concentrated into a Depression over the westcentral & adjoining northwest BoB off north Andhra Pradesh & South Odisha in the early morning (0530 hours IST/0000 UTC) of the 31st August, 2024.
- It moved northwestwards and lay over north Andhra Pradesh coast, close to southwest of Kalingapatnam in the midnight (2330 hours IST/1800 UTC) of 31st August, 2024. Moving further northwestwards, it crossed north Andhra Pradesh & south Odisha coasts near Kalingapatnam between 0030 and 0230 hrs IST (1900 UTC and 2100 UTC of 31st August) of the 1st September.
- It moved west-northwestwards and weakened into a Well Marked Low Pressure Area over central parts of Vidarbha and neighbourhood in the evening (1730 hours IST) of the 02nd September, 2024.
- It lay as low pressure area over west Vidarbha & neighbourhood in the morning (0830 hours IST/0300 UTC) of 3rd September, 2024. The observed track of the system is presented in Fig.2.6.1.

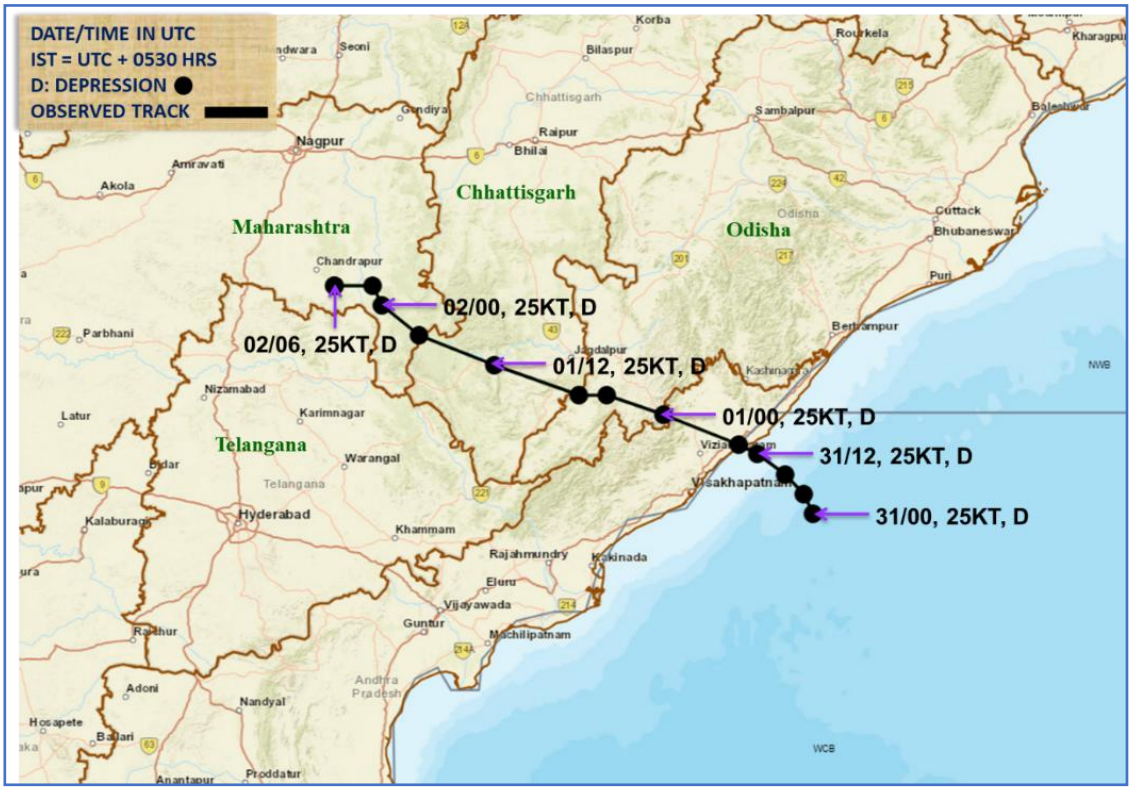


Fig. 2.6.1: Observed track of Depression over Westcentral Bay of Bengal

Table 2.6.1: Best track positions and other parameters of the Depression over Northwest and adjoining Westcentral Bay of Bengal during 31st August-02nd September 2024

Date	Time (UTC)	Lat.	Long.	C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (KT)	Estimated Pressure drop at the Centre (hPa)	Grade
31.08.24	0000	17.5	84.6	1.5	998	25	3	D
	0300	17.7	84.5	1.5	997	25	3	D
	0600	17.9	84.3	1.5	996	25	3	D
	1200	18.1	84.0	1.5	997	25	4	D
	1800	18.2	83.8	1.5	997	25	4	D
	crossed north Andhra Pradesh & south Odisha coasts near Kalingapatnam between 1900-2100 UTC							
01.09.24	0000	18.5	83.0	1.5	997	25	4	D
	0300	18.7	82.4	1.5	998	25	3	D
	0600	18.7	82.1	1.5	999	20	3	D
	1200	19.0	81.2	1.5	999	20	3	D
	1800	19.3	80.4	1.5	999	20	3	D
02.09.24	0000	19.6	80.0	1.5	999	20	3	D
	0300	19.7	79.7	1.5	999	20	3	D
	0600	19.8	79.5	1.5	999	20	3	D
	1200	Weakened into a well-marked low-pressure area over central parts of Vidarbha and neighbourhood.						

KT: Knots (nautical mile per hour), 1 KT=1.85 kmph, D: Depression, DD: Deep Depression

2.6.2. Brief life history - Genesis Intensification and movement

2.6.2.1 Genesis

A low pressure area was formed over central and adjoining north BoB in the morning (0830 hours IST/0300 UTC) of the 29th August, 2024. It became well marked low pressure area over westcentral & adjoining northwest BoB off north Andhra Pradesh & South Odisha coasts in the morning (1130 hours IST/0600 UTC) of 30th August, 2024. It concentrated into a Depression over the westcentral & adjoining northwest BoB off north Andhra Pradesh & South Odisha in the early morning (0530 hours IST/0000 UTC) of the 31st August, 2024.

At 0300 UTC of 31st August, the Madden Julian Oscillation (MJO) index was in phase 5 with amplitude greater than 1. It moved across the same phase during the next 5 days with amplitude remaining higher than 1 throughout.

The sea surface temperature over the BoB and Arabian Sea was 28-29°C. Tropical Cyclone Heat Potential (TCHP) was high (>100 kJ/cm²) over central BoB. The low-level relative vorticity was positive and was around 150×10^{-5} s^{-1} over central BoB with extension up to mid-tropospheric levels. Low-level convergence was 10×10^{-5} s^{-1} to the south of the

low-pressure area and upper-level divergence was $20x10^{-5}$ s^{-1} around the system area extending up to southwest BoB. The vertical wind shear was low to moderate over central and north BoB. Lower-level winds indicate broadscale circulation developing over the central BoB.

At 0300 UTC of 1st September, the depression lay over south Odisha and adjoining south Chhattisgarh & north Andhra Pradesh, the low-level relative vorticity was positive and was around $100x10^{-5}$ s^{-1} over coastal Andhra Pradesh with extension up to mid-tropospheric levels. Low-level convergence was $30x10^{-5}$ s^{-1} to the southwest of the system area, and upper-level divergence was $20x10^{-5}$ s^{-1} to the west of the system area. The vertical wind shear was moderate over the system area and is likely to be high along the predicted path.

At 0300 UTC of 2nd September, in association with the depression over east Vidarbha and adjoining Telangana, the low-level relative vorticity has decreased and was around $60\text{-}80x10^{-5}$ s^{-1} over Vidarbha with extension up to mid-tropospheric levels. Low-level convergence was $15\text{-}20x10^{-5}$ s^{-1} to the southwest of the system area. Upper-level divergence was $05\text{-}10x10^{-5}$ s^{-1} to the west of the system area. The vertical wind shear was moderate (15-20) over the system area and along the forecast track. The depression lay close to coast and hence there was land interaction. Under such circumstances, it did not intensify further.

2.6.3. Monitoring

India Meteorological Department (IMD) maintained round the clock watch over the north Indian Ocean (NIO) and the system was monitored well in advance since 22nd August in Extended range outlook. The system was monitored with the help of available satellite observations from INSAT 3D and 3DR, polar orbiting satellites, available ships & buoy observations in the region and coastal observations on the day of landfall. 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 system. A digitized forecasting system of IMD was utilized for analysis and comparison of various models' guidance, decision making process and warning products generation.

2.6.3.1. Features observed through satellite

Satellite monitoring of the system was mainly done by using INSAT-3D and 3DR imageries. Satellite imageries of other international geostationary satellites, high resolution polar orbiting satellites and scatterometer imageries from ASCAT were also considered for monitoring of the system. Typical INSAT-3D enhanced colored imageries, visible/ IR, brightness temperature and water vapour imageries are presented in **Fig.2.6.2 (a) to (d)**. During the entire life cycle, the clouds were organized in shear pattern. The convective clouds were sheared to the southwest sector of the system. The detailed features from the satellite pictures are discussed in this section.

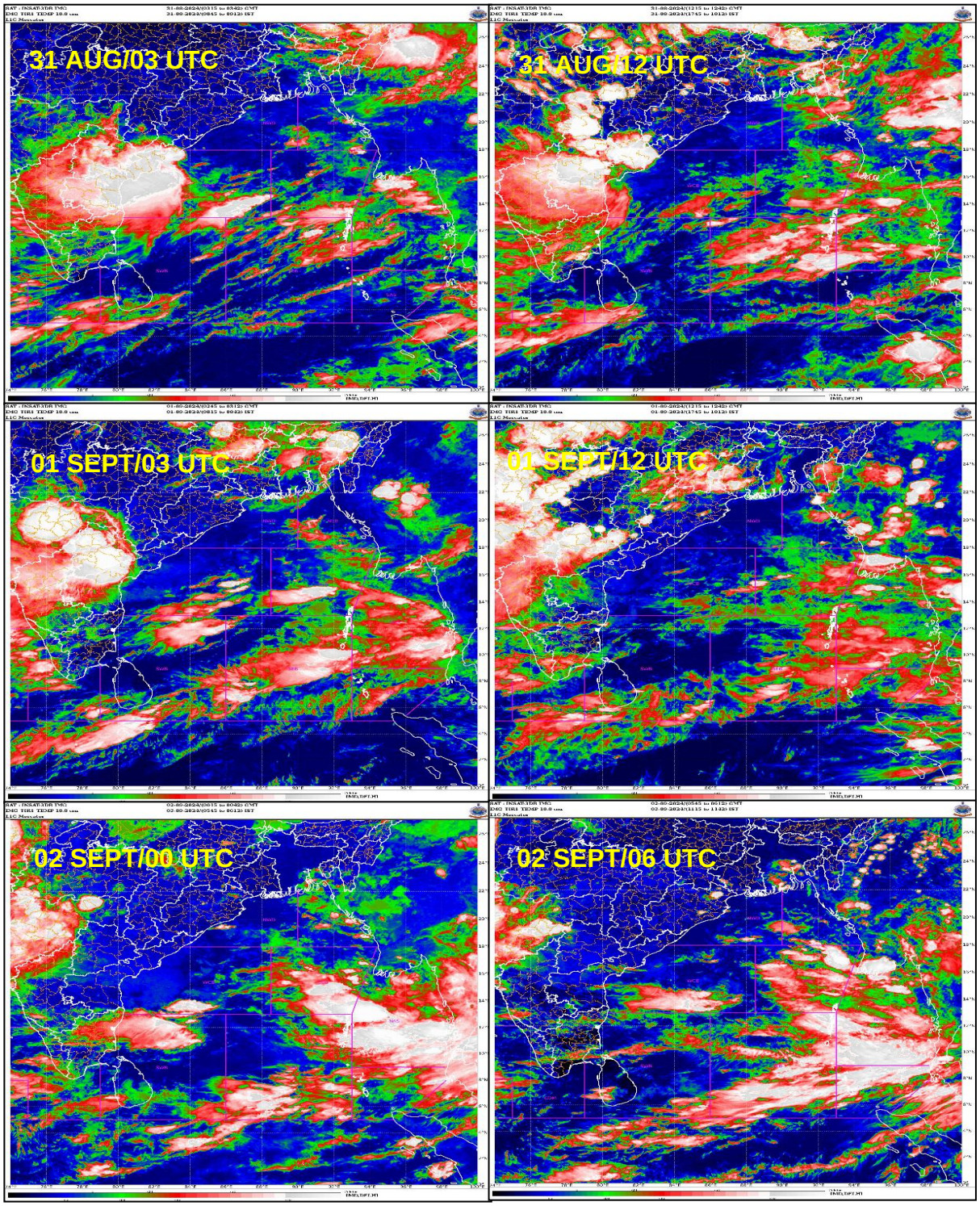


Fig.2.6.2(a): INSAT-3D enhanced colored imageries during life cycle of Depression over Northwest and adjoining Westcentral Bay of Bengal during 31 August-2 September, 2024.

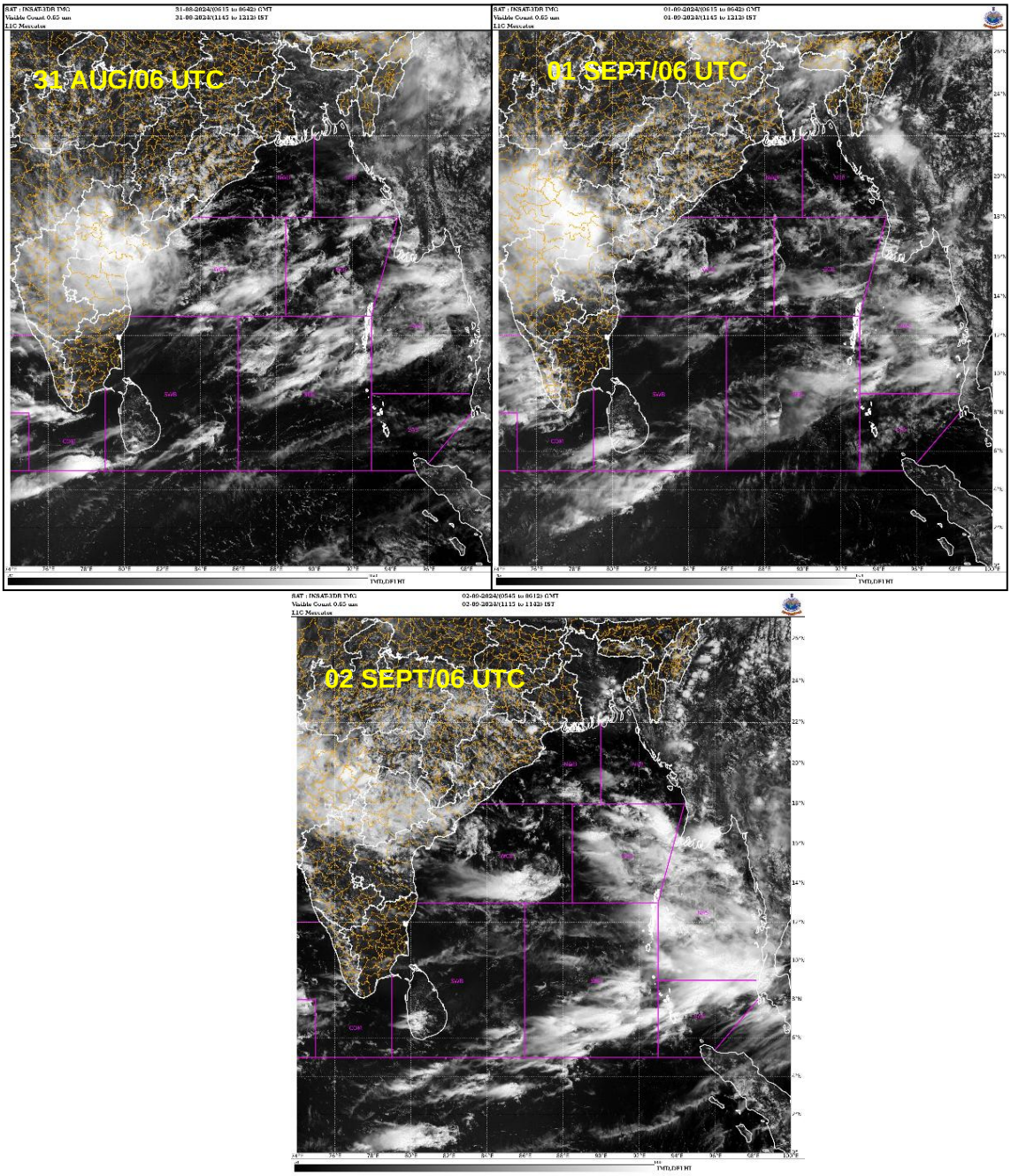


Fig.2.6.2 (b): INSAT-3D Visible imageries during life cycle of Depression over Northwest and adjoining Westcentral Bay of Bengal during 31 August-2 September, 2024.

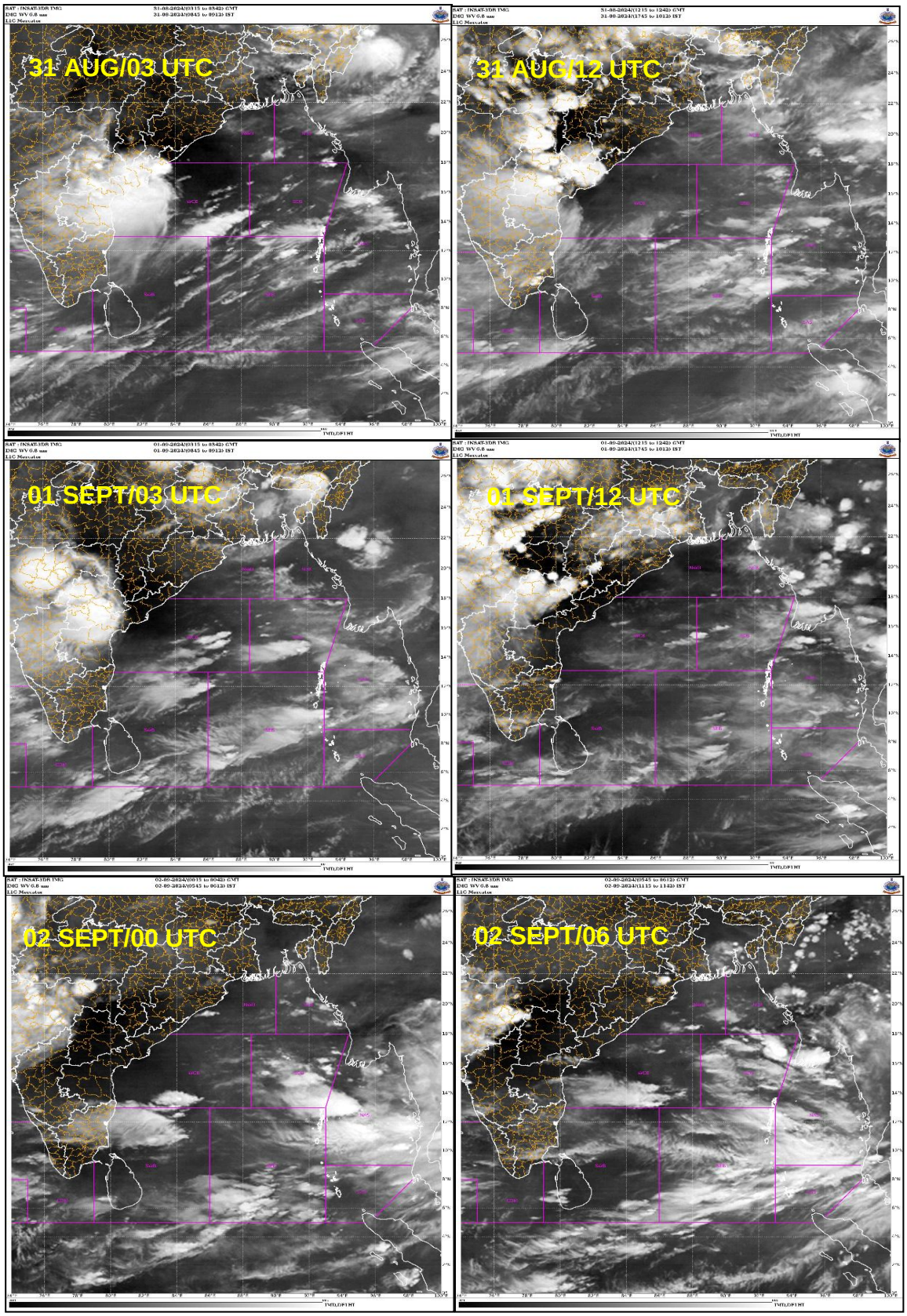


Fig.2.6.2(c): INSAT-3D IR imageries during life cycle of Depression over Northwest and adjoining Westcentral Bay of Bengal during 31 August-2 September, 2024.

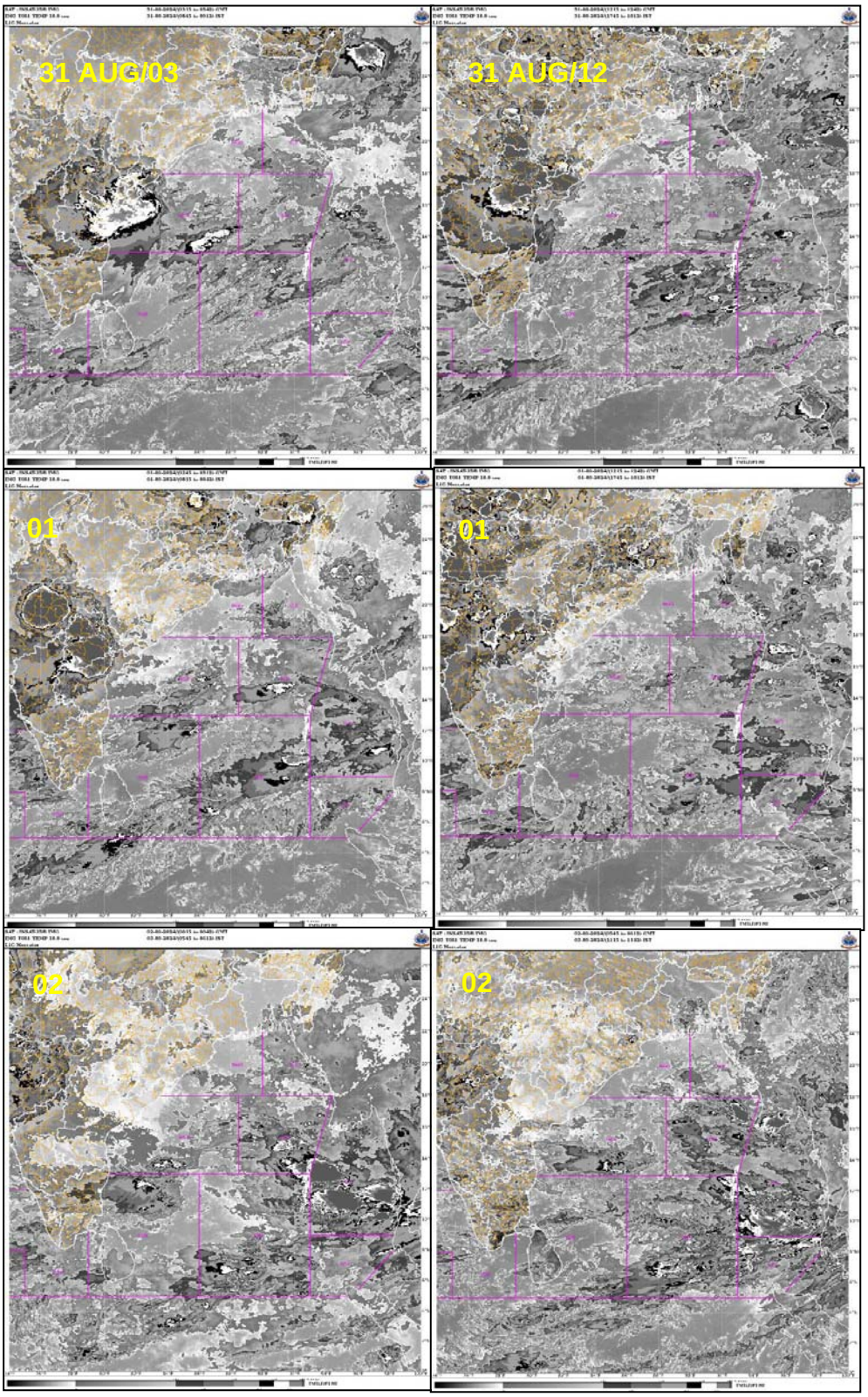


Fig.2.6.2 (d): INSAT-3D Brightness Temperature imageries during life cycle of Depression over Northwest and adjoining Westcentral Bay of Bengal during 31 August-2 September, 2024

ASCAT winds in figure 4, clearly indicated that the circulation associated with the depression over westcentral Bay of Bengal.

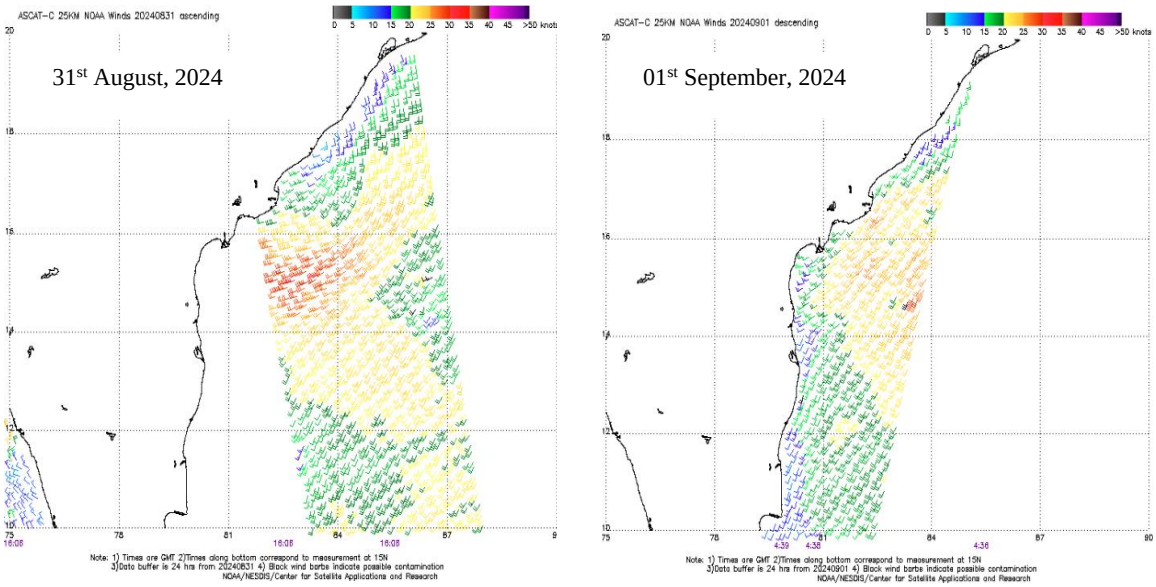


Fig.2.6.3: ASCAT winds during 31st August to 01st September, 2024

2.6.4. Dynamical Features

IMD GFS (T1534) daily analyses at 0000 UTC of mean sea level pressure (MSLP), winds at 10 m, 850, 500 and 200 hPa levels from 19th July to 20th July are presented in **Fig. 2.6.4(a) to (c)** respectively.

The MSLP analysis field indicated a system over westcentral BoB near 18.0°N/84.0°E. GFS model was correctly capturing the initial conditions on 31st August. The model showed that vertically, the system extended up to 500 hPa level.

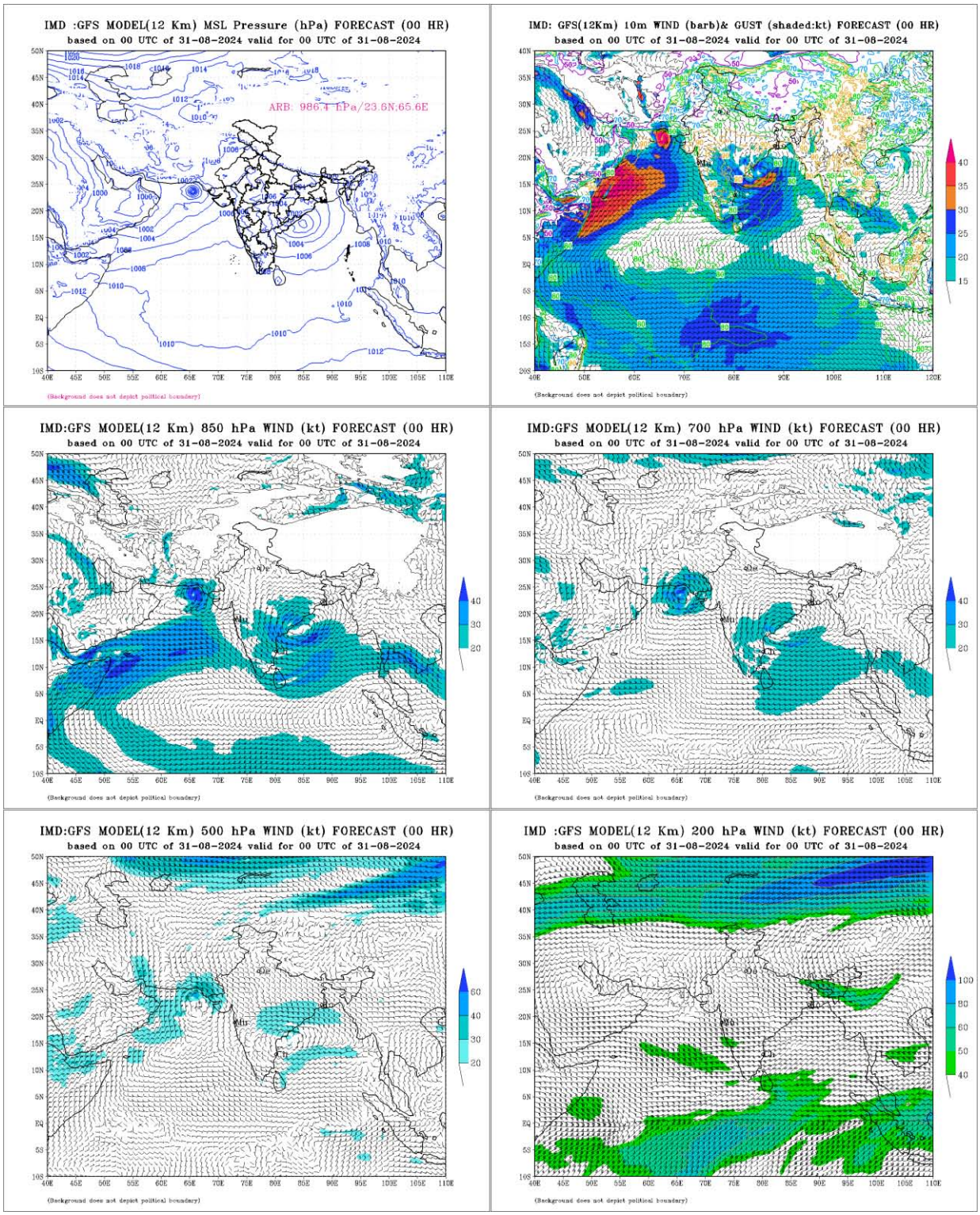


Fig. 2.6.4(a): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 31st August 2024.

At 0000 UTC of 1st September, the MSLP analysis field indicated depression over coastal Andhra Pradesh and adjoining South Odisha. The model showed that vertically, the system extended upto 500 hPa level.

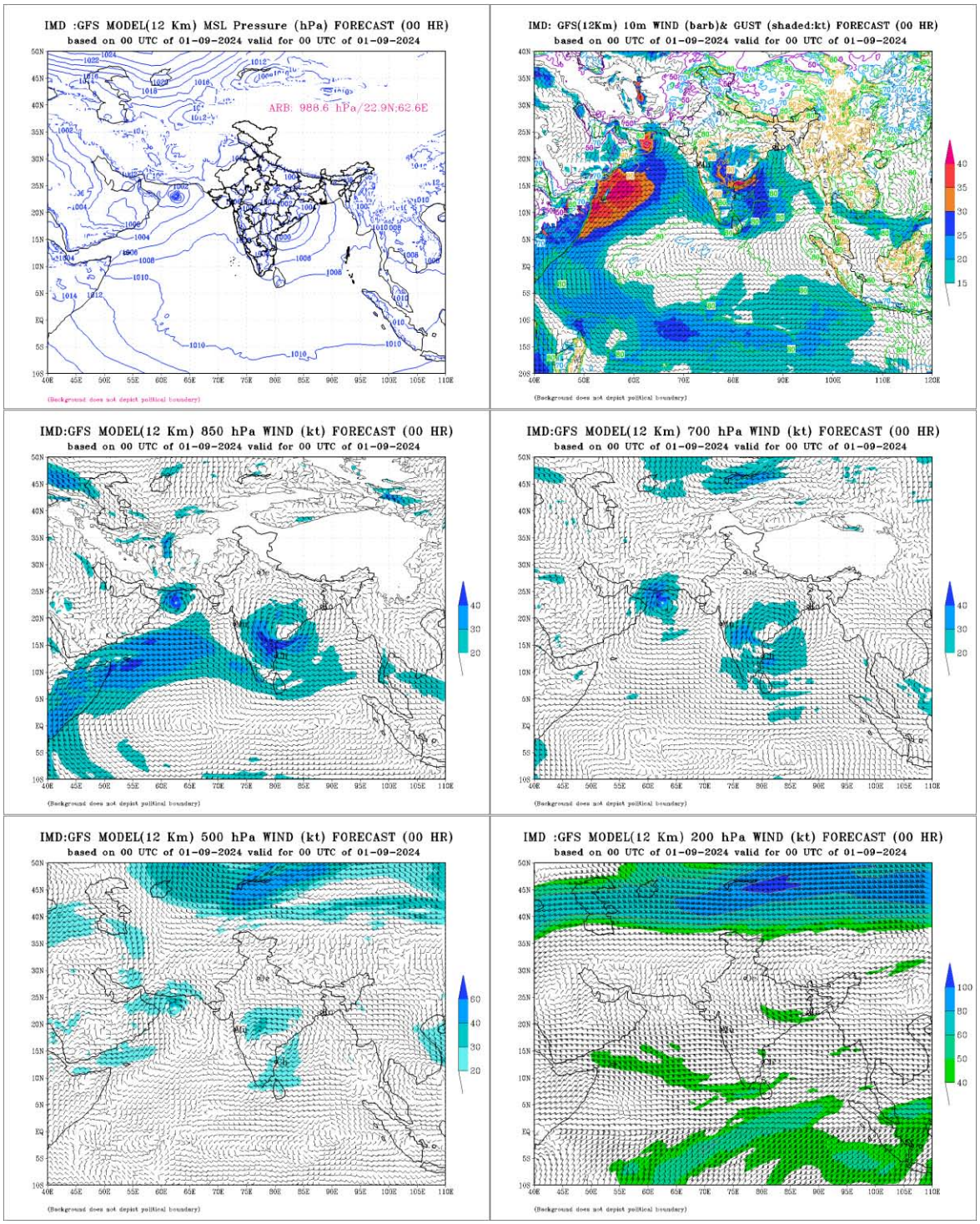


Fig. 2.6.4(b): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 1st September 2024.

At 0000 UTC of 2nd September, the MSLP analysis field indicated that the system lay over Vidarbha and neighbourhood as well marked low pressure area. The model showed that the system has extended extended upto 500 hPa level.

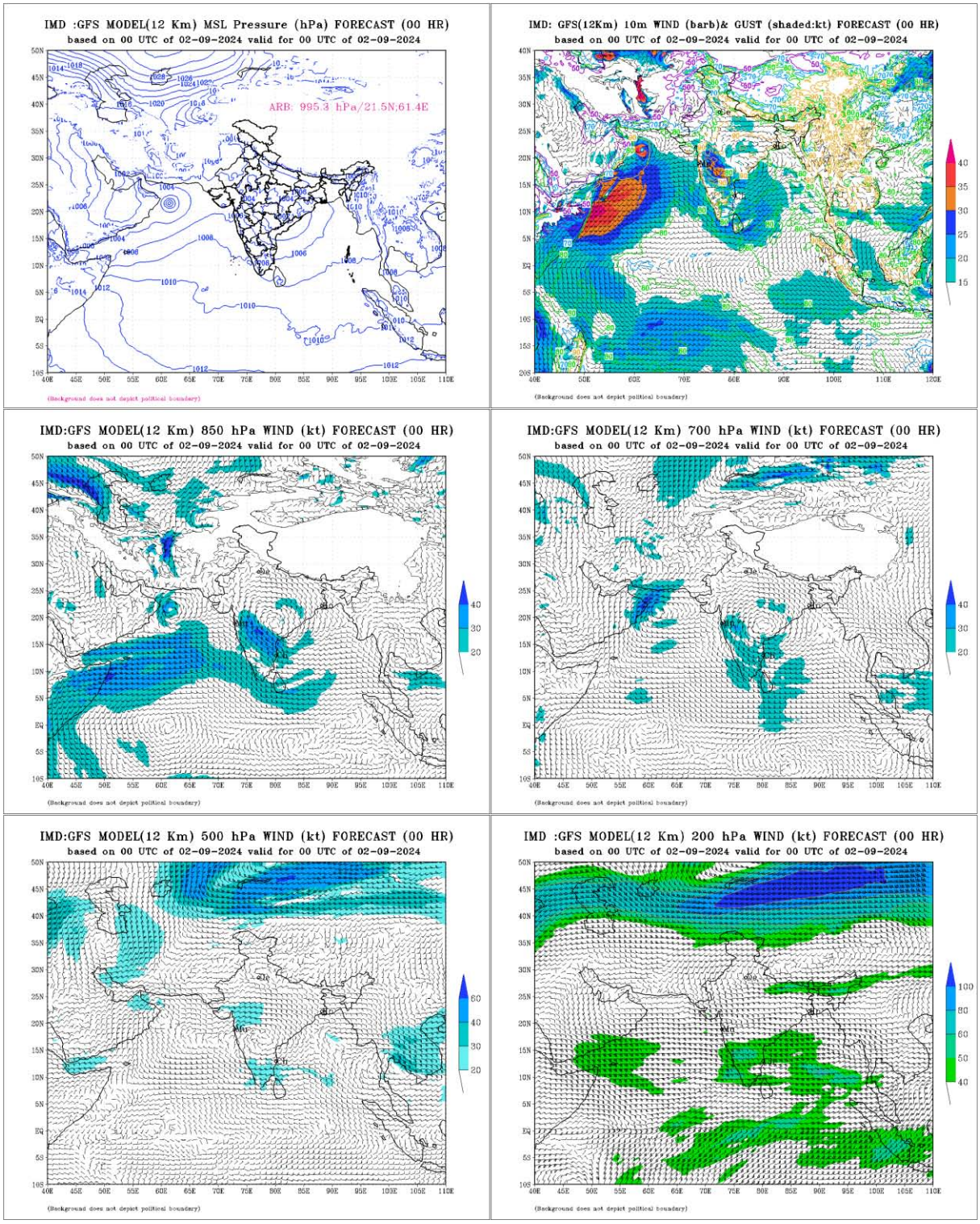


Fig. 2.6.4(c): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 2nd September 2024

2.6.5. Realized Weather

Rainfall associated with the deep depression based on IMD-NCMRWF satellite gauge merged data are depicted in Fig 2.6.5. It is seen that heavy to very heavy rainfall occurred at many places over coastal Andhra Pradesh, and at isolated places over south coastal Odisha.

Heavy to very heavy rainfall occurred at isolated places over Telangana, Vidarbah on 1st September and at isolated places over Madhya Pradesh on 2nd September. Moderate to heavy rainfall occurred at isolated places over east Gujarat, Rajasthan on 2nd September.

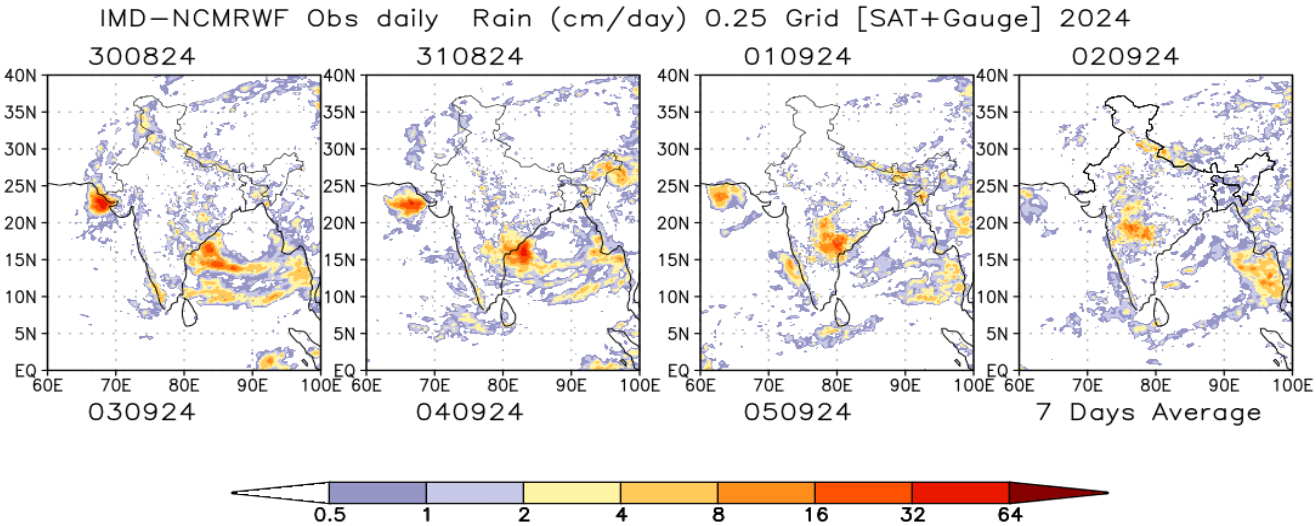


Fig. 2.6.5: NCMRWF-IMD satellite gauge merged data plots of realized 24 hours accumulated rainfall from 31st to 02nd Sept, 2024.

2.6.5.1 Rainfall forecast verification

The forecast for heavy to extremely heavy rainfall episodes in association with the system are verified with the 24 hours accumulated rainfall realized at various stations. The details of the day-wise verification are given in Table -2.6.2.

Table 2.6.2: Day wise daily 24 hours cumulative rainfall forecast verification with station observations

Date/Base Time of observation	24 hr Heavy rainfall warning ending at 0300 UTC of next day	Realised 24-hour heavy rainfall (≥ 7 cm) ending at 0300 UTC of date
31.08.2024 / 0830	**Odisha and Chhattisgarh:** Heavy to very heavy rainfall at isolated places on 31st August & 1st September over south Odisha and south Chhattisgarh. **Coastal Andhra Pradesh:** Heavy to very heavy rainfall	**01.09.2024/ 0830** **Telangana:** Mahabubabad 37, Kodada 35, Manuguru, Kusumanchi 32 each, Chilkur 31, Mattampally, Huzur Nagar 30 each, Parvathagiri, Burgampadu 29 each, Madhira, Banswada 28 each, Kodakandla 27, Dornakal, Chinthakam, Tadwai Mlg, Noothankal 26 each, Gudurwrgl 25,

	at a few places and extremely heavy rainfall at isolated places on 31st August. Light to moderate rainfall at most places with isolated heavy rainfall on 1st September. **Telangana:** Heavy to very heavy rainfall at a few places and extremely heavy rainfall at isolated places on 31st August and isolated heavy to very heavy rainfall on 1st September.	Palawancha 24, Bhadrachalam, Khammam 23 each, Aswapuram, Thollada 22 each, Sadasivanagar, Bonakal 21 each, Mothey, Bhiknur, Chennaraopet 20 each, Jajireddigudem, Konijerla, Suryapet 19 each, Bayyaram, Kamareddy 18 each, Garla, Kothagudem, Wyra Kvk 17 each Dhar Palle, Tadwai, Kothaguda, Kalwakurthy 16 each, Govindaraopet, Domakonda, Miryalaguda, Zaffergadh, Sathupalle 15 each, Jammikunta, Vangoor, Tekulapalle, Devaruppal, Achampeta, Devarakonda, Medak, Yellandu 14 each, Thimmajipeta, Kollapur 13 each, Mustabad, Papannapet, Midjil, Nanganur, Mominpet 9, Maganoor, Velpur, Narmetta, Atmakurwrgl, Nawabpetmbn, Sultanabad, Nawabpet, Chigurumamidy, Tamsi, Pebbair, Nangnoor, Bomraspeta, Nidamanur, Doma, Narayanpet, Boath, Gangadhara, Hathanoora, Bachhanpet, Kothakota, Jagadevpur 9 each, Talamadugu, Peddamandadi, Jangaon, Kondurg, Yadagirigutta, Veepangandla, Julapalle, Atmakur Wnp, Ramannapeta, Nallabelly, Bazarhathnoor, Vicarabad, Pargi, Tandur, Wargal, Chegunta, Atmakur M, Pedda_adiserlapalle, Yacharam, Ghatkesar, Kondapak, Naga Reddipet, Maheswaram, Konaraopeta, Navipet, Wankdi, Utnur 8 each, Bhuvanagiri, Dindigul, Narva, Asifabad 7 each, Tandur, Huzurabad, Chandrugonda, Neredcherla, Varni, Thimmapur, Shadnagar, Khammam Urban 13 each, Jadcherla, Kodangal, Kosgi, Yellandu, Kowdipalle, Chandur, Bhoothpur, Gandeed, Khila Ghanpur, Choppadandi, Karimnagar, Mulakalapalle 12 each, Alladurg, Narsampet, Mahbubnagar, Nalgonda, Sangem, Khanapur, Maddur, Narsapur, Hanwada, Lingampet, Damaragidda, Koilkonda, Julurpad, Pochampalle, Gandhari, Tekmal, Yellareddypeta, Pinapaka 11 each, Regode, Wanaparthy, Enkuru, Aswaraopeta, Chandurthi, Palakurthi,

		Shankarapatnam, Bheemgal, Nagarjuna Sagar, Yellareddy, Chevella, Ibrahimpatnam, Ramayampet, Gopalpet, Choutuppal, Chinna Chinta Kunt 10 each, Jogipet 9, Pitlam, Peddemul, Bala Nagar, Peddapalle, Nagar Kurnool, Ghanpur, Bejjanki, Kagaznagar, Daira, Palem, Addakal, Asifabad, Mulug, Raghunathpalle, Esci_gachibowli, Saroornagar, Venkatapuram, Kondapur, Sirsilla, Sangareddy, Mudhole, Kukatpally Jntu, Marriguda, Utkoor, Venkatapur, Nirmal, Sarangapurnrl, Dubbak, Kammar Palle, Kathlapur 7 each, **Coastal Andhra Pradesh & Yanam:** Amaravati, Tiruvuru 26 each, Guntur 23, Kukunoor 20, Atchampet 19, Tenali 18, Mangalagiri, Nandigama, Piduguralla, Macherla 17 each, Velairpad 16, Nuzvid 14, Mundlamuru, Kunavaram 14 each, Jangamaheswarapuram, Bapatla, Vijayawada 13 each, Santhamaguluru, Vararamachandrapur 12 each, Avanigada, Addanki, Vijayawada A.p., Chintur 11 each, Karamchedu 10, Kaikalur, Sattenapalle, Repalle 9 each, Anakapalle, Yelamanchili, Markapur, Chimakurthi 8 each, Podili, Ongole, Gudivada 7 each. **Vidarbha:** Kalamb 12, Digras 11, Deoli, Mahagaon 10 each, Pandherikawara, Umerkhed, Babulgaon, Ralegaon, Yeotmal 9 each, Zarizamni 8, Pusad, Arni, Ghatanji, Maregaon, Wani, Yeotmal 7 each. **Marathwada:** Kinwat 18, Himayatnagar 17, Mahur 11, Hadgaon 9, Bhokar, Umarga 7 each. **Odisha:** Padia 14, Chhattisgarh: Dornapal 11, Konta 10, East **Madhya Pradesh:** Harrai, Kirnapur 9 each. **West Madhya Pradesh:** Maksudangarh 7. **Rayalaseema:** Nandikotkur, Jupadu Bungalow, Atmakur 9 each, Pagidyala 8.
01.09.2024 / 0830	**South Odisha and south Chhattisgarh:** Heavy rainfall at isolated places on	**02.09.2024/ 0830** **Marathwada:** Manvat 31, Dhalegaon - 26, Mantha, Pathri 23 each, Partur 22,

	1st September. **North Andhra Pradesh:** Isolated heavy to very heavy rainfall. **Telangana:** Heavy to extremely heavy rainfall at isolated places over Telangana on 1st September and isolated heavy rainfall over north Telangana on 2nd September. **Vidarbha:** Heavy to extremely heavy rainfall at a few places and extremely heavy rainfall at isolated places on 1st and 2nd September. **Marathwada:** Heavy to very heavy rainfall at isolated places on 1st and 2nd September. **East Madhya Pradesh:** Heavy to very heavy rainfall at isolated places is on 1st and 2nd September. **West Madhya Pradesh:** Heavy rainfall at isolated places on 1st and heavy to very heavy rainfall at isolated places on 2nd September. **Gujarat region:** Heavy rainfall at isolated places on 1st and heavy to very heavy rainfall at isolated places on 2nd September.	Sonpeth 20, Selu, Ardhapur 19 each, Udgir 16, Ambad 15, Nanded - 14, Jintur, Ghansawangi , Deoni, Parbhani 13, Ambejogai / Mominabad 13 each, Georai, Udgir, Dharur, Palam 12 each, Hingoli - Hydromet, Aundha Nagnath, Sillod, Bhokardan 11 each, Wadawani, Jalkot, Kandhar, Purna 10 each, Gangakhed, Mudkhed, Latur, Bhokar, Hadgaon, Vasmat, Ahmedpur, Washi 9 each, Phulambri, Badnapur, Kallamnuri, Renapur, Kaij 8 each, Beed, Dharmabad, Chakur, Parli Vaijnath, Kallamb, Sambhajinagar, Mukhed, Mahur, Shirur Anantpal, Bhum, Manjlegaon, Paithan, Loha, Naigaon Khairgaon, Patoda 7 each. **Telangana:** Sadasivanagar, Tadwai 24 each, Lingampet 23, Kamareddy 22, Jainoor 19, Papannapet, Utnur, Gandhari 17 each, Mirdoddi, Yellareddy, Naga Reddipet, Gambhiraopet 15 each, Khanpur 14, Laxmanchanda, Dubbak 13 each, Balkonda, Tekmal, Metpalle, Nirmal, Yellareddypeta, Kondapak, Mallapur, Alladurg, Dandepalle 12 each, Kampasagar, Sarangapur, Bhiknur, Bejjanki, Mortad, Banswada, Navipet 11 each, Domakonda, Peddapalle, Nanganur, Medak, Elagaid, Sangem, Husnabad, Dilawarpur, Belampalle, Jangaon 10 each. **West Madhya Pradesh:** Bhagwanpura, Bhikangaon 13 each, Khargone 10, Gogawan, New Harsud 9 each, Khandwa, Dabra 7 each, **East Rajasthan:** Jaipur Aero 12, Nasirabad 11, Sanganer Tehsil Sr 9, Thanagazi, Bassi 8 each, Srimadhopur, Vijaynagar Sr 7 each, **Gujarat Region:** Waghai 11, Bodeli 7. **Madhya Maharashtra:** Pathardi 9, **West Rajasthan:** Nawa 7, **Vidarbha:** Pusad 10, Digras 7.
02.09.2024 / 0830	**Gujarat region:** Very heavy to extremely heavy rainfall at isolated places on 2st and 3rd September. **Madhya Maharashtra:**	**03.09.2024/ 0830** **Gujarat Region:** Valia 37, Songadh, Mangrol 25 each, Vyara 22, Maktampur_aws 20, Bharuch 19, Nadiad, Netrang, Tilakwada 17 each, Dolvan 16,

	Very heavy to extremely heavy rainfall at isolated places on 2nd September and isolated heavy rainfall on 3rd September. **Marathwada:** Heavy to very heavy rainfall at isolated places on 2nd September. **Vidarbha:** Heavy to very heavy rainfall at a few places on 2nd September and isolated heavy rainfall on 3rd September. **East Madhya Pradesh:** Heavy rainfall at isolated places on 2nd September. **West Madhya Pradesh:** Heavy to very heavy rainfall at isolated places on 2nd and 3 rd September. **East Rajasthan:** Heavy rainfall at isolated places on 2nd September. **Telangana:** Heavy rainfall over north Telangana on 2nd September. **Saurashtra & Kachchh:** Heavy rainfall at isolated places on 2st and very heavy rainfall on 3rd September.	Vansda, Uchchhal, Subir 15 each, Daman 14, Bayad, Kapadvanj 13 each, Karjan, Lunawada, Valod, Nandod, Valsad, Mandvi, Prantij 12 each, Kathalal, Himatanagar, Bayad, Mahesana 11 each, Waghai, Garudeshwar, Umerpada, Virpur, Vagra, Balasinor, Kamrej 10 each. **Madhya Maharashtra:** Navapur 16, Nandgaon 9, Gaganbawada, Gidhade 7 each, **West Madhya Pradesh:** Gandhwani 16, Kukshi 14, Sardarpur, Bagh 13 each, Jabot 12, Jhabua, Dahi, Rama 11 each, Alirajpur 10, Udaigarh, Meghnagar 8 each, Ranapur, Manawar, Khalwa 7 each, **Telangana:** Tekmal 11, Papannapet, Kowdipalle 8 each, Naga Reddipet, Yellareddy 7 each, **East Rajasthan:** Bhungra 11, Devel, Sajjangarh, Kherwara 10 each, Ganeshpur, Kesarpura, Sallopat 7 each, **Vidarbha:** Mangrulpir 8.

2.6.6. Damage due to the system

No damage was reported in association with this system.

2.7. Deep Depression over Westcentral and adjoining Northwest Bay of Bengal during 8th to 10th September, 2024

2.7.1. Introduction

- A low pressure area formed over Westcentral & adjoining Northwest Bay of Bengal (BoB) off north Andhra Pradesh & adjoining south Odisha coasts in the morning (0830 hours IST/0300 UTC) of 5th September, 2024. It lay as a Well-Marked Low Pressure Area over the northwest and adjoining central BoB in the morning (0830 hours IST/0300 UTC) of 7th September, 2024.
- It concentrated into a **Depression** in the early morning (0530 hours IST) of the 8th September, 2024 over westcentral and adjoining northwest BoB.
- It intensified into a **Deep Depression** in the same mid-night (2330 hours IST) of 8th September, 2024 over the same region.
- It moved northwestwards and crossed Odisha coast close to north of Puri around 0500 UTC of 9th September, 2024. Continuing to move northwestwards, it weakened into a **Depression** in the mid-night (2330 hours IST) of 9th September, 2024 over interior Odisha.
- It moved northwestwards and weakened into a **Well-Marked Low pressure area** over Northeast Madhya Pradesh and neighbourhood in the evening (1730 hours IST) of 10th September.
- The observed track of the system is presented in **Fig.2.7.1**. Best Track parameters associated with the system are presented in Table 2.7.1.

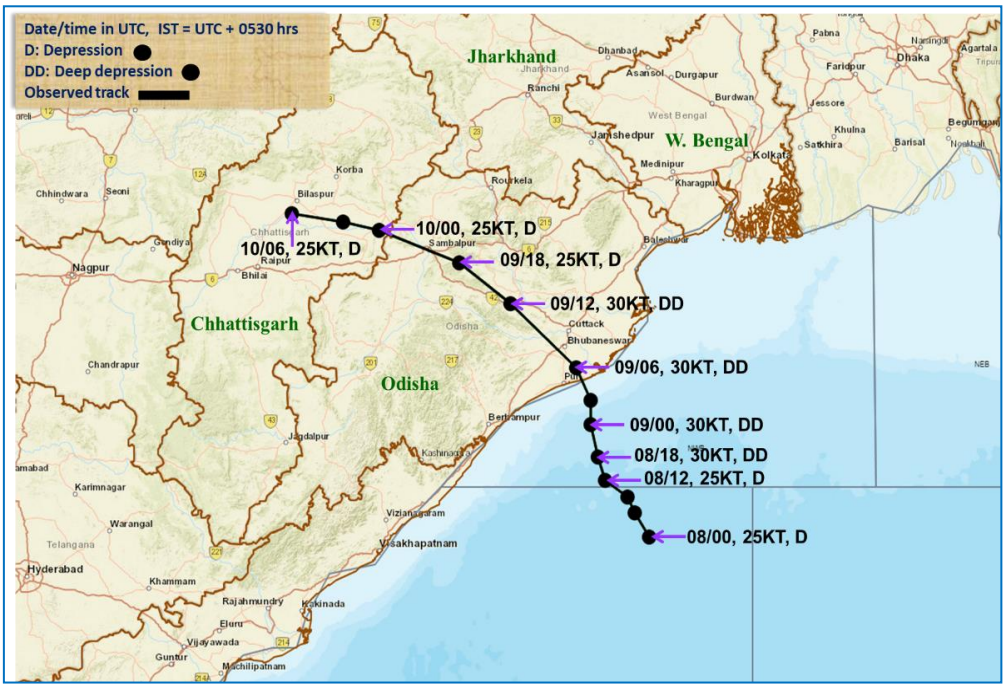


Fig. 2.7.1: Observed track of Deep Depression over Westcentral and Southwest Bay of Bengal during 8th September – 10th September, 2024

Table 2.7.1: Best track positions and other parameters of the Deep Depression over Westcentral and adjoining Northwest Bay of Bengal during 08th Sept – 10th Sept, 2024.

Date	Time (UTC)	Lat.	Long.	ECP	ΔP	MSW (kt)	Category
08.09.24	0000	17.9	87.0	998	3	25	D
	0300	18.2	86.8	998	3	25	D
	0600	18.4	86.7	997	3	25	D
	1200	18.6	86.4	995	4	25	D
	1800	18.9	86.3	993	5	30	DD
09.09.24	0000	19.3	86.2	991	6	30	DD
	0300	19.6	86.2	991	6	30	DD
		Crossed Odisha coast close to north of Puri around 0500 UTC of 9th September, 2024					
	0600	20.0	86.0	992	6	30	DD
	1200	20.8	85.1	994	5	30	DD
	1800	21.3	84.4	995	4	25	D
10.09.24	0000	21.7	83.3	995	4	25	D
	0300	21.8	82.8	996	3	25	D
	0600	21.9	82.1	996	3	25	D
	1200	Weakened into a well-marked low-pressure area over Northeast Madhya Pradesh and neighbourhood.					

KT: Knots (nautical mile per hour), 1 KT=1.85 kmph, D: Depression.

2.7.2. Brief life history - Genesis Intensification and movement

2.7.2.1. Genesis

A low pressure area formed over westcentral & adjoining northwest Bay of Bengal off north Andhra Pradesh & adjoining south Odisha coasts in the morning (0830 hours IST/0300 UTC) of 5th September, 2024. It organized further and lay as a Well-Marked Low Pressure Area over the northwest and adjoining central Bay of Bengal in the morning (0830 hours IST/0300 UTC) of 7th September, 2024. Subsequently, it concentrated into a Depression in the early morning (0530 hours IST/0000 UTC) of the 8th September, 2024 over westcentral and adjoining northwest Bay of Bengal.

The large-scale environmental parameters indicated that the depression over westcentral Bay of Bengal (BoB) was in a favourable condition for its genesis and further inensification. Sea Surface Temperature was 29-30°C over westcentral & adjoining eastcentral BoB. It was higher around 32°C over northwest BoB off Odisha coast. Tropical Cyclone Heat Potential was 60-80 KJ/cm^2 near system location. It was slightly higher over northwest BoB (100 KJ/cm^2). Thus, during its north-northwestwards movement, it entered into warm oceanic area.

The Madden Julian Oscillation (MJO) index was in phase 5 with amplitude less than 1. It continued in same phase during next 4 days. Thus, MJO signal supported the enhancement of convective activity over north BoB. The NCICS product-based guidance on equatorial waves indicated strong westerly winds (5-7 mps) along with Equatorial Rossby Waves over south BoB and strong easterly winds (5-7mps) over North BoB. These zonal wind features and equatorial wave activity supported further intensification of the system.

2.7.2.2. Intensification and movement

The low level convergence increased to reach a value around $30x10^{-6}$ s^{-1} southwest of system centre at 0300 UTC of 8th September. The Upper level divergence also increased and was around $20x10^{-6}$ s^{-1} to the south west of system centre. The vertical wind shear (VWS) was low (05-10 kt) over system area as well as along the forecast track. The vorticity field at 850 hPa level increased and was around $200x10^{-6}$ s^{-1} to the southwest of system area due to superposition of both cyclonic and shear vorticities. Under these favourable dynamical features, the system intensified into a deep depression in the same mid-night (2330 hours IST/1800 UTC) of 8th September, 2024 over the same region.

The maximum low-level convergence zone situating to the west of the system center decreased to 20 x $10^{-6}s^{-1}$ at 1800 UTC of 8th September. However, the upper-level divergence increased to 30 x $10^{-6}s^{-1}$ over an area west of the system center and another zone of 10 x $10^{-6}s^{-1}$ to the east of the system center. The VWS was continued to be low (5-10 knots) over the system area and also along the forecast track. The relative vorticity at the 850 hPa level was around 150 x $10^{-6}s^{-1}$ oriented surrounding the system from south which was extended vertically up to the 500 hPa level.

At 0300 UTC of 9th September, the low-level convergence decreased slightly to 15 x $10^{-6}s^{-1}$ to the southwest of the system center. But the upper-level divergence remained around $30x10^{-6}s^{-1}$ over the zone southwest of the system center and decreased to $5x10^{-5}s^{-1}$ over another zone east of the system. The wind shear was low (5-10 knots) over the system area and along the forecast track which supported the system to maintain its intensity. The relative vorticity at the 850 hPa level persisted around $150x10^{-6}s^{-1}$ to the south of the system area vertically extending up to the 500 hPa level.

The low-level convergence at 1200 UTC of 9th September, was around 20 x $10^{-6}s^{-1}$ located at southwest of the system center. But during the same time, the upper-level divergence decreased to a value around 10 x $10^{-6}s^{-1}$ situating southwest of the system center. The wind shear was low (5-10 knots) over the system area and along the forecast track. The relative vorticity at the 850 hPa level decreased to 100 x $10^{-6}s^{-1}$ surrounding from the south of the system. The vertical extension was up to the 500 hPa level. The mid-level anticyclonic shear indicated that the system was still in a moderately favourable environment.

At 0300 UTC of 10th September, the low-level convergence maintained around 20 x $10^{-6}s^{-1}$ to the southwest of the system center. The upper-level divergence again increased to 20 x $10^{-6}s^{-1}$ over an area southwest of the system center. The wind shear was low (5-10 knots) over the system area and along the forecast track. The maximum relative vorticity at the 850 hPa was around 100 x $10^{-6}s^{-1}$ and remained south of the system area and vertically extended up to the 500 hPa level with gradual decrease to a value of 60 x $10^{-6}s^{-1}$. The anticyclonic mid-level shear was favouring the system.

2.7.2.3. Weakening

At 1200 UTC of 10th September, the depression lay over north Chhattisgarh and was located in a moderately favourable environment. The Madden Julian Oscillation (MJO) index was in Phase 5 with an amplitude of less than 1 and likely to continue in the same phase during the next 2-3 days. Thus, the MJO supported the enhancement of convective activity over east and central India. NCICS products provided guidance on equatorial waves which indicated strong westerly winds (5-7 m/s) along with Equatorial Rossby Waves over central parts of India and strong easterly winds (5-7 m/s) over northern parts of India during the next

3-4 days. Considering these dynamical features which support the enhancement of convective activities, the re-intensification of the system was not ruled out.

However, it moved northwestwards and weakened into a **Well-Marked Low pressure area** over Northeast Madhya Pradesh and neighbourhood in the evening (1730 hours IST) of 10th September.

2.7.3. Monitoring

India Meteorological Department (IMD) maintained round the clock watch over the north Indian Ocean (NIO) and the system was monitored well in advance. The system was monitored with the help of available satellite observations from INSAT 3D and 3DR, polar orbiting satellites and available ships & buoy observations in the region. 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 system. A digitized forecasting system of IMD was utilized for analysis and comparison of various models' guidance, decision making process and warning products generation.

2.7.3.1. Features observed through satellite

Satellite monitoring of the system was mainly done by using half hourly 3DR imageries. Satellite imageries of other international geostationary satellites, high resolution polar orbiting satellites and scatterometer imageries from ASCAT were also considered for monitoring of the system. Typical INSAT-3DR visible/ IR imageries, enhanced colored imageries are presented in **Fig. 2.7.2 (a) to (e)**. The organized cloud mass sheared characteristics was tracked and observed during the life cycle of the depression. The detailed features from the satellite pictures are discussed in this section.

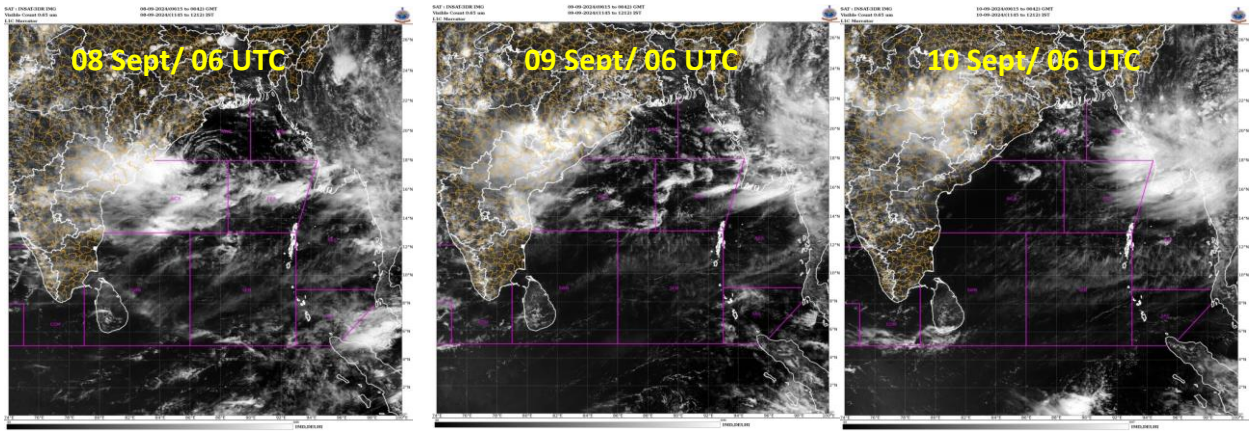


Fig. 2.7.2 (a): INSAT-3DR Visible imageries during life cycle of Deep Depression over Westcentral & adjoining Bay of Bengal during 8th September - 10, 2024

At 0300 UTC of 8th September, the intensity of the system was characterized as T1.5. Clouds were organized in a shear pattern. The area of intense convection was sheared to the southwest of the system center. INSAT satellite imagery detected associated scattered to broken low and medium clouds with embedded intense to very intense convection lying over central and adjoining northwest Bay of Bengal, coastal Odisha, and north coastal Andhra Pradesh. The minimum cloud top temperature was between minus 85-

93°C. Total precipitable water imagery indicated warm moist air incursion into the system core from the southern sector.

At 1800 UTC of 8th September, the intensity of the system was characterized as T2.0. An intense cloud mass was seen over west-central Bay of Bengal and adjoining areas of north coastal Andhra Pradesh. According to INSAT 3DR imagery at 1715 UTC, associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over central and adjoining northwest Bay of Bengal, south coastal Odisha, and north coastal Andhra Pradesh. The minimum cloud top temperature was -93°C.

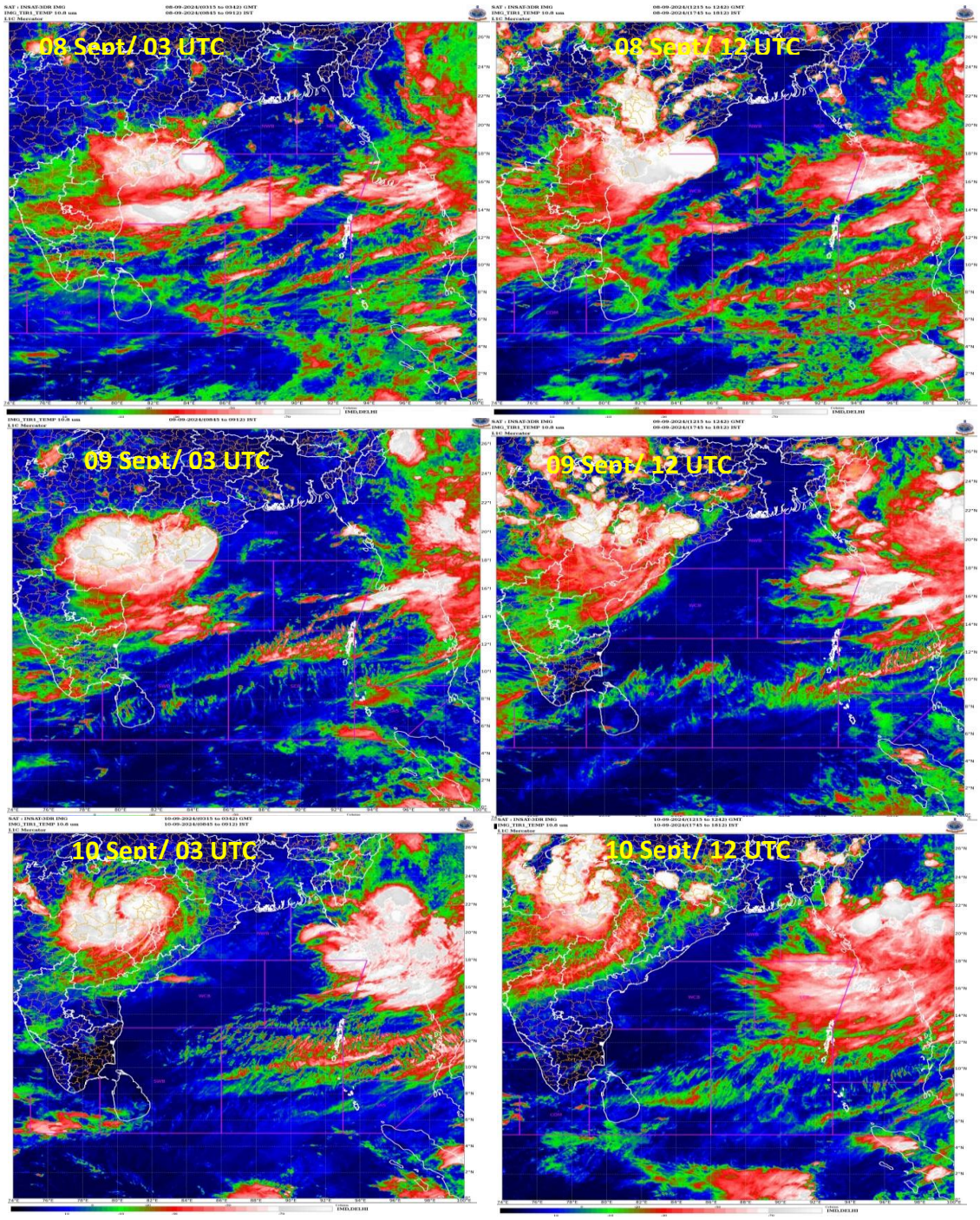


Fig. 2.7.2 (b): INSAT-3DR enhanced colored imageries during life cycle of Deep Depression over Westcentral & adjoining Bay of Bengal during 8th September - 10, 2024

At 0300 UTC of 9th September, the intensity of the system was characterized as T2.0. According to INSAT 3DR imagery at 0315 UTC, associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over northwest and adjoining west-central Bay of Bengal, north coastal Andhra Pradesh, south Odisha, south Chhattisgarh, Vidarbha, and Telangana. The minimum cloud top temperature was -93°C.

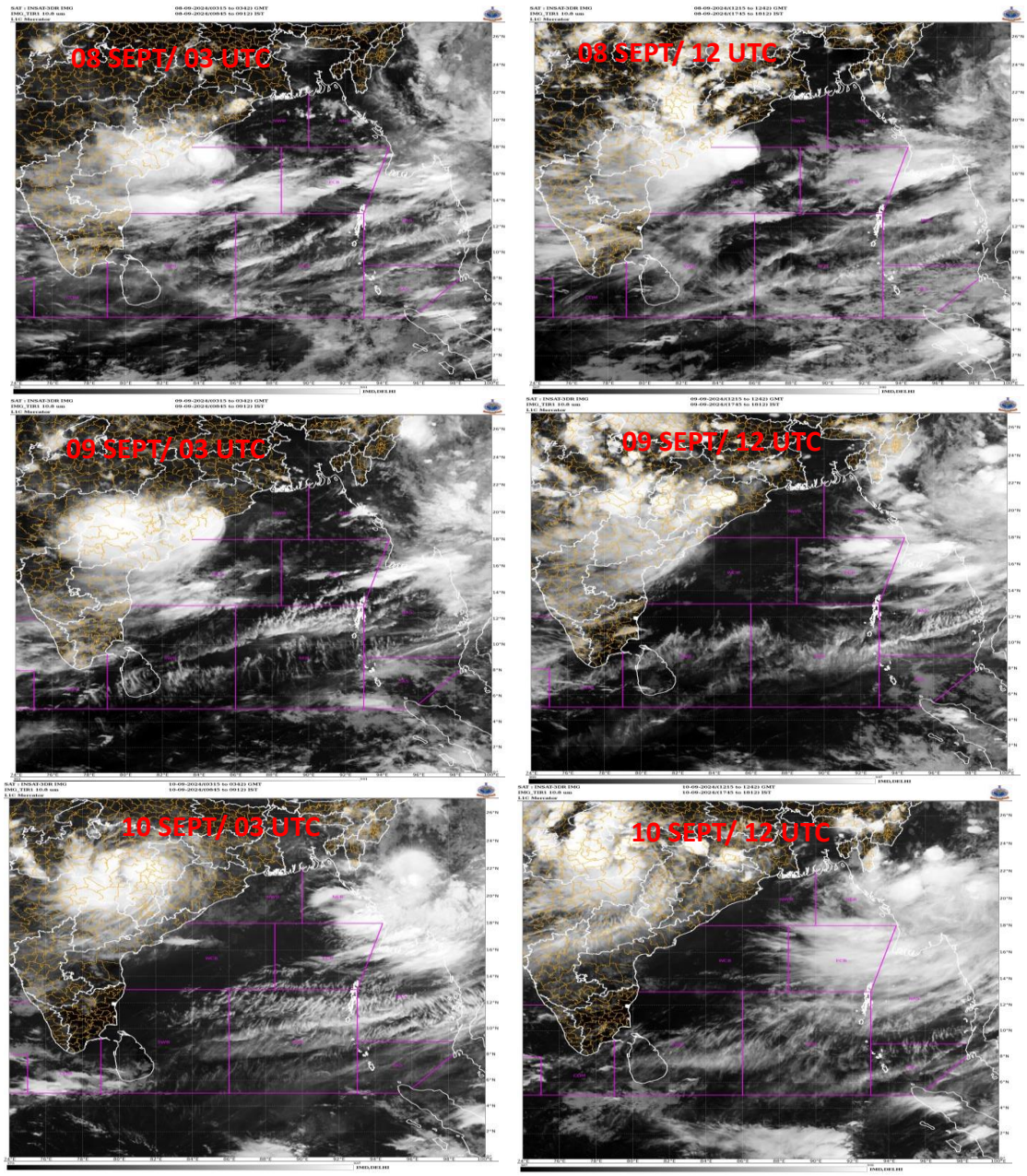


Fig. 2.7.2(c): INSAT-3DR IR imageries during life cycle of Deep Depression over Westcentral & adjoining Bay of Bengal during 8th September - 10, 2024

At 1200 UTC of 9th September According to INSAT 3DR imagery at 1200 UTC, associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over north Odisha, south Chhattisgarh, and Vidarbha, with a minimum cloud top temperature of -90°C. Moderate to intense convection lay over Rayalaseema, north coastal Andhra Pradesh, northeast and north interior Karnataka, and Marathwada.

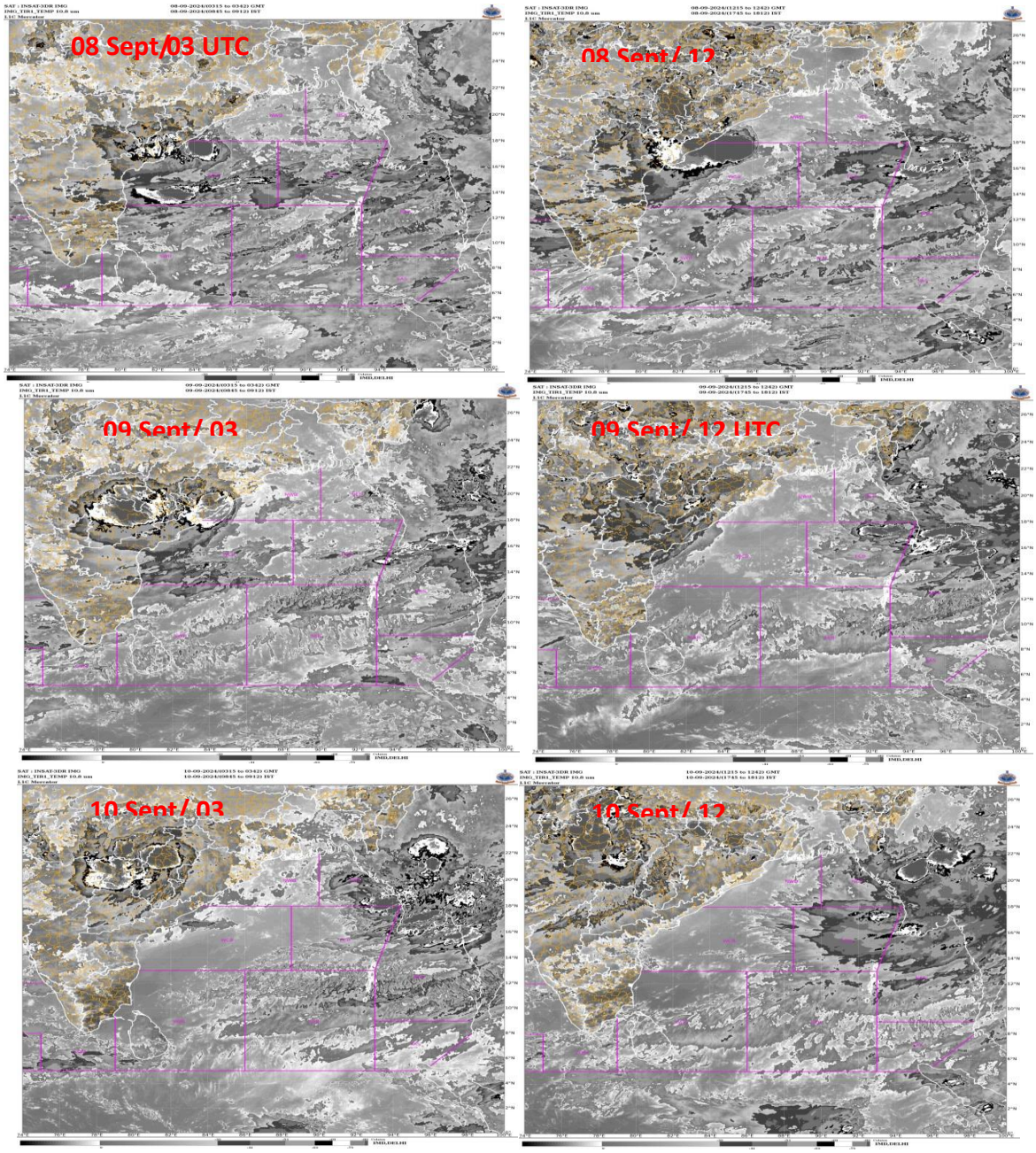


Fig. 2.7.2 (d): INSAT-3DR BD imageries during life cycle of Deep Depression over Westcentral & adjoining Bay of Bengal during 8th September - 10, 2024

At 0300 UTC of 10th September According to INSAT 3DR imagery at 0300 UTC, associated broken low and medium clouds with embedded intense to very intense convection lay over west Odisha, Chhattisgarh, east Madhya Pradesh, Vidarbha, and adjoining Telangana, with a minimum cloud top temperature of -93°C. Moderate to intense convection lay over Telangana and north coastal Andhra Pradesh.

At 0300 UTC of 9th September According to INSAT 3DR imagery at 1200 UTC, associated broken low and medium clouds with embedded intense to very intense convection lay over west Odisha, Chhattisgarh, east Madhya Pradesh, Vidarbha, and adjoining Telangana, with a minimum cloud top temperature of -93°C. Moderate to intense convection lay over Telangana and north coastal Andhra Pradesh.

2.7.3. Dynamical features

IMD GFS (T1534) daily analyses at 0000 UTC of mean sea level pressure (MSLP), winds at 10 m, 850, 500 and 200 hPa levels from 8th September to 10th September are presented in **Fig. 2.7.3(a) to (d)** respectively.

The MSLP analysis [Fig. 3(a)] at 0000 UTC of 8th September with two closed isobars clearly depicts the intensity of the low pressure system reached to the stage of depression over northeast & adjoining eastcentral Bay of Bengal. The spatial coverage by the central closed isobars was indicating the small size of the system. The 10 m wind field over north Bay of Bengal with a cyclonic circulation over northwest BoB also indicated the depression with area of maximum sustained wind located southeast sector of the system.

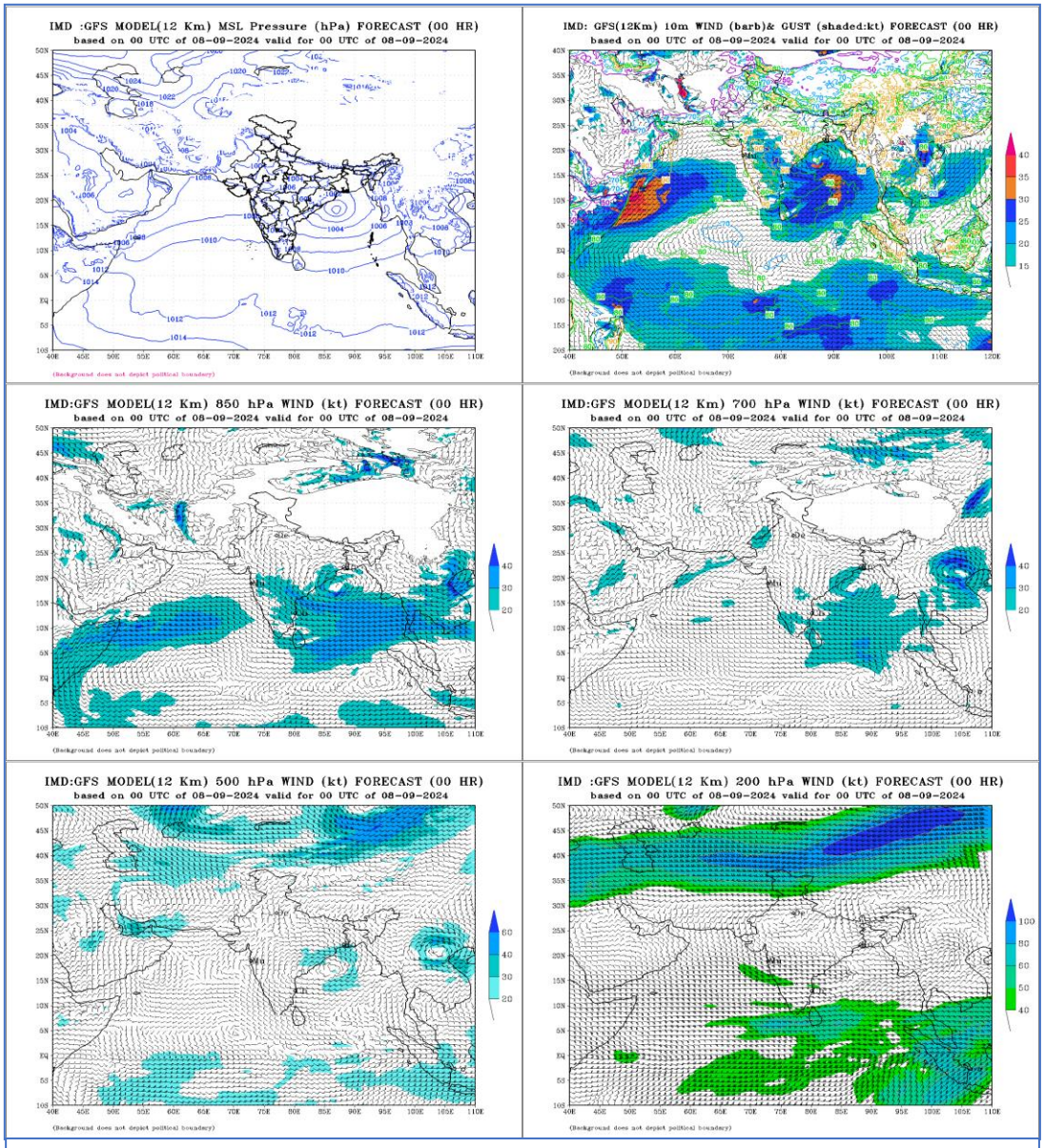


Fig. 2.7.3(a): IMD GFS mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 8th September, 2024

It was evident that the system structure was modulated by the strong southwesterly flow of monsoon season. The wind fields at 700 and 500 hPa indicated that the system was extended up to mid-tropospheric levels. The easterly winds prevailed in the upper level at

200 hPa above the system center. A ridge along 22°N situating north of the system ensured a steering for west-northwestwards movement.

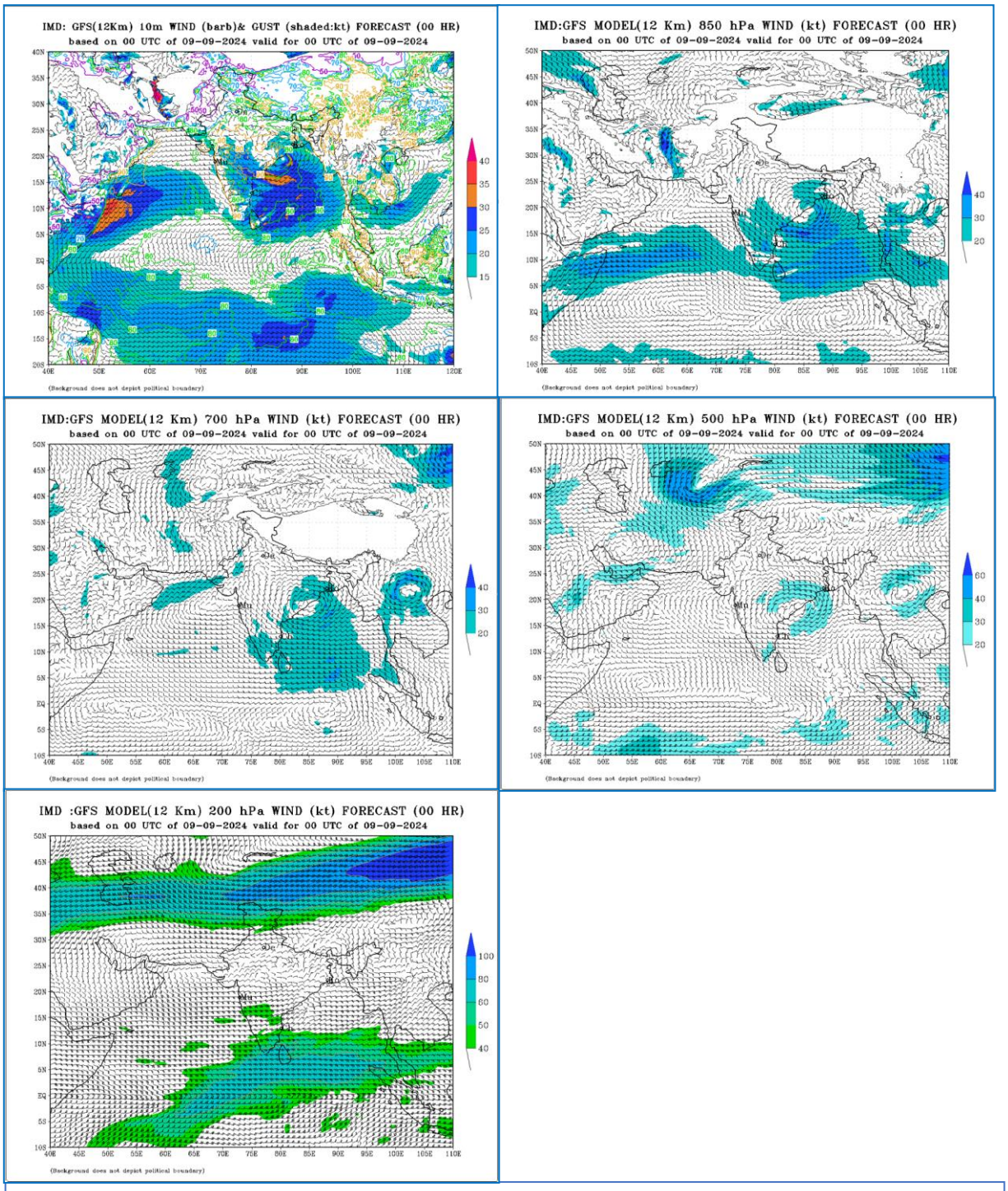


Fig. 2.7.3(b): IMD GFS (T1534) winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 9th September, 2024.

The Fig. 2.7.3(b) illustrates the model analyses winds at different levels valid at 0000 UTC of 9th September. Around this time the system reached its maximum intensity and was

located over the northwest BoB just off Odisha coast as indicated by the center of the cyclonic circulation in the 10 m wind field.

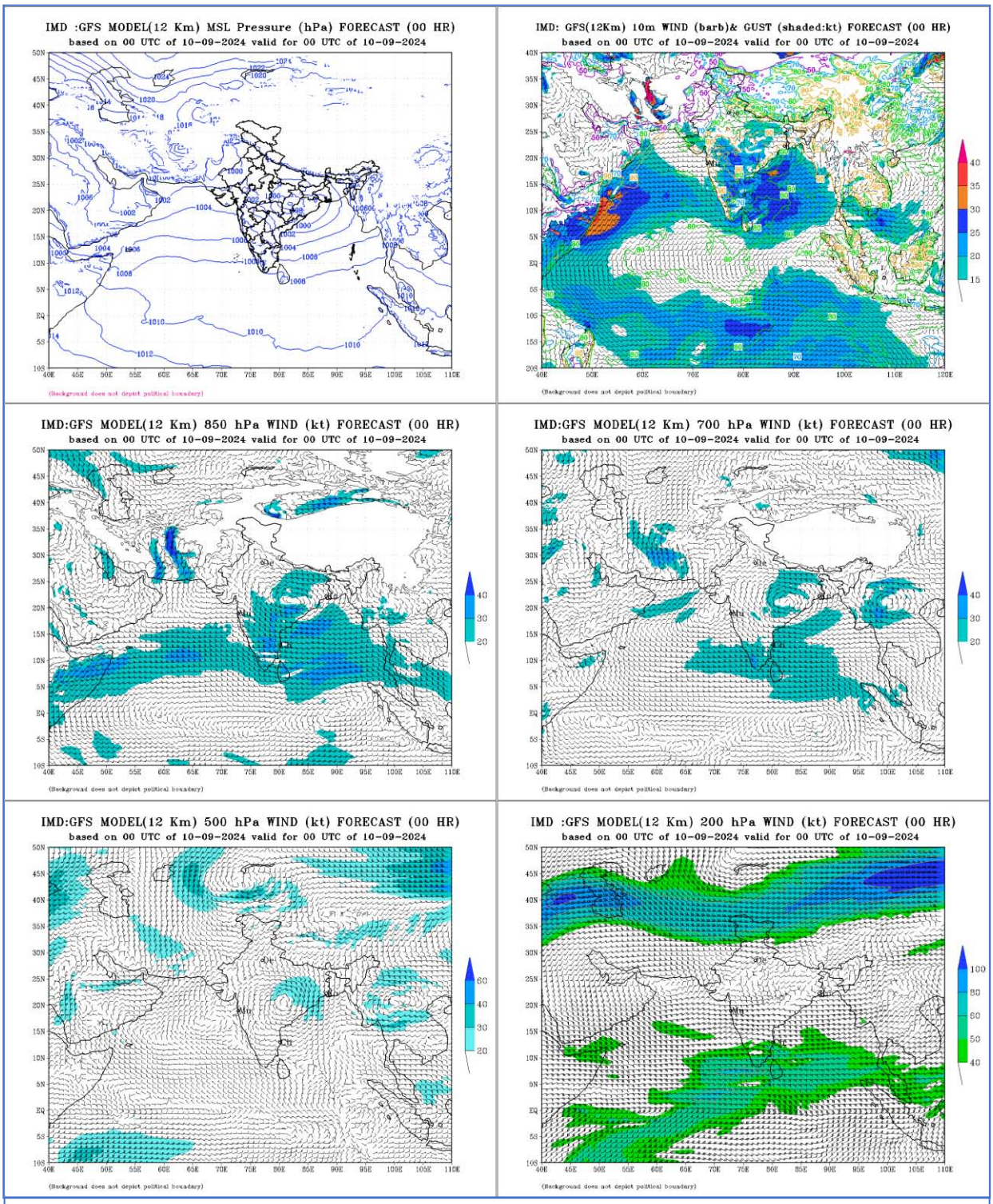


Fig. 2.7.3(c): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 10th September, 2024

The model analyses of MSLP and winds at different heights at 10 m, 850, 500 and 200 hPa pressure levels valid at 0000 UTC of 10th September are plotted in the panels of

Fig. 2.7.3(c) sequentially from the top to bottom. The isobaric analysis indicated the system was over interior Odisha with 2 closed isobars. Therefore, it illustrated that the system was over land with a intensity of a depression. The cyclonic circulation with strong winds around system center mainly south of the system indicated the intense stage of the system. Associated cyclonic circulations was extended vertically up to 500 hPa pressure level. However, the spatial coverage of the strong winds surrounding the system reduced significantly compared to previous days. The upper level wind flow pattern at 200 hPa suggested that the system was steered by the easterly flow above as the ridgeline along 23°N latitude extending from anticyclone over northeast India to the anticyclonic flow at the top of the system.

2.7.4. Realized Weather

Rainfall associated with the depression based on IMD-NCMRWF GPM-gauge merged analyses and station-wise rainfalls are depicted in Fig 2.7.4 respectively.

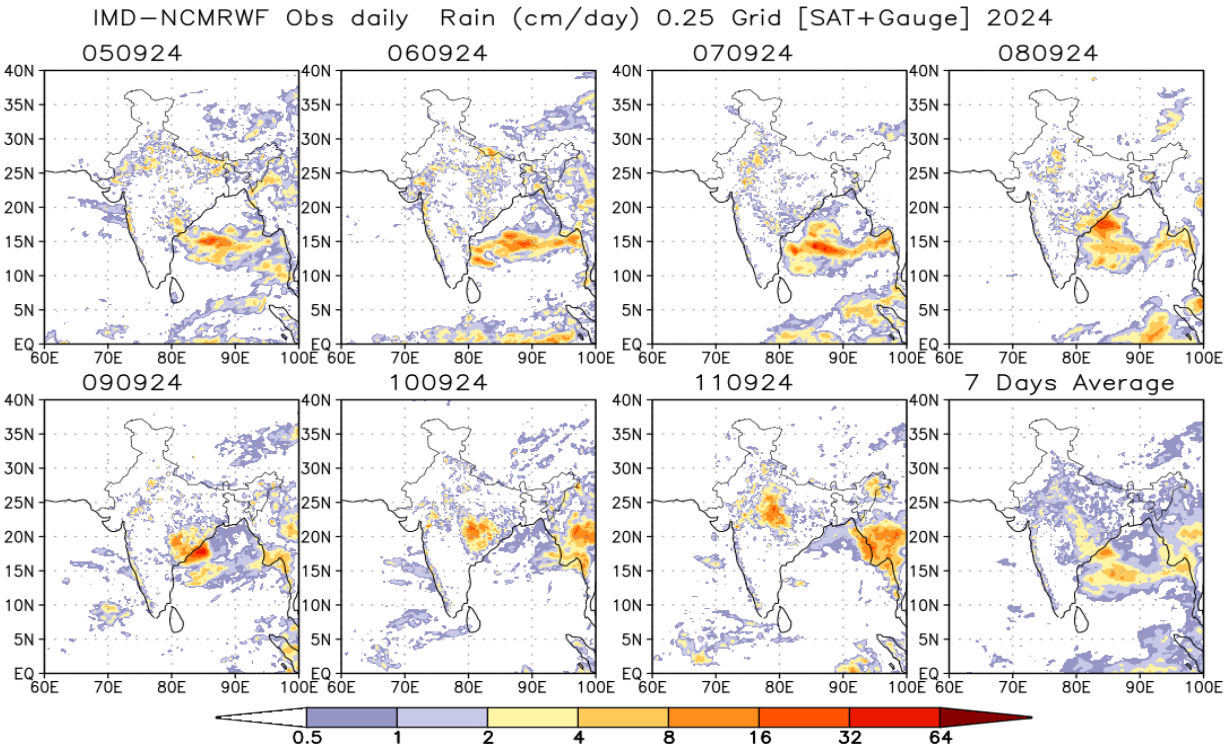


Fig. 2.7.4: IMD-NCMRWF Rain gauge and satellite merged rainfall plots during 5th September to 11th September, 2024 weekly average rainfall (cm/day)

The Fig. 2.7.4(a) represents daily observed and weekly average rainfalls distribution for the week over Indian region.

It is seen that light to moderate rainfall occurred at many places over Odisha, Chhattisgarh on 08th September.

Light to moderate rainfall occurred at many places with extremely heavy rainfall at isolated places over Odisha and heavy to very heavy rainfall at few places over Chhattisgarh, Vidarbha and heavy rainfall at a few places over Coastal Andhra Pradesh on 09th September.

Light to moderate rainfall occurred at many places with extremely heavy rainfall at isolated places over Vidarbha, Odisha & Chattisgarh and heavy to very heavy rainfall at isolated places over East Madhya Pradesh and heavy rainfall at isolated places over West Madhya Pradesh on 10th September.

Light to moderate rainfall occurred at many places with extremely heavy rainfall at a few places over East Madhya Pradesh; at isolated places over West Madhya Pradesh and heavy rainfall at isolated places over Chhattisgarh, East Rajasthan and West Uttar Pradesh on 11th September

2.7.4.1 Rainfall forecast verification

The forecasts for heavy to extremely heavy rainfall episodes are verified with the 24 hours accumulated rainfall at various stations exceeding 7 cm. The details of the day-wise verification are given in Table -2.7.2.

Table 2.7.2: Day wise daily 24 hours cumulative rainfall forecast verification with station observations

Date/Base Time of observation	24 hours Heavy rainfall warning ending at 0300 UTC of next day Heavy: H, Very Heavy: VH, Extremely Heavy: EH	Realised 24-hour heavy rainfall (≥ 7 cm) ending at 0300 UTC of respective date
08.09.2024 / 0830	**Coastal Andhra Pradesh & Yanam:** H to VH rainfall at a few places and EH rainfall at isolated places on 08th and 9th and H rainfall on 10th September. **Odisha:** H to VH rainfall at isolated places on 8th , H to VH rainfall at a few places and EH rainfall at isolated places over south Odisha on 9th; H to VH rainfall on10th and H rainfall on 11th September. **Telangana:** H to VH rainfall at isolated places very likely on 08th& 9th; H rainfall on 10th September. **Chhattisgarh:** H to VH rainfall at isolated places during 08th -10 th and H rainfall on 11th September. **Gangetic West Bengal:** H to VH rainfall at isolated places very likely during 9 th & 10th and H rainfall at isolated places 12th September. **Jharkhand:** H rainfall at isolated places on 9th; H to VH rainfall	**09.09.2024/ 0830** **Odisha:** Malkangiri 25, hitrakunda K Guma 23, Korukunda 20, Mathili 15, Lamataput 13, Ambadola 12, Padia & Chhatrapur 10 each, Digapahandi, Gopalpur, Jeypore & Similiguda 9 each, Madanpur Rampur, Ranpur, Kotpad, Chikiti, Nandapur & Lanjigarh 8 each and Ullunda, Nandahandi, Ganjam, Berhampur, Rangeilunda, Chandahandi, Koksara, Koraput, Th Rampur, Udala & Nawana 7 each. **Chhattisgarh:** Bhairamgarh, Bijapur & Kutaru 21 each, Chhotedongar, Orcha & Kohkameta 20 each, Narayanpur 19, Tongpaal 18, Sukma 17, Gangalur 16, Gadiras, Gidam, Bastanar & Antagarh 14 each, Bade Bacheli 13, Dantewara, Dornapal, Kuakonda, Pakhanjur & Jagargunda 11 each, Bhopalpatnam, Dhanora, Nangur, Bhanupratappur, Konta, Kanker & Pharasgaon 10 each, Keshkal, Usoor & Lohandiguda 9 each, Charama 8 and Barsur, Baderajpur & Belargaon 7 each, **Vidarbha:** Bhamragad 16, Etapalli and Ahiri 7 each.

	during 10 th -11 th and H rainfall on 12th September.	**Coastal Andhra Pradesh & Yanam:** Chintapalle 13, Ranastalam 11, Pusapatirega, Bondapalle & Bheemunipatnam 10 each, Merakamudidam, Cheepurupalle, Visakhapatnam Ap & Garividi 9 each, Denkada, Visakhapatnam, Narsipatnam, Gajapathinagaram, & Srungavarapukota 8 each and Vepada, Vizianagaram, Yelamanchili, Chodavaram and Tuni, Therlam & Araku Valley 7 each.
09.09.2024 / 0830	**Odisha:** H to VH rainfall at a few places with EH rainfall at isolated places over south Odisha and isolated H to VH rainfall over north Odisha on 9th; H to VH rainfall at isolated places over Odisha on 10th and isolated H rainfall over interior Odisha on 11th September. **Chhattisgarh:** H to VH rainfall at a few places and EH rainfall at isolated places on 9th and H rainfall at isolated places on 10th September. **Vidarbha:** H to VH rainfall at a few places and EH at isolated places on 9 th and H to VH rainfall at isolated places on 10th and H rainfall at isolated places on 11th September. **Coastal Andhra Pradesh & Yanam:** H to VH rainfall at a few places on 9th and H rainfall on 10th September. **Telangana:** H to VH rainfall at isolated places very likely on 9 th September. **Jharkhand:** H rainfall at isolated places over South Jharkhand during 9 th to 10 th September.	**10.09.2024/ 0830** **Vidarbha:** Gondia Ap 29 & Deori, Gondia 21 each, Salekasa 20, Sadakarjuni 19, Goregaon 18, Korchi 15, Arjuni Morgaon & Amgaon 14 each, Lakhandur & Desaiganj 13 each, Sakoli 12, Kuhi & Sindewahi 10 each, Lakhani, Mulchera, Gadchiroli, Bramhapuri & Dhanora 9 each, Chamorshi, Saoli & Bhamragad 8 each and Kurkheda, Pauni, Nagbhir & Etapalli 7 each. **Chhattisgarh:** Lal Bahadur Nagar 24, Sukma, Dongargarh & Gurur 19 each, Rajnandgaon & Bhanupratappur 18 each, Khairagarh 17, Balod, Durgkondal & Baloda Bazar 16 each, Mohla, Lawan, Chhuria, Dhanora, Dongargaon, Bhatapara & Marri Bangla Deori 15 each, Pallari, Charama, Pithora, Dhamtari, Keshkal, Gangalur, Doundi, Pakhanjur & Khadgaon 14 each, Nerharpur, Suhela, Kukrel, Sonakhan & Antagarh 13 each, Manpur, Labhandih, Arjunda, Darbha, Kanker, Kashdol, Raipur and Bhakhara & Komakhan 12 each. **Odisha:** Lanjigarh 23, Madanpur Rampur 22, Tikarpara 15, Ambadola 14, Nawapara 13, Kotpad, Belgaon & Birmaharajpur 11 each, Malkangiri, Bissem-cuttack & Athmalik 10 each, Barmul & Lamataput 9 each, Kosagumda & Harabhanga 8 each and Mathili, Nawarangpur, Padia, Gaisilet, Nawarangpur Pto, Tarva, Sonepur, Nandahandi, Jeypore, Dabugan, Narla, Borigumma & Rairakhol 7 each. **East Madhya Pradesh:** Kirnapur 20,

		Matiyari & Baihar 13 each, Lanji 12, Lalburra 10, Bichhia 9, Dhanora, Paraswada and Harrai 7 each. **West Madhya Pradesh:** Raoti 10, Satwas & Gogawan 9 each, Nasrullahganj and Petlawad 7 each.
10.09.2024 / 0830	**Chhattisgarh:** H to VH rainfall at a few places on 10th September. **East Madhya Pradesh:** H to VH rainfall at a few places and EH falls at isolated places on 10th and H to VH rainfall at isolated places during 11th to 14th September. **West Madhya Pradesh:** H to VH rainfall at isolated places on 10th; H to VH rainfall at a few places with EH rainfall at isolated places on 11th ; H to VH rainfall at a few places during 12th to 14th September. **Vidarbha:** H to VH rainfall at a few places on 10th and 11th September. **South Uttar Pradesh:** H rainfall at isolated places on 10th and H to VH at isolated places during 11th – 13th September. **Odisha:** H rainfall at isolated places over northwest Odisha on 10th September.	**11.09.2024/ 0830** **East Madhya Pradesh:** Shahgarh 30, Patharia 28, Buxwaha 24, Damoh-aws Hatta & Banda 21 each, Baihar, Jabalpur-aws, Jabera, Rehli, & Seoni 19 each, Tendukheda, Panagar & Narsinghpur-aws 18 each, Garhakota, Tendukheda, Kareli & Matiyari 17 each, Deori & Bichhia 16 each, Badamalhera & Mohgaon 15 each, Patera & Sagar-aws 14 each, Kesli & Niwas 13 each and Kumdam, Batiyagarh, Patan & Barghat 12 each. **West Madhya Pradesh:** Udaipura 25, Bareli & Pipariya 16 each, Narwar 15, Bhander 12, Seoni Malwa, Sultanpur, Pachmarhi & Navibagh Aet 11 each, Karera, Deori & Bankhedi 10 each, Gairatgang, Raghogarh, Bhitarwar, Thandla, Sohagpur, Begumganj & Narsingarh 9 each and Bhopal Arera Hills, Badi, Ganjbasoda, Babai, Kolaras, Chinor & Alot 8 each. **Chhattisgarh:** Gandai 11, Rengakhar Kala 9, Tilda 8 and Sahaspurlohara 7. **East Rajasthan:** Khushalgarh 11, Banera 9, Ganeshpur 8 and Shahpura, Mounntabu Tehsil, Chaksu, Baseri, Phagi, Bansur, & Jaipur Aero 7 each. **West Uttar Pradesh:** Mahroni, Muzaffarnagar, Jhansi, Mauranipur & Madawara 9 each and Pali 7.

2.7.5. Damage due to the system

No damage was reported in association with this system.

2.8 Depression over Northeast Madhya Pradesh during 11th-13th September 2024

2.8.1 Introduction

- The well-marked low-pressure area has formed over Northeast Madhya Pradesh and neighborhood in the evening (1730 hours IST/1200 UTC) of 10th September.
- It moved nearly north-northwestwards and intensified into a depression over Northeast Madhya Pradesh by the morning of 11th September (0830 hours IST/0300 UTC).
- It then moved north-northeastwards and lay centered over north Madhya Pradesh adjacent to northwest Uttar Pradesh as depression on 0530 IST/0000 UTC of 12th September.
- It continued to move north-northeastwards and weakened into a well marked low (WML) pressure area over northwest Uttar Pradesh & neighborhood in the morning (0830 hours IST/0300 UTC) of the 13th September.
- The observed track of the system is presented in **Fig. 2.8.1** and the best track is given in **Table 2.8.1**.

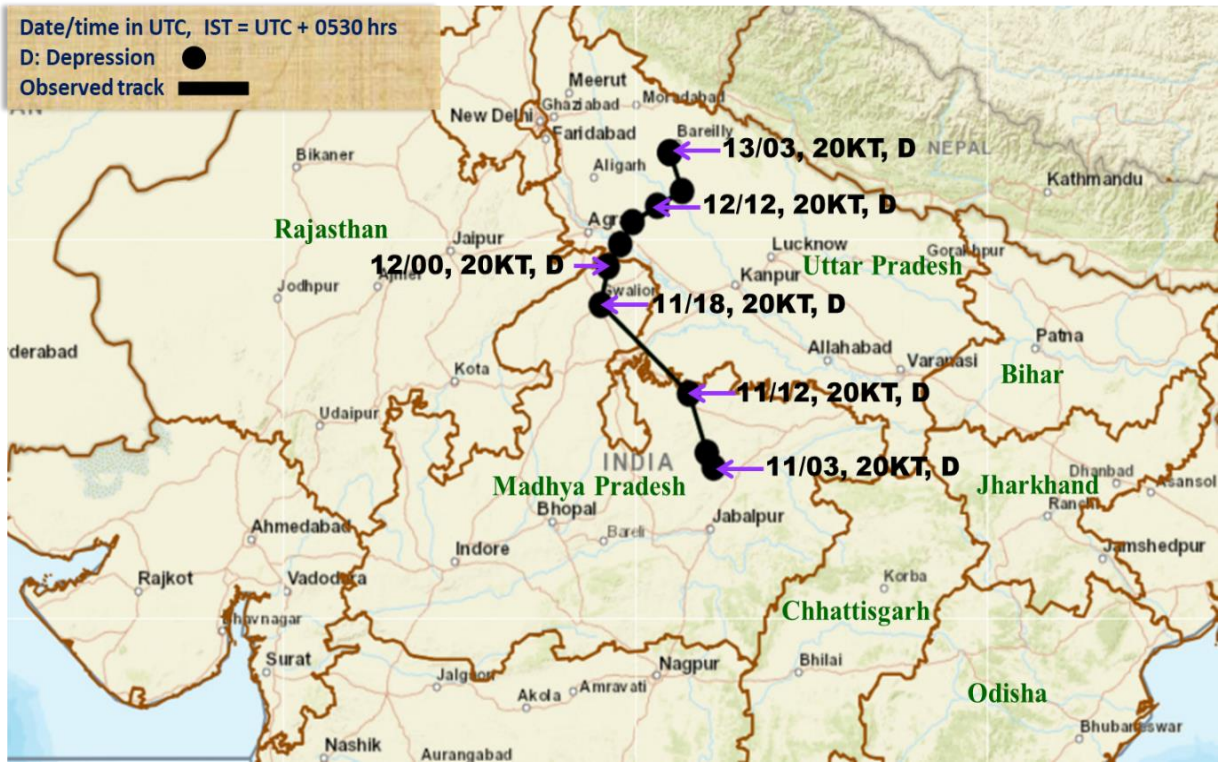


Fig. 2.8.1: Observed track of Depression over Northeast Madhya Pradesh.

Table2.8.1: Best track positions and other parameters of the Depression over Northeast Madhya Pradesh during 11th Sept – 13th Sept, 2024.

Date	Time (UTC)	Lat.	Long.	ECP	ΔP	MSW (kt)	Category
11.09.24	0300	24.0	80.0	995	3	20	D
	0600	24.2	79.9	995	3	20	D
	1200	25.0	79.6	994	4	25	D
	1800	26.2	78.2	994	4	25	D

12.09.24	0000	26.7	78.3	994	4	25	D
	0300	27.0	78.5	994	4	25	D
	0600	27.3	78.7	994	4	25	D
	1200	27.5	79.1	995	3	20	D
	1800	27.7	79.5	995	3	20	D
13.09.24	0000	28.2	79.3	995	3	20	D
	0300	Weakened into a well-marked low-pressure area over northwest Uttar Pradesh & neighbourhood.					

Kt: Knots (nautical mile per hour), 1 KT=1.85 kmph, D: Depression,

2.8.2 Brief life history - Genesis Intensification and movement

2.8.2.1 Genesis, movement and intensification

The well-marked low-pressure area formed over Northeast Madhya Pradesh and neighbourhood in the evening (1730 hours IST/1200 UTC) of 10th September, moved nearly north-northwestwards and intensified into a depression over Northeast Madhya Pradesh by the morning of 11th September (0830 hours IST/0300 UTC). By 1130 hours IST/0600 UTC on the same day, the depression was centered near latitude 24.2°N and longitude 79.9°E, about 60 km northeast of Damoh (Madhya Pradesh), 90 km south of Khajuraho (Madhya Pradesh), 100 km west-southwest of Satna (Madhya Pradesh), and 190 km southeast of Jhansi (Uttar Pradesh).

On 11th September, the Madden-Julian Oscillation (MJO) index was observed to be in Phase 5, with an amplitude of less than 1. This phase of the MJO supported an enhancement of convective activity over East and Central India. Additionally, guidance from the NCICS indicated the presence of strong westerly winds (5-7 m/s) along with Rossby waves over central India. Strong easterly winds (5-7 m/s) were also observed over the northern parts of India. The environmental conditions during this period were favorable, with low-level convergence around $10 \times 10^{-6}s^{-1}$, and upper-level divergence at approximately $20 \times 10^{-6}s^{-1}$ over the system area. Wind shear was moderate (15-20 kt) in the vicinity of the system, with stronger shear (>20 kt) to the north. Vorticity at the 850 hPa level was about $150 \times 10^{-6}s^{-1}$, extending vertically up to the 500 hPa level. The mid-level shear was cyclonic over the system area, indicating a moderately favorable environment for intensification.

By the morning of 12th September, the depression over Northeast Madhya Pradesh moved north-northwestwards and lay centered over Southwest Uttar Pradesh near latitude 27.0°N and longitude 78.5°E, about 50 km east-southeast of Agra (Uttar Pradesh), and 90 km north-northeast of Gwalior (Madhya Pradesh). The system remained in a favorable environment, with low-level convergence around $20 \times 10^{-6}s^{-1}$ and upper-level divergence at about $20 \times 10^{-6}s^{-1}$. Wind shear over the system area was moderate (10-15 kt), with higher shear (>20 kt) to the north. Vorticity at the 850 hPa level was around $200 \times 10^{-6}s^{-1}$, extending up to 500 hPa.

By 13th September, the Madden-Julian Oscillation (MJO) index remained in Phase 5, with an amplitude greater than 1. The system had been in this phase for several days, but the support from the MJO for convective activity was gradually diminishing. The MJO was expected to move into Phase 6 during the following week, which would further reduce the

support for the system.

On the morning of 13th September, the low-level convergence remained about 20 × $10^{-6}s^{-1}$ around the system area, while upper-level divergence was still around 20 × $10^{-6}s^{-1}$. Wind shear was low to moderate (5-15 kt) over the system area, but high wind shear (>20 kt) persisted to the north of the system. Vorticity at the 850 hPa level was approximately 100 × $10^{-6}s^{-1}$, with vertical extension up to the 700 hPa level. The system was gradually experiencing the influence of high vertical wind shear, as the westerly wind trough in the upper troposphere began to move eastward.

Given these unfavorable environmental conditions, the depression over Southwest Uttar Pradesh began to weaken. By the morning of 13th September, it had weakened into a Well-Marked Low-Pressure Area over northwest Uttar Pradesh and its surroundings. With the environmental conditions no longer conducive to sustaining its intensity, the system weakened and dissipated.

2.8.3 Monitoring

India Meteorological Department (IMD) maintained round the clock watch over the north Indian Ocean (NIO) and the system was monitored well in advance since 10th October since it has been evolved from a previous system. The system was monitored with the help of available satellite observations from INSAT 3D and 3DR, polar orbiting satellites, available ships & buoy observations in the region and coastal observations on the day of landfall. 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 system. 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 Features observed through satellite

Satellite monitoring of the system was mainly done by using half hourly INSAT-3D and 3DR imageries, satellite imageries of other international geostationary satellites, high resolution polar orbiting satellites. Typical INSAT-3D enhanced colored imageries, visible/ IR and brightness temperature imageries are presented in Fig.2.8.2 (a) to 2.8.2 (d). During the entire life cycle, the clouds were organized in shear pattern. The detailed features from the satellite pictures are discussed in this section.

As per the INSAT-3DR imagery at 0300 UTC on 11th September, the system was associated with scattered to broken low and medium clouds, with embedded intense to very intense convection. These clouds were observed over Uttar Pradesh, eastern Rajasthan, and Madhya Pradesh, with a minimum cloud top temperature of -93°C. Moderate to intense convection was also seen over Vidarbha and Chhattisgarh.

According to the INSAT-3DR imagery at 0300 UTC on 12th September, the convective clouds were sheared towards the northeast under the influence of an approaching westerly trough in the middle and upper tropospheric levels. The associated scattered to broken low and medium clouds, with embedded intense to very intense convection, were observed over eastern Rajasthan, western Madhya Pradesh, western Uttar Pradesh, and Uttarakhand, with minimum cloud top temperatures ranging from -80°C to -93°C. Moderate to intense convection was also visible over Himachal Pradesh, Haryana, Delhi, eastern Uttar Pradesh, and eastern Madhya Pradesh, with minimum cloud top temperatures between -50°C and -70°C.

As per the INSAT-3DR imagery at 0300 UTC on 13th September, scattered to broken low and medium clouds with embedded intense to very intense convection were observed over Uttarakhand and western Uttar Pradesh, with minimum cloud top temperatures of -75°C. Moderate to intense convection was seen over eastern Himachal Pradesh, eastern Rajasthan, and northwest Madhya Pradesh, with minimum cloud top temperatures ranging from -50°C to -60°C. Weak to moderate convection was also present over eastern Ladakh, western Himachal Pradesh, eastern Punjab, Haryana, Delhi, and eastern Uttar Pradesh.

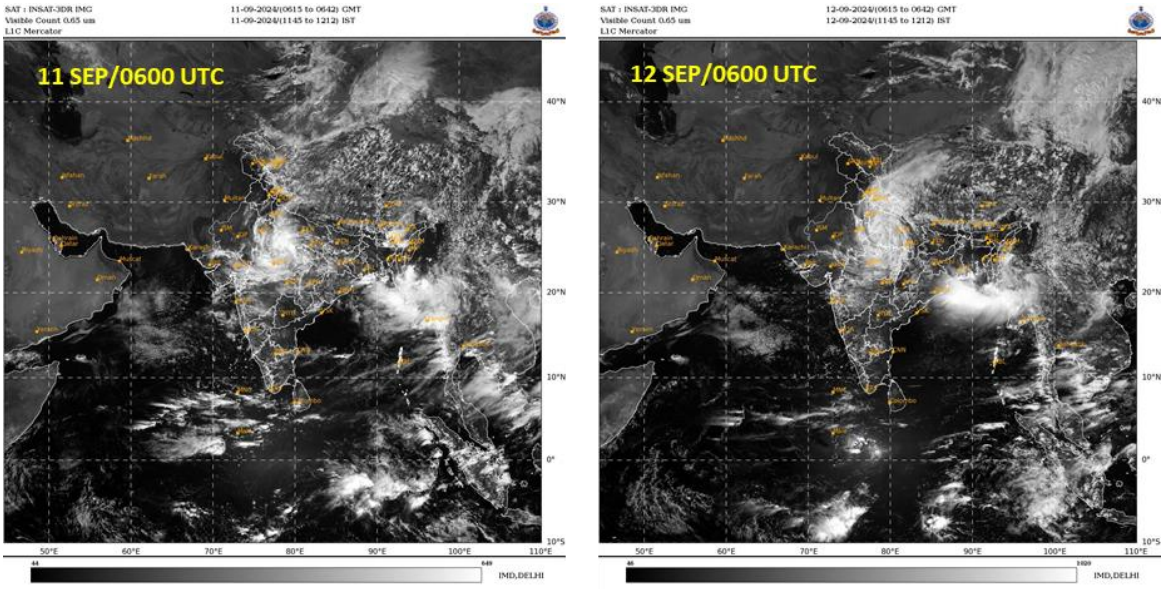


Fig.2.8.2 (a): INSAT-3D Visible imageries during life cycle of Depression over Northeast Madhya Pradesh during 11th September -13th September, 2024

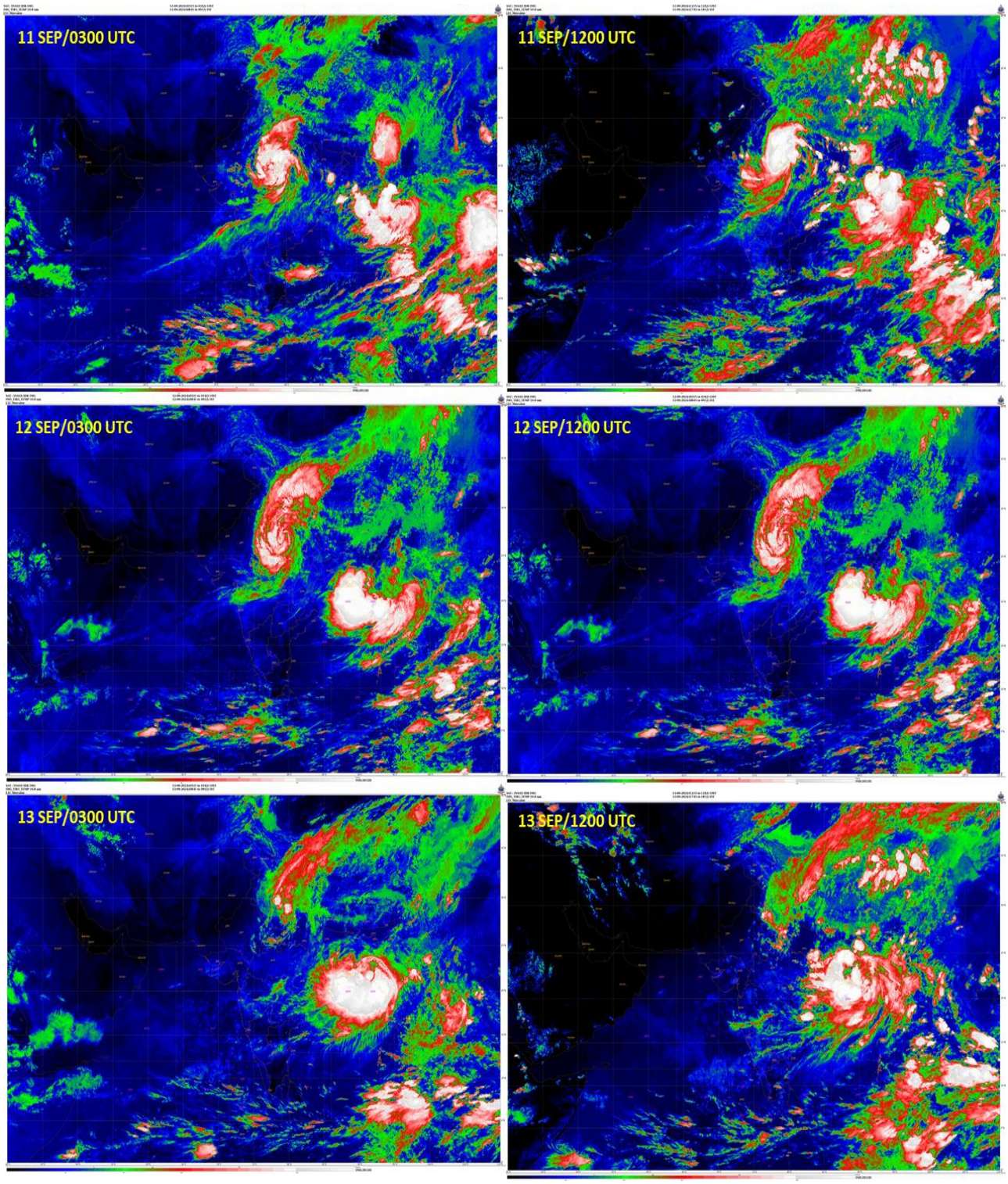


Fig.2.8.2(b): INSAT-3D enhanced colored imageries during life cycle of Depression over Northeast Madhya Pradesh during 11th September -13th September, 2024

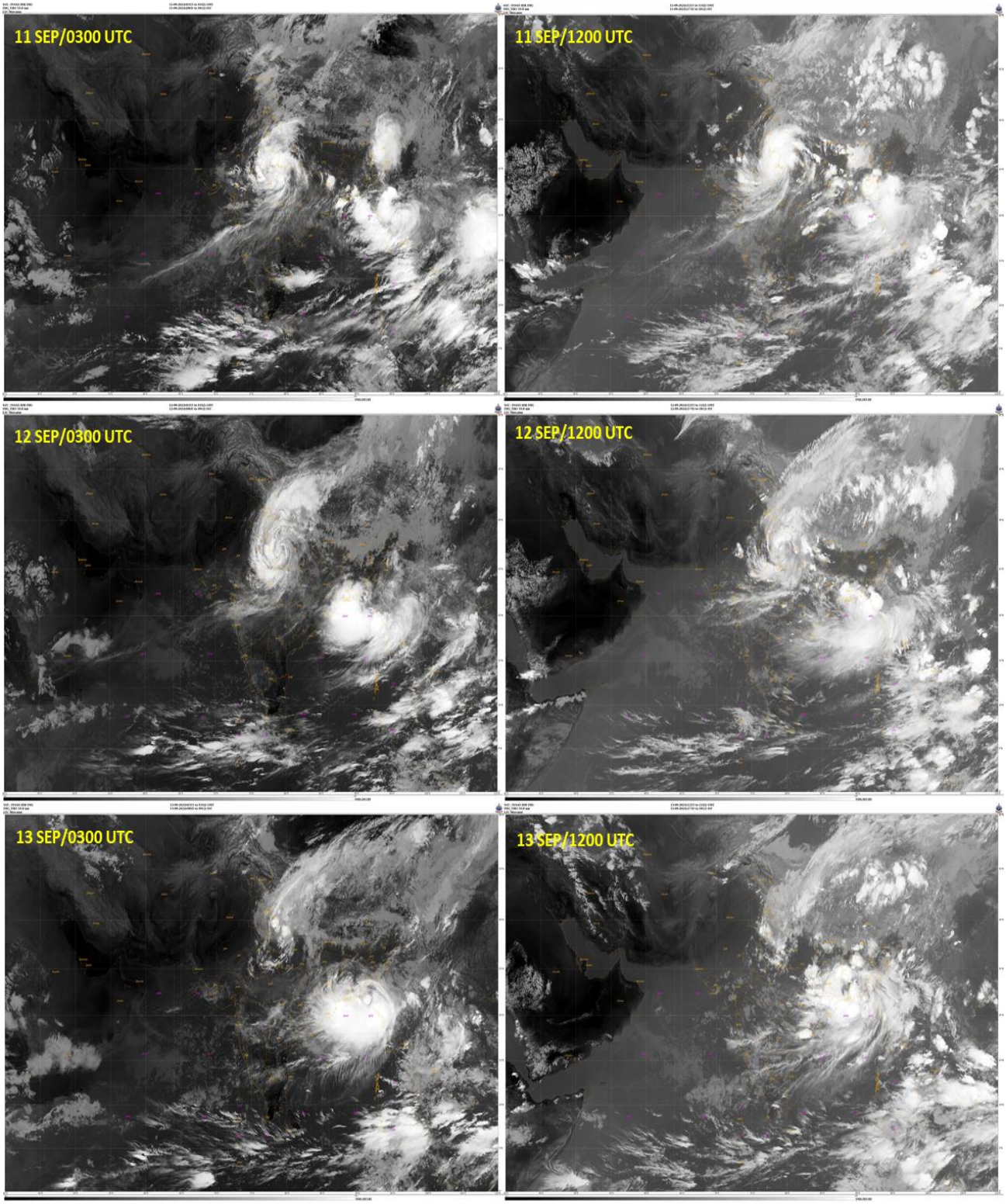


Fig.2.8.2(c): INSAT-3D IR imageries during life cycle of Depression over Northeast Madhya Pradesh during 11th September -13th September, 2024

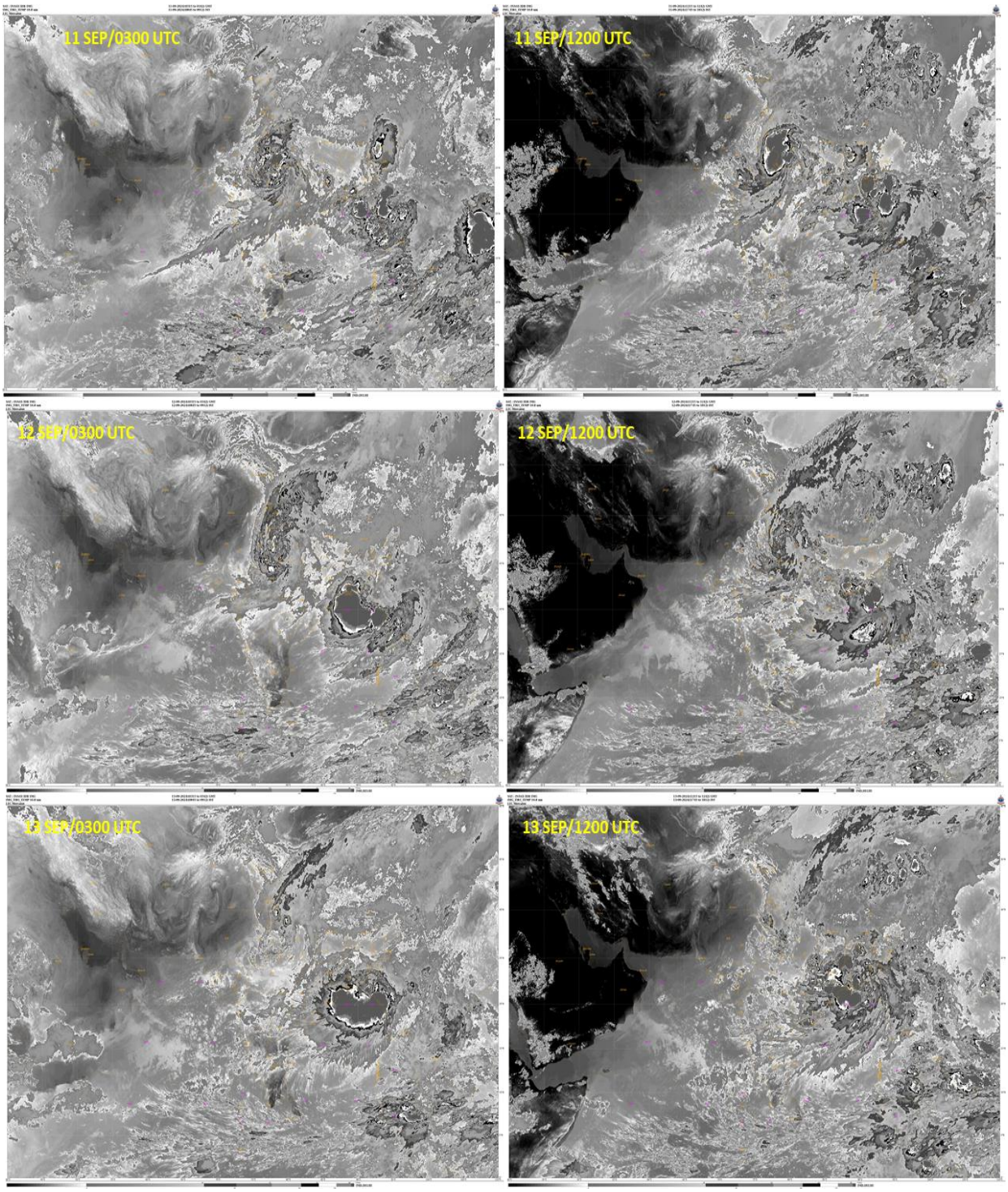


Fig.2.8.2 (d): INSAT-3D enhanced infrared imageries during life cycle of Depression over Northeast Madhya Pradesh during 11th September -13th September, 2024

2.8.5 Dynamical Features

IMD GFS (T1534) daily analyses at 0000 UTC of mean sea level pressure (MSLP), winds at 10 m, 850, 500 and 200 hPa levels from 11th Sept to 13th Sept are presented in **Fig. 2.8.3(a) to 2.8.3(c)** respectively.

At 0000 UTC of 11th September, the MSLP analysis field indicated a depression centered at 23.5.0°N/79.0°E. Actually, the system was located near at 24.0°N/80°E at 0000 UTC based on the best track, indicating its northeast ward movement. GFS, analysis accurately indicated the systems location and intensity.

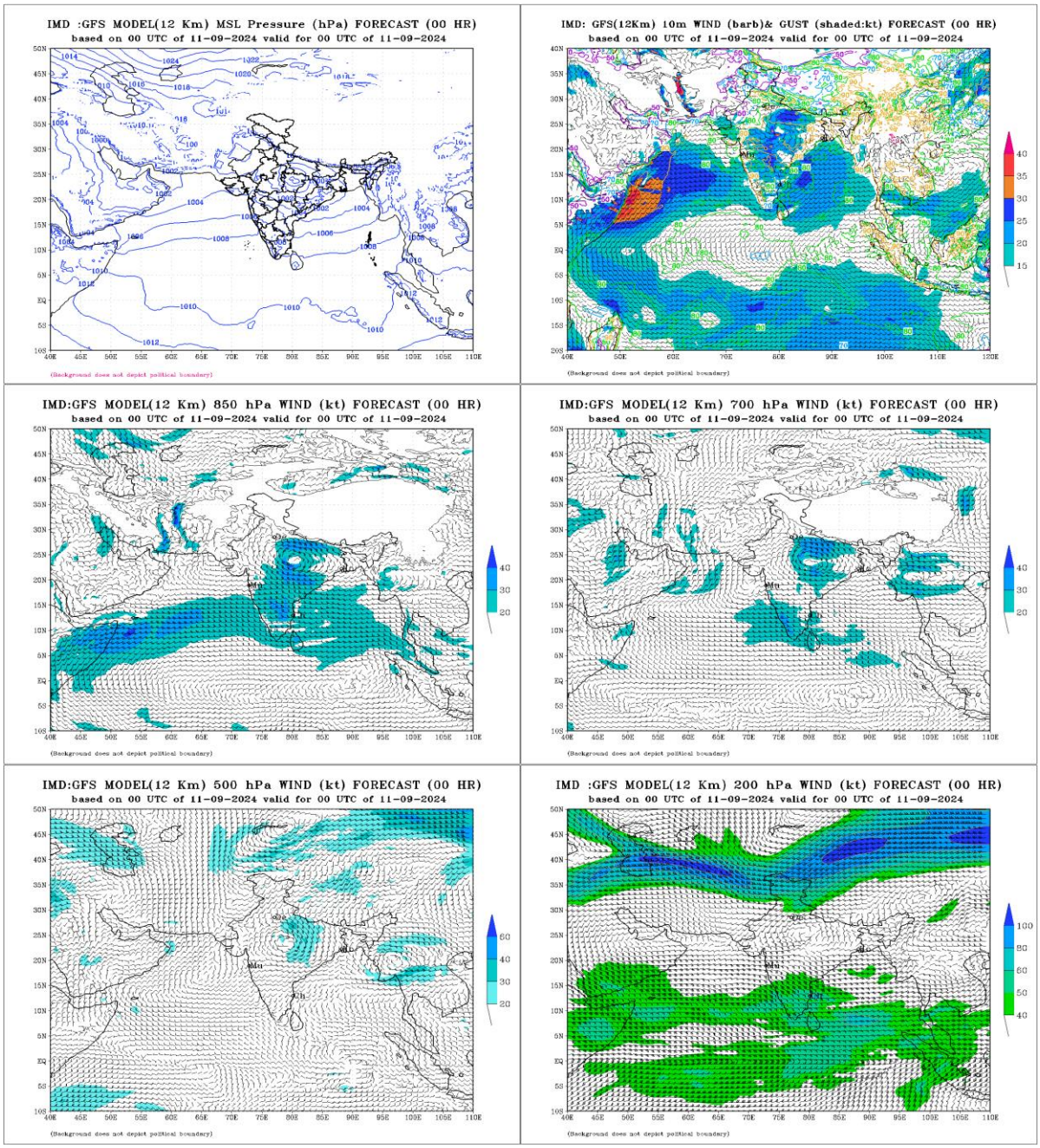


Fig. 2.8.3(a): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 11th September 2024

At 0000 UTC of 12th September, the MSLP analysis field indicated a depression centered at 26.5°N/78.5°E. Actually, the system was located near at 26.7°N/78.3°E at 0000 UTC of 12th September based on the best track. Hence, GFS analysis accurately indicated the systems location and intensity.

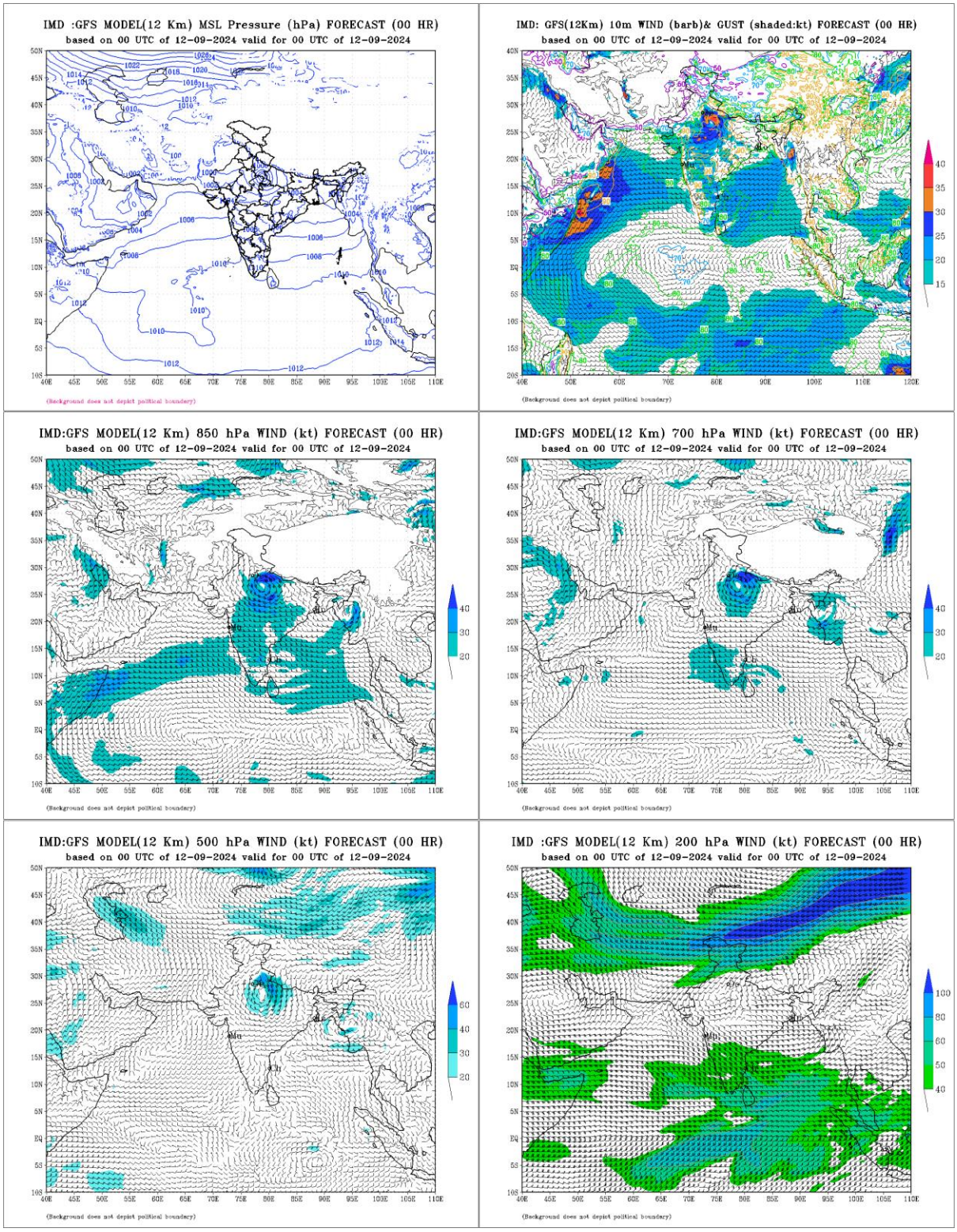


Fig. 2.8.3(b): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500, and 200 hPa levels based on 0000 UTC of 12th September 2024

At 0000 UTC of 13th September, the MSLP analysis field indicated a depression over northwest Uttar Pradesh. Actually, the system was located over northwest Uttar Pradesh based on the best track at 0000 UTC of 13th September.

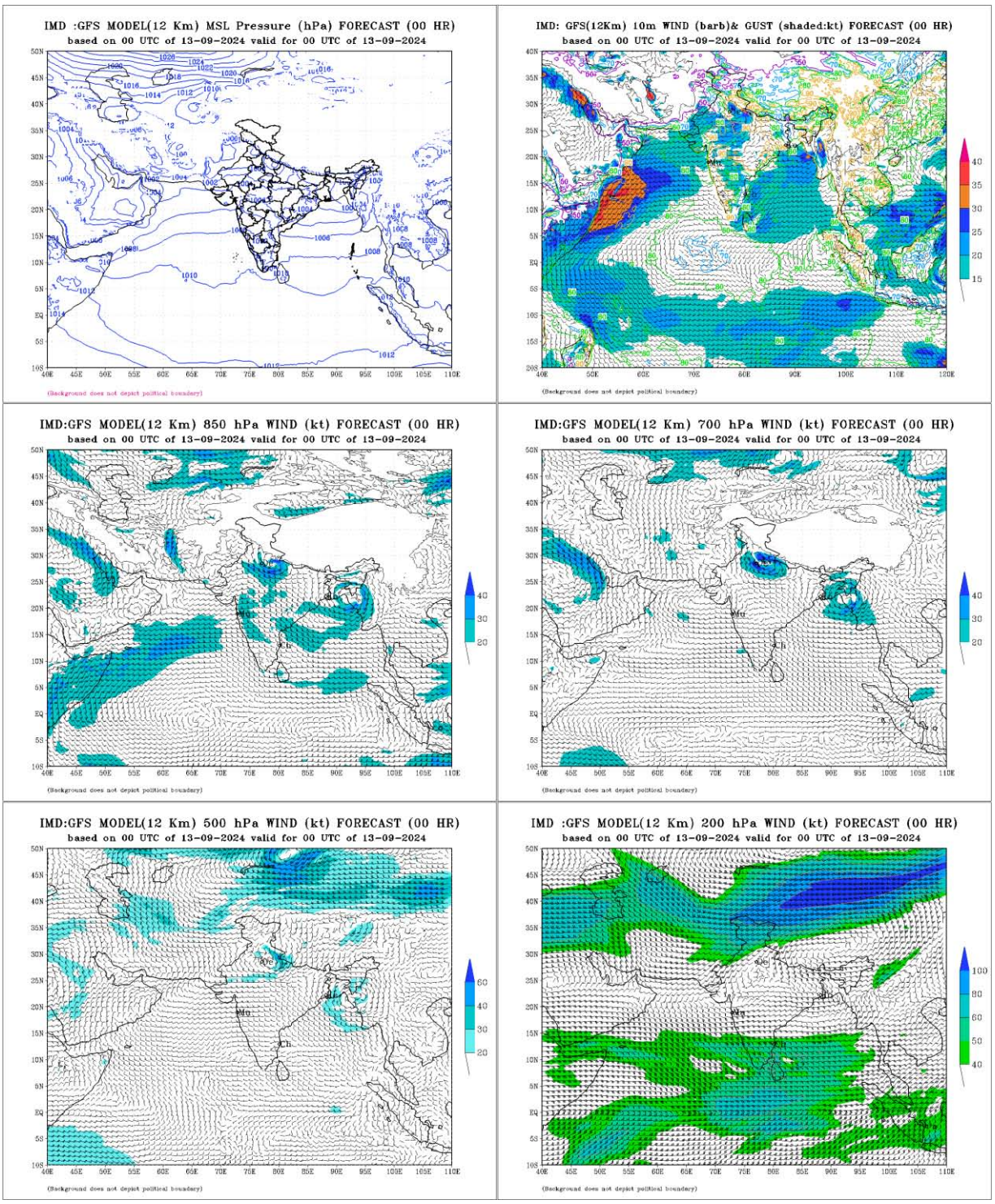


Fig. 2.8.3(c): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 13th September 2024

2.8.6 Realized Weather

Rainfall associated with the deep depression based on IMD-NCMRWF satellite gauge merged data are depicted in Fig 2.8.4. It is seen that light to moderate rainfall occurred at a few places over Madhya Pradesh, West Uttar Pradesh on 11th September. Light to moderate rainfall occurred at most places with extremely heavy rainfall at isolated places and heavy to very heavy rainfall at many places over West Madhya Pradesh, West Uttar Pradesh, light to moderate rainfall at many places with heavy to very heavy rainfall at a few places over East Madhya Pradesh, East Rajasthan and isolated heavy rainfall over Uttarakhand and East Uttar Pradesh on 12th September. Light to moderate rainfall occurred at many places with extremely heavy rainfall at isolated places over Uttarakhand and heavy to very heavy rainfall at a few places over Uttar Pradesh and isolated heavy rainfall over East Rajasthan, Delhi, Bihar, West Madhya Pradesh on 13th September. Light to moderate rainfall occurred at many places with heavy to very heavy rainfall at a few places over Haryana- Chandigarh, Gangetic West Bengal, Uttarakhand and heavy rainfall at isolated places over Odisha, Bihar, Uttar Pradesh, Himachal Pradesh, Delhi, Jharkhand, Chhattisgarh and Sub-Himalayan West Bengal on 14th September.

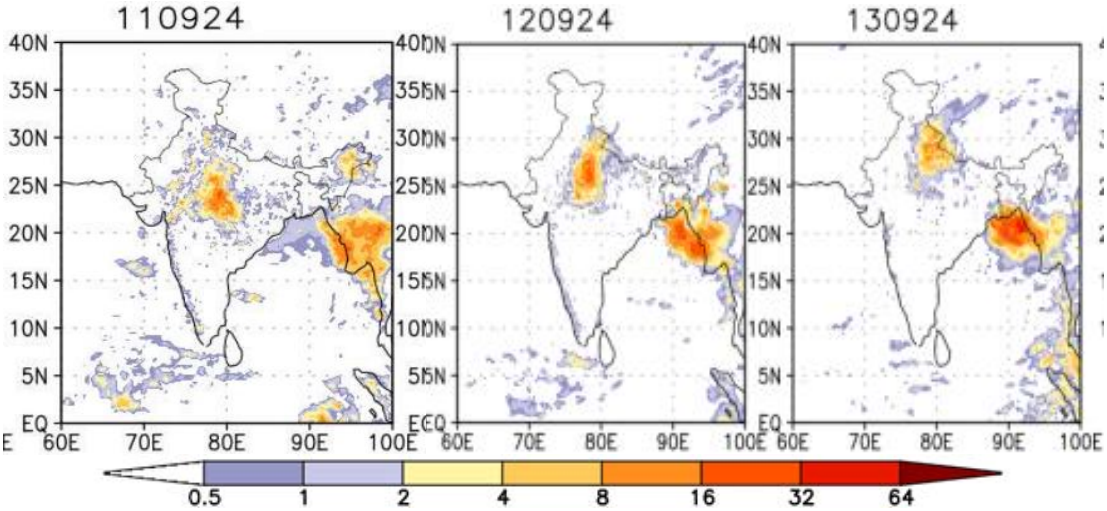


Fig. 2.8.4: NCMRWF-IMD satellite gauge merged data plots of realized 24 hours accumulated rainfall from 11th to 13th Sept, 2024.

2.8.6.1 Rainfall forecast verification

The forecast for heavy to extremely heavy rainfall episodes in association with the system are verified with the 24 hours accumulated rainfall realized at various stations. The details of the day-wise verification are given in Table -2.8.2

Table 2.8.2: Day wise daily 24 hours cumulative rainfall forecast verification with station observations

Date/Base Time of observation	24 hr Heavy rainfall warning ending at 0300 UTC of next day	Realized 24-hour heavy rainfall (≥ 7 cm) ending at 0300 UTC of date
11.09.2024 / 0830	**East Madhya Pradesh:** Heavy to very heavy rainfall at a few places and extremely heavy rainfall at	**12.09.2024/ 0830** **West Madhya Pradesh:** Biaora 36, Gohad & Karera 22 each, Narwar &

	isolated places on 11th; heavy to very heavy rainfall at few places on 12th and heavy rainfall at isolated places on 13th and 14th September. **West Madhya Pradesh:** Heavy to very heavy rainfall at a few places and extremely heavy rainfall at isolated places on11 th & 12 th; heavy to very heavy rainfall at a few places on 13 th & 14th September and heavy rainfall at a few places on 15th September. **West Uttar Pradesh:** Heavy to very heavy rainfall at a few places and extremely heavy rainfall at isolated places on11th, 12th and 13th and heavy rainfall at a few places on 14th & 15th September. **East Uttar Pradesh:** Heavy rainfall at isolated places on 11th; heavy to very heavy rainfall at a few places and extremely heavy rainfall at isolated places on 12th and heavy rainfall at a few places on 13th, 14th & 15th September. **East Rajasthan:** Heavy to very heavy rainfall at a few places on 11th, 12th & 13th and heavy rainfall at isolated places on 14th & 15th September. **West Rajasthan:** Heavy rainfall at a few places on 11th & 12th September.	Rajgarh 21 each, Gwalior & Mau 20 each, Bhander , Sabalgarh and Datia 19 each, Dabra 18, Ater , Ambah , Porsa , Ghatigaon and Bhitarwar 17 each, Mihona , Mehgaon and Lahar 16 each, Chinor , Gormi , Bhindaws and Badoda 15 each, Alipur 14, Morena , Narsingarh , Pachmarhi and Roan 12 each, Badarwas & Shivpuri 11 each, Vijaypur & Pichhore 10 each, Seodha , Shamshabad , Khaniyadana and Indergarh 9 each, Bamori & Kailaras 9 each, Navibagh Aet , Kolaras and Ashoknagar 8 each, Bairad & Sheopur 7 each. **West Uttar Pradesh:** Agra 29, Jalesar & Sadabad 23 each, Sikandra Rao 20, Hathras 19, Tundla , Khairagarh , Kasganj and Sahawar 17 each, Tahrauli 15, Jhansi 14, Fatehabad 13, Etawah , Sasani , Sahaswan and Vrindavan 12 each, Talbehat , Moth , Narora , Etah , Jasrana and Aligarh 11 each, Karhal & Etmadpur 10 each, Bah , Auraiya , Gunnaur , Madawara and Mainpuri 9 each, Shikohabad , Kurawali , Mauranipur , Kalpi Tehsil , Kalpi, Moradabad, Moradabad and Bareilly 8 each, Pali , Moradabad , Kasba Tanda , Aliganj , Etawah and Ghiror 7 each. **East Rajasthan:** Rajakhera 24, Dholpur Tehsil 19, Sawaimadhopur Tesil 16, Aklera 13, Sapau, Bari and Shahabad 11 each, Manohar Thana , Baseri and Bharatpur Tehsil 10 each, Rupbas & Pipalda 9 each, Kathumer , Sarmathura, Kumher, Khandar, Beir and Deeg 8 each, Lalsot , Nagar, Nadbai , Bayana , Karauli , Baran , Atru and Dhariabad 7 each. **East Madhya Pradesh:** Prithvipur 23, Orchha 15, Niwari & Chahtarpur 12 each, Nowgong 11, Mohangarh 10, Lidhora 9, Rajnagar 8, Patera , Banda and Lavkushnagar 7 each, **Uttarakhand:** Banbasa 12, Champawat 9, Pantnagar & Lohaghat 8 each,

		Haldwani 7, **East Uttar Pradesh:** Itwa 11, Bhanpur 7.
12.09.2024 / 0830	**Uttarakhand:** Heavy to very heavy rainfall at a few places and extremely heavy rainfall at isolated places on 12th & 13th; heavy rainfall at isolated places on14th September. **West Uttar Pradesh:** Heavy to very heavy rainfall at a few places and extremely heavy rainfall at isolated places on 12th, heavy to very heavy rainfall at isolated places on 13th and heavy rainfall at a few places on 14th September. **East Uttar Pradesh:** Heavy rainfall at a few places on 12th and at isolated places on 13th & 14th September. **West Madhya Pradesh:** Heavy to very heavy rainfall at a few places over northwest Madhya Pradesh on 12th; heavy rainfall at isolated places on 13th & 14th September. **East Madhya Pradesh:** Heavy rainfall at few places over northeast Madhya Pradesh on 12th and heavy rainfall at isolated places on 13th and 14th September. **East Rajasthan:** Heavy to very heavy rainfall at an isolated places over northeast Rajasthan on 12th and heavy rainfall at isolated places on 14th September. **Haryana:** Heavy to very heavy rainfall at a few places over south Haryana on 12th and heavy rainfall at isolated places on 13th & 14th September.	**13.09.2024/ 0830** **Uttarakhand:** Lohaghat 26, Champawat 20, Banbasa & Khatima 13 each, Kashipur & Pithoragarh 11 each, Jaspur , Mukteshwar , Pantnagar , Pati and Haldwani 9 each, Almora 8, Betalghat , Ranikhet , Nainital , Haridwar and Gairsain 7 each. **West Uttar Pradesh:** Bijnor 18, Kasganj & Sahawar 15 each, Budaun 14, Mirganj , Sahaswan and Pawayan 13 each, Baheri & Nauganva Sadat 12 each, Sikandra Rao , Amroha and Moradabad 11 each, Hasanpur , Dhampur , Dataganj and Aligarh 10 each, Bilari 10, Moradabad , Thakurdwara , Kasba Tanda , Jansath , Jasrana , Nagina , Moradabad, Shahjahapur Obsy and Bisauli 9 each, Narora , Aonla , Mawana , Nawabganj , Aliganj , Etawah , Chandpur , Bareilly and Suar 8 each, Agra , Gunnaur , Chandausi , Pilibhit Tehsil , Shahjahanpur , Tundla , Bisalpur and Bareilly 7 each. **East Uttar Pradesh:** Muhammadi 14, Ankinghat 12, Nighasan , Neemsar , Dhaurahara and Kaimganj 11 each, Mahsi & Katarniaghat 10 each, Nanpara & Hardoi 9 each, Dabri Fmo 8, Kheri Lakhimpur , Chhibramau , Bahraich and Shardanagar 7 each. **East Rajasthan:** Viratnagar & Asnawar 8 each, Bharatpur Tehsil & Shahabad 7 each. **Haryana-Chandigarh-Delhi:** Hassanpur & Delhi Ridge 7 each. **West Madhya Pradesh:** Ambah, Karhal and Porsa 7 each. **Bihar:** Barauni 7.
13.09.2024 / 0830	**Uttarakhand:** Heavy to very heavy rainfall at a few places and extremely heavy rainfall at	**14.09.2024/ 0830** **Haryana-Chandigarh:** Pataudi 21, Nahar Rev & Kosli 13 each, Palhawas

	isolated places on 13th and heavy rainfall at isolated places on 14th September. **Himachal Pradesh:** Heavy rainfall at isolated places on 13th September. **Uttar Pradesh:** Heavy to very heavy rainfall at isolated places on 13th and heavy rainfall at isolated places on 14th September. **Haryana:** Heavy rainfall at isolated places on 13th & 14th September.	Rev 9, Taoru & Faridabad 8 each, Dadri , Sohana , Nuh and Bhadkal 7 each. **Gangetic West Bengal:** Contai 18, Durgachack 17, Digha 12, Bagati & Sagar Island 11 each, Durgapur 10, Diamond Harbour , Panagarh and Suri 9 each, Jangipur , Dum Dum , Alipore , Salar and Suri 8 each, Basirhat , Kalyani , Berhampore , Hetampur , Tilpara Barrage , Mo Saltlake , Sri Niketan and Gheropara 7 each. **Uttarakhand:** Champawat 18, Haldwani 16, Nainital 15, Lohaghat 11, Pantnagar 9, Pithoragarh 9, Ghansali 8, Banbasa & Bhagwanpur 7 each. **Odisha:** Kusumi 14, Bhograi 10, Jaleswar 7; **Bihar:** Beldaur & Khaira 9 each, Lakhisarai, Nabinagar, Halsi and Jamui 8 each, Gogri, Bausi and Begusarai 7 each. **West Uttar Pradesh:** Kasba Tanda 9, Bijnor 8, Suar 7. **Himachal Pradesh:** Kataula 8, Palampur 7; **Delhi:** Palam 8, Aya Nagar, Lodi Road 7 each. **Jharkhand:** Giridih, Bengbad and Bengabad 8 each, Sujani & Pakuria 7 each. **Chhattisgarh:** Surajpur 7. **Sub-Himalayan West Bengal:** Malda 7. **East Uttar Pradesh:** Katarniaghat 7.

2.8.7 Damage due to the system

No damage was reported in association with this system.

2.9. Deep Depression over Northeast Bay of Bengal and adjoining Bangladesh during 13th Sept – 18th Sept, 2024

- Under the influence of an upper air cyclonic circulation over southeast Bangladesh and neighbourhood, a low-pressure area formed over southeast Bangladesh and neighbourhood around mid-night (2330 hours IST / 1800 UTC) of 12th September, 2024.
- It moved west-northwestwards and lay as a well marked low pressure area over northeast Bay of Bengal (BoB) and adjoining southeast Bangladesh coast in the morning (0830 hours IST / 0300 UTC) of the 13th September, 2024.
- Continuing to move west-northwestwards, it concentrated into a Depression over northeast BoB close to Bangladesh coast in the same evening (1730 hours IST / 1200 UTC) of the 13th September, 2024.
- Continuing to move further west-northwestwards, it intensified into a Deep Depression over Bangladesh and adjoining Gangetic West Bengal in the early morning (0530 hours IST / 0000 UTC) of 14th September, 2024. Thereafter, it made a loop and moved across Gangetic West Bengal during 14th -15th and across Jharkhand on 16th September.
- Continuing to move further west-northwestwards, it weakened into a Depression over Jharkhand and adjoining north Chhattisgarh in the early morning (0530 hours IST / 0000 UTC) of 17th September, 2024.
- Continuing to move further west-northwestwards, it weakened into a Well-Marked Low-Pressure Area over northeast Madhya Pradesh and adjoining southwest Uttar Pradesh in the early morning (0530 hours IST / 0000 UTC) of 18th September 2024.

The observed track of the system is presented in **Fig. 2.9.1** and the best track is given in **Table 2.9.1**.

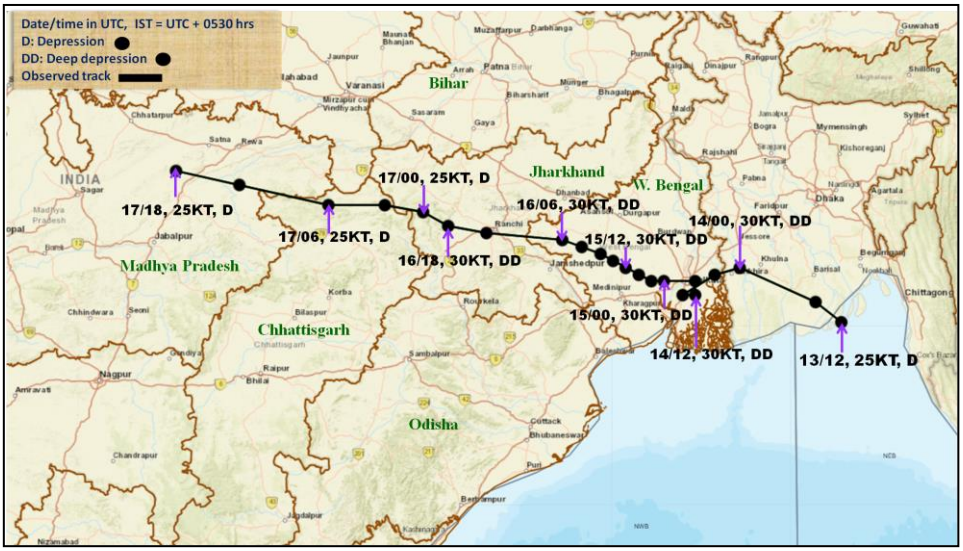


Fig. 2.9.1. Observed track of Deep Depression over Northeast BoB and adjoining Bangladesh during 13th – 18th September, 2024

Table 2.9.1. Best track positions and other parameters of the Deep Depression over Northeast BoB and adjoining Bangladesh during 13th – 18th September, 2024

Date	Time (UTC)	Lat.	Long.	C.I No.	ECP	ΔP	MSW (kt)	Category
13.09.24	1200	22.0	90.8	1.5	993	3	20	D
	Crossed Bangladesh coast close to Patuakhali (Bangladesh) between 1700 to 1800 UTC of 13th September (2230 to 2330 hrs IST of 13th September) as a depression with wind speed of 45-55 gusting to 65 kmph							
	1800	22.3	90.4	-	992	4	25	D
14.09.24	0000	22.5	89.6	-	990	5	30	DD
	0300	22.7	88.8	-	990	5	30	DD
	0600	22.4	88.3	-	990	5	30	DD
	1200	22.4	88.5	-	989	6	30	DD
	1800	22.6	88.5	-	989	6	30	DD
15.09.24	0000	22.6	88.0	-	989	6	30	DD
	0300	22.6	87.8	-	990	5	30	DD
	0600	22.7	87.6	-	990	5	30	DD
	1200	22.8	87.4	-	990	5	30	DD
	1800	22.9	87.2	-	990	5	30	DD
16.09.24	0000	23.0	87.0	-	990	5	30	DD
	0300	23.1	86.7	-	990	5	30	DD
	0600	23.2	86.4	-	990	5	30	DD
	1200	23.3	85.2	-	990	5	30	DD
	1800	23.4	84.6	-	991	5	30	DD
17.09.24	0000	23.6	84.2	-	992	4	25	D
	0300	23.7	83.7	-	993	4	25	D
	0600	23.7	82.7	-	995	3	20	D
	1200	24.0	81.3	-	995	3	20	D
	1800	24.2	80.3	-	995	3	20	D
18.09.24	0000	Weakened into a well-marked low-pressure area over northeast Madhya Pradesh and adjoining southwest Uttar Pradesh						

KT: Knots (nautical mile per hour), 1 KT=1.85 kmph, D: Depression, DD: Deep Depression

2.9.1. Brief life history - Genesis Intensification and movement

2.9.1.1 Genesis

A low-pressure area formed over southeast Bangladesh and neighbourhood in the midnight (1800 UTC) of 12th September. At 1800 UTC of 12th September, the MJO index was in phase 5 with an amplitude of less than 1 and was likely to continue in same phase during next 2-3 days. Thus, MJO was favourable for enhancement of convective activity over the north BoB and adjoining areas for the next 2-3 days. The NCICS CFS model analysis field indicated prevalence of westerly wind anomaly (5-7 mps) and Equatorial Rossby waves during 12th-16th Sep over central India & central BoB with easterly wind anomaly (3-5 mps) over north BoB and northeastern parts of India. The low-level convergence was about 20 x $10^{-6}s^{-1}$ over northeast BoB & adjoining Myanmar. Upper-level divergence was about $20x10^{-6}s^{-1}$ over northeast BoB & adjoining Myanmar. The vertical wind shear (VWS) was low to moderate (5-15 kt) over coastal Bangladesh & neighbourhood. The relative vorticity at 850 hpa level was around $70\text{-}100x10^{-6}s^{-1}$ over northeast BoB & adjoining Myanmar with vertical extension upto 500 hPa level. Under these favorable conditions the upper air cyclonic circulation over southeast Bangladesh and neighbourhood lay as a low-pressure area over southeast Bangladesh and neighbourhood at 1800 UTC of 12th September, 2024.

Similar features prevailed and the low-pressure area over southeast Bangladesh moved west-northwestwards and lay as a well-marked low pressure area over northeast BoB and adjoining southeast Bangladesh coast on 13th September morning (0300 UTC).

At 1200 UTC 13th September 2024, the sea surface temperature (SST) was 28-30°C over the north BoB. Tropical cyclone heat potential (TCHP) was 80-100 KJ/cm² near the system centre. Low-level convergence was around $20x10^{-6}s^{-1}$, and upper-level divergence was around $20x10^{-6}s^{-1}$ over the north BoB. The VWS was low (5-10 knots) over the system area and along the forecast track. The relative vorticity at the 850 hPa was around $200x10^{-6}s^{-1}$ over the north BoB, extending upto the 200 hPa level. Under these favorable conditions the well-marked low pressure area over northeast BoB and adjoining southeast Bangladesh coast concentrated into a Depression over northeast BoB close to Bangladesh coast at 1200 UTC of the 13th September, 2024.

2.9.1.2 Intensification and movement

At 0000 UTC of 14th September, similar sea conditions prevailed. Low-level convergence increased and was around $20\text{-}30x10^{-6}s^{-1}$ over Gangetic West Bengal and northeast BoB. Upper-level divergence also increased and was around $20\text{-}30x10^{-6}s^{-1}$ over the north BoB and adjoining areas of West Bengal and Odisha. The VWS was low to moderate (10-15 knots) over the system area and increasing along the forecast track. The relative vorticity at the 850 hPa level was around $150x10^{-6}s^{-1}$ over the north BoB and neighborhood, extending up to the 200 hPa level. Under these favorable conditions, the depression over northeast BoB intensified into a

Deep Depression over Bangladesh and adjoining Gangetic West Bengal at 0000 UTC of the 14th September 2024.

During 14th - 16th September, similar favourable environmental features (MJO, equatorial Rossby waves, moisture carrying southwesterly winds from Arabian Sea, favourable low level positive relative vorticity, low level convergence and upper-level divergence) continued and the system maintained its intensity of deep depression over land during 14th to 16th September, 2024.

At 0000 UTC 17 September 2024, MJO index entered into phase 6 (unfavorable). The NCICS-based forecast indicated the persistence of westerly winds (3-5 mps) over the central parts of India, along with easterly winds (3-5 mps) over northeastern parts of India. The equatorial Rossby wave had moved away. The low-level convergence decreased and was around $20x10^{-6}s^{-1}$ over the system area. Upper-level divergence also decreased and was around $30x10^{-6}s^{-1}$ over the system area. TheVWS was moderate to high (15-20 knots) over the system area and along the forecast track. The relative vorticity at the 850 hPa level decreased and was around $120x10^{-6}s^{-1}$ to the south of the system center and extended up to the 500 hPa level ($40\text{-}50x10^{-6}s^{-1}$), indicating a decrease in the depth of convection. Thus, environmental features indicated gradual weakening of the system. Under these unfavorable conditions the deep depression over central parts Jharkhand weakened into a depression over west Jharkhand and adjoining north Chhattisgarh at 0000 UTC of the 17th September 2024. It weakened into a well-marked low-pressure area over northeast Madhya Pradesh and adjoining southwest Uttar Pradesh at 0530 IST(00 UTC) of 18th September 2024.

2.9.2. Monitoring

India Meteorological Department (IMD) maintained round the clock watch over the north Indian Ocean (NIO) and the system was monitored well in advance since 12th September. The system was monitored with the help of available satellite observations from INSAT 3D and 3DR, polar orbiting satellites, available ships & buoy observations in the region and coastal observations on the day of landfall. 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 system. A digitized forecasting system of IMD was utilized for analysis and comparison of various models' guidance, decision making process and warning products generation.

2.9.2.1. Features observed through satellite

Satellite monitoring of the system was mainly done by using half hourly INSAT-3D and 3DR imageries. Satellite imageries of other international geostationary satellites, high resolution polar orbiting satellites and scatterometer imageries from ASCAT, OCEANSAT-3 were also considered for monitoring of the system. Typical INSAT-3D enhanced colored imageries, visible/ IR, brightness temperature and water vapour imageries are presented in **Fig. 2.9.2(a) to (e)**. During

the entire life cycle, the clouds were organized in shear pattern. The detailed features from the satellite pictures are discussed in this section.

At 1200 UTC 13th September 2024, the intensity of the system was characterized as T 1.5. The associated scattered to broken low and medium clouds had embedded intense to very intense convection over East Odisha, Gangetic West Bengal, Meghalaya, Bangladesh, North & adjoining Central BoB, Arakan Coast and Myanmar (minimum cloud top temperature (CTT) -80 to -93 °C). There was moderate to intense convection over Mizoram and Tripura (minimum CTT of -60 to -70 °C).

At 0000 UTC of 14 September 2024, associated broken low and medium clouds with embedded intense to very intense convection was observed over Bihar, Jharkhand, West Bengal, Odisha, Tripura, Mizoram, Bangladesh, and north adjoining central BoB (minimum CTT -80 to -93°C).

At 1200 UTC 14th September 2024, associated broken low and medium clouds with embedded intense to very intense convection lay over Bihar, east Jharkhand, south Gangetic West Bengal, north Odisha, Tripura, Mizoram, Bangladesh, and north & adjoining central BoB (minimum CTT -80 to -93 °C). Moderate to intense convection lay over south Chhattisgarh, south Odisha, north Gangetic West Bengal, and Sub-Himalayan West Bengal.

At 0300 UTC 15th September 2024, associated scattered to broken low and medium clouds with embedded intense to very intense convection was observed over southwest Bihar, north Chhattisgarh, Jharkhand, north Odisha, Gangetic West Bengal, Bangladesh, and north BoB (minimum was -80 to -93 °C). Moderate to intense convection was detected over southeast Uttar Pradesh, south Odisha, sub-Himalayan West Bengal, Meghalaya, Assam, Manipur, Mizoram, and Tripura (minimum CTT was -60 to -70 °C).

At 1200 UTC 15th September 2024, spiral band organization of clouds continued. Associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over north Chhattisgarh, Jharkhand, north Odisha, Gangetic West Bengal, Bangladesh, Meghalaya, Tripura, Mizoram, and north BoB (minimum CTT was -70 to -90 °C). Moderate to intense convection lay over Bihar, west Assam, and Sub-Himalayan West Bengal (minimum CTT -60 to -70 °C).

At 0300 UTC 16th September 2024, a spiral band organization of clouds continued. Associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over Jharkhand, north Odisha, Gangetic West Bengal, Bangladesh, and northwest BoB (minimum CTT -70 to -90 °C). Moderate to intense convection lay over east Madhya Pradesh, north Chhattisgarh, Bihar, Sub-Himalayan West Bengal, Meghalaya, and West Assam (minimum CTT -50 to -70 °C). At 1200 UTC 16th September 2024, a spiral band organization of clouds continued. Associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over east Uttar Pradesh, east Madhya Pradesh, Jharkhand, north Chhattisgarh, north Odisha, Gangetic West Bengal, and north

Bangladesh (minimum CTT -70 to -90 °C). Moderate to intense convection lay over Bihar, Sub-Himalayan West Bengal, south Chhattisgarh, and south Odisha (minimum CTT -50 to -70 °C).

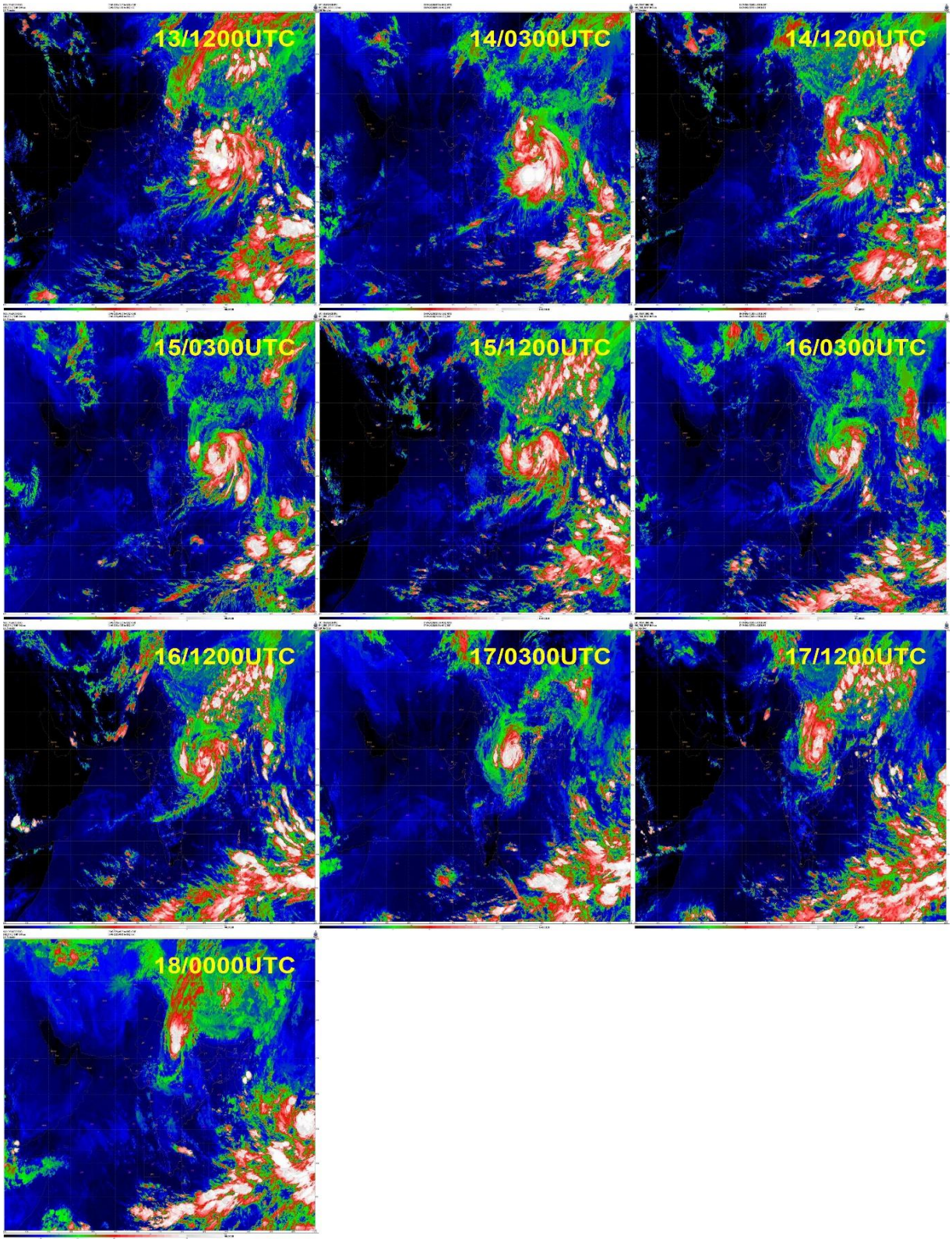


Fig. 2.9.2(a): INSAT-3R Enhanced Color Curve imageries during life cycle of Deep Depression over Northeast BoB during 13th – 18th September, 2024

At 0000 UTC 17th September 2024, associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over south Bihar, southeast Uttar Pradesh, northeast Madhya Pradesh, Jharkhand, north Chhattisgarh, north Odisha, Gangetic West Bengal, and north Bangladesh (minimum CTT -70 to -90 °C). Moderate to intense convection lay over Gangetic West Bengal (minimum CTT was -50 to -70 °C).

At 1200 UTC 17th September 2024, associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over west Bihar, Uttar Pradesh, east Madhya Pradesh, south Jharkhand, north Chhattisgarh, and north Odisha (minimum CTT was -70 to -90 °C). Moderate to intense convection lay over east Gangetic West Bengal, Sub-Himalayan West Bengal, and Bangladesh (minimum CTT -50 to -70 °C).

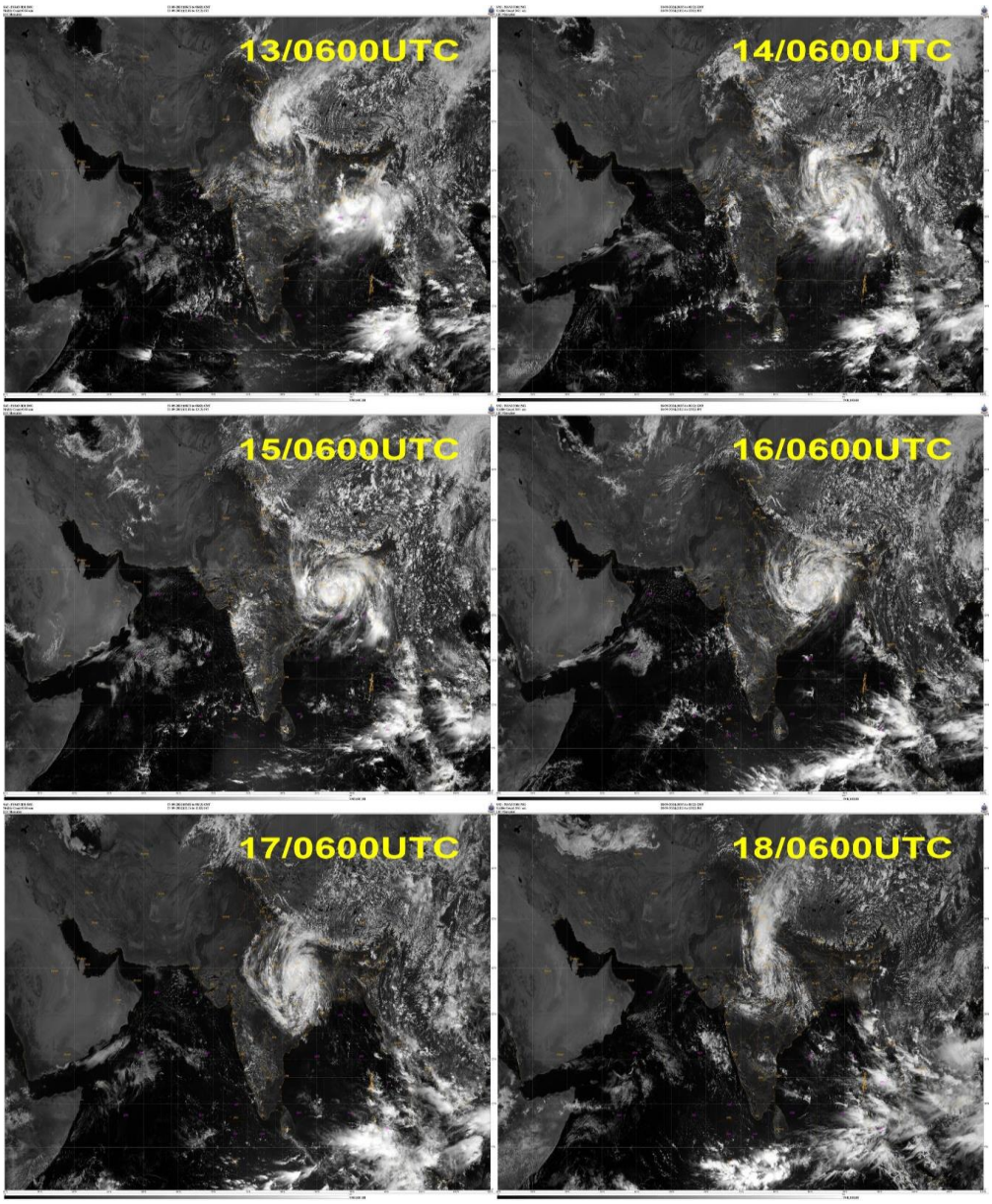


Fig. 2.9.2 (b): INSAT-3R Visible imageries during life cycle of Deep Depression over Northeast BoB during 13th – 18th September, 2024

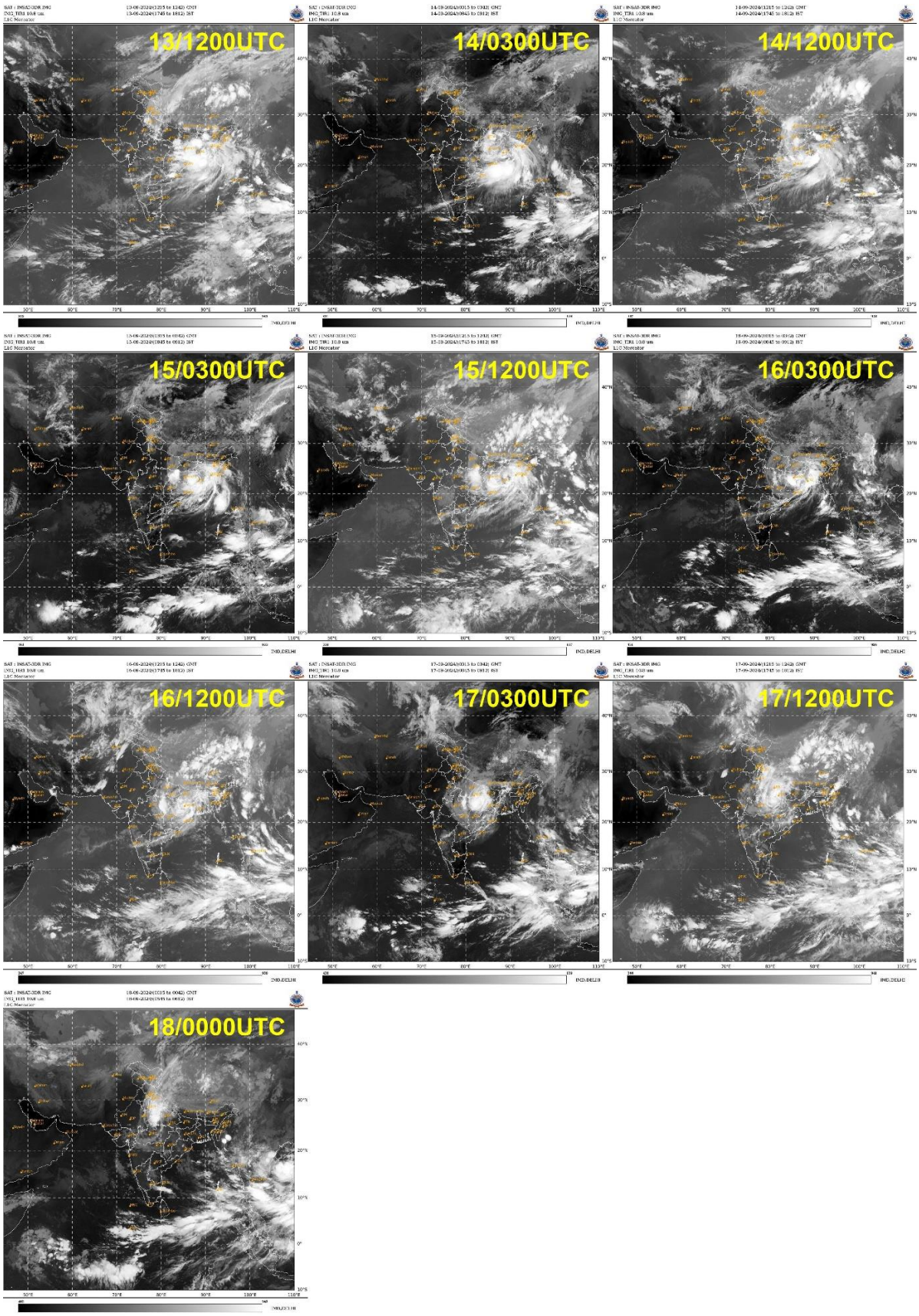


Fig. 2.9.2(c): INSAT-3D IR imageries during life cycle of Deep Depression over Northeast BoB during 13th – 18th September, 2024

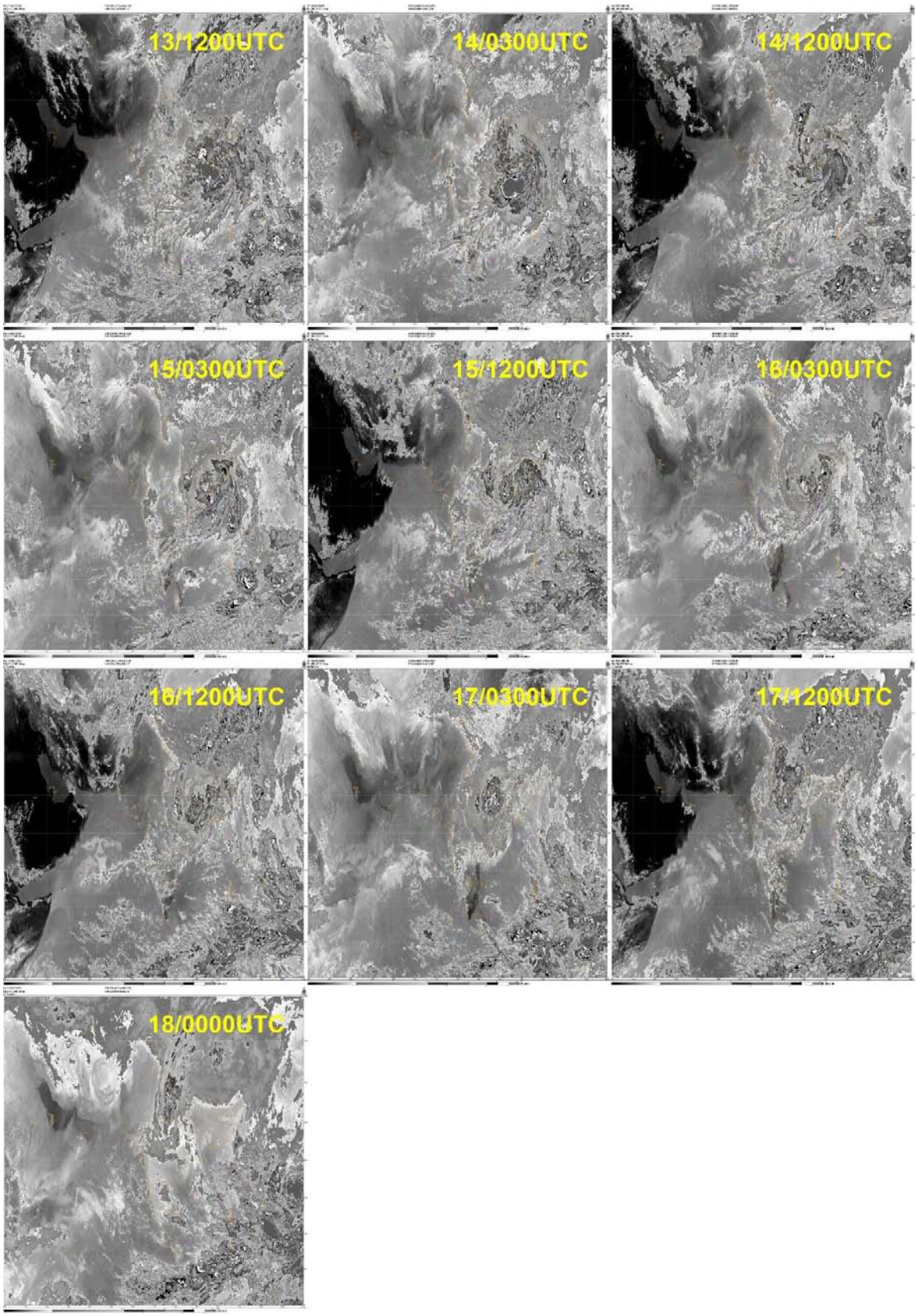


Fig. 2.9.2 (d): INSAT-3D enhanced IR imageries during life cycle of Deep Depression over Northeast BoB during 13th – 18th September, 2024

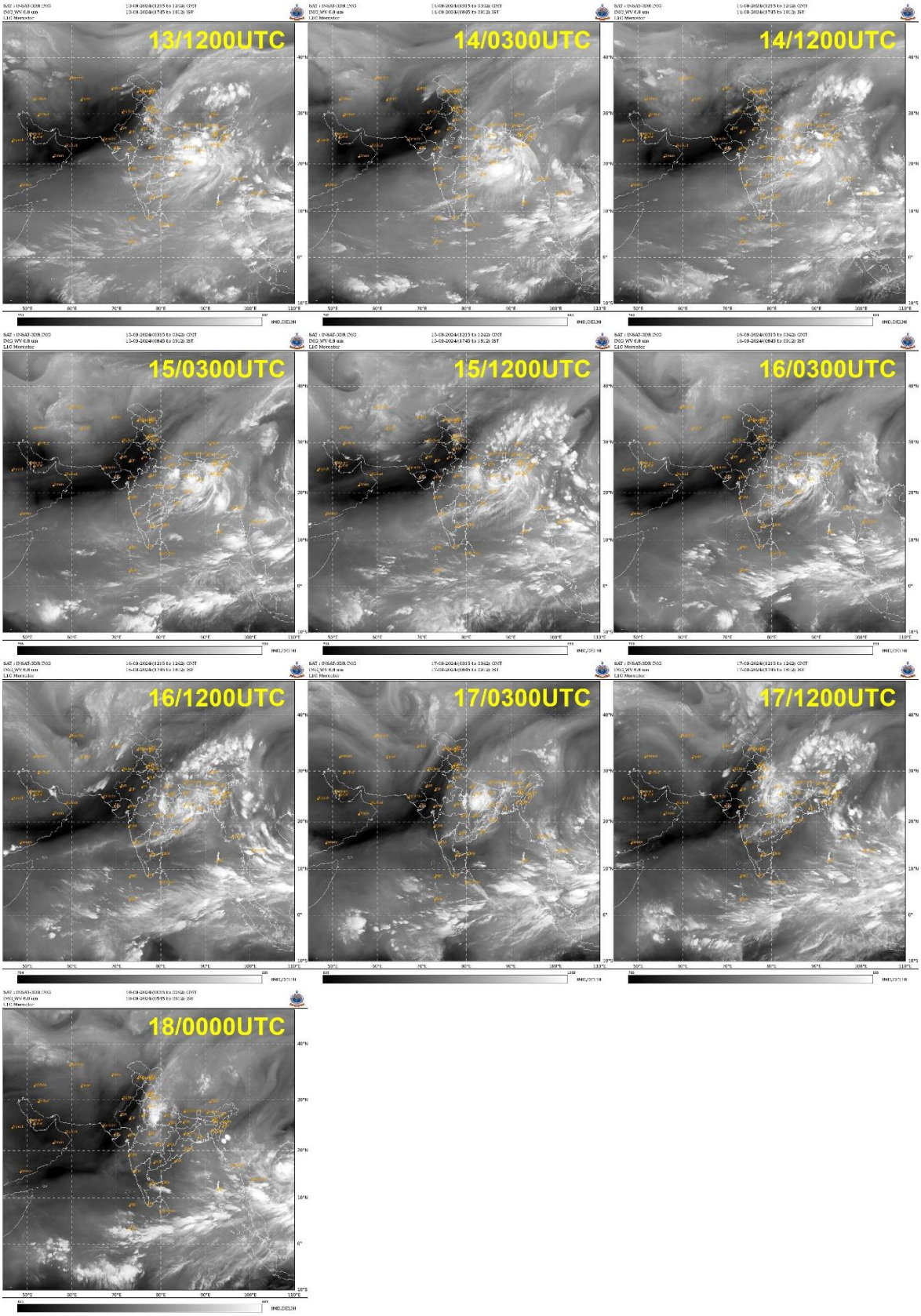


Fig. 2.9.2 (e): INSAT-3D Water Vapour imageries during life cycle of Deep Depression over Northeast BoB during 13th – 18th September, 2024

2.9.3. Dynamical Features

IMD GFS (T1534) analysis field of mean sea level pressure (MSLP), winds at 10 m, 850, 500 and 200 hPa levels at 0000 UTC during 13th to 18th September, 2024 are presented in **Fig. 2.9.3(a) to (f)** respectively.

At 0000 UTC of 13th September, the model indicated an upper air cyclonic circulation over northwest BoB and adjoining southeast Bangladesh. However, at that time, it lay as a low-pressure area over southeast Bangladesh and neighbourhood. Thus, the model underestimated the intensity of the system. However, location was correctly captured.

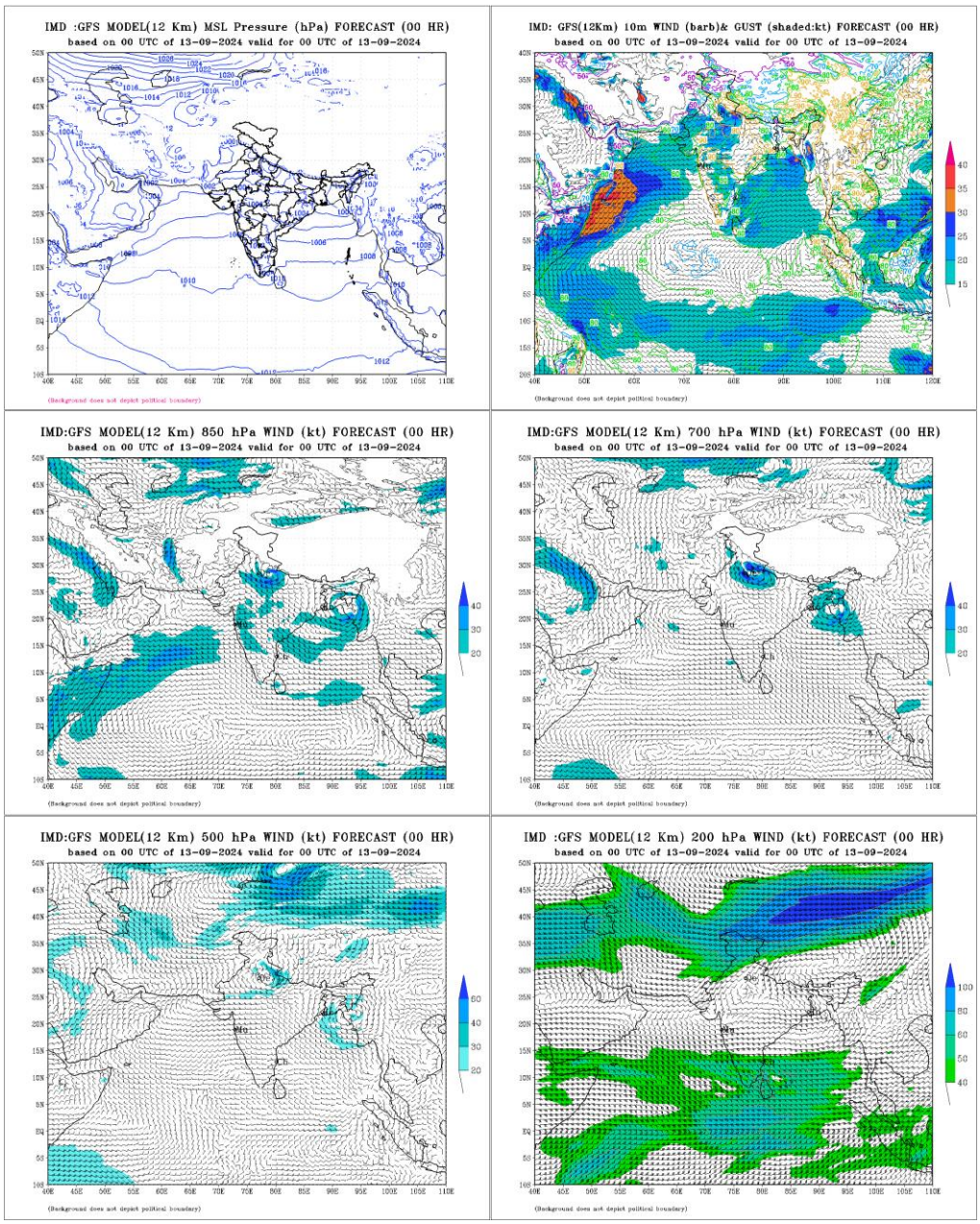


Fig. 2.9.3(a): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 700, 500 and 200 hPa levels based on 0000 UTC of 13th September 2024

At 0000 UTC of 14th September, the model indicated a deep depression over southwest Bangladesh and neighbourhood near 22.5N/89.0E. At that time, it lay as a

deep depression over southeast Bangladesh and neighbourhood near 22.8^0 N/89.2^{0}E. Thus, the model captured the location and intensity of the system correctly.

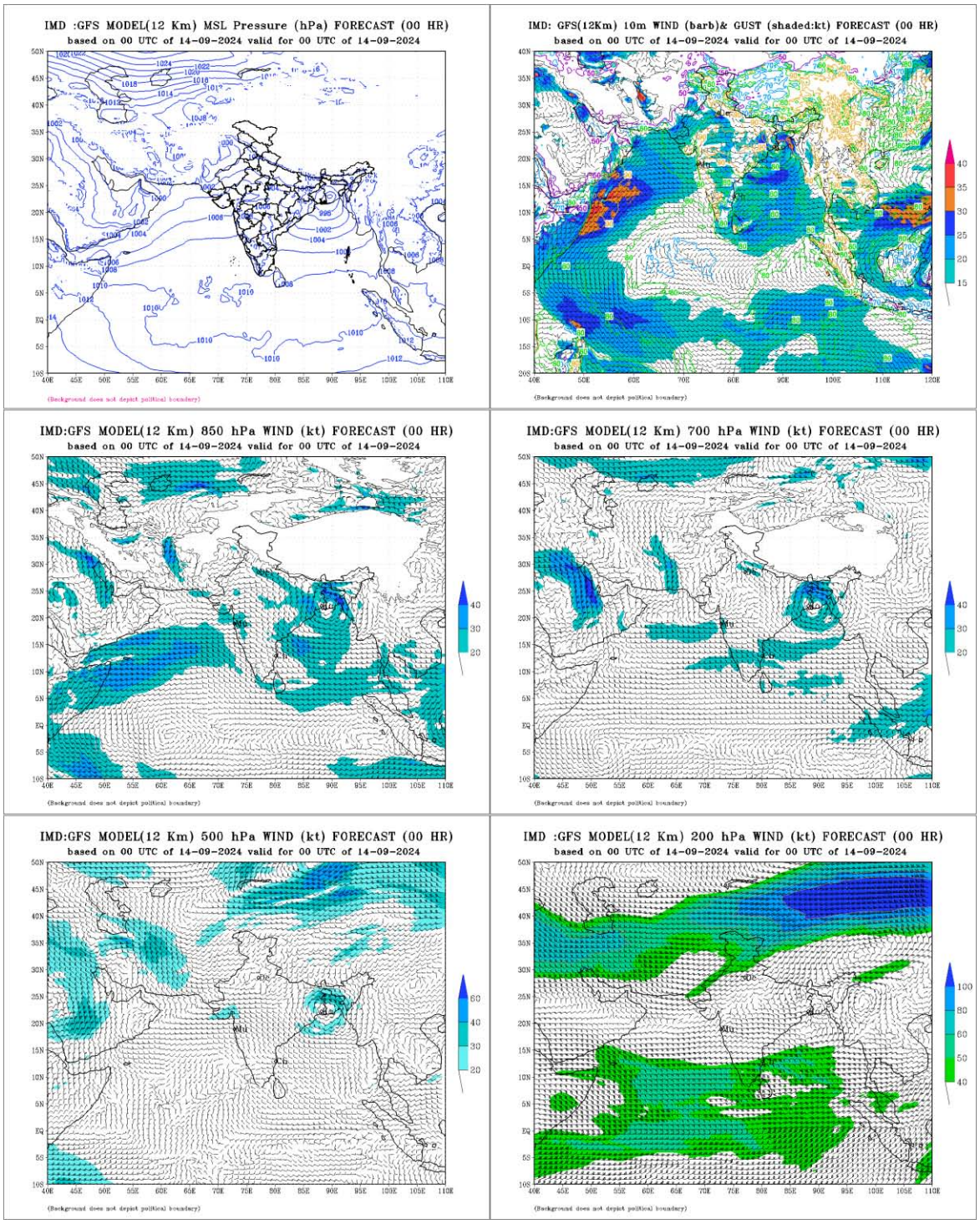


Fig. 2.9.3(b): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 700, 500 and 200 hPa levels based on 0000 UTC of 14th September 2024

At 0000 UTC of 15th September, the model indicated slight intensification of the system over Gangetic West Bengal and neighbourhood near 23.0^{0}N/88.0^{0}E. At that time, it lay as a deep depression over Southeast Bangladesh and adjoining Gangetic West Bengal near 22.6^{0}N/88.0^{0}E. Thus, the model slightly overestimated

the intensity of the system and could'nt capture movement correctly. Vertically, the system extended upto 500 hPa level with no significant tilting.

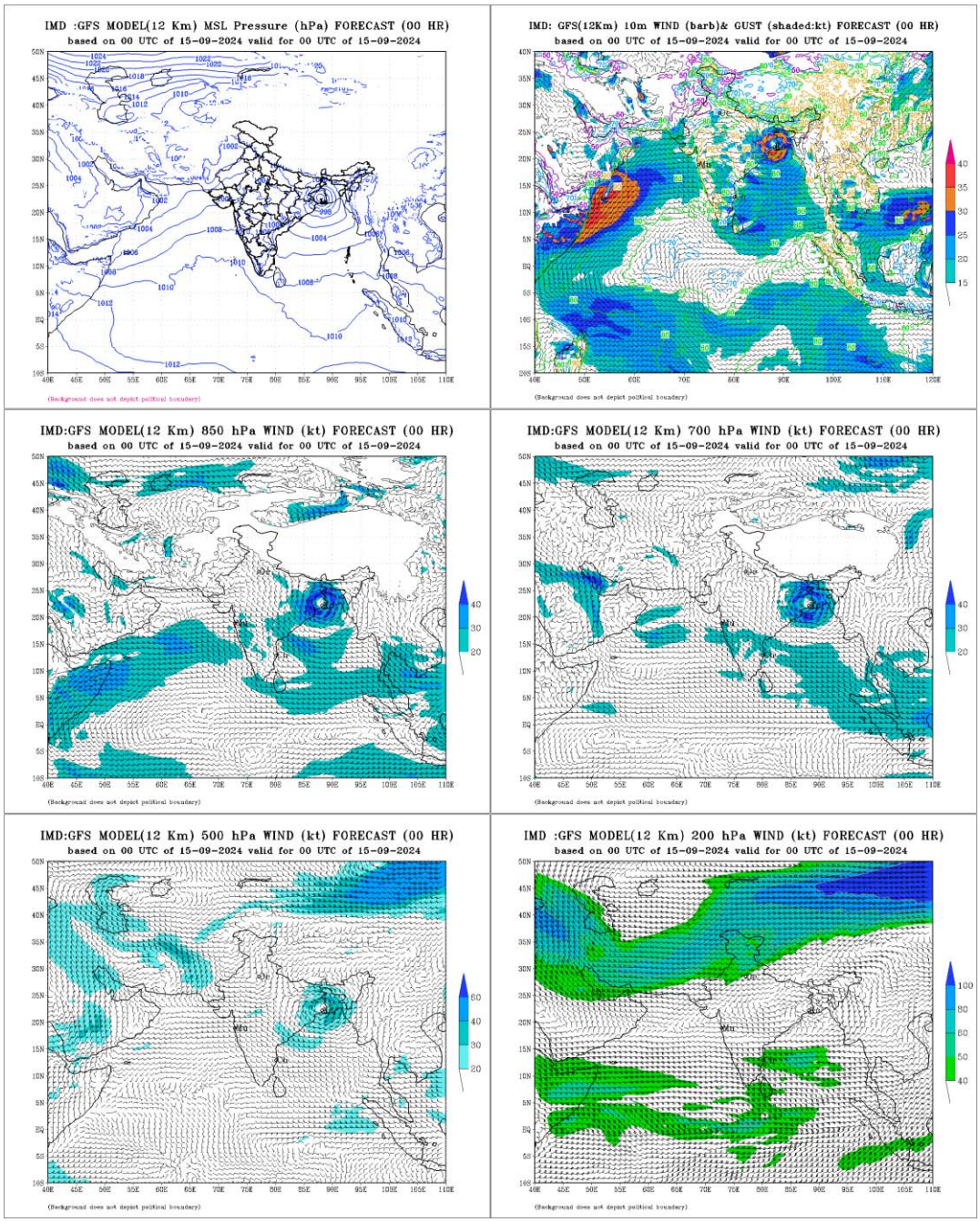


Fig. 2.9.3(c): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 700, 500 and 200 hPa levels based on 0000 UTC of 15th September 2024

At 0000 UTC of 16th September, the model indicated slight intensification of the system over Gangetic West Bengal and neighbourhood near 23.0^{0}N/88.0^{0}E. At that time, it lay as a deep depression over Southeast Bangladesh and adjoining Gangetic West Bengal near 22.6^{0}N/88.0^{0}E. Vertically, the system extended upto 500 hPa level

with no significant tilting. Thus, the model slightly overestimated the intensity of the system and could not capture movement correctly.

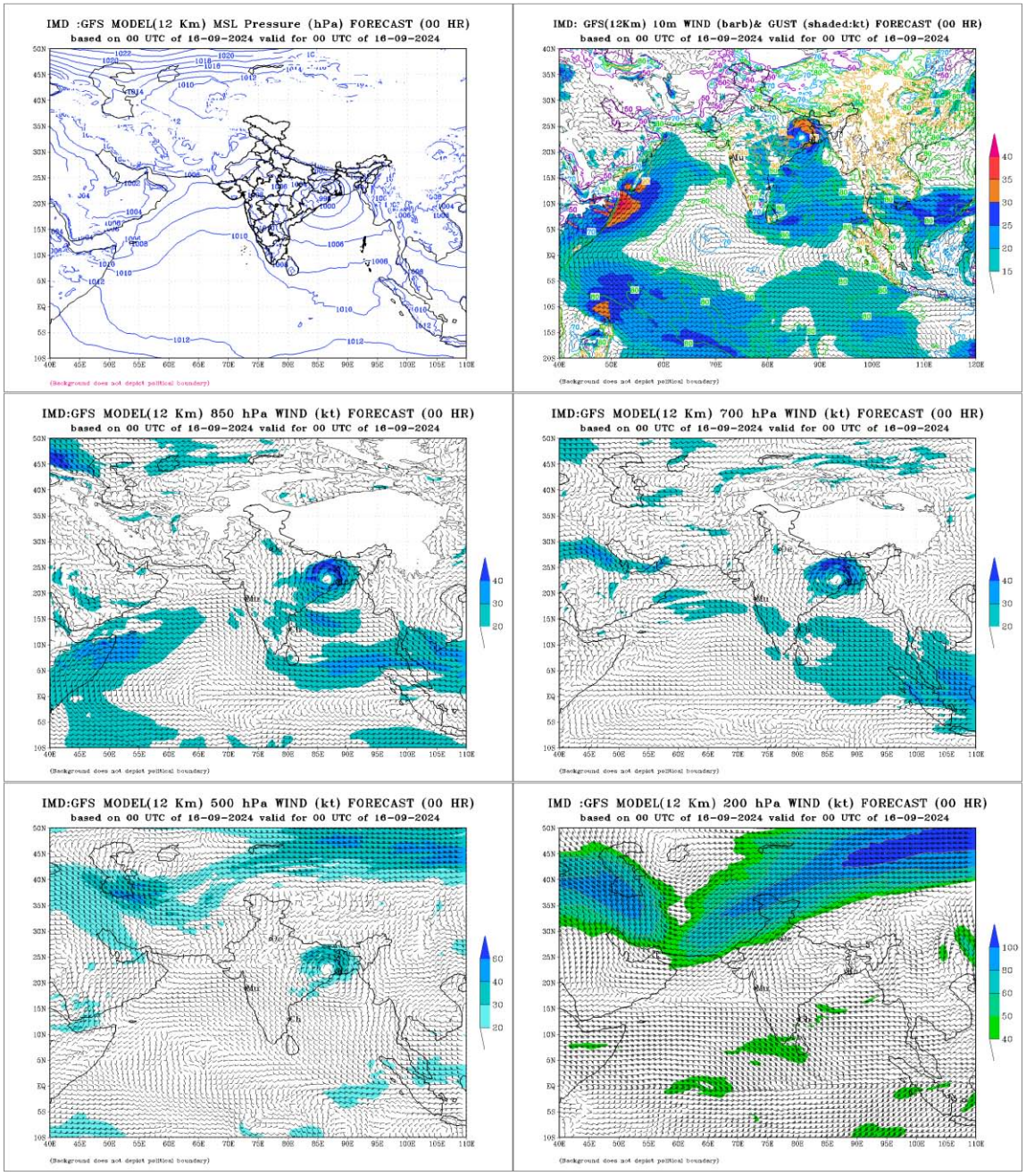


Fig. 2.9.3(d): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 700, 500 and 200 hPa levels based on 0000 UTC of 16th September 2024

At 0000 UTC of 17th September, the model indicated weakening of the system into a depression Jharkhand and adjoining north Chhattisgarh & southeast Uttar Pradesh near 24.0N/83.8E. At that time, it lay as a depression over Jharkhand and adjoining north Chhattisgarh near 23.6^{0}N/84.2^{0}E. Vertically, the system extended upto 500 hPa level with no significant tilting. Thus, the model could correctly capture the weakening and movement of the system.

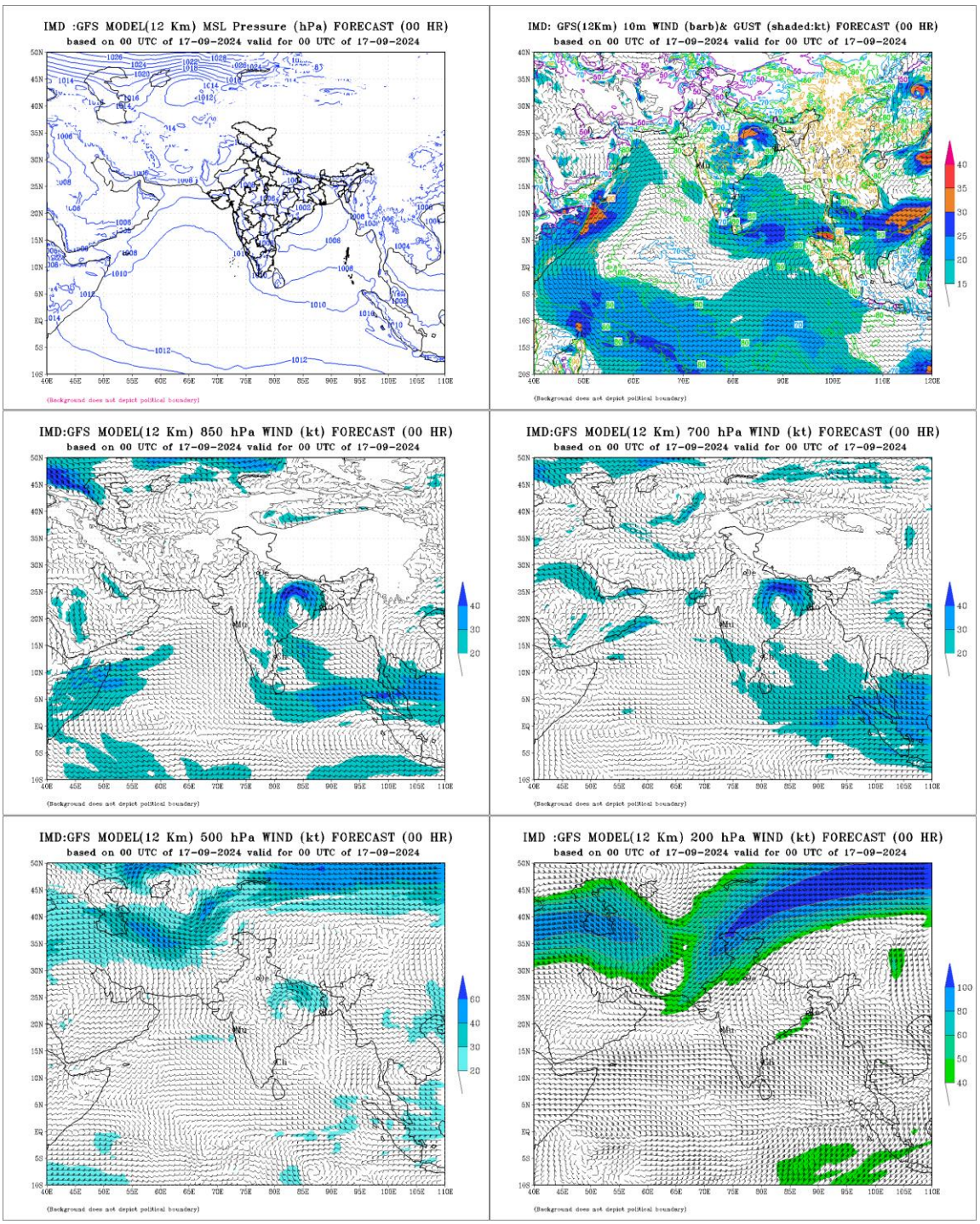


Fig. 2.9.3(e): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 700, 500 and 200 hPa levels based on 0000 UTC of 17th September 2024

At 0000 UTC of 18th September, the model indicated slight weakening of the system over northeast Madhya Pradesh and adjoining southwest Uttar Pradesh near 24.5N/79.0E. At that time, it lay as a depression over Jharkhand and adjoining north Chhattisgarh near 23.6^{0}N/84.2^{0}E. Vertically, the system extended upto 700 hPa level with no significant tilting. Thus, the model could correctly capture the weakening and movement of the system

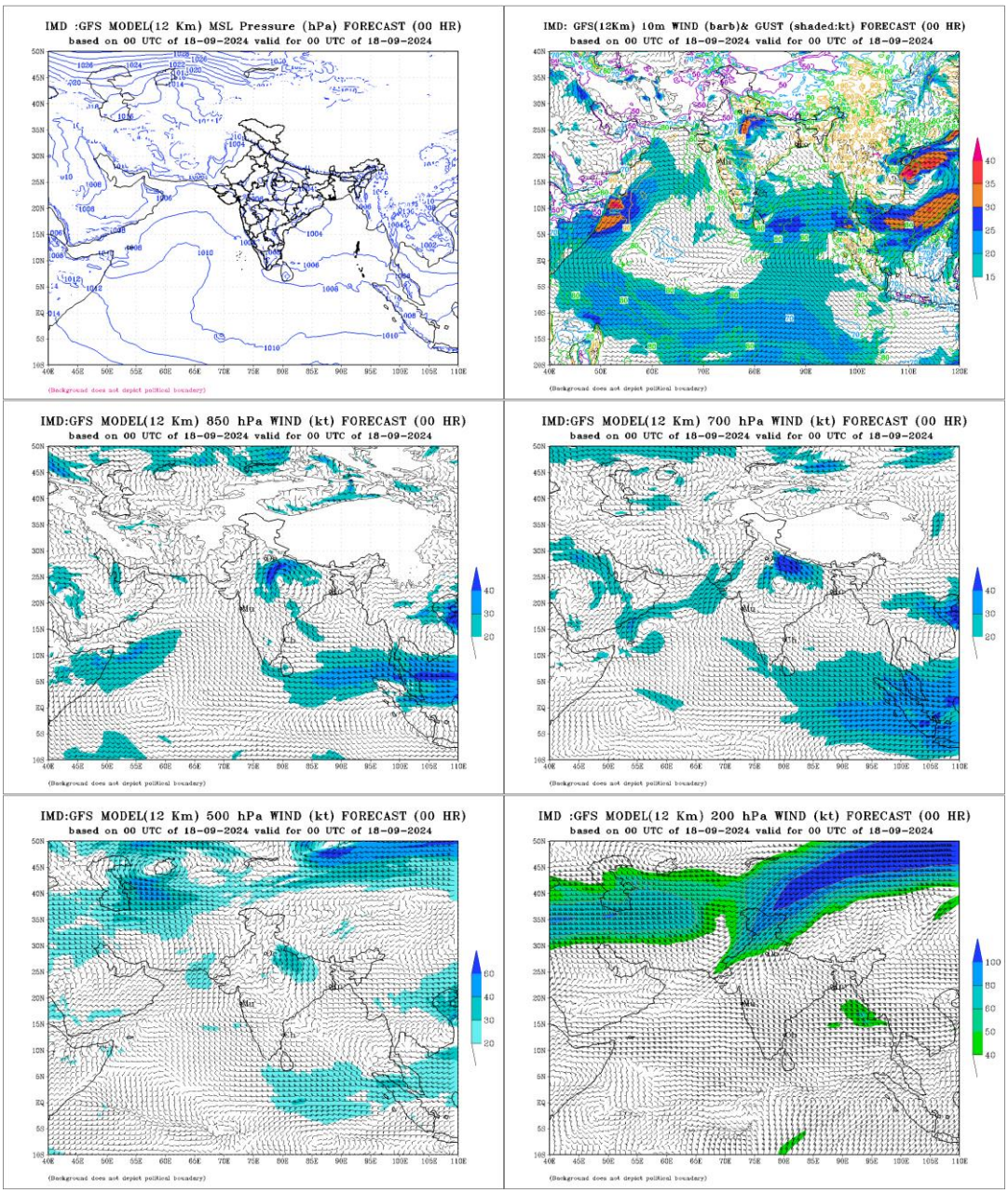


Fig. 2.9.3(f): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 700, 500 and 200 hPa levels based on 0000 UTC of 18th September 2024

Overall, IMD GFS could correctly capture the genesis, intensification and movement of the system.

2.9.4. Realized Weather

Rainfall associated with the deep depression based on IMD-NCMRWF satellite gauge merged data are depicted in **Fig 2.9.4**.

- It is seen that light to moderate rainfall occurred at many places over Gangetic West Bengal and Uttarakhand on 12th September.
- Light to moderate rainfall occurred at many places with heavy to very heavy rainfall at isolated places over Gangetic West Bengal, Uttarakhand, Odisha

and heavy rainfall at isolated places over Bihar, West Uttar Pradesh, Himachal Pradesh, Delhi, Jharkhand, Chhattisgarh, Sub-Himalayan West Bengal, East Uttar Pradesh on 13th September.

- Light to moderate rainfall occurred at many places with heavy to very heavy rainfall isolated places over Gangetic West Bengal, Jharkhand and heavy rainfall at isolated places over Odisha, Himalayan West Bengal and West Uttar Pradesh on 14th September.
- Light to moderate rainfall occurred at many places with heavy to very heavy rainfall isolated places over Jharkhand, Gangetic West Bengal, Chhattisgarh, Odisha and heavy rainfall at isolated places over Madhya Pradesh, East Uttar Pradesh, Bihar and Sub-Himalayan West Bengal on 15th September.
- Light to moderate rainfall occurred at many places with heavy to very heavy rainfall isolated places over Chhattisgarh and East Madhya Pradesh.

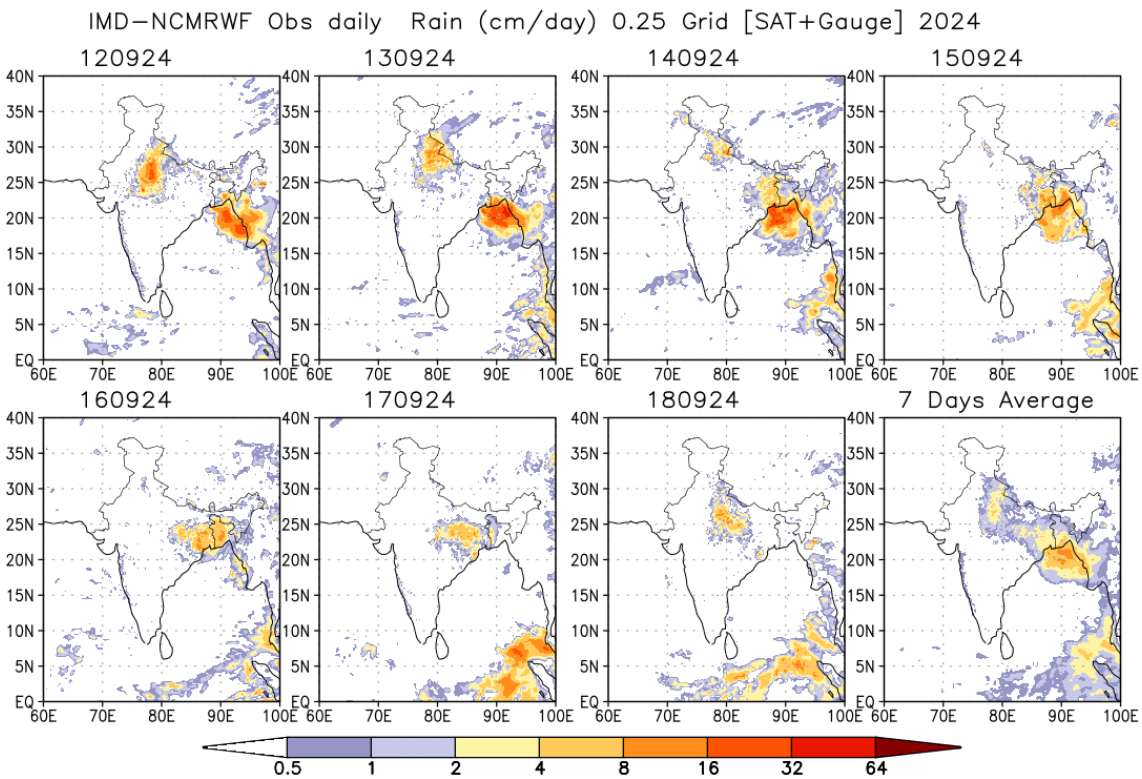


Fig. 2.9.4: NCMRWF-IMD satellite gauge merged data plots of realized 24 hours accumulated rainfall ending at 0830 IST of date from 13th to 18th September, 2024.

2.9.4.1 Rainfall forecast verification

The forecast for heavy to extremely heavy rainfall episodes in association with the system are verified with the 24 hours accumulated rainfall realized at various stations. The details of the day-wise verification are given in **Table-2.9.2.**

Table 2.9.2: Rainfall forecast verification

Date/Base Time of observation	24-hour Heavy rainfall warning ending at 0300 UTC of next day	Realized 24-hour heavy rainfall (≥ 7 cm) ending at 0300 UTC of date
13.09.2024 / 0830	**Uttarakhand:** Heavy to very heavy rainfall at a few places and extremely heavy rainfall at isolated places on 13th and heavy rainfall at isolated places on14th September. **Himachal Pradesh:** Heavy rainfall at isolated places on 13th September. **Uttar Pradesh:** Heavy to very heavy rainfall at isolated places on 13thand heavy rainfall at isolated places on 14th September.	**13th September:** **Gangetic West Bengal:** Contai 18, Durgachack 17, Digha 12, Bagati & Sagar Island 11 each, Durgapur 10, Diamond Harbour, Panagarh & Suri 9 each, Jangipur, Dum Dum, Alipore, Salar & Suri 8 each and Basirhat, Kalyani, Berhampore, Hetampur, Tilpara Barrage, Saltlake, Sri Niketan & Gheropara 7 each. **Uttarakhand:** Champawat 18, Haldwani 16, Nainital 15, Lohaghat 11, Pantnagar & Pithoragarh 9 each, Ghansali 8 and Banbasa & Bhagwanpur 7each; **Odisha**: Kusumi 14, Bhograi 10 and Jaleswar 7, **Bihar:** Beldaur & Khaira 9 each, Lakhisarai, Nabinagar, Halsi & Jamui 8 each and Gogri, Bausi & Begusarai 7each; **West Uttar Pradesh:** Kasba Tanda 9, Bijnor 8 and Suar 7; **Himachal Pradesh:** Kataula 8 and Palampur 7; **Delhi:** Palam 8 and Aya Nagar & Lodi Road 7 each; **Jharkhand:** Giridih Bengbad & Bengabad 8 each and Sujani & Pakuria 7 each; **Chhattisgarh:** Surajpur 7; **Sub-Himalayan West Bengal:** Malda 7; **East Uttar Pradesh:**
14.09.2024 / 0830	**Gangetic West Bengal (including Kolkata):** Heavy to very heavy rainfall at few places over Gangetic West Bengal and extremely heavy rainfall at isolated places over south Gangetic West Bengal on 14th; heavy rainfall at isolated places on 15th September. **Sub-Himalayan West Bengal**: Heavy rainfall at isolated places on 14th September. Odisha: Heavy to very heavy rainfall at a few places over Odisha and extremely heavy rainfall at isolated places over north Odisha on 14th and heavy to very heavy rainfall at isolated places on 15th and heavy rainfall at isolated places over Odisha 16th September. **Jharkhand:** Heavy to very heavy rainfall at isolated	

	places and extremely heavy rainfall over south Jharkhand on 14th &15th and heavy rainfall at isolated places over Odisha 16th September. **Bihar**: Heavy rainfall at isolated places very likely on 14th & 15th and heavy rainfall at isolated places over Odisha 16th September. **Chhattisgarh:** Heavy to very heavy rainfall at a few places on 14th & 15th and extremely very heavy rainfall over north Chhattisgarh on 15th September and heavy rainfall at isolated places on 16th September. **East Madhya Pradesh:** Heavy to very heavy rainfall at isolated places on 15th; heavy to very heavy rainfall at a few places with Extremely very heavy rainfall at isolated places over northeast Madhya Pradesh Chhattisgarh on 16th September and heavy to very heavy rainfall at isolated places on 17th September. **East Uttar Pradesh**: Heavy rainfall at isolated places on 16th & 17th September. **West Madhya Pradesh:** Heavy rainfall at isolated places on 17th & 18th September. **Mizoram & Tripura**: Heavy rainfall during 14th -16th September. **Assam & Meghalaya**: Isolated heavy rainfall on 14th September.	Katarniaghat 7; **14th September:** **Gangetic West Bengal:** Jhargram 19, Contai 15, Amtala 14, Kharidwar, Bankura, Lalgarh & Kansabati 13 each, Kalyani, Tusuma & Digha 12 each, Asansol, Phulberia, D.P.Ghat, Asansol, Bagati & Bankura 11 each, Kharagpur 10, Panagarh, Barrackpur, Harinkhola, Narayanpur, Debagram, Mohanpur, Midnapore & Durgachack 9 each, Basirhat, Midnapore, Burnpur, Sri Niketan, Purihansa, Durgapur & Hetampur 8 each and Suri, Salar, Luchipur, Burdwan, Labpur, Kakdwip, Rajnagar & Gheropara 7 each; **Jharkhand:** Meral 15, Garhwa 14, Burmu, Daltonganj & Chakulia 11 each, Potka, Dhalbhumgarh, Garu, Palamu, Latehar & Balumat 9 each, Panchet 8 and Boram, Panchet, Rajdhanwar, Nandadih, Maithon, Gurabandha, Chandwa, Hendigir, Messenjor & Saryu 7each; **Odisha:** Bhograi 13, Rajghat 12, Suliapada 11, Udala & Jaleswar 10 each, Tensa9, Rasagovindapur, Betanati, Chandua Kuliana, Kaptipada, Jamsolaghat & Bangiriposi 8 each and Sarasakan, Bijatala, G B Nagar 7each;
15.09.2024 / 0830	**Gangetic West Bengal (including Kolkata):** Heavy to very heavy rainfall at few	**West Uttar Pradesh:** Saharanpur 10; **Chhattisgarh:** Kusmi 7;

	places over Gangetic West Bengal and extremely heavy rainfall at isolated places over south Gangetic West Bengal on 15th; heavy rainfall at isolated places on 16th September. **Sub-Himalayan West Bengal:** Heavy rainfall at isolated places on 15th September. **Odisha:** Heavy to very heavy rainfall at a few places over Odisha and extremely heavy rainfall at isolated places over north Odisha on 15th and heavy to very heavy rainfall at isolated places on 16th September. **Jharkhand:** Heavy rainfall at isolated places and extremely heavy rainfall over south Jharkhand on 15th and heavy to very heavy rainfall at isolated places over Jharkhand 16th September. **Bihar:** Heavy to very heavy rainfall at isolated places very likely on 15th & 16th and heavy rainfall at isolated places over Bihar 17th September. **Chhattisgarh:** Heavy to very heavy rainfall at a few places on 15th & 16 th September and heavy rainfall at isolated places on 17th September. **East Madhya Pradesh:** Heavy rainfall at isolated places on 15th, heavy to very heavy rainfall at isolated places 16th & 17th September. **West Madhya Pradesh:**	**Sub-Himalayan West Bengal:** Darjeeling 7. **15th September:** **Jharkhand:** Tandwa 16, Lawalong 15, Simaria & Maithon 14 each, Maithon 13, Gurabandha & Gobindpur 12 each, Sindri, Putki, Chandrapura , Chandankiary , Panchet , Panchet, Ghatsila , Latehar Balumat, Musabani 11each, Potka , Chakulia , Karmatand , Jamshedpur Aero , Dhalbhumgarh , Parsabad 10each, Jamtara , Putki, Bariyatu , Jamshedpur , Koderma, Bau Kanke 9each, Hazaribagh, Majhgaon , Shilaichak , Dumri 8 each, Rajdhanwar , Chandil , Chandwa , Maheshpur , Messenjor , Jamtara, Tonto , Nimdih , Nawadih , Dhurki , Bagodari , Phusro , Balumath , Chaibasa , Garhwa , Kharsema , Tenughat 7each; **Gangetic West Bengal:** Asansol , Asansol , Suri 15each, Suri , Kharidwar 13each, Burnpur 12, Purihansa , Luchipur 11each, Bankura , Harinkhola , Gheropara 10each, Sri Niketan , Tusuma , Rajnagar , Phulberia 9each, Purulia , Bankura , Mankar , Simula , Tantloi , Amtala , Lalgarh , Rampurhat , Panagarh 8each, Narayanpur , Labpur , Nalhati , Durgapur , Tilpara Barrage , Hetampur , Amfu Kharagpur , Kalaikunda 7each; **Chhattisgarh:** Ramchandrapur 15, Kusmi 13,

	Heavy rainfall at isolated places on 17th & 18th September. **East Uttar Pradesh:** Light to moderate rainfall at most places with heavy rainfall at isolated places on 16th & 17th September. **Mizoram & Tripura:** Isolated heavy rainfall during 15th -16th September. **Assam & Meghalaya:** Isolated heavy rainfall on 15th September.	Samari 12, Wandrafnagar 11, Ramanujganj , Rajpur , Raghunath Nagar , Chando 8each, Pratappur 7; **Odisha:** Udala 14, G B Nagar , Nawana , Balimundali 12each, Raruana , Betanati , Karanjia , Bahalda 11each, Kaptipada , Balasore , Joshipur , Jaipur 10each, Sarasakana , Tiring , Nh5 Gobindpur , Kusumi , Bijatala 9each, Nilgiri , Joda , Jaleswar , Remuna , Jamsolaghat , Rasagovindapur , Baripada , Rajghat , Bhograi , Rairangpur & Muruda 8 each and Bangiriposi, Suliapada, Samakhunta & Chandua Kuliana, Sukruli 7 each; **East Madhya Pradesh:** Chitrangi 11 and Mauganj 8; **East Uttar Pradesh:** Churk 10, Chopan 8 and Robertsganj & Dudhi 7each; **Bihar:** Sanjhauli & Chakai 8 each and Rajauli 7; **Sub-Himalayan West Bengal:** Rongo & Lava 8 each and Jhallong 7. **16th September:** **Chhattisgarh:** Kusmi 15, Ramchandrapur 14, Samari & Biharpur 12 each, Ramanujganj 11, Odagi, Sonhat & Chando 9 each, Pondi Bachra & Balrampur 8 each and Rajpur, Bhaiyathan, Manora & Pasaan 7 each; **East Madhya Pradesh:** Churhat 14, Panagar 12, Bilhari, Jabalpur & Bargi 10 each, Mada 9 and Bijadandi,
16.09.2024 / 0830	**Jharkhand:** Heavy to very heavy rainfall at a few places & isolated extremely heavy rainfall over south Jharkhand & isolated heavy to very heavy rainfall over North Jharkhand on 16th September. Heavy to very heavy rainfall at isolated places over Jharkhand on 17th September. **Gangetic West Bengal:** Heavy rainfall at isolated places over Gangetic West Bengal on 16 th September. **Odisha:** Heavy to very heavy rainfall at isolated places over North Odisha on 16th September and heavy rainfall at isolated places over Northwest Odisha on 17th September. **Bihar:** Heavy rainfall at isolated places is very likely over South Bihar on 16th and 17th September. **Chhattisgarh:** Heavy to very heavy rainfall at isolated places over North Chhattisgarh during 16th to17th September.	

	Madhya Pradesh: Heavy to very heavy rainfall at isolated places is likely over Northeast Madhya Pradesh on 16th & 17th September and heavy rainfall at isolated places on 18 th September. Heavy rainfall at isolated places over Northwest Madhya Pradesh during 17th to 18th September. **Uttar Pradesh:** Heavy to very rainfall at isolated places over Southeast Uttar Pradesh during 16th and 17th September. Heavy to very rainfall at isolated places over West Uttar Pradesh on 17th and heavy rainfall at isolated places on 18th September.	Sarai, Nowrozabad & Chitrangi 7 each. **17th September:** **East Uttar Pradesh:** Attarra 16, Kanpur & Mau 12 each, Beberu, Manikpur, Rajapur & Karwi 11 each, Kanpur, Banda & Lalganj 10 each, Tirwa & Koraon 9 each, Chhibramau 8 and Karchhana, Ghorawal, Kannauj, Prayagraj, Mirzapur, Prayagraj Sadar & Bhognipur 7 each; **West Uttar Pradesh:** Rath 22, Hamirpur 13, Etawah & Chakkar Nagar 12 each, Shikohabad 8 and Orai & Bharthana 7 each;
17.09.2024 / 0830	**Jharkhand:** Heavy rainfall at isolated places over Jharkhand on 17th September. **Bihar:** Heavy rainfall at isolated places is very likely over South Bihar on 17 th September. **Uttar Pradesh:** Heavy to very rainfall at isolated places over Southeast Uttar Pradesh on 17th September. Heavy rainfall at isolated places over Southwest Uttar Pradesh on 17th and 18th September. **Madhya Pradesh:** Heavy to very heavy rainfall at isolated places is likely over North Madhya Pradesh on 17th September and heavy rainfall at isolated places on 18th September over Northwest Madhya Pradesh. **Chhattisgarh:** Heavy rainfall at isolated places over North	**East Madhya Pradesh:** Hanumana 13, Chitrangi, Rewa & Gaurihar 10 each, Mauganj, Sarai & Ajaigarh 9 each, Mangawan, Nowgong & Churhat 8 each and Devendranagar, Naigarhi, Sidhi, Nagode, Birsingpur, Raipurkarchuliyan, Sihawal, Gudh, Jawa, Shahgarh and Unchehra 7each; **Jharkhand:** Lohardaga & Kharsema 8 each; **West Madhya Pradesh:** Roan 15, Lahar 12, Mihona, Gohad & Mau 11 each, Gwalior, Ambah, Bhander & Dabra 9 each, Bhind, Porsa & Datia 8 each and Ater, Ghatigaon, Gormi & Seodha 7 each; **Odisha:** Dhenkanal & Dhenkanal 13 each, Bhuban 12 and Banki & Korei 10 each.

	Chhattisgarh on 17th September. **East Rajasthan:** Heavy rainfall at isolated places on 17th September.	

2.9.5. Damage due to the system

- As a result of heavy rainfall and discharge of water from Damodar Valley Corporation severe flooding occurred in southern West Bengal, claiming three lives and affecting over 2.5 lakh residents.
- Six districts were significantly impacted, including Birbhum, Bankura, Howrah, Hooghly, North and South 24 Parganas, East and West Medinipur, and Paschim Bardhaman.
- Worst affected Area: Ghatal in West Medinipur and Uday Narayanpur in Howrah. The release of water from the dams and reservoirs worsened the situation in Ghatal. The Dwarakeswar River breached as well causing floods in Hooghly. This led people to leave their homes in search of a safe and secure shelter.
- The flooding also caused a lot of damage to the crops as they got washed away. Panskura railway station and it's adjoining bus stand in East Medinipur district sinked after flood completely becoming inaccessible to commuters.
  (Situation Report 1 Floods in West Bengal Date: 20th September 2024 (Friday) Time: 12:00 PM (IST) Source: Sphere India)

2.10 Depression over central Arabian Sea during13th October-15th October 2024

2.10.1 Introduction

- An upper air cyclonic circulation lay over South Kerala & neighbourhood in the morning (0300 UTC/0830 hours IST) of the 7th October, 2024.
- Under its influence, a LowPressure Area formed over Lakshadweep and adjoining southeast &eastcentral Arabian Sea (AS) in the morning (0300 UTC/0830 hours IST) of the 9th October, 2024.
- It lay as a Well Marked Low Pressure Area over eastcentral AS off Karnataka-Goa coasts in the morning (0300 UTC/0830 hours IST) of the 10th October 2024.
- It intensified into a Depression in the evening (1200 UTC/1730 hours IST) of the 13th October, 2024 over central AS.
- It moved northwestwards and crossed Oman coast near latitude 19.35°N and longitude 57.7°E, close to Duqm (Oman) between 2230 and 2330 hours IST(1700 UTC and 1800 UTC).
- Continuing to move northwestwards, it weakened into a Well Marked Low Pressure Area over coastal Oman in the same midnight (1800 UTC/2330 hours IST) of the 15th October, 2024. Observed track of the depression is presented in **Fig.2.10.1**. Best Track parameters associated with the system are presented in Table 2.10.1.

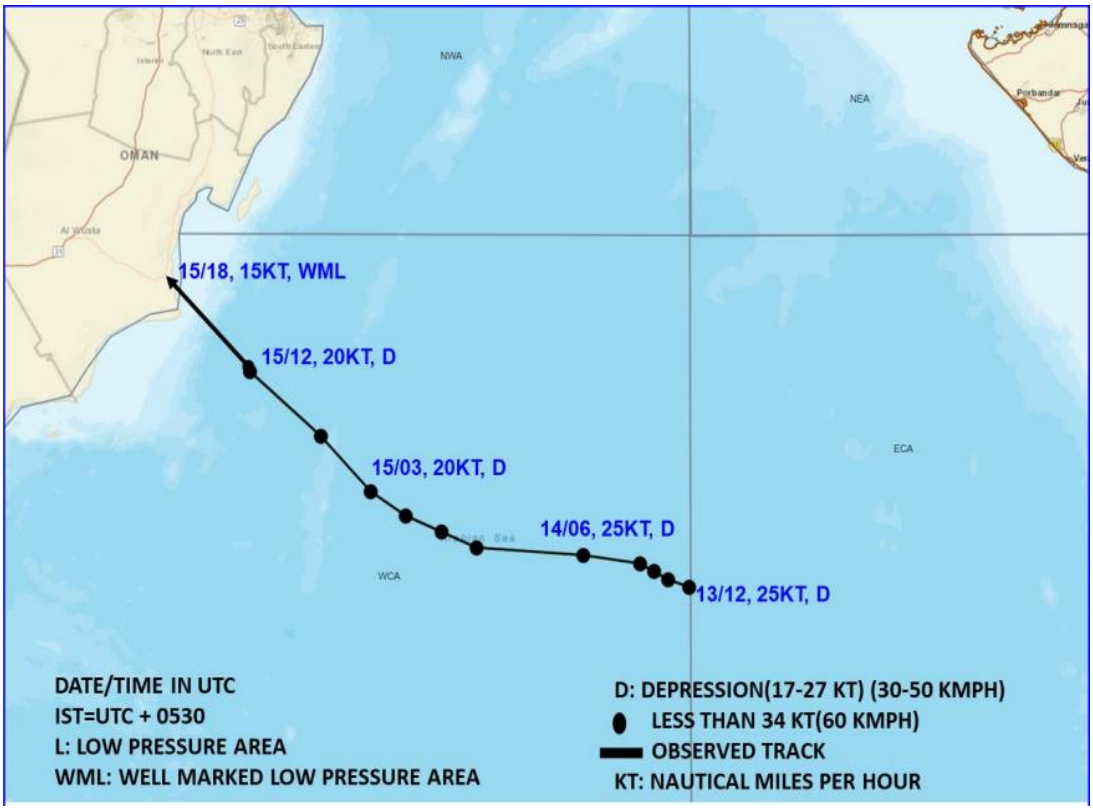


Fig. 2.10.1: Observed track of Depression over central ASduring13th Oct – 15th Oct, 2024.

Table 2.10.1: Best track positions and other parameters of the Depression over central ASduring 13th Oct– 15th Oct, 2024

Date	Time (UTC)	Lat.	Long.	ECP	ΔP	MSW (kt)	Category
13.10.24	1200	15.6	65.0	1002	3	20	D
	1800	15.7	64.7	1002	3	20	D
14.10.24	0000	15.8	64.5	1002	3	20	D
	0300	15.8	64.3	1001	4	25	D
	0600	16.0	64.0	1001	4	25	D
	1200	16.1	62.0	1001	4	25	D
	1800	16.1	61.5	1001	4	25	D
15.10.24	0000	16.1	61.0	1002	3	20	D
	0300	16.8	60.5	1002	3	20	D
	0600	17.5	59.8	1002	3	20	D
	1200	18.3	58.8	1002	3	20	D
	Crossed North Oman coast close to Duqm (41291, Oman) between 1700 to 1800 UTC of 15th October near latitude 19.35°N and longitude 57.7°E as a depression with wind speed of 40-50 gusting to 60 kmph						
15.10.24	1800	Weakened into a well-marked low-pressure area over Oman coast					

KT: Knots (nautical mile per hour), 1 KT=1.85 kmph, D: Depression, DD: Deep Depression

2.10.2 Brief life history - Genesis Intensification and movement

At 0300 UTC of 13th October, the Madden-Julian Oscillation (MJO)index was in phase 4, with amplitude more than 1 and was predicted to continuein same phase during next 4 days with further increasing amplitude. Thus, the MJO was not favourable for cyclogenesis over AS. The guidance from NCICS model predicted presence of strong westerly winds (7-9 mps) over south AS and strong easterly winds (7-9 mps) over central AS along with eastward moving Kelvin waves & MJO and westwards moving large equatorial Rossby wave extending from south Bay of Bengal to south AS during next 3 days. The sea surface temperature (SST) was 28-30°Cover eastcentral AS and around 27°C over the westcentral and southwest parts of AS. The tropical cyclone heat potential (TCHP) was 60-70 KJ/cm^2 over eastcentral AS and it was less than 50 KJ/cm² over westcentral AS & off Oman coast. Total precipitable water imagery indicated continuous warm moist air incursion into the core. Low-level relative vorticity was around 50-60 x $10^{-6}s^{-1}$ over the system area with vertical extension upto 500 hPa level. Low-level convergence was around $5x10^{-6}s^{-1}$ over eastcentral AS. Positive upper-level divergence was around 10 $x10^{-6}s^{-1}$over system area. Deep layer vertical wind shear (VWS) was low to moderate (05-15 knots) over system area and along the expected path. Upper tropospheric ridge ran along 20°N.

Under these favourable features, the well marked low pressure area over eastcentral AS intensified into a depression over central AS in the evening (1200 UTC/1730

hours IST) of the 13th October, 2024.

Similar features prevailed till 14th evening (1200 UTC). At 1200 UTC of 14th October, low-level relative vorticity decreased and was around 50 x $10^{-6}s^{-1}$over the system area with vertical extension upto 500 hpa level. Low-level convergence increased and was around $10x10^{-6}$ s^{-1} over system area. Positive upper-level divergence increased and was around $20x10^{-6}$ s^{-1} to the northwest of system area. Deep layer VWS remained moderate (15 knots) over system area and along the expected path. The system maintained its intensity of depression.

At 1200 UTC of 15th October, the low-level relative vorticity remained around 50 x $10^{-6}s^{-1}$over the system area with vertical extension upto 500 hpa level. Low-level convergence was around $20x10^{-6}$ s^{-1} over system area. Positive upper-level divergence was around 05-10 $x10^{-6}$ s^{-1} to the northwest of system area. Deep layer VWS remained moderate (15 knots) over system area and along the expected path.Under these features, the system maintained its intensity and crossed North Oman coast close to Duqm (41291, Oman) between 1700 to 1800 UTC of 15th October (2230 to 2330 hrs IST of 15th October) as a depression.

Thereafter, due to land interactions and disruption of moisture supply, it weakened into a Well Marked Low Pressure Area over coastal Oman in the same midnight (1800 UTC/2330 hours IST) of the 15thOctober, 2024.

2.10.3 Monitoring

India Meteorological Department (IMD) maintained round the clock watch over the north Indian Ocean (NIO) and the system was monitored well in advance since 10thOctober. The system was monitored with the help of available satellite observations from INSAT 3D and 3DR, polar orbiting satellites, available ships & buoy observations in the region and coastal observations on the day of landfall. 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 system. A digitized forecasting system of IMD was utilized for analysis and comparison of various models' guidance, decision making process and warning products generation.

2.10.3.1Features observed through satellite

Satellite monitoring of the system was mainly done by using half hourly INSAT-3D and 3DR imageries. Satellite imageries of other international geostationary satellites, high resolution polar orbiting satellites and scatterometer imageries from ASCAT were also considered for monitoring of the system. Typical INSAT-3D enhanced colored imageries, visible/ IR, brightness temperature and water vapour imageries are presented in **Fig. 2.10.2 (a) to (d)**. The detailed features from the satellite pictures are discussed in this section.

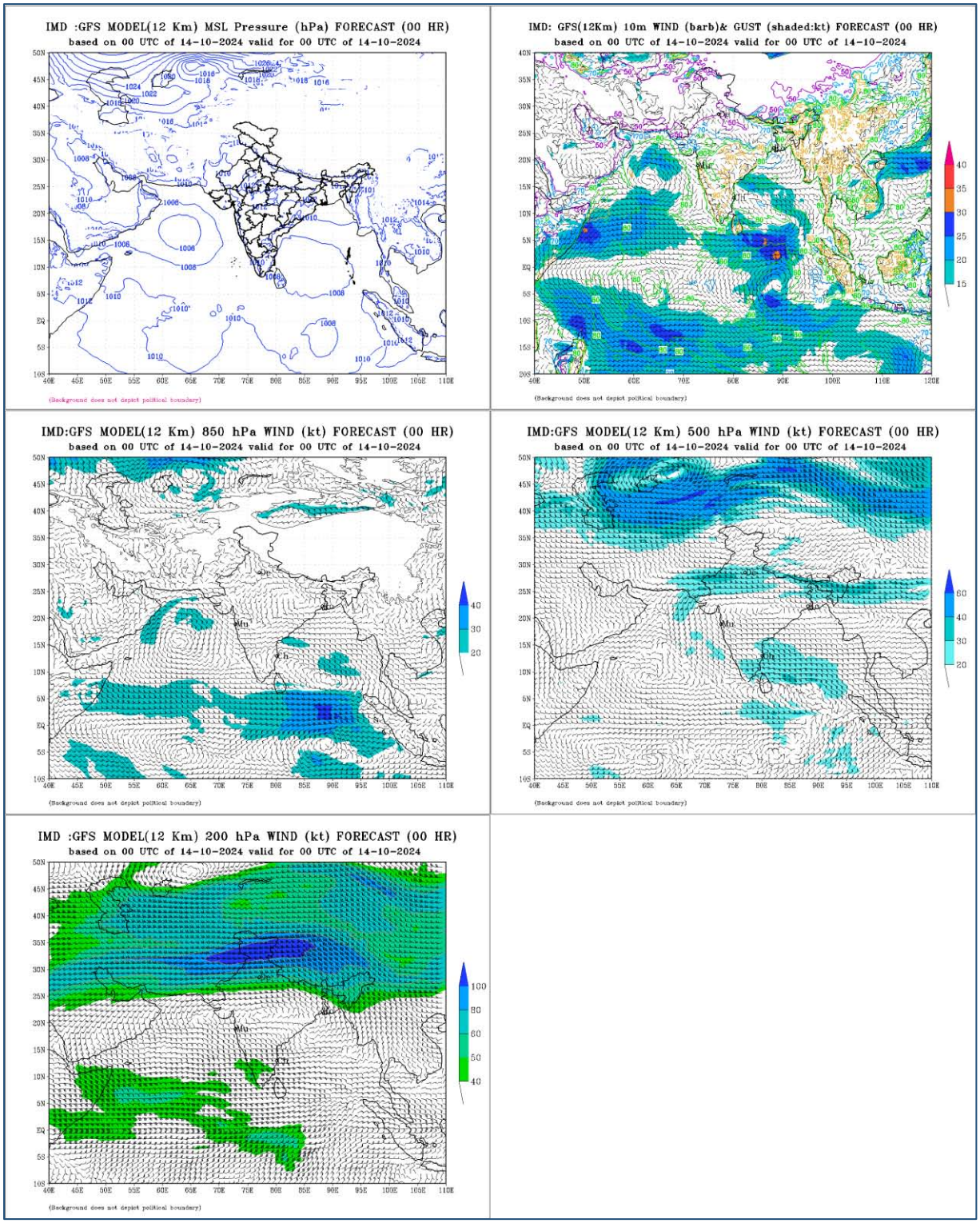


Fig. 2.10.3(b): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 14th October 2024

At 0000 UTC of 15th October, the MSLP analysis field indicated further weakening of the system into a low pressure area over westcentral AS off Oman coast near 16.8°N/58.0°E. Actually, the system lay as a depression over westcentral AS near 16.1°N/61.0°E at 0000 UTC of 15th October, 2024. Thus, GFS model couldn't capture the initial conditions correctly.

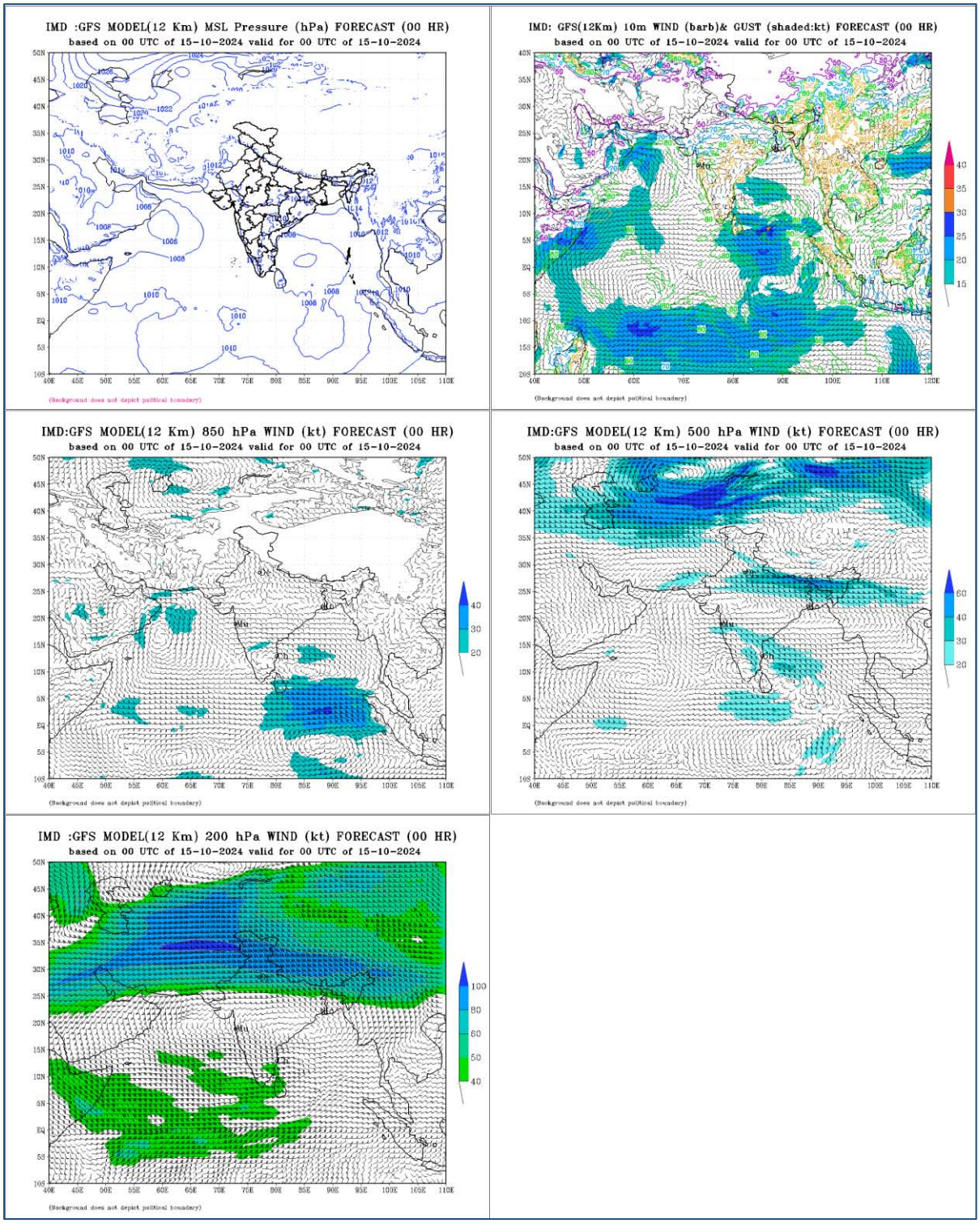


Fig. 2.10.3(c): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 15th October 2024

2.11. Depression over Southwest Bay of Bengal during 15th–17th October

2.11.1.Introduction

- An upper air cyclonic circulation lay over southeast Bay of Bengal (BoB) and adjoining North Equatorial Indian Ocean in the morning (0300 UTC/0830 hours IST) of the 12th October, 2024.
- Under its influence, a **Low Pressure Area** formed over southeast BoB in the early morning (0000 UTC/0530 hours IST) of the 14th October 2024.
- It lay as a **Well Marked Low Pressure Area** over the central parts of south BoB in the early morning (0000 UTC/0530 hours IST) of 15th October 2024.
- It intensified into a **Depression** over southwest BoB in the same evening (1200 UTC/1730 hours IST). It moved west-northwestwards and crossed north Tamil Nadu - South Andhra Pradesh coasts between Puducherry and Nellore, close to north of Chennai, near latitude 13.5°N and longitude 80.2°E around 2300 UTC (0430 hrs IST) of the 17th October.
- Subsequently, it weakened into a Well Marked Low Pressure Area and lay over South coastal Andhra Pradesh and adjoining North coastal Tamil Nadu in the early morning (0000 UTC/0530 hrs IST) of the 17th October, 2024.
- The observed track of the system is presented in Fig.2.11.1. Best Track parameters associated with the system are presented in Table 2.11.1.

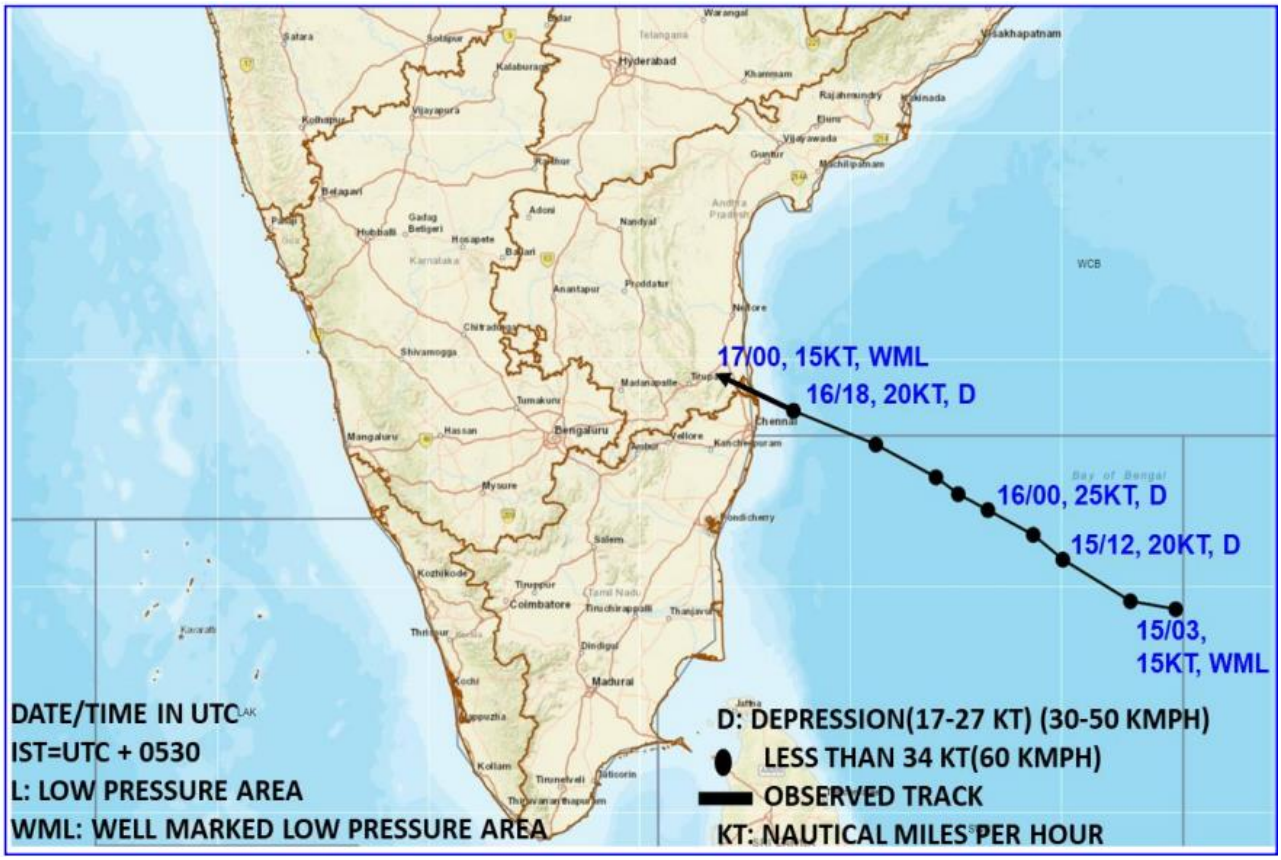


Fig. 2.11.1: Observed track of Depression over Southwest BoB

Table 2.11.1: Best track positions and other parameters of the Depression over Southwest BoB during 15th October-17th October 2024

Date	Time (UTC)	Lat.	Long.	C.I no	ECP	ΔP	MSW (kt)
15.10.24	1200	11.4	84.4	1.5	1002	3	20
	1800	11.8	84.0	1.5	1002	3	20
16.10.24	0000	12.1	83.4	1.5	1002	3	20
	0300	12.3	83.0	1.5	1000	4	25
	0600	12.5	82.7	1.5	1000	4	25
	1200	12.9	81.9	1.5	1000	4	25
	1800	13.4	80.8	1.5	1000	4	25
	Crossed north Tamil Nadu – south Andhra Pradesh coast between Puducherry and Nellore, close to north of Chennai around 2300 UTC of 16th October (0430 hrs IST of 17th October) as a depression with wind speed of 25 gusting to 35 knots						
17.10.24	0000	Weakened into a well-marked low-pressure area over south coastal Andhra Pradesh and adjoining north coastal Tamil Nadu					

KT: Knots (nautical mile per hour), 1 KT=1.85 kmph, D: Depression, DD: Deep Depression

2.11.2.Brief life history – Genesis, Intensification and movement

At 0000 UTC of 14th October, the Madden-Julian Oscillation (MJO) was in phase 4, with amplitude more than 1, and it was predicted to move across phase 4 during next 4 days with further increasing amplitude. Thus, MJO was likely to support enhancement of convective activity over BoB during next 4 days. NCICS based forecast indicated strong westerly winds (5-7 mps) over south BoB and adjoining Equatorial Indian Ocean and strong easterly winds (5-7 mps) over Westcentral BoB. MJO & Kelvin waves along with Rossby waves were also predicted to prevail over the BoB during next 4 days. Thus, Equatorial waves and MJO were supporting convective activity over BoB during next 4 days.

Under these favourable features, a Low Pressure Area formed over southeast BoB in the early morning (0530 hours IST/0000 UTC) of the 14th October 2024. It became a Well Marked Low Pressure Area over the central parts of south BoB in the early morning (0530 hours IST/0000 UTC) of 15th October 2024.

At 1200 UTC of 15th October, a zone of positive cyclonic vorticity of 50 x $10^{-6}s^{-1}$ was seen over Southwest BoB. Positive low-level convergence of 5-10x$10^{-6}s^{-1}$ was seen over Southwest BoB and westcentral BoB. Positive upper-level divergence was around 10-20x$10^{-6}s^{-1}$ over southwest BoB. Vertical wind shear (VWS) was low (5-10 knots) over central and adjoining areas of South BoB (over the system area). Under these favourable

features, the Well Marked Low Pressure Area over the central parts of south BoB intensified into a Depression over southwest BoB in the same evening (1730 hours IST) of 15th October, 2024.

At 0300 UTC of 16th October, low-level vorticity was around 60-70x10^{-6} s^{-1} over Southwest BoB off Tamil Nadu & north Sri Lanka coasts. Positive low-level convergence increased and was around 20x10^{-6} s^{-1} over Southwest BoB off Tamil Nadu coast to the west of system centre. Positive upper-level divergence was around 30x$10^{-6}s^{-1}$ over interior Tamil Nadu to the west of system area. The VWS was low to moderate (05-15 knots) over central and adjoining areas of south BoB (around the system area). The system maintained its intensity.

At 1200 UTC of 16th October, low-level vorticity reduced slightly and was around 50-60x$10^{-6}s^{-1}$ over Southwest BoB off Tamil Nadu & North Sri Lanka coasts. Positive low-level convergence also decreased and was around 5x$10^{-6}s^{-1}$ over Andhra Pradesh coast to the Northwest of system centre. Positive upper-level divergence was around 5x$10^{-6}s^{-1}$ over interior Karnataka to the west of system area. The VWS remained low to moderate over the system area. The system maintained its intensity. The southeasterly winds prevailing over the system area steered it northwestwards.

Under these features, the system maintained its intensity and crossed north Tamil Nadu – south Andhra Pradesh coast between Puducherry and Nellore, around 2300 UTC of 16th October (0430 hrs IST of 17th October) as a depression.

Thereafter, due to land interactions and reduction of moisture supply, it weakened into a Well Marked Low Pressure Area over South coastal Andhra Pradesh and adjoining North coastal Tamil Nadu in the early morning (0000 UTC /0530 hrs IST) of the 17th October, 2024.

2.11.3.Monitoring

India Meteorological Department (IMD) maintained round the clock watch over the north Indian Ocean (NIO) and the system was monitored well in advance since 3rd October (12 days ahead of formation of depression). The movement towards north Tamil Nadu – south Andhra Pradesh was also indicated in the Extended Range Outlook issued on 3rd October. For monitoring the system, IMD utilized all available data sources like satellite observations from INSAT 3D and 3DR, polar orbiting satellites, available ships & buoy observations in the region and coastal observations on the day of landfall. 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 system. A digitized forecasting system of IMD was utilized for analysis and comparison of various models' guidance, decision making process and warning products generation.

2.11.3.1 Features observed through satellite

Satellite monitoring of the system was mainly done by using half hourly INSAT-3D and 3DR imageries. Satellite imageries of other international geostationary satellites, high resolution polar orbiting satellites and scatterometer imageries from ASCAT were also considered for monitoring of the system. Typical INSAT-3D enhanced coloured imageries, visible/ IR, brightness temperature and water vapour imageries are presented in **Fig.2.11.2 (a) to (d)**.

During the entire life cycle, the clouds were organized in shear pattern. The detailed features from the satellite pictures are discussed in this section.

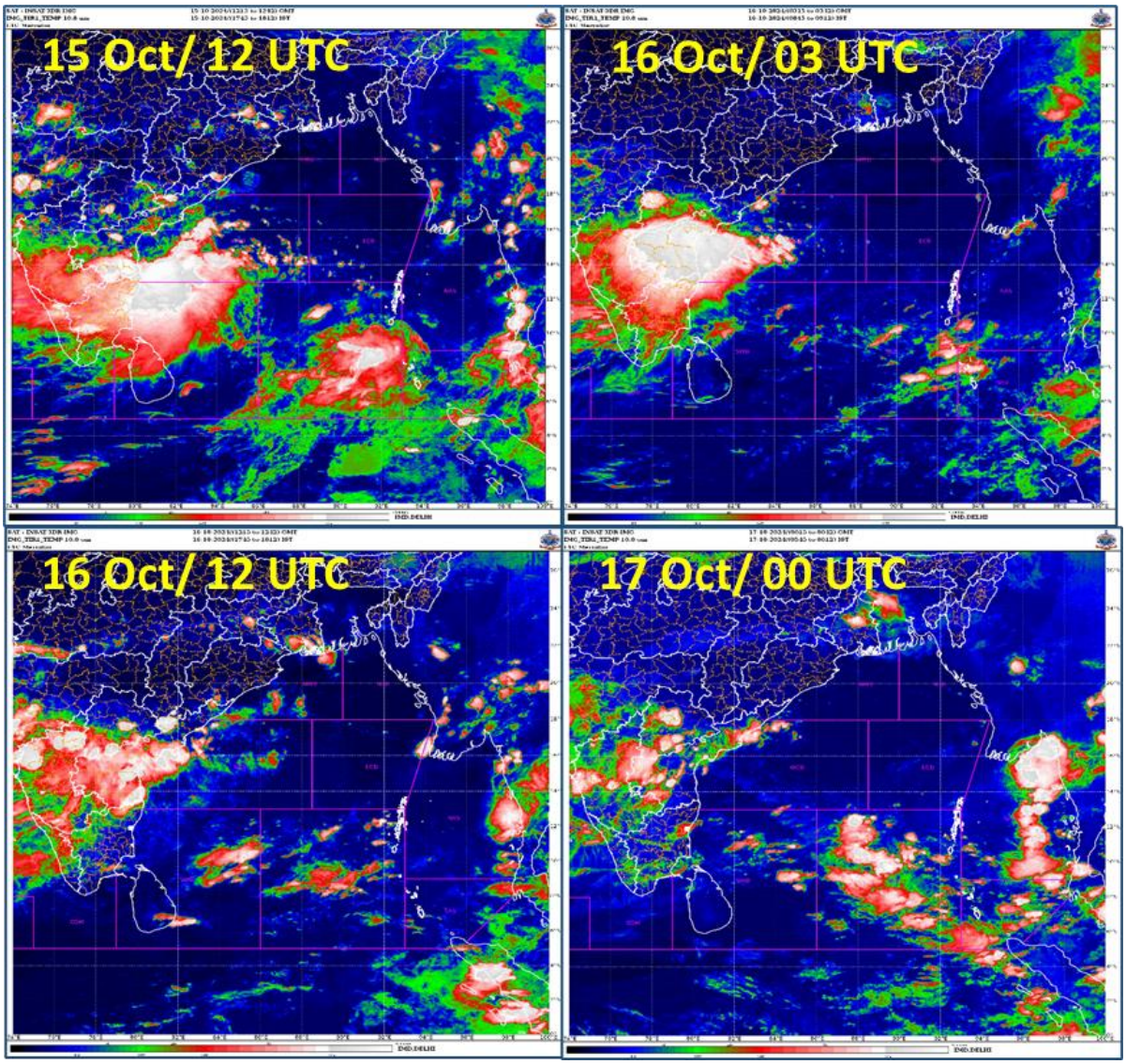


Fig. 2.11.2(a): INSAT-3D enhanced coloured imageries during life cycle of Depression over Southwest BoB during 15th Oct-17th Oct 2024

At 1200 UTC of 15th October, the intensity of the system was characterised as T1.5. Associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over west-central and south BoB. Minimum Cloud Top Temperature was minus 80-93°C.

At 0300 UTC of 16th October, the INSAT-3D imagery indicated shearing of the cloud mass to the northwest of the system centre. Intensity of the system was characterised as T1.5. Intense convection was seen over Andhra Pradesh, Rayalaseema, North Tamilnadu, South Telangana, and south interior Karnataka. Associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over BoB between latitude 9.0N to 16.0N and west of longitude 85.0E, and minimum cloud top temperature was minus 80-93°C.

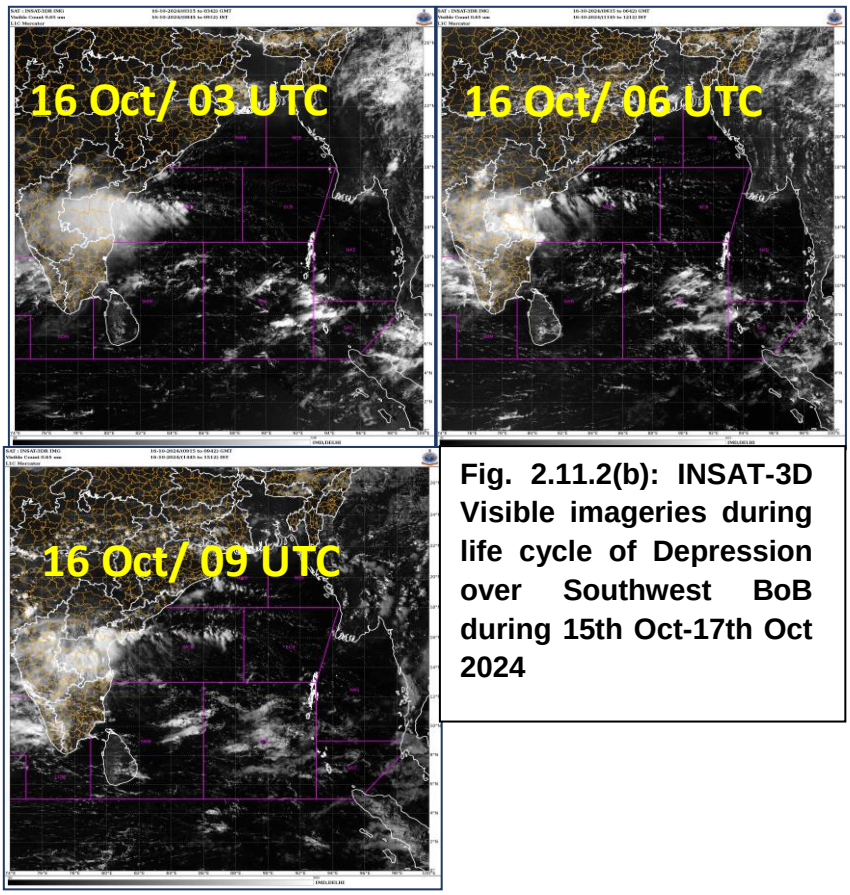


Fig. 2.11.2(b): INSAT-3D Visible imageries during life cycle of Depression over Southwest BoB during 15th Oct-17th Oct 2024

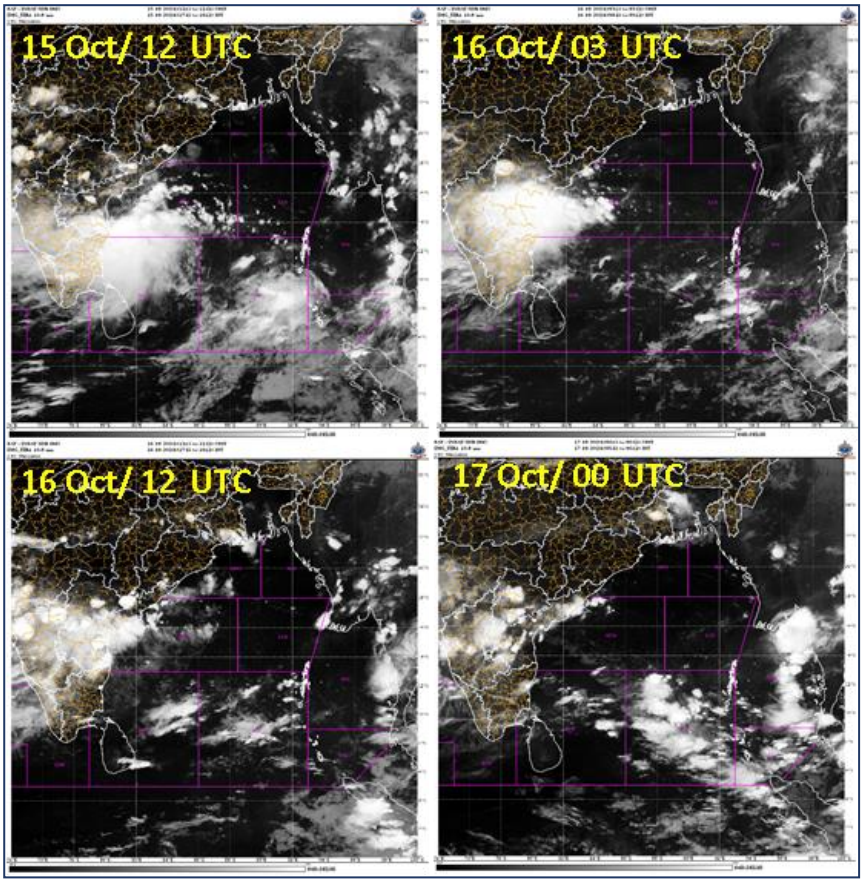


Fig. 2.11.2(c): INSAT-3D IR imageries during life cycle of Depression over Southwest BoB during 15th Oct-17th Oct 2024

At 1200 UTC of 16th October, the INSAT-3D imagery indicated the intensity of the system was characterised as T 1.5. Intense to very intense convection was seen over BoB between latitude 9.0°N to 16.0°N and west of longitude 85.0E and south coastal Andhra Pradesh, Rayalaseema, and adjoining south interior Karnataka. Minimum cloud top temperature was minus 80°C.

At 0000 UTC of 17th October, the INSAT-3D imagery indicated intense to very intense convection over Karnataka, Telangana, Rayalaseema, coastal Andhra Pradesh. Minimum cloud top temperature was minus 70°-80°C. Moderate to intense convection was seen over Tamil Nadu and Kerala.

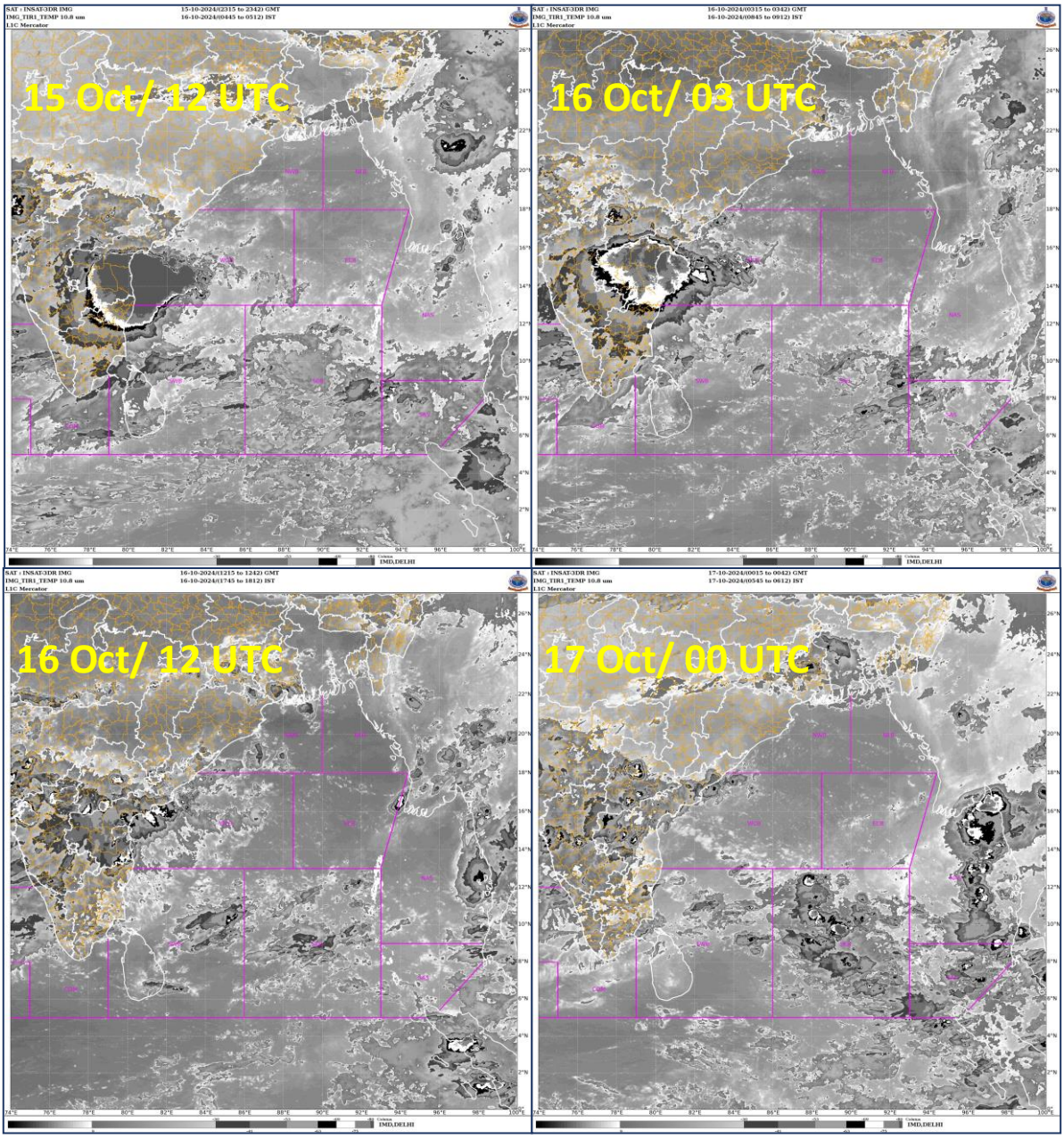


Fig. 2.11.2(d): INSAT-3D BD curve imageries during life cycle of Depression over Southwest BoB during 15th Oct-17th Oct 2024

2.11.4.Dynamical Features

IMD GFS (T1534) analysis of mean sea level pressure (MSLP), winds at 10 m, 850, 500 and 200 hPa levels at 0000 UTC from 15th October to17th October are presented in **Fig. 2.11.3(a) to (c)** respectively.

At 0000 UTC of 15th October, it indicated a low pressure area over southwest BoB near 11.5°N/84°E. However, at that time the system lay as a depression over southwest BoB near 11.4°N/84.4°E. Vertically the system extended upto 500 hPa levels. East-southeasterly winds prevailing over the system area at 500 hPa levels steered the system nearly northwestwards. Thus, the model correctly captured the location and movement but underestimated the intensity of the system.

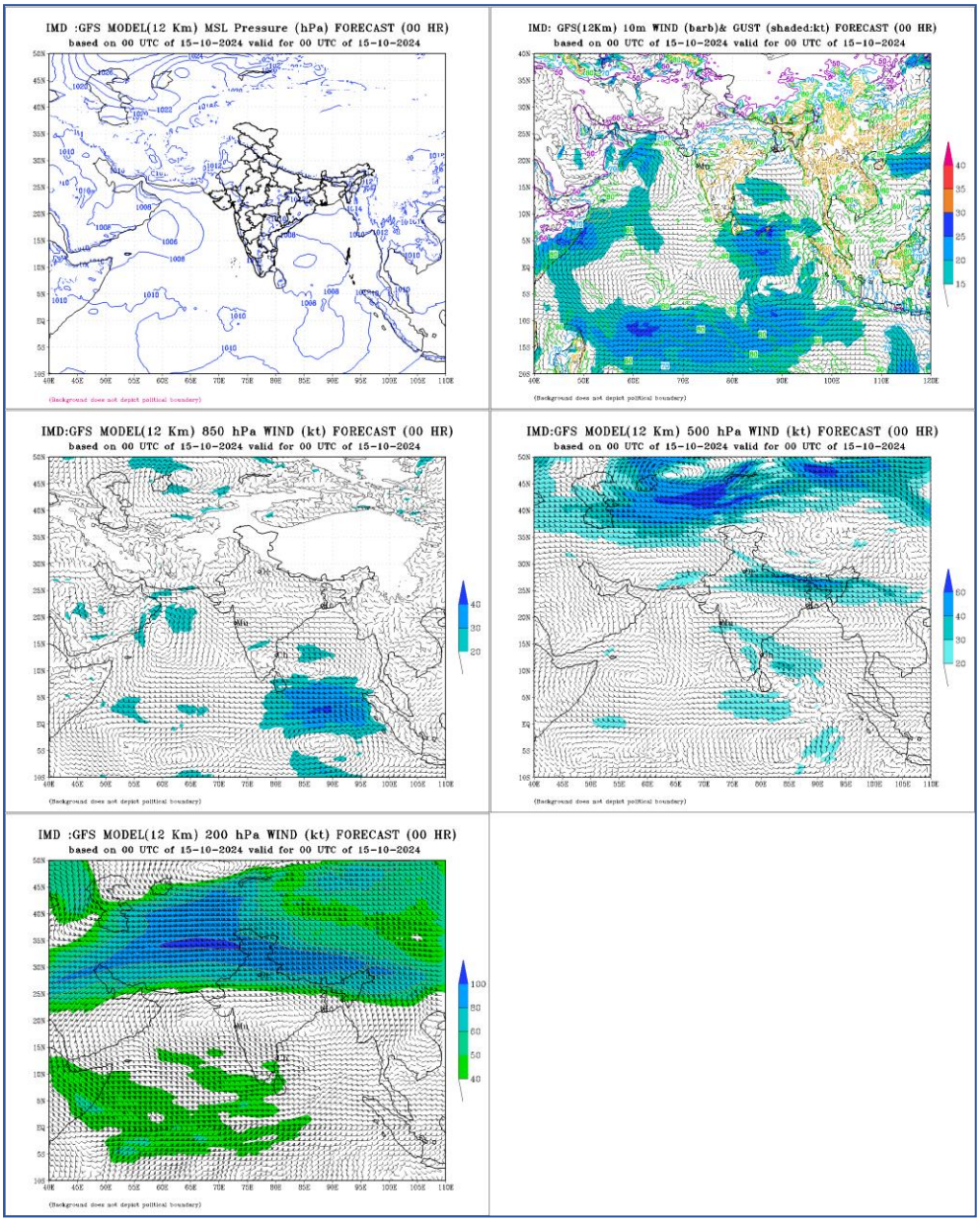


Fig. 2.11.3(a): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 15th Oct 2024

The analysis fields at 0000 UTC of 16th October indicated gradual intensification into a well marked low pressure area over southwest & adjoining westcentral BoB near 12.5°N/83.0°E. However, at that time the system lay as a depression over southwest BoB near 12.1°N/83.4°E. Vertically the system extended upto 500 hPa levels tilting southwestwards with height. Southeasterly winds prevailing over the system area at 500 hPa levels steered the system nearly northwestwards. Thus, the model captured the location and movement but underestimated the intensity of the system.

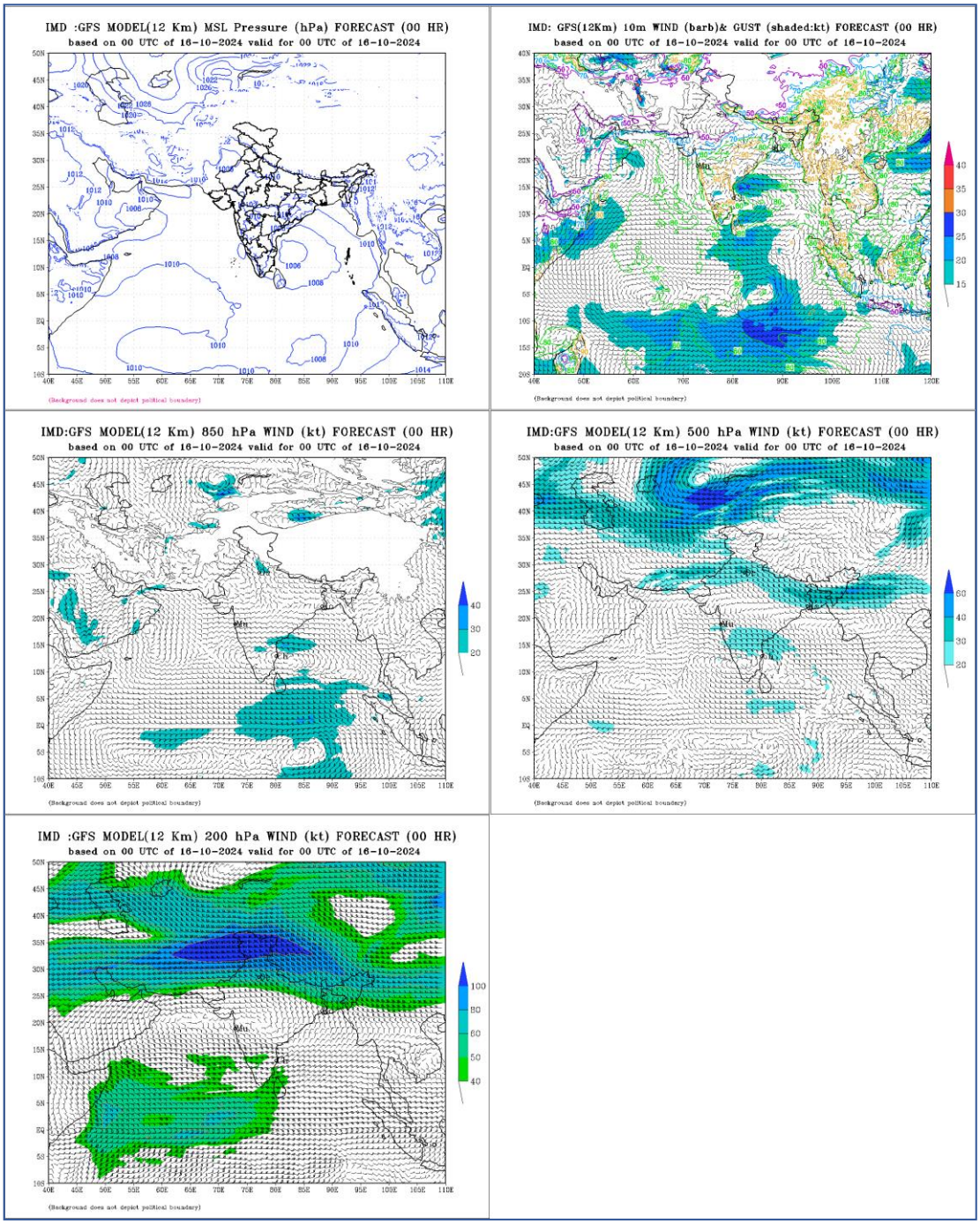


Fig. 2.11.3(b): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 16th Oct 2024

The analysis fields at 0000 UTC of 17th October indicated weakening of the system into a low pressure area over south coastal Andhra Pradesh near 14.8°N/80.0°E. However, at that time the system lay as a well marked low pressure area over south coastal Andhra Pradesh and adjoining north coastal Tamil Nadu. Thus, the model captured the location and movement but underestimated the intensity of the system.

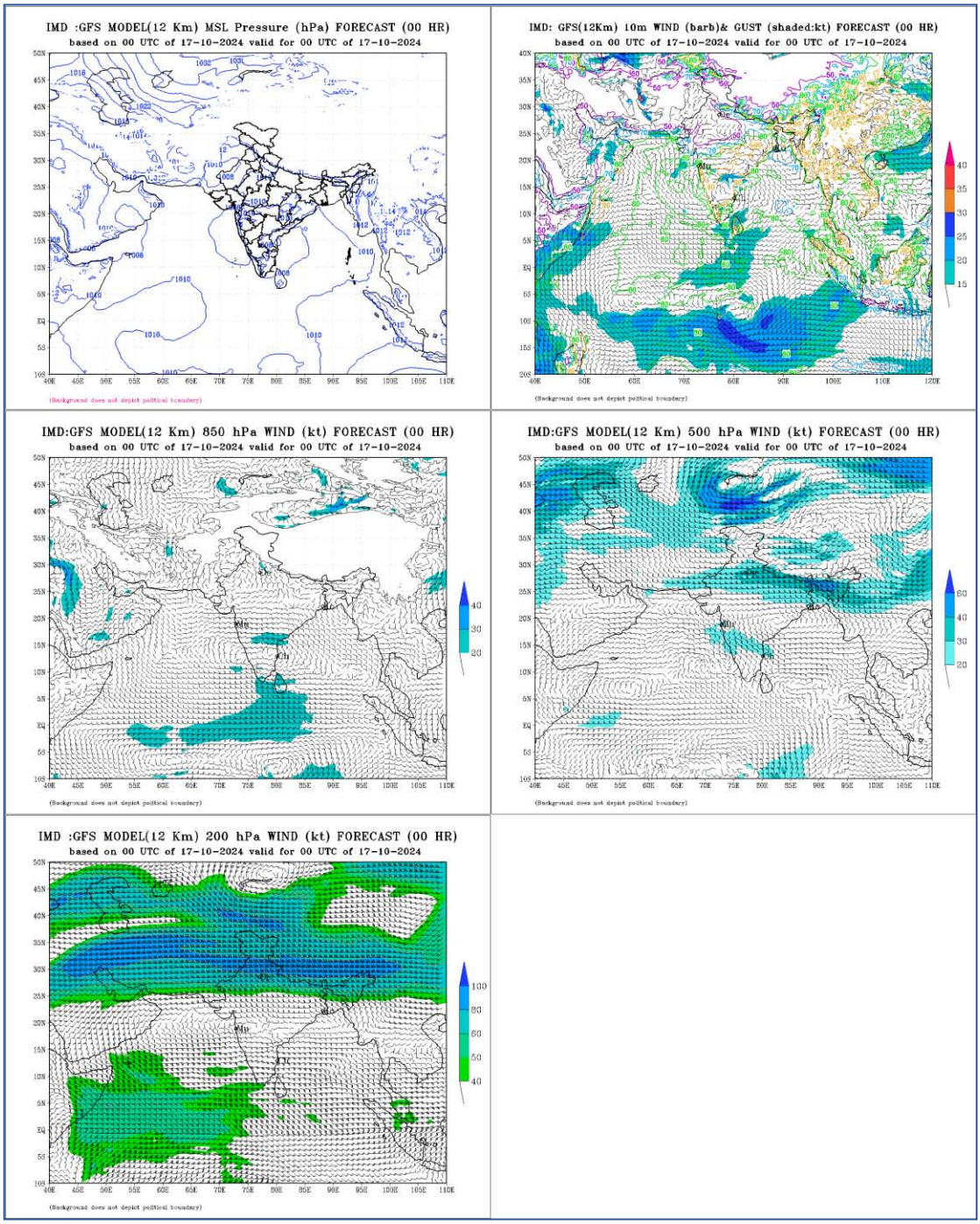


Fig. 2.11.3(c): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 17th Oct 2024

Thus, throughout its life period IMD GFS could capture the location & movement of the system correctly but intensity was underestimated.

2.11.5.Realized Weather

Rainfall associated with the depression based on IMD-NCMRWF satellite gauge merged data are depicted in Fig. 4 respectively.

It is seen that light to moderate rainfall occurred at a few places over coastal Tamil Nadu, Puducherry & Karaikal, Rayalaseema and south Andhra Pradesh on 15th October.

Light to moderate rainfall occurred at most places with extremely heavy rainfall at isolated places and heavy to very heavy rainfall at many places over coastal Tamil Nadu, Puducherry & Karaikal, light to moderate rainfall at a few places with heavy to very heavy rainfall at isolated places over Rayalaseema, south Andhra Pradesh and isolated heavy rainfall over south interior Karnataka on 16th October.

Light to moderate rainfall at a few places with isolated heavy rainfall over Rayalaseema, south Andhra Pradesh, south interior Karnataka and Kerala on 17th October

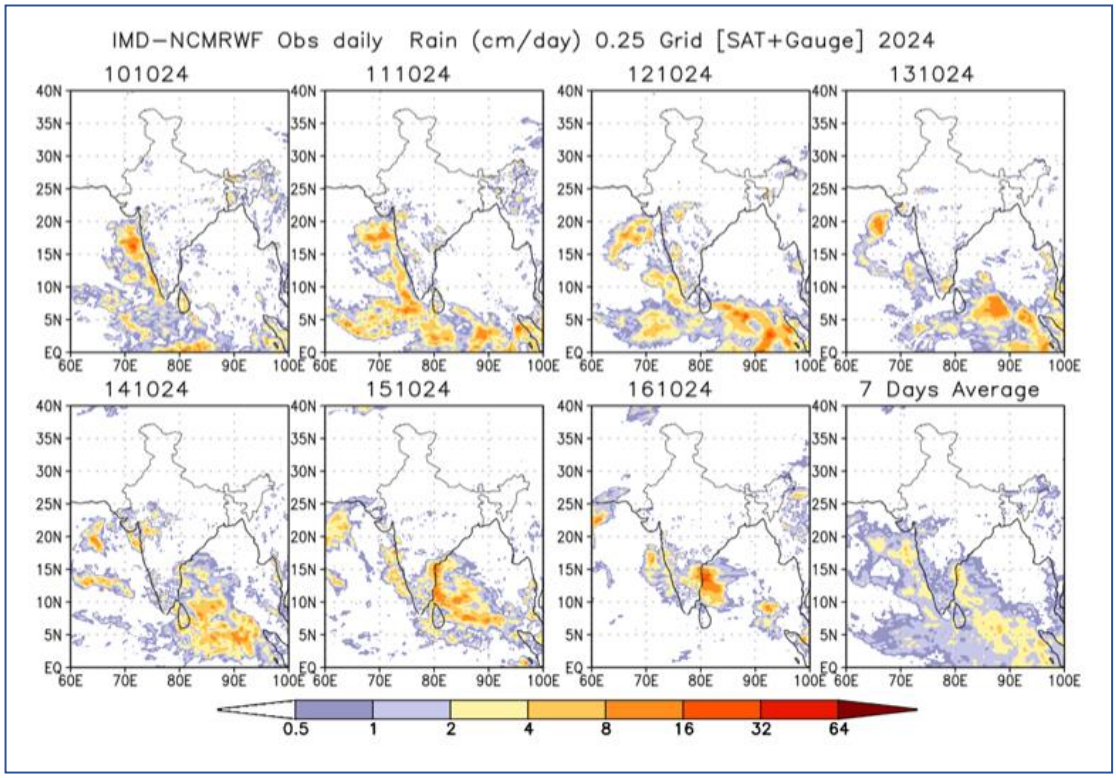


Fig. 2.11.4: IMD-NCMRWF Rain gauge and satellite merged rainfall plots ending at 0300 UTC of 10th Oct to 16th Oct, 2024 (cm/day)

2.11.6. Rainfall forecast verification

The forecast for heavy to extremely heavy rainfall episodes in association with the system are verified with the 24 hours accumulated rainfall realized at various stations. The details of the day-wise verification are given in Table -2.11.2.

Table 2.11.2: Verification of Heavy Rainfall Forecast

Date/Base Time of observation in UTC	24 hr Heavy rainfall warning ending at 0300 UTC of date	Realised 24-hour heavy rainfall (≥ 7 cm) ending at 0300 UTC of date
15.10.2024 / 0300	**Tamil Nadu & Puducherry:** Heavy to very heavy rainfall at isolated places over Tamil Nadu & Puducherry and extremely heavy rainfall at isolated places over north Tamil Nadu on 15th October. Heavy to very heavy rainfall at a few places with extremely heavy rainfall at isolated places over north Tamil Nadu & Puducherry on 16th October and isolated heavy to very heavy rainfall over north interior Tamil Nadu on 17th October. Heavy rainfall at isolated places over south Tamil Nadu during 15th to 17th October. **South Andhra Pradesh & Rayalaseema** Heavy to very heavy rainfall at isolated places on 15th; heavy to very heavy rainfall at a few places with extremely heavy rainfall at isolated	**<u>16th October:</u>** **Tamil Nadu, Puducherry & Karaikal:** Cholavaram (Tiruvallur) 30, Red Hills (Tiruvallur) 28, Avadi (Tiruvallur) 25, Kathivakkam (Chennai) 23, Manali (Chennai) 21, T.V.K Nagar (Chennai) 19, Kolathur (Chennai), Adyar (Chennai), Puzhal (Tiruvallur) & Ambattur (Chennai) 18 each, Thiruvottiyur (Chennai), Perungudi (Chennai), Manali (Chennai), Hindustan_University (Kancheepuram) & Ennore (Chennai) 17 each, Perambur (Chennai), Malar Colony (Chennai), Good Will School Villivakkam (Tiruvallur), Puzhal (Chennai), Ayanavaram Taluk Office (Chennai), Anna University (Chennai), Ponneri (Tiruvallur) & Thamaraipakkam (Tiruvallur) 16 each, Ambathur (Chennai), Anna University (Chennai), MGR Nagar (Chennai), Sholinganallur (Chennai), Thiru-Vi-Ka Nagar (Chennai), Tondiarpet (Chennai), Royapuram (Chennai) & Adayar (Chennai) 15 each, Madhavaram (Chennai), Tondiarpet (Chennai), Chennai(N) (Chennai), CD Hospital Tondaiarpet (Chennai), YMCA Nandnam (Chennai) & Kodambakkam (Chennai) 14 each, Anna Nagar (Chennai), Vanagaram (Chennai), Chennai Collector Office (Chennai), Kodambakkam (Chennai), DGP Office (Chennai) & Royapuram (Chennai) 13 each, Ice House (Chennai), Pallikaranai (Chennai), Teynampet (Chennai), Alandur (Chennai), Chennai (AP) (Chennai), Meenambakkam (Chennai) & Maduravoyal (Chennai) 12 each, Meenambakkam (Chennai), Kolapakkam (Kancheepuram), Valasaravakkam (Chennai), Uthandi (Chennai), GCC (Chennai), Tiruvottiyur (Chennai) & Adyar Eco Park (Chennai) 11 each, Mugalivakkam (Chennai), Jaya Engg College (Tiruvallur), Perungudi (Chennai), Sholinganallur (Chennai) & Tiruppur (Tiruppur) 10 each, Gummidipoondi (Tiruvallur), Perungudi (Chennai), Uthukottai (Tiruvallur), Manimutharu

	places on 16th October and heavy rainfall at isolated places on 17th October. **Kerala & south Interior Karnataka:** Heavy to very heavy rainfall at isolated places over Kerala and south Interior Karnataka during 15th to 17th October.	Dam (Kallakurichi), Tiruvallur (Tiruvallur), Kachirayaopalayam (Kallakurichi), Mahabalipuram (Chengalpattu), Satyabama (Kancheepuram), Poonamallee (Tiruvallur) & Chembarabakkam (Kancheepuram) 9 each, ACS Medical College (Kancheepuram), Bhuvanagiri (Cuddalore), VIT Chennai (Chengalpattu), Valavanur (Villupuram), Mahabalipuram (Chengalpattu), Koratur (Tiruvallur) & Koliyanur (Villupuram) 8 each, Uthangarai (Krishnagiri), Tiruttani (Tiruvallur), Pallipattu (Tiruvallur), Kundrathur (Kancheepuram), Tambaram (Chengalpattu) & Tiruppur South (Tiruppur) 7 each; **Rayalaseema:** Sullurpeta (Tirupati) 22, Tada (Tirupati) 12, Tirupati Aero (Tirupati) 11, Satyavedu (Tirupati) 10, Porumamilla (YSR) 9, Srikalahasti (Tirupati), Thottambedu (Tirupati), Venkatagiri (Tirupati), Penagaluru (Annamayya), Kodur (YSR) & Nagari (Chittoor) 8 each, Gudur (Tirupati) & Pullampeta (Annamayya District) 7 each; **Coastal Andhra Pradesh & Yanam:** Kavali (Nellore) 18, Nellore (Nellore) 13, Kandukur (Nellore) 10, Seetharamapuram (Nellore) 10, Vinjamur (Nellore) & Udayagiri (Nellore) 9 each; **South Interior Karnataka:** Bengaluru Hal Ap (Bengaluru Urban) 9, Hesaraghatta (Bengaluru Urban) 7, Bellur (Mandya) & Bengaluru City (Bengaluru Urban) 7 each.
16.10.2024 / 0300	**Tamil Nadu & Puducherry:** Heavy to very heavy rainfall at a few places with extremely heavy rainfall at isolated places over north Tamil Nadu & Puducherry on 16th October and isolated heavy to very heavy rainfall over north interior Tamil Nadu on 17th October. Heavy rainfall at isolated places over south Tamil Nadu during 16th to 17th October. **South Andhra Pradesh & Rayalaseema:** Heavy to very heavy rainfall at a few places with extremely heavy rainfall at isolated places is likely on 16th October and heavy rainfall at isolated places is	**<u>17th October:</u>** **Rayalaseema:** Kodur (YSR) 14, Pullampeta (Annamayya) 10, Penu Konda (Sri Sathyasai) 9, Ramagiri (Sri Sathyasai) & Nandikotkur (Nandyal) 8 each, Chenne Kothapalle (Sri Sathyasai), Jupadu Bungalow (Nandyal), Rajampet (Annamayya), Venkatagiri (Tirupati), Srikalahasti (Tirupati), Nallamada (Sri Sathyasai), Gorantla (Sri

	likely on 17th October. **Kerala & south Interior Karnataka:** Heavy to very heavy rainfall at isolated places is likely over Kerala and south Interior Karnataka during 16th to 17th October.	Sathyasai), Penagaluru (Annamayya) & Tirupati (Tirupati) 7 each; **Coastal Andhra Pradesh & Yanam:** Nellore (Nellore) 7; **Kerala:** Kozhikode (Kozhikode) 7; **South Interior Karnataka:** Davanagere (Davangere) & Davanagere (Davangere) 9 each, Y N Hoskote (Tumakuru) & Chitradurga (Chitradurga) 7 each.

2.12 Severe Cyclonic Storm "DANA" over the Bay of Bengal (22nd – 26th October, 2024)

2.12.1 Life History of "DANA":

- A cyclonic circulation was seen over central Andaman Sea in the early morning (0530 hours IST/0000 UTC) of 19th October and it lay over North Andaman Sea in the early morning (0530 hours IST/0000 UTC) of 20th October 2024.
- Under its influence, a Low-Pressure Area formed over the Eastcentral Bay of Bengal (BoB) and adjoining north Andaman Sea in the evening (1730 hours IST/ 1200 UTC) of 20th October.
- Moving west-northwestwards, it concentrated into a well-marked low-pressure area over Eastcentral BoB in the noon (1130 hours IST) of 21st October.
- Continuing to move west-northwestwards, it intensified into a Depression over Eastcentral BoB in the early morning (0530 hours IST/0000 UTC) of 22nd October. It then moved northwestwards and intensified into a deep depression over Eastcentral BoB in the same evening (1730 hours IST/ 1200 UTC).
- Continuing to move further northwestwards, it intensified into a cyclonic storm (CS) "DANA" over eastcentral BoB in the early morning (0530 hours IST/ 0000 UTC) of 23rd October.
- It then moved north-northwestwards and intensified into a severe cyclonic storm (SCS) over central & adjoining northwest BoB in the mid-night (2330 hours IST/1800 UTC) of 23rd October, 2024.
- Continuing to move north-northwestwards, it crossed north Odisha coast close to Habalikhati Nature Camp (Bhitarkanika) and Dhamara during 0130 hrs IST to 0330 hrs IST of 25th October (2000 to 2200 UTC of 24th October) as a severe cyclonic storm with a wind speed of 100-110 kmph gusting to 120 kmph.
- The landfall process commenced in the midnight (2330 hours IST/1800 UTC) of 24th October and continued for 9 hours till 0830 hours IST/ 0300 UTC of 25th October.
- Continuing to move further north-northwestwards slowly, it weakened into a CS over north coastal Odisha in the forenoon (0830 hours IST/0300 UTC) of 25th October, into a deep depression in the afternoon (1430 hours IST/0900 UTC). Thereafter, it gradually moved westwards, weakened into a depression over interior Odisha in the midnight (2330 hours IST/1800 UTC) of 25th October and into a well-marked low-pressure area over North Odisha in the early morning (0530 hours IST/ 0000 UTC) of 26th October.
- The best track parameters are presented in **Table 2.12.1**. The observed track of the severe cyclonic storm "DANA" is presented in **Fig. 2.12.1**.

Table 2.12.1: Best track positions and other parameters of the Severe Cyclonic Storm "DANA" over Eastcentral Bay of Bengal during 22nd – 26th October, 2024

D: Depression, DD: Deep Depression, CS: Cyclonic Storm, SCS: Severe Cyclonic Storm, kt: Knot (1 Knot=1.85 kmph)

Date	Time (UTC)	Lat.	Long.	CI No.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained surface wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
22.10.24	0000	15.4	91.6	1.5	1003	20	3	D
	0300	15.5	91.4	1.5	1002	20	3	D
	0600	15.5	91.3	1.5	1000	25	4	D
	1200	15.6	90.9	2.0	999	30	5	DD
	1800	15.8	90.5	2.0	998	30	6	DD
23.10.24	0000	16.2	89.8	2.5	997	35	7	CS
	0300	16.5	89.6	2.5	996	35	8	CS
	0600	16.7	89.2	2.5	995	40	9	CS
	0900	16.9	89.1	3.0	994	45	10	CS
	1200	17.2	88.9	3.0	992	45	12	CS
	1500	17.6	88.7	3.0	992	45	12	CS
	1800	17.9	88.5	3.0	990	50	14	SCS
	2100	18.3	88.3	3.0	990	50	14	SCS
24.10.24	0000	18.6	88.2	3.5	988	55	16	SCS
	0300	18.9	88.0	3.5	988	55	16	SCS
	0600	19.2	87.8	3.5	988	55	16	SCS
	0900	19.4	87.6	3.5	986	60	18	SCS
	1200	19.8	87.5	3.5	986	60	18	SCS
	1500	20.1	87.3	3.5	986	60	18	SCS
	1800	20.5	87.1	3.5	988	55	16	SCS
		Crossed North Odisha coast close to Habalikhati Nature Camp (Bhitarkanika) & Dhamara between 2000 to 2200 UTC of 24th October						

		(0130 to 0230 hrs IST of 25th October) as a Severe Cyclonic Storm with wind speed of 100-110 gusting to 120 kmph						
24.10.24	2100	20.7	87.0	-	988	55	16	SCS
25.10.24	0000	21.0	86.8	-	990	50	14	SCS
	0300	21.2	86.7	-	994	45	10	CS
	0600	21.3	86.6	-	997	35	7	CS
	0900	21.4	86.4	-	998	30	6	DD
	1200	21.4	86.3	-	999	30	5	DD
	1800	21.4	86.2	-	1000	25	4	D
26.10.24	0000	Weakened into a Well-Marked Low-Pressure Area over North Odisha						

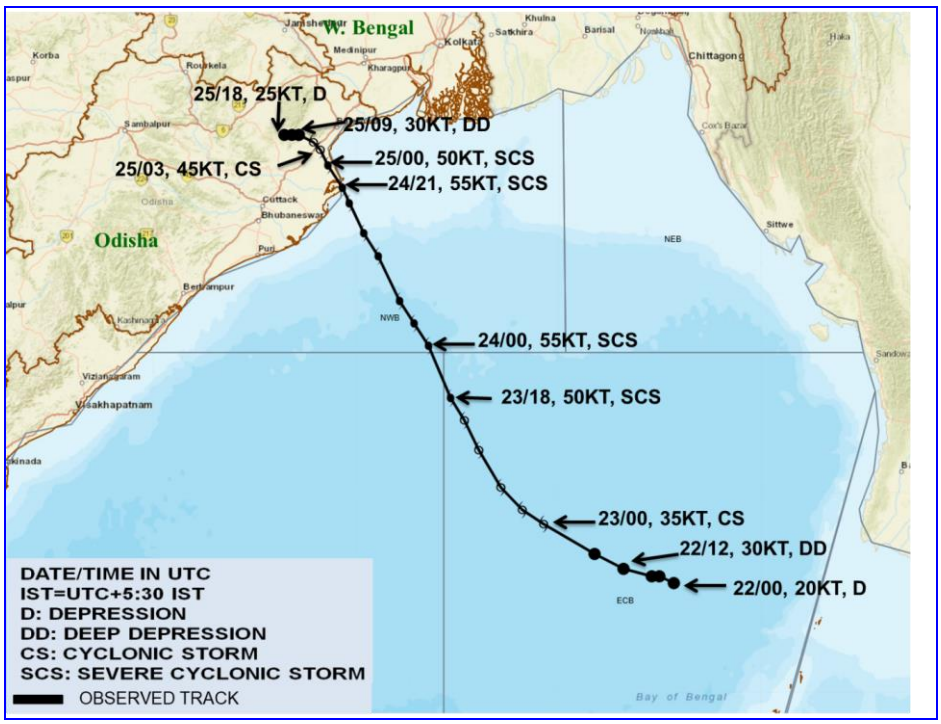


Fig. 2.12.1: Observed track of severe cyclonic storm "DANA" over eastcentral Bay of Bengal during 22-26 October, 2024

2.12.2 Salient Features:

2.12.2.1 Salient features compared to climatology:

It was the 2nd cyclone of the year 2024 over the BoB after the SCS "REMAL" during 24 to 28 May. Climatologically, 4 SCSs & above category storms formed from the depressions that developed in the region 12^0-17^0N and 90^0-100^0E over the eastcentral BoB and North Andaman Sea which crossed Odisha coast in October during the period 1965-2023 (**Fig.2.12.2**). The SCS in 1985 formed over eastcentral

BoB on 13th October and crossed North Odisha coast to the south of Balasore around 2300 UTC of 15th October as an SCS (50 kt). Other storm in 1999, developed over eastcentral BoB on 15th October and crossed Odisha coast near Gopalpur in the early morning of 18th October, (0230 hrs IST of 18th October/ 2100 UTC of 17th October) as an extremely severe cyclonic storm (90 kt). In 1999, the Super Cyclone of Odisha developed from a depression over North Andaman Sea. It moved northwestwards and crossed Odisha coast in the morning (0930-1200 hrs IST) of 29th October, 1999 (120 kt). It moved very slowly during & after landfall and remained almost stationary over the Odisha coast near Cuttack & Bhubaneswar for about 30 hours, moved southwestwards and dissipated over the Odisha coast after 45 hours. In 2013, extremely severe cyclonic storm "Phailin" developed from a depression over North Andaman Sea. It moved northwestwards initially and then north-northwestwards and crossed Odisha coast as VSCS (64-89 kt) in the night (2230 hrs IST/1700 UTC) of 12th October, 2013.

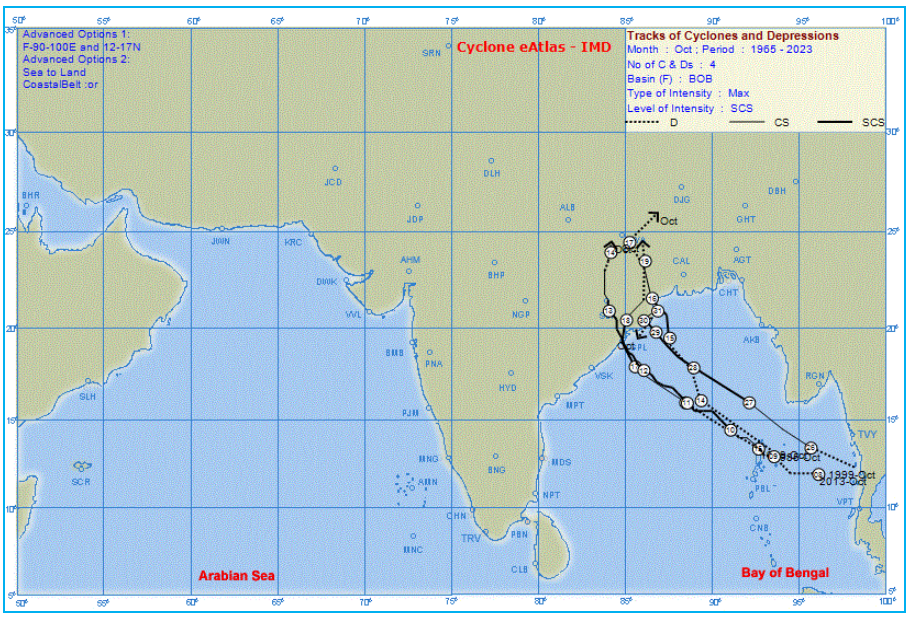


Fig. 2.12.2: Tracks of cyclonic storms developing from a depression in the grid (12^0-17^{0}N and 90^0-100^{0}E) crossing Odisha coast in the month of October during the period 1965-2023

2.12.2.2 Movement:

The six hourly average translational speed of "DANA" was 10.8 kmph against the normal speed of 16.7 kmph for SCS category over the BoB during the post-monsoon season (October-December). It moved slower than the average translational speed during the entire life cycle (**Fig. 2.12.3**). However, during landfall and particularly after landfall, on 25th October, it moved further slowly. As a result, the landfall process which commenced in the midnight (2330 hours IST/1800 UTC) of 24th October, continued for 9 hours till morning (0830 hours IST/ 0300 UTC) of 25th October. The northward movement of the system was restricted mainly due to north-northwesterly to northerly winds prevailing over the system area in association with the anticyclonic circulation centred near Kachchh region. After landfall, it moved slowly west-northwestwards after landfall and weakened into a CS by 0830 IST, DD by 1730 IST, a depression by 2330 hrs IST and into a well marked low pressure area over North Odisha in the early morning (0000 UTC) of 26th October.

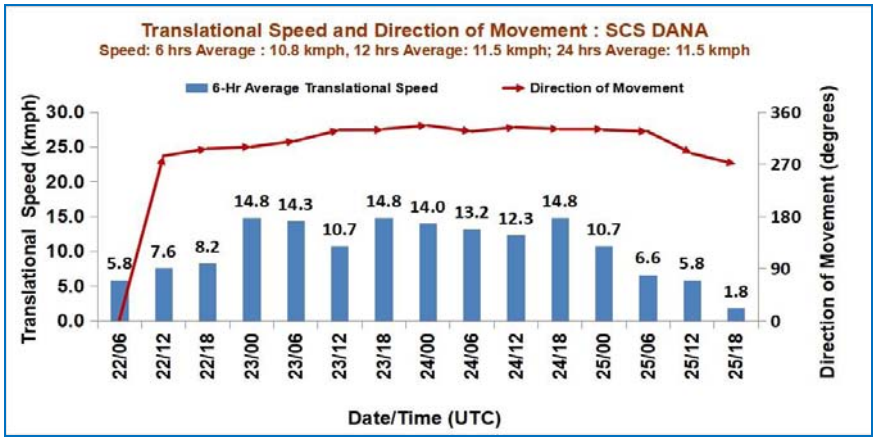


Fig. 2.12.3: Six hourly average translational speed and direction of movement during life cycle of "SCS DANA"

2.12.2.3 Maximum sustained wind speed (MSW) and estimated central pressure (ECP):

The system intensified in the normal rate during early stages of its development i.e. from low pressure area stage (1730 hours IST of 20th October) to well-marked low-pressure area (1130 hours IST of 21st October) to depression (0530 hours IST of 22nd October), deep depression (1730 hours IST of 22nd October) and cyclonic storm (0530 hrs IST of 23rd). However, no rapid intensification (increase in intensity by at least 30 kt in 24 hours) was observed till landfall of the system. After landfall, the system weakened rapidly, mainly due to land interactions and cold dry air incursion from northwest into the core. The system attained peak intensity of 60 kts in the evening of 24th October (1730 hours IST/ 1200 UTC) (**Fig. 2.12.4**) over northwest BoB when the system entered into an area of high sea surface temperature (≥ 30^0C). Thereafter, due to land interactions and cold dry air incursion from northwest, it weakened gradually and crossed coast with wind speed of 55 knots (100-110 gusting to 120 kmph). After landfall, it rapidly weakened from the evening (1830 hours IST/ 1200 UTC) of 25th October to a well-marked low-pressure area in the early morning (0530 hours IST/ 0000 UTC) of 26th October (within 12 hours).

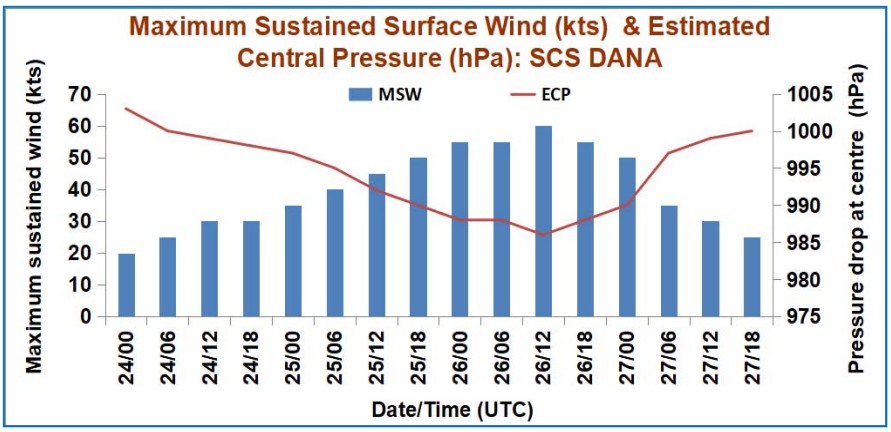


Fig.2.12.4: Six hourly Maximum sustained wind speed and estimated central pressure during life cycle of "SCS DANA"

3 **Track length:**

The total track length of severe cyclonic storm “DANA” was 1780 km against average track length of 930 km of SCS in post-monsoon season.

4 **Life Period:**

The total life period (depression to depression) of “DANA” was 4 days against the normal of 4 days & 4 hours for SCS category over the BoB in post-monsoon season based on the data of 1990-2013.

5 **Accumulated Cyclone Energy and Power Dissipation Index:**

The Velocity Flux, Accumulated Cyclone Energy (a measure of damage potential) and Power Dissipation Index (a measure of loss) were 4.8×10^2 knots, 2.36×10^4 knots^2 and 1.21×10^6 knots^3 respectively against normal of 3.88×10^2 knots, 1.83×10^4 knots^2 and 0.90×10^6 knots^3 respectively over the BoB.

2.12.3 Genesis, intensification, Landfall and Weakening

2.12.3.1 Genesis

At 0000 UTC of 19th October, a **Cyclonic Circulation** lay over central Andaman Sea. It lay over North Andaman Sea in at 0000 UTC of 20th October 2024. Under its influence, a **Low-Pressure Area** formed over the Eastcentral BoB and adjoining north Andaman Sea at 1200 UTC of 20th October. Moving west-northwestwards, it concentrated into a **Well-Marked Low-Pressure area** Eastcentral BoB at 0600 UTC of 21st October. Continuing to move west-northwestwards, it intensified into a **Depression** over Eastcentral BoB at 0000 UTC of 22nd October. The madden-julian oscillation (MJO) was in phase 5, with amplitude more than 1, and expected to move across phase 5 during next 7 days with further increasing amplitude. Thus, MJO supported enhancement of convective activity over the BoB during next 5 days. The guidance from North Carolina Institute of Climate Studies (NCICS) based forecast over BoB indicated westerly winds (1-3 mps) over south BoB and adjoining Equatorial Indian Ocean and easterly winds (1-3 mps) over westcentral BoB. Eastward moving MJO & Kelvin waves along with Equatorial Rossby waves were likely over the central BoB during next 5-7 days. These features indicated highly favourable environment for cyclogenesis (formation of depression) over the central parts of the BoB. The sea surface temperature (SST) was 30°C over the central and northern BoB. The tropical cyclone heat potential (TCHP) was greater than 100 kJ/cm² over the west-central BoB and less than 80 kJ/cm² over the northwest BoB. A zone of positive relative vorticity, measuring $100 \times 10^{-6} s^{-1}$, was present to the south of the system's center over the east-central BoB, extending vertically up to the 500 hPa level. The low-level convergence of $10 \times 10^{-6} s^{-1}$ was observed to the south of the system area, along with upper-level divergence of $20 \times 10^{-6} s^{-1}$ in the same region. The Vertical wind shear (VWS) was low to moderate over the central BoB and high over the northern BoB. Total precipitable water imagery indicated a warm, moist air incursion into the core of the system.

2.12.3.2 Intensification

The Depression then moved northwestwards and intensified into a **Deep Depression** over Eastcentral BoB at 1200 UTC of 22nd October. Continuing to move further northwestwards, it is intensified further into a CS **“DANA”** over eastcentral BoB in the early morning (0530 hours IST/ 0000 UTC) of 23rd October. It then moved north-northwestwards and intensified into an SCS over central & adjoining northwest BoB in the mid-night (2330 hours IST/1800 UTC) of 23rd October, 2024.

At 1200 UTC of 22nd October the MJO was in phase 5, with amplitude more than 1, and was expected to move across phase 5 during next 7 days with further increasing amplitude. Thus, MJO supported enhancement of convective activity over central and north BoB during next 5 days. The guidance from NCICS based forecast over BoB indicated eastward moving MJO & kelvin waves along with equatorial Rossby waves over the central BoB during next 5 days. These features indicated highly favourable environment for intensification of system over the central & north parts of the BoB. The SST was 30°C over central & north BoB. The TCHP was >100 KJ/cm^2 over westcentral BoB, <80 kJ/cm^2 over northwest. The relative vorticity at low level increased in past 6 hours and was 150x 10^{-6}s-1 around system centre over eastcentral BoB with vertical extension upto 500 hPa level. The low-level convergence increased and was 30 x10^{-6}s^{-1} to the north of system area. The upper-level divergence was 20x10^{-6}s^{-1} to the northeast of system area. The VWS was low to moderate (05-15 kt) over central BoB.

At 0000 UTC of 23rd and 24th October the similar MJO, equatorial Rossby wave and Kelvin waves prevailed alongwith similar SST and TCHP. The relative vorticity at low level increased and was 150x 10^{-6}s-1 around system centre over eastcentral BoB with vertical extension upto 500 hPa level. The low-level convergence increased and was 30 x10^{-6}s^{-1} to the northwest of system area at 00 UTC of 23rd. The upper-level divergence also increased and was 30x10^{-6}s-1 around the northeast of system area. The VWS was moderate to high (10-20 kt) over central BoB

The relative vorticity at low level has increased in 1800 UTC of 23rd and was 200x 10^{-6}s^{-1} around system centre over eastcentral BoB with vertical extension upto 200 hPa level. The low-level convergence was 20 x10^{-6}s^{-1} to the southwest of system area. The upper-level divergence was also same and was 10x10^{-6}s^{-1} to the southwest of system area. The VWS was low-moderate (10-15kt) over central BoB. Enhanced poleward outflow was seen in midlatitude westerlies. High SST, poleward outflow, moderate wind shear supported further intensification of the system into SCS.

2.12.3.3 Landfall

Continuing to move north-northwestwards, the SCS **"DANA"** crossed **north Odisha coast close to Habalikhati Nature Camp (Bhitarkanika) and Dhamara** during **0130 hrs IST to 0330 hrs IST of 25th October** (2000 to 2200 UTC of 24th October) as a severe cyclonic storm with a wind speed of 100-110 kmph gusting to 120 kmph. The landfall process commenced in the midnight (2330 hours IST/1800 UTC) of 24th October and continued for 9 hours till 0830 hours IST/ 0300 UTC of 25th October.

At 15 UTC of 24th, the relative vorticity at low level was 250 x 10^{-6}s^{-1} around system area with vertical extension upto 200 hPa level. The low-level convergence was 10 x10^{-6}s^{-1} to the southwest of system area. The upper-level divergence was also same and was 10x 10^{-6}s^{-1} to the northeast of system area. The VWS was low (10-15 kt) over northwest BoB. The upper tropospheric ridge was around 20^{0}N. The system was tracking north-northwesterly under the influence of south-southeasterly winds to the south of ridge.

At 2100 UTC of 24 October, the relative vorticity at low level decreased further to 150x 10^{-6}s^{-1} around system area with vertical extension upto 500 hPa level. Low-level convergence was 15 x10^{-6}s^{-1} to the southwest of system area. The upper-level divergence was also same and was 10x10^{-6}s^{-1} to the northeast of system area. The VWS was increased to moderate (10 kt) over northwest BoB. The upper tropospheric ridge was around 20^{0}N.

At 0000 UTC of 25 October, the relative vorticity at low level was $200x10^{-6}s^{-1}$ around system area with vertical extension upto 500 hPa level. Low-level convergence was 20 $x10^{-6}s^{-1}$ to the southwest of system area. The upper-level divergence was also same and was $10x10^{-6}s^{-1}$ to the east of system area and extending westwards upto eastcentral Bay of Bengal. Vertical wind shear (VWS) was moderate (10-20 kt) over system area and to its west. The upper tropospheric ridge was around 20^0 N and an anticyclonic circulation over Chhattisgarh (India).

2.12.3.4 Weakening

Continuing to move further north-north westwards slowly, the SCS **"DANA"** weakened into a CS over north coastal Odisha at 0300 of 25 October, into a **deep depression** at 0900 UTC of 25 October. Thereafter, it gradually moved westwards, weakened into a **depression** over interior Odisha in the midnight (2330 hours IST/1800 UTC) of 25th October and into a **well-marked low-pressure area** over North Odisha in the early morning (0530 hours IST/ 0000 UTC) of 26th October.

At 0300 UTC of 25 October, the relative vorticity at low level was 200 x $10^{-6}s^{-1}$ around system area with vertical extension upto 500 hPa level. Low-level convergence was 15 x $10^{-6}s^{-1}$ to the south of system area. The upper-level divergence was also same and was 20x $10^{-6}s^{-1}$ to the south of system area and extending westwards upto eastcentral Bay of Bengal. The VWS was low (05-10 kt) over system area and to its west. The upper tropospheric ridge was around 20^0 N and an anticyclonic circulation over Chhattisgarh (India).

At 0900 UTC of 25 October, the relative vorticity at low level was 200 x $10^{-6}s^{-1}$ around system area with vertical extension upto 500 hPa level. Low-level convergence was around $20x10^{-6}s^{-1}$ to the system area. The upper-level divergence was also same and was $30x10^{-6}s^{-1}$ to the system area and extending westwards upto eastcentral BoB. The VWS was low (05-10 kt) over system area and to its west. The upper tropospheric ridge was around 20^0N and an anticyclonic circulation lay over Chhattisgarh (India). East-southeastwrly winds prevailing in upper tropospheric levels were steering the system nearly westwards.

At 1800 UTC of 25 October, the relative vorticity at low level was 200 x $10^{-6}s^{-1}$ to the southeast of system centre with vertical extension upto 500 hPa level. Low-level convergence was around 20 $x10^{-6}s^{-1}$ to the west of system area. The upper-level divergence was $5x10^{-6}s^{-1}$ to the system area and extending south-southwestwards upto southern India. The VWS was low (05-10 kt) over system area and to its west. The upper tropospheric ridge was around 20^0N. East-southeasterly winds prevailing in upper tropospheric levels are likely to steer the system nearly west-southwestwards.

2.12.4 Monitoring SCS "DANA":

India Meteorological Department (IMD) maintained round the clock watch over the north Indian Ocean and the cyclone was monitored since 16th October, about 6 days prior to formation of depression on 22nd October. First information about likely formation of a cyclonic circulation over Andaman Sea with an advisory for continuous watch was issued in the Daily Report under Tropical Cyclone Forecasting Programme dated 16th October (about 4 days ahead of formation of cyclonic circulation on 20th October). Subsequently, the extended range outlook issued on 17th October (about 5 days ahead of formation of depression over the Bay of Bengal and 7.5 days ahead of landfall) indicated with high confidence (67-100% probability) likelihood of the formation of a depression over the Eastcentral BoB around 23rd

October and movement towards Odisha coast (**Fig. 2.12.5**). Actually, the depression formed over Eastcentral BoB on 22nd October.

- **Pre-cyclone watch** for Odisha and West Bengal coasts was issued at 1330 hours IST of 20th October at the stage of an upper air cyclonic circulation which lay over North Andaman Sea (about 4.5 days ahead of landfall).
- **Cyclone Alert** (Yellow Message) for Odisha and West Bengal coasts was issued at 2030 hours IST of 22nd October with the formation of Deep Depression over eastcentral BoB at 1730 hours IST of 22nd October (about 2 days ahead of landfall).
- The landfall close to Bhitarkanika and Dhamara during early hours of 25th October was first indicated in the first bulletin issued at 1430 hrs IST of 21st October in the graphical track forecast issued by IMD (about 3 days and 9 hours ahead of landfall).
- **Cyclone Warning** (Orange Message) for Odisha and West Bengal coasts was issued at 1145 hours IST of 23rd October at the stage of cyclonic storm over eastcentral BoB (about 36 hours ahead of landfall).
- **Cyclone Warning** (Red Message) for Odisha and West Bengal coasts was issued on 0230 hours IST of 24th October on formation of severe cyclonic storm over central & adjoining northwest BoB (about 24 hours ahead of landfall)
- **Post Landfall Outlook** (Red Message) for interior districts of Odisha was issued at 1630 hours IST of 24th October (about 10 hours ahead of landfall).

The cyclone was monitored with the help of available satellite observations from INSAT 3DR, SCATSAT (OCEANSAT 3), ASCAT, microwave imageries, doppler weather Radar at Paradip & Gopalpur, available ships, buoys observations & coastal observations in the region. Various global models and dynamical-statistical models run by Ministry of Earth Sciences (MoES) institutions including IMD, NCMRWF, IITM & INCOIS and guidance from models from various international agencies under bilateral arrangement were utilized to predict the genesis, track and intensity of the cyclone as well as associated severe weather.

The forecasts were mainly based on multi-model ensemble technique developed by IMD which were further modulated by analysis of observations and forecasters intervention at IMD through their knowledge, experience and expertise. An indigenously developed digitized forecasting system of IMD (Decision Support System) was utilized for analysis and comparison of various observations and numerical weather prediction model's guidance, decision making process and warning products generation. Typical satellite and radar-based products utilised for monitoring the system are presented in **Fig. 2.12.6**.

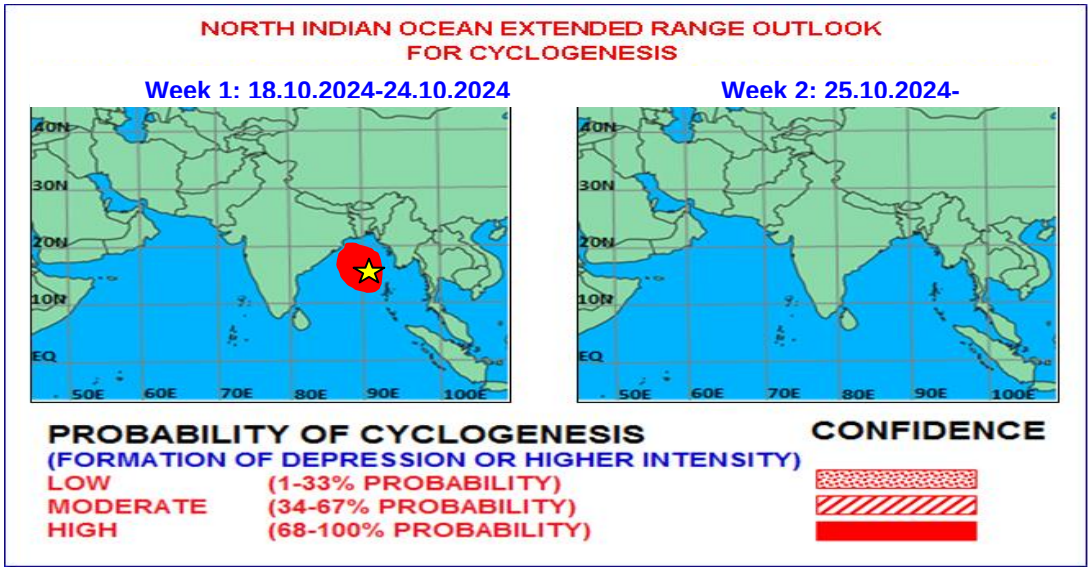


Fig. 2.12.5: Extended Range Outlook issued on 17th October, indicating probable area of genesis (formation of depression) and likely movement towards Odisha coast with High confidence.

: Probable Area of cyclogenesis, : Actual Point of genesis

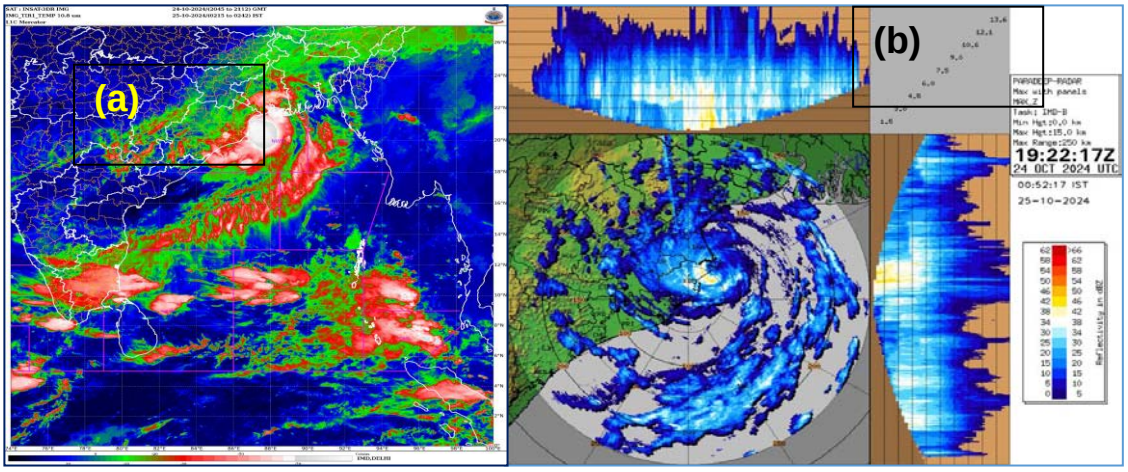


Fig. 2.12.6: Typical (a) INSAT 3D imagery at 0215 IST of 25th October and (b) Doppler Weather Radar Paradip imagery at 0052 IST of 25th during severe cyclonic storm "DANA"

2.12.4.1 Features observed through satellite

At **0300UTC of 19 October** scattered to broken low and medium clouds with embedded intense to very intense convection lay over westcentral BoB, off Andhra Pradesh coast, eastcentral BoB, south BoB & Andaman Sea (minimum cloud top temperature (CTT) minus 75-90^{0}C). Scattered low and medium clouds with embedded moderate to intense convection lay over north BoB, off Gangetic West Bengal & Bangladesh coasts, Gulf of Martaban, and Tenasserim coast.

At **0300 UTC of 20 October** scattered to broken low and medium clouds with embedded intense to very intense convection lay over eastcentral adjoining northeast & southeast BoB and Andaman Sea, Tenasserim coast, Gulf of Martaban (minimum CTT

minus 80 -93 ^{0}C). Scattered low and medium clouds with embedded moderate to intense convection lay over rest of Bay of Bengal.

At **0300 UTC of 21 October** scattered low and medium clouds with embedded intense to very intense convection lay over northeast and eastcentral BoB, north Andaman Sea, Tenasserim coast, gulf of Martaban (minimum CTT minus 80-93 ^{0}C). Scattered low and medium clouds with embedded moderate to intense convection lay over northwest and westcentral BoB, Arakan coast and south Andaman Sea.

At **0000 UTC of 22 October** clouds are organised in shear pattern. The associated CI No. Was **1.5**. Scattered to broken low/med clouds with embedded intense to very intense convection over northeast, central and south BoB, north Andaman Sea & neighbourhood (minimum CTT: minus 80-90 ^{0}C).

At **0300 UTC of 22 October** banding features are appearing in cloud organisation. The intensity is characterised as **CI 1.5**. Scattered to broken low/med clouds with embedded intense to very intense convection lay over east BoB, Andaman Islands, north Andaman Sea & neighbourhood (minimum CTT: minus 80-93 ^{0}C).

At **1200 UTC of 22 October** the cloud mass shows further organisation in past six hours. Banding features are seen in cloud organisation. The intensity is characterised as CI**2.0**. Scattered to broken low & medium clouds with embedded intense to very intense convection lay over central & adjoining north Bay of Bengal, north Andaman Sea & neighbourhood. Minimum CTT was minus 80-93^{0}C. Multisatellite winds indicate stronger winds in northeast sector. Total precipitable water imagery indicates warm moist air incursion into the core. IR/WV difference indicates deep convection upto upper tropospheric levels. ASCAT pass indicates stronger winds in northeast sector.

At **0000 UTC of 23 October** the cloud mass shows further organisation in past six hours. The satellite imagery shows that the system is shear pattern. The intensity is characterised as **CI2.5**. The very intense convective cloud mass associated with the system lies over west sector of the system centre. Minimum CTT minus 93 degrees Celsius. Associated scattered to broken low/medium clouds with embedded intense to very intense convection over central & north BoB between latitude 12.0^{0}N to 21.0^{0}N and longitude 84.0^{0}E to 93.0^{0}E (minimum CTT is minus 80-93 ^{0}C).

At **0300 UTC of 23 October** the cloud mass shows irregular CDO pattern. Visible imagery depicts low level cyclonic circulation (LLCC) embedded in north-east sector of CDO. Diameter size of CDO is about 160 km yields CF2 and BF = 0.5 which yields DT = 2.5. Met T= 2.5 with normal intensification and PT = 2.5. The intensity is characterised as **T2.5**. Associated scattered to broken low/medium clouds with embedded intense to very intense convection lies over central & north BoB between latitude 13.0^{0}N to 21.5^{0}N and longitude 84.0^{0}E to 93.0^{0}E. Minimum CTT is minus 80-93 ^{0}C. IR/WV difference imagery indicates intense convection upto upper tropospheric levels. Total precipitable imagery indicate warm moist air incursion into the core. Multi-satellite winds indicate stronger winds in the northern sector.

At **0900 UTC of 23 October** vortex (dana) over eastcentral BoB with centred near 16.8^{0}N / 89.0^{0}E with intensity CI**3.0** and associated scattered to broken low/medium clouds with embedded intense to very intense convection over central & north bay between latitude 13.0^{0}N to 21.5^{0}N and longitude 84.0^{0}E to 93.0^{0}E (minimum CTT minus 80-93 ^{0}C). Scattered to broken low/medium clouds with embedded intense to very intense convection over north, southeast & central BoB (minimum CTT minus 80-93 ^{0}C) with scattered low/medium clouds with embedded moderate to intense convection over southwest BoB, Andaman Sea, Arakan coast & Tenasserim coast.

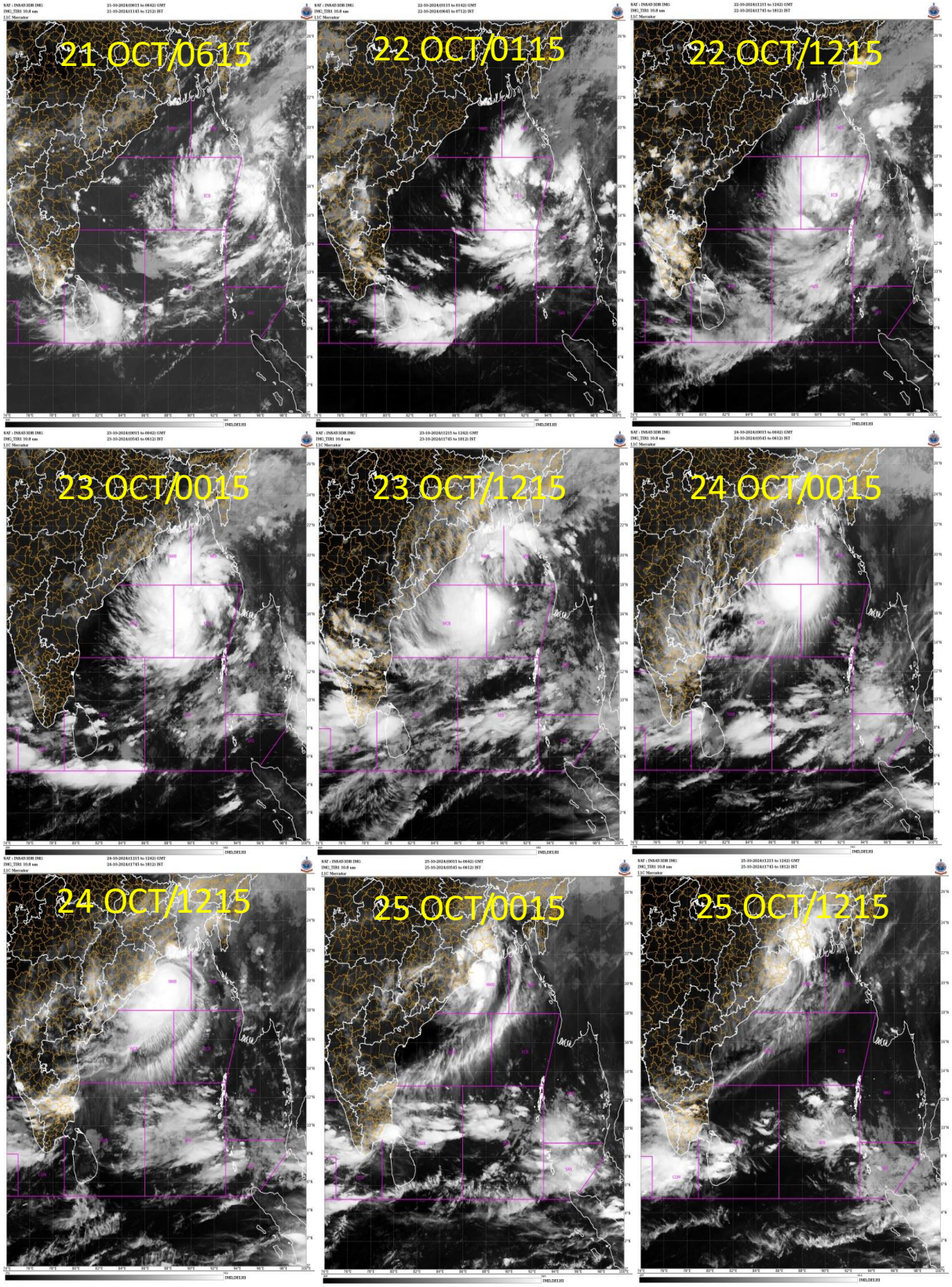


Fig. 2.12.7(a): INSAT-3D IR imageries during life cycle of SCS DANA (22nd-26th October, 2024)

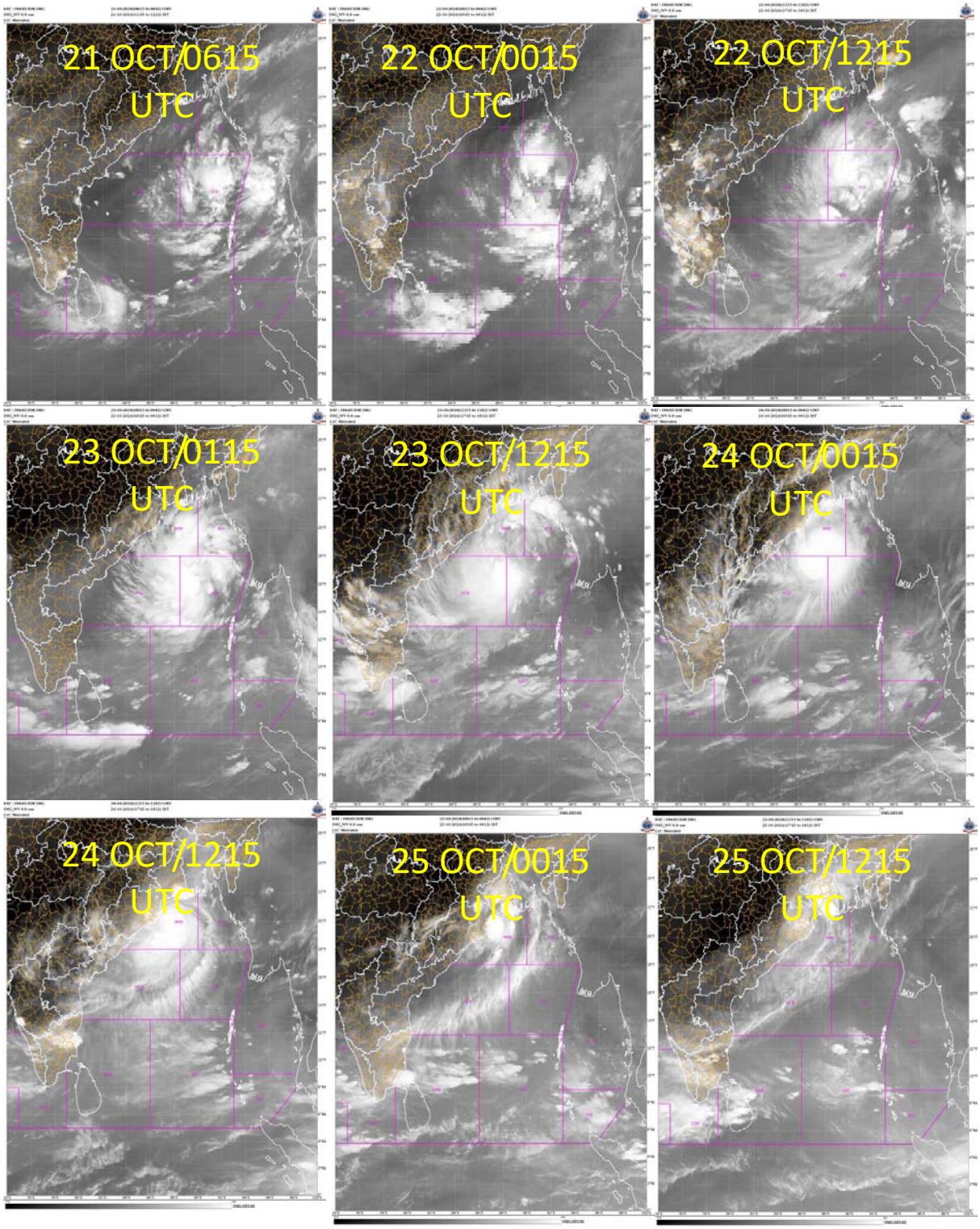


Fig. 2.12.7(b): INSAT-3D Water Vapour imageries during life cycle of SCS DANA (22nd-26th October, 2024)

At **0000 UTC of 24 October** severe cyclonic storm "Dana" intensity CI**3.5** with associated scattered to broken low/medium clouds with embedded intense to very intense convection over central & north BoB between latitude 15.0N & 21.0N and longitude 85.0^{0}E to 90.0^{0}E. Minimum CTT is minus 93°C.

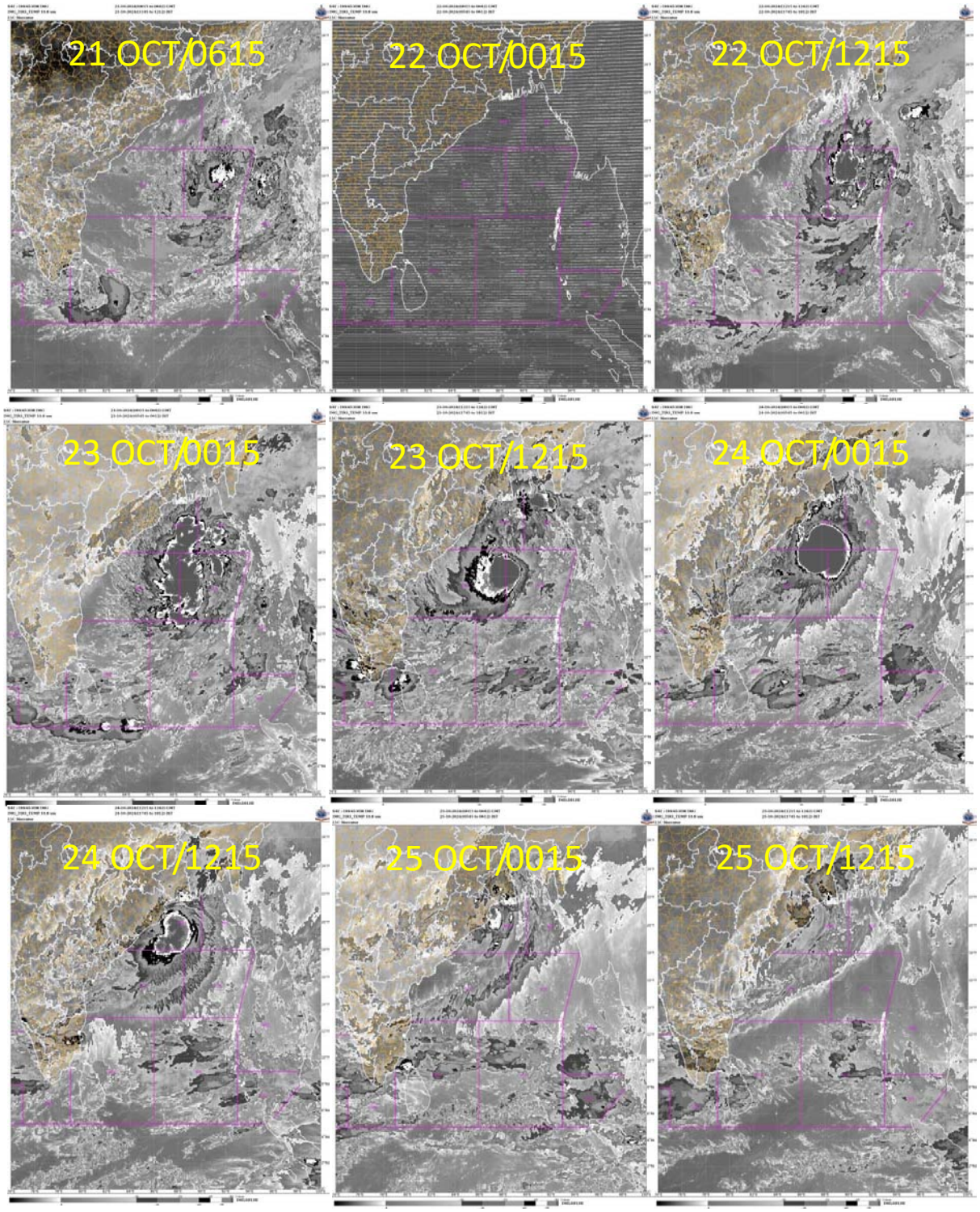


Fig. 2.12.7(c): INSAT-3D enhanced IR BD imageries during life cycle of SCS DANA (22nd-26th October, 2024)

At **0300 UTC of 24 October** the cloud mass is organised in CDO pattern. Current intensity is characterised as **CI3.5**. IR/VIS imagery depicts LLCC embedded in north-east sector of CDO. Diameter size of CDO is about 150 kms yields CF=3, BF = 0.5 yields DT = 3.5 MET and PT agree hence FT based on DT + BF= 3.0+0.5=3.5. Associated scattered to broken low/medium clouds with embedded intense to very intense convection lies over

central & north BoB between latitude 15.0N & 21.0N and longitude 85.0E to 90.0E. Minimum CTT is minus 93°C. Total precipitable water imagery indicate warm moist air incursion into the core from southwest. Multisatellite winds indicate stronger winds in northeast sector.

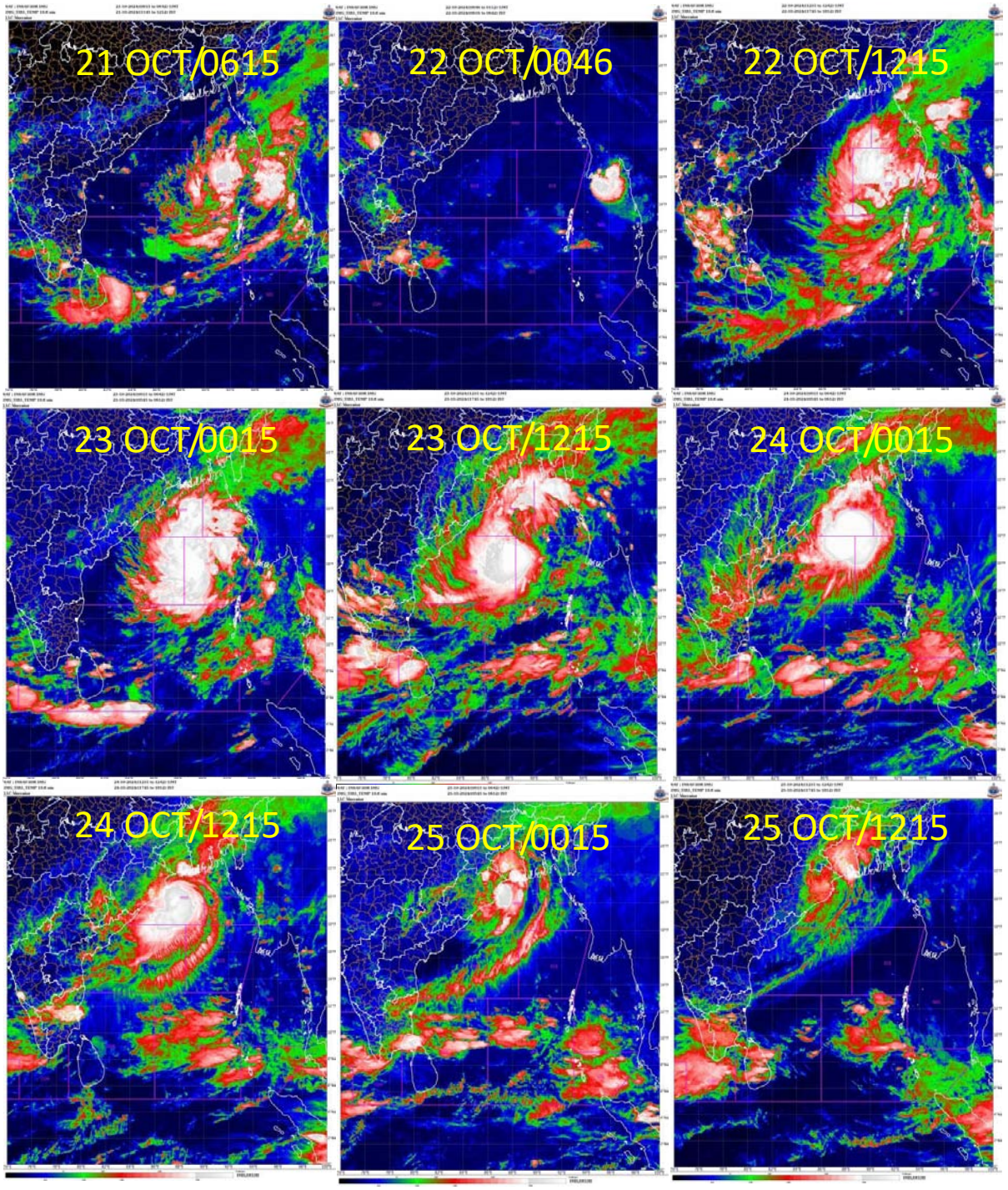


Fig. 2.12.7(d): INSAT-3D IR enhanced colour imageries during life cycle of SCS DANA (22nd-26th October, 2024)

At **0300 UTC of 25 October** the current intensity was characterised as **CI3.0.** Associated scattered to broken low/medium clouds with embedded intense to very intense convection lay over northeast Odisha. Minimum CTT is minus 75-90°C. Moderate to intense convection lay over Gangetic west Bengal, northwest Odisha, southeast Jharkhand and Bangladesh.

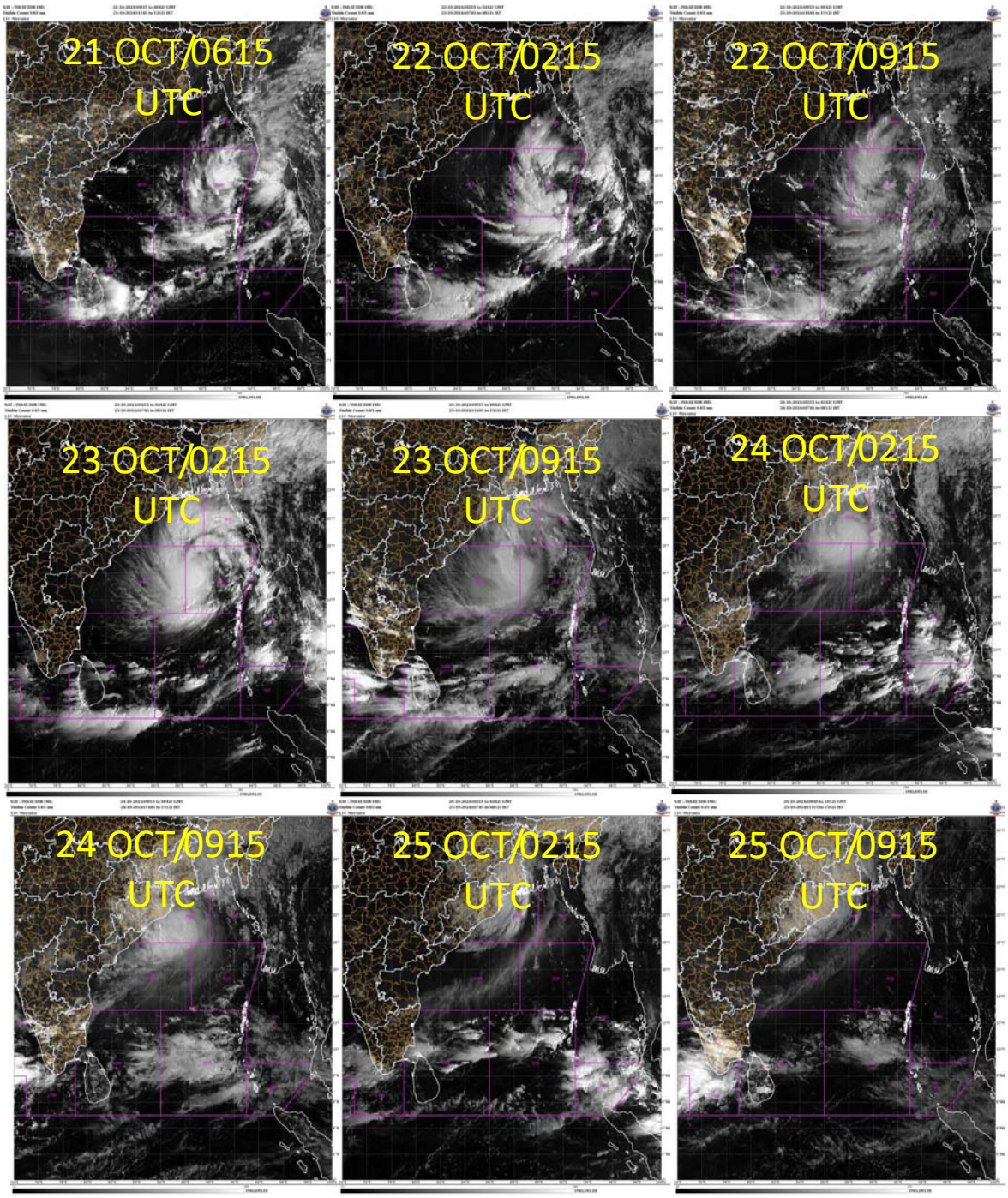


Fig. 2.12.7(e): INSAT-3D Visible imageries during life cycle of SCS DANA (22nd-26th October, 2024)

At **0900UTC of 25 October** as per the satellite imagery, the associated scattered to broken low/medium clouds with embedded intense to very intense convection lay over northeast Odisha. Minimum CTT is minus 75-90°C. Moderate to intense convection over Gangetic west Bengal, southeast Jharkhand and north Bay of Bengal.

`Typical INSAT-3D visible/IR imageries, enhanced colored imageries and cloud top brightness temperature imageries are presented in **Fig. 2.12.7(a) – 2.12.7(e)**. The system

showed curved band pattern during genesis and developing stage spiral band pattern during the mature stage. It showed sheared pattern after landfall.

2.12.4.2 Features observed through Doppler Weather Radar (DWR)

`The SCS "DANA" reached near coast of north Odisha close to Habalikhati Nature Camp (Bhitarkanika) and Dhamara during 0130 hrs IST to 0330 hrs IST of 25th October (2000 to 2200 UTC of 24th October) as an SCS with a wind speed of 100-110 kmph gusting to 120 kmph. The landfall process commenced in the midnight (2330 hours IST/1800 UTC) of 24th October and continued for 9 hours till 0830 hours IST/ 0300 UTC of 25th October. **Fig. 2.12.8(a) to 2.12.8(d**) are displaying sequentially different radar imageries (PPI_V and Max dBZ) at different times on 25th and 26th December during the landfall of the cyclone. Every plot in the figure is representing Max (dBZ) plot of radar reflectivity with vertical cross sections in East-West and North-South directions. The radar imageries starting 00:12 UTC of 25 October to 11:42 UTC of 26 October was showing the movement of the cyclone during this period.

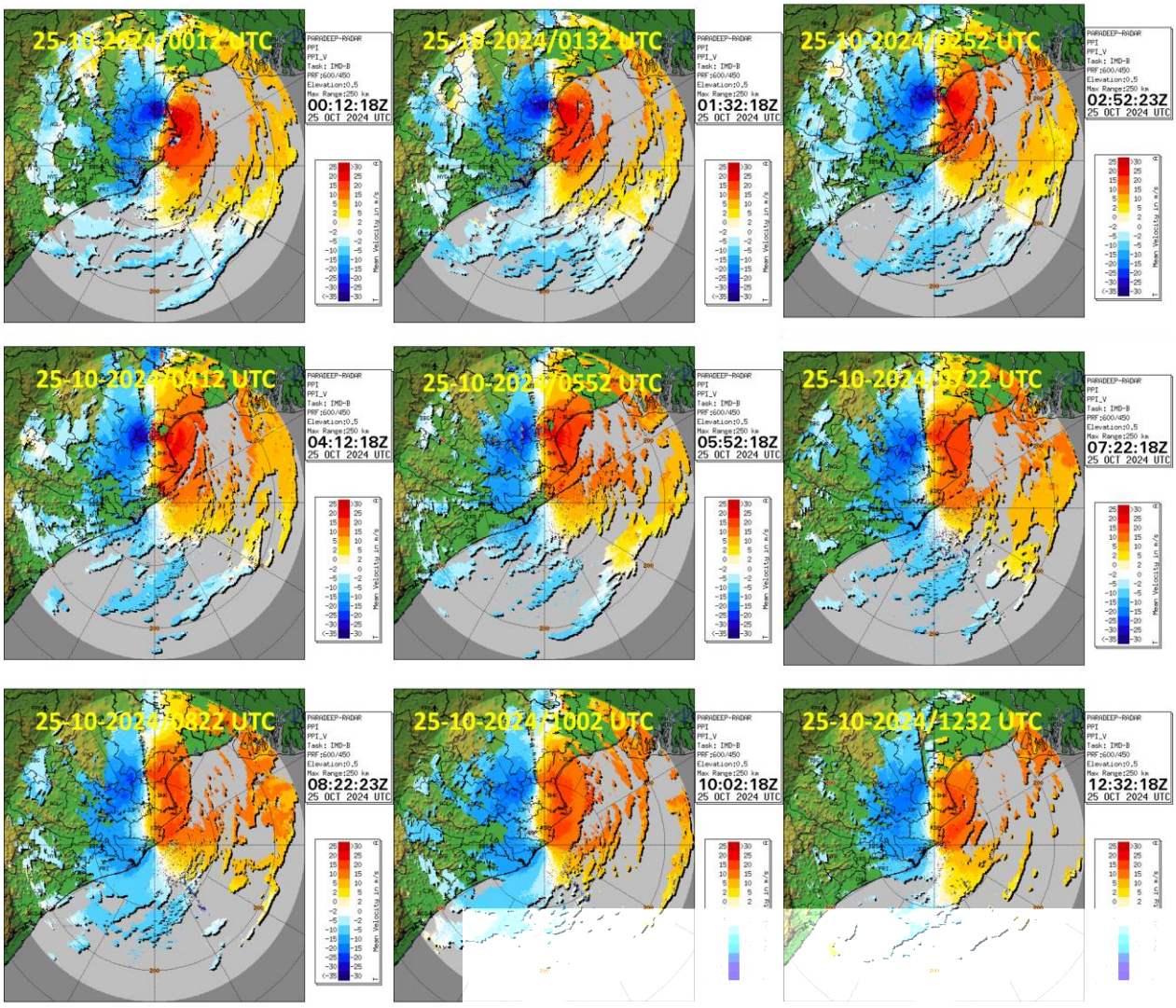


Fig. 2.12.8(a): DWR Paradip PPI_V during the day of landfall (25th October, 2024)

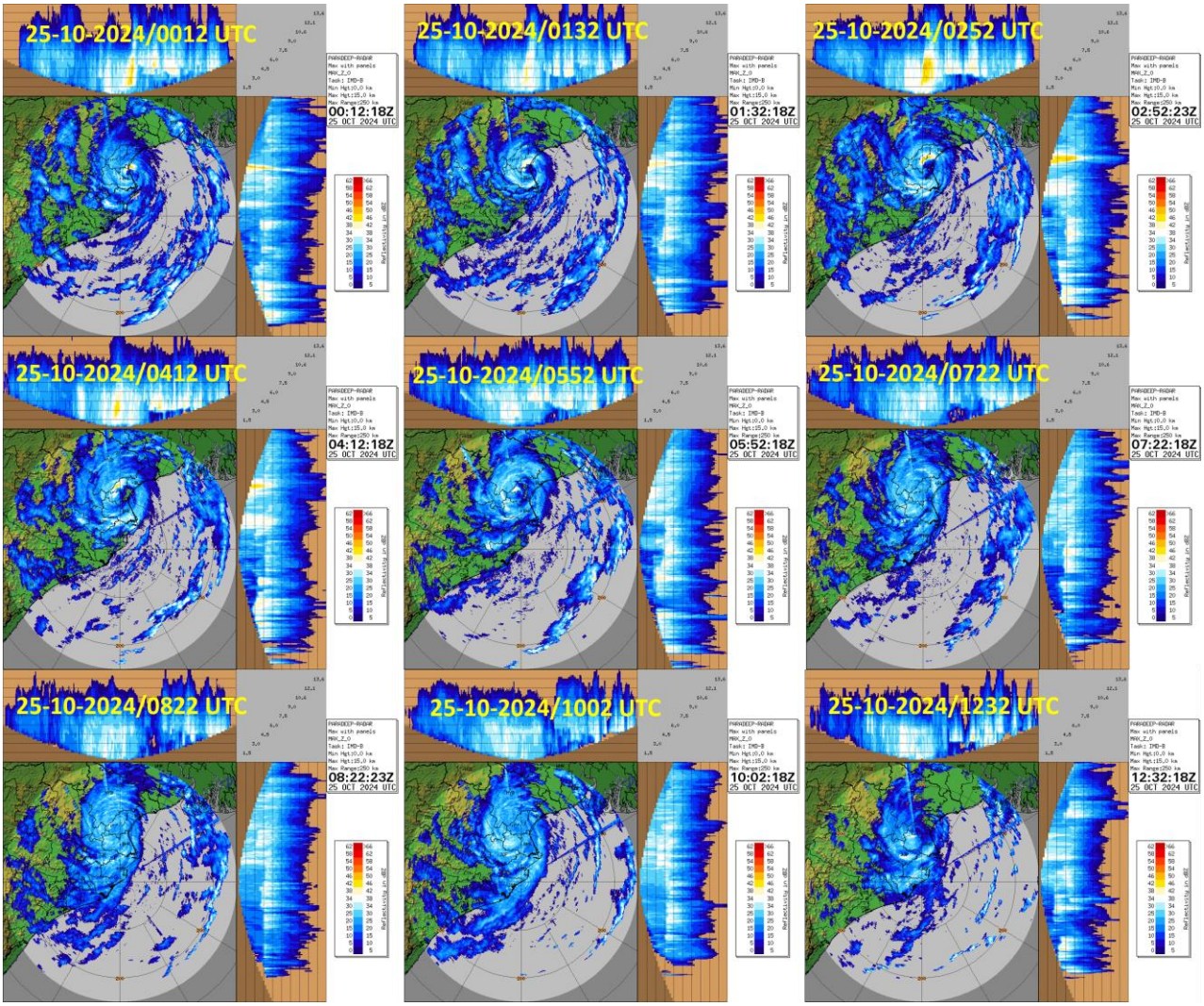


Fig. 2.12.8(b): DWR Paradip Max (dBZ) imageries of reflectivity during the day of landfall (25 October, 2024)

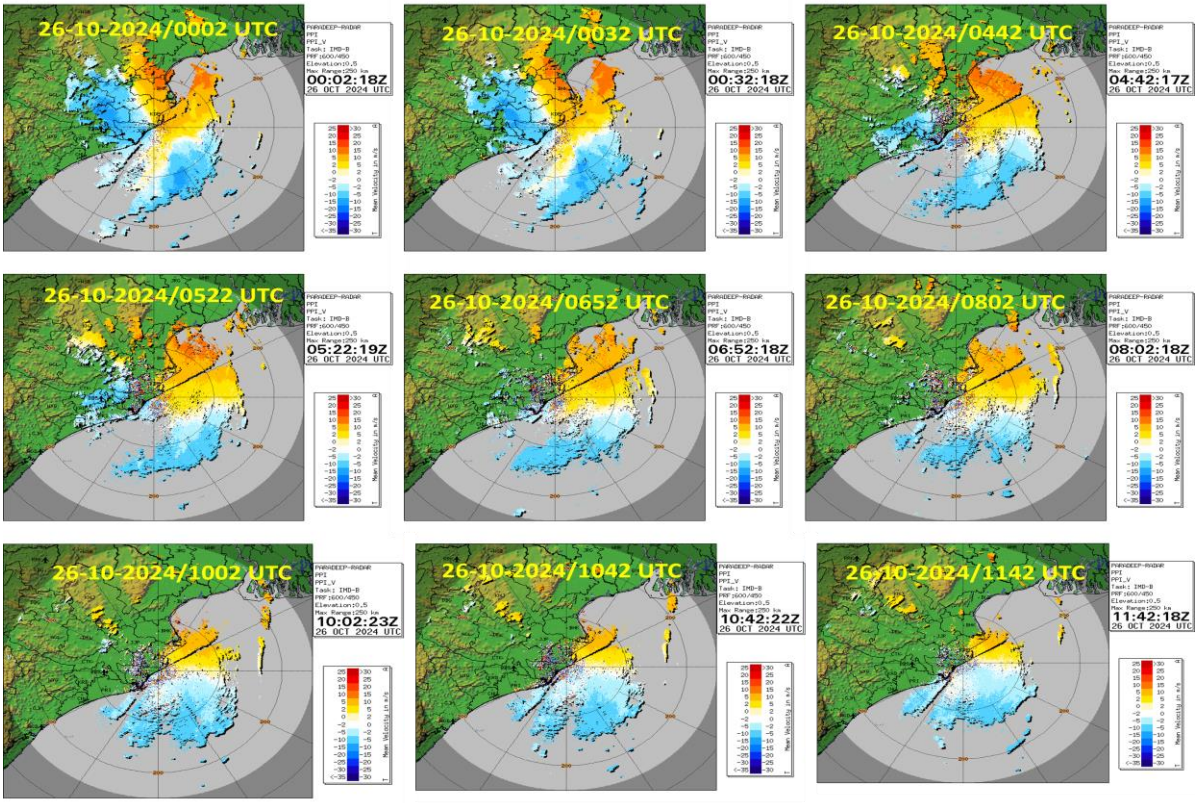


Fig. 2.12.8(c): DWR Paradip PPI_V images during (26 October, 2024)

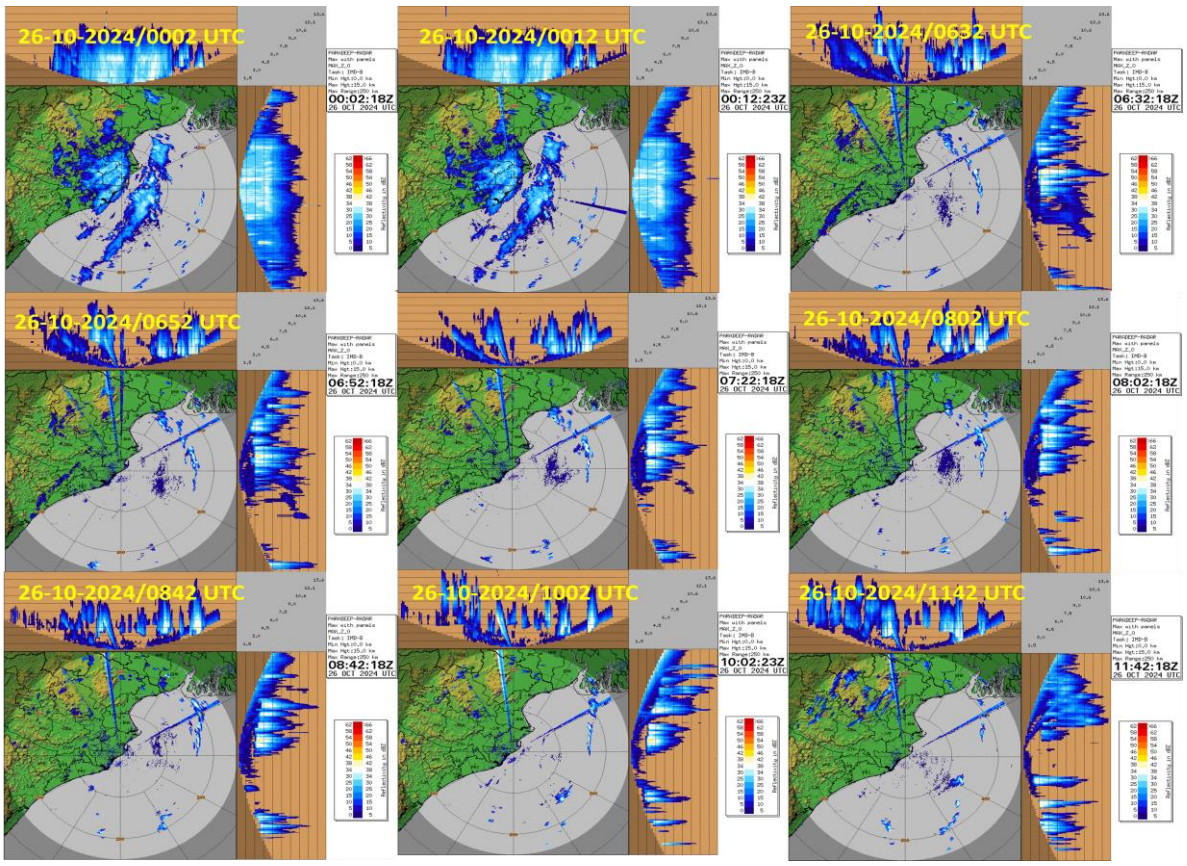


Fig. 2.12.8(d): DWR Paradip Max (dBZ) imageries of reflectivity during the day of landfall (26 October, 2024)

2.12.5 Dynamical features

The analyses of IMD GFS (T1534) model for mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa pressure levels valid at 0000 UTC of everyday during 22nd October – 26th October are presented in **Fig. 2.12.9.1 – 2.12.9.5 indicating the location, movement and intensity of the system during its life period.**

The top two panels of Fig. 2.12.9.1 are showing the surface MSLP and 10 m wind characteristics at 0000 UTC of 22nd October, 2024.

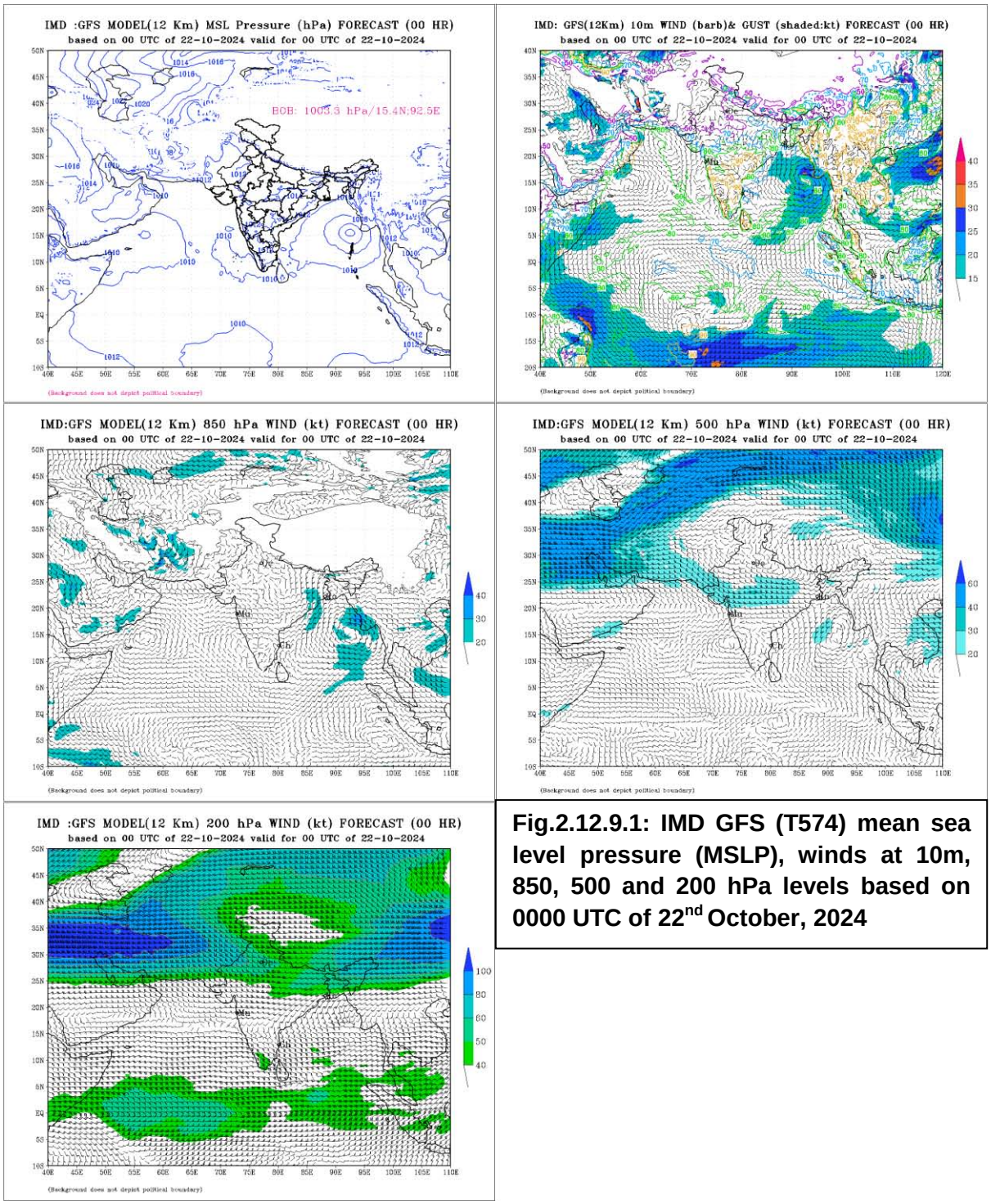


Fig.2.12.9.1: IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 22nd October, 2024

The model was indicating 3 closed isobars with outer one covering a large area and center over eastcentral BoB and adjoining areas of north Andaman Sea. It indicated that the system attained the stage of depression. The associated cyclonic circulations were found to be

extended from the surface up to 500 hPa pressure level. The upper-tropospheric winds at 200 hPa indicated southeasterly winds at the top of the system with a major poleward outflow. The isobaric analysis in the top MSL panel and in top panel of wind 10 m above the surface are clearly showing the location of the of cyclonic storm over eastcentral BoB at 0000 UTC of 23rd October 2024.

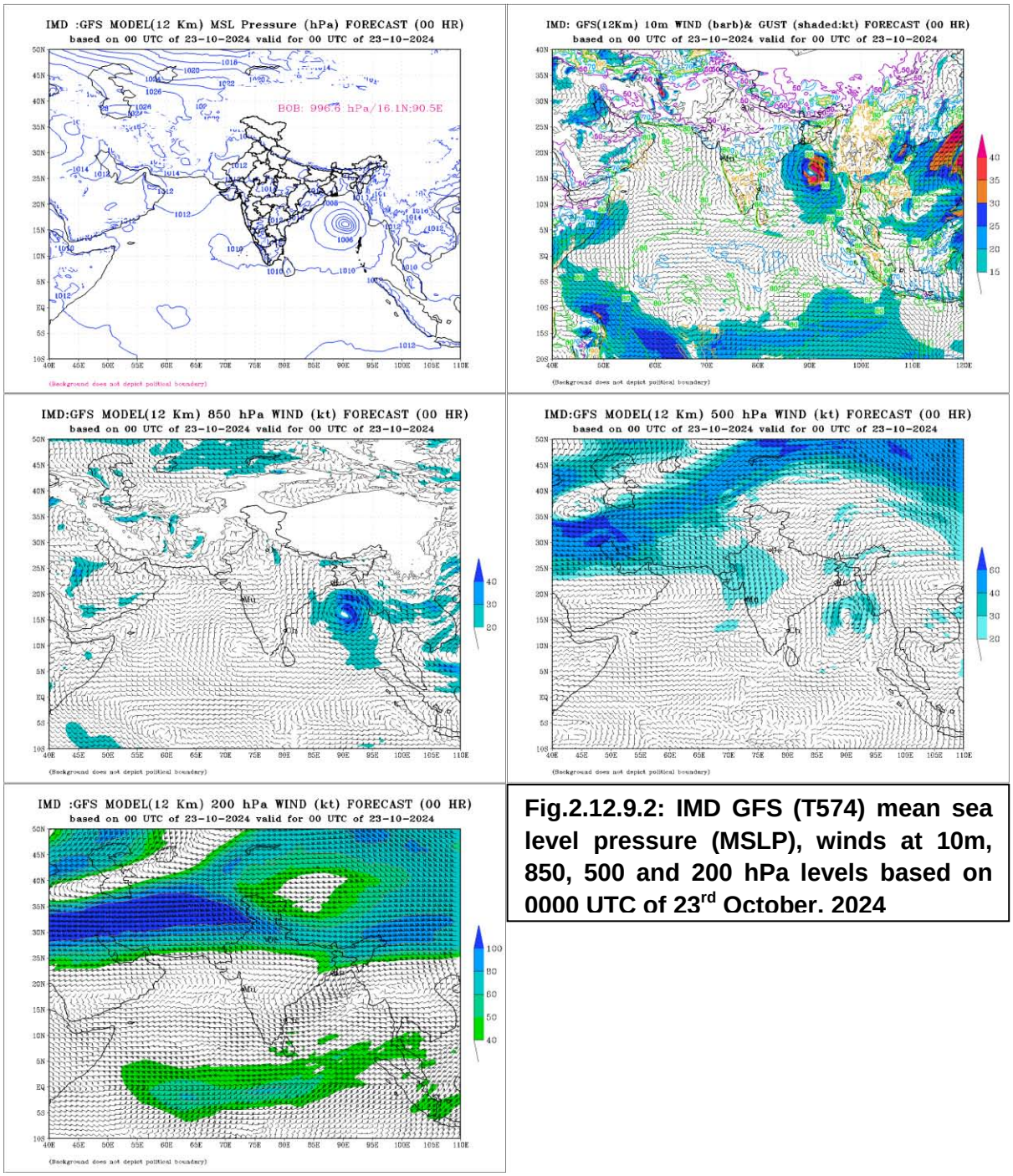


Fig.2.12.9.2: IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 23rd October. 2024

Comparing the Fig. 2.12.9.1 and 2.12.9.2 it is clear that the cyclonic storm moved west-northwestwards and intensified further into a cyclonic storm with more than 4 closed isobars and maximum sustained wind speed crossed 35 knots in the plot of 10 m wind. The associated cyclonic circulations in upper levels were also showing stronger winds with a

circular structure vertically extending up to 500 hPa level. However, the radiuses of maximum winds at southeast and northeast sectors were larger than other sectors.

The environmental upper-tropospheric winds at 200 hPa pressure level were modulated by the outflow of the cyclonic storm mostly poleward at the top finally merging with the mid-l atitude westerlies situating north of the system.

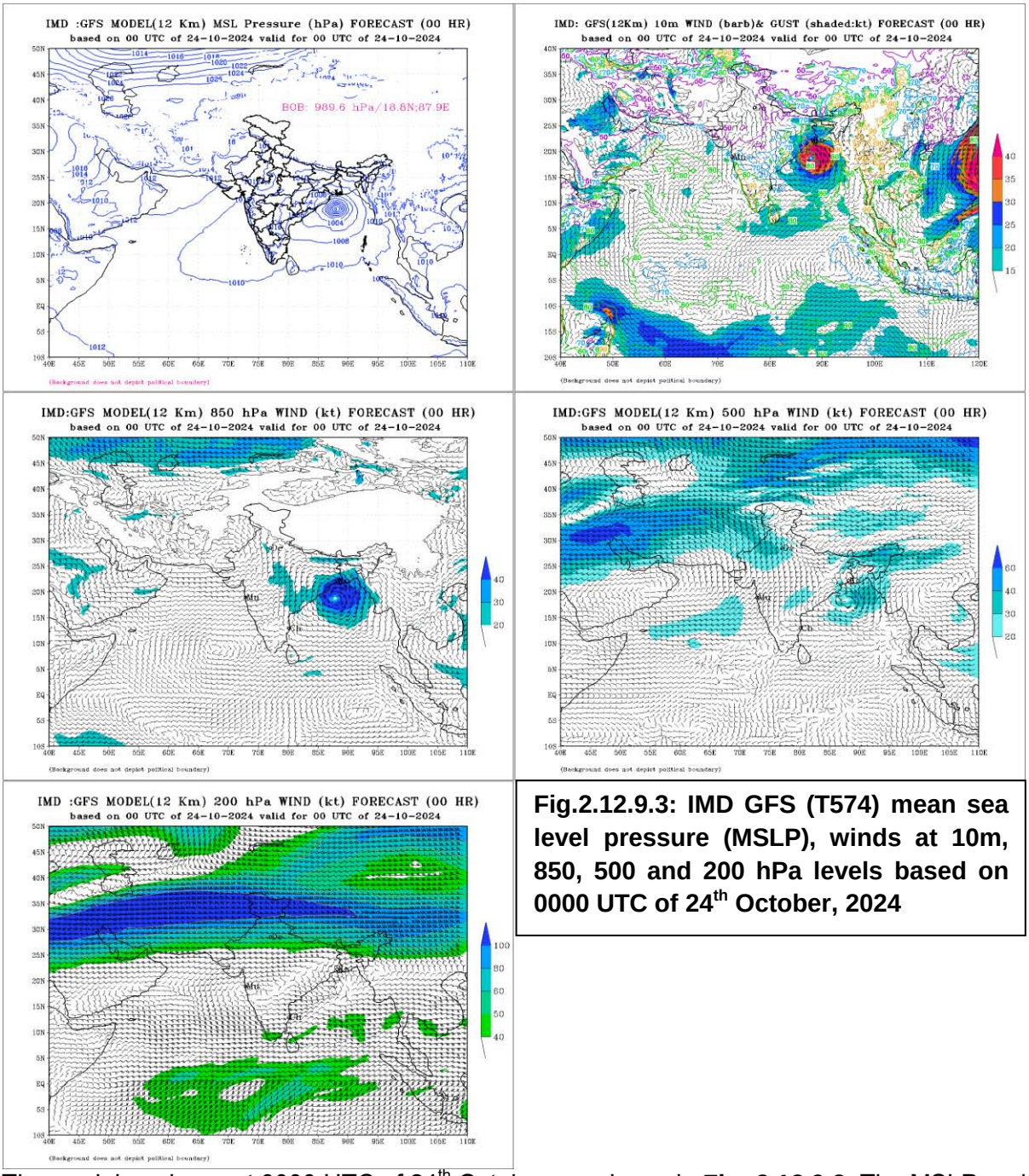


Fig.2.12.9.3: IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 24th October, 2024

The model analyses at 0000 UTC of 24th October are shown in **Fig. 2.12.9.3.** The MSLP and 10 m wind are showing further movement of the system in west-northwest direction with the center of the storm located over northwest BoB. As the number of closed isobars increased and MSW at 10 m winds also crossed 40 knots in their respective plots, it clearly captured the intensity of the system to the stage of severe cyclonic storm. The horizontal wind distributions at 850 and 500 hPa pressure levels retained the asymmetry of the storm as it was found in the previous day with larger RMW at southeast and northeast sectors

compared to others. The outflow at the top of the storm was influenced by the upper-tropospheric westerlies north of the system at 200 hPa pressure level.

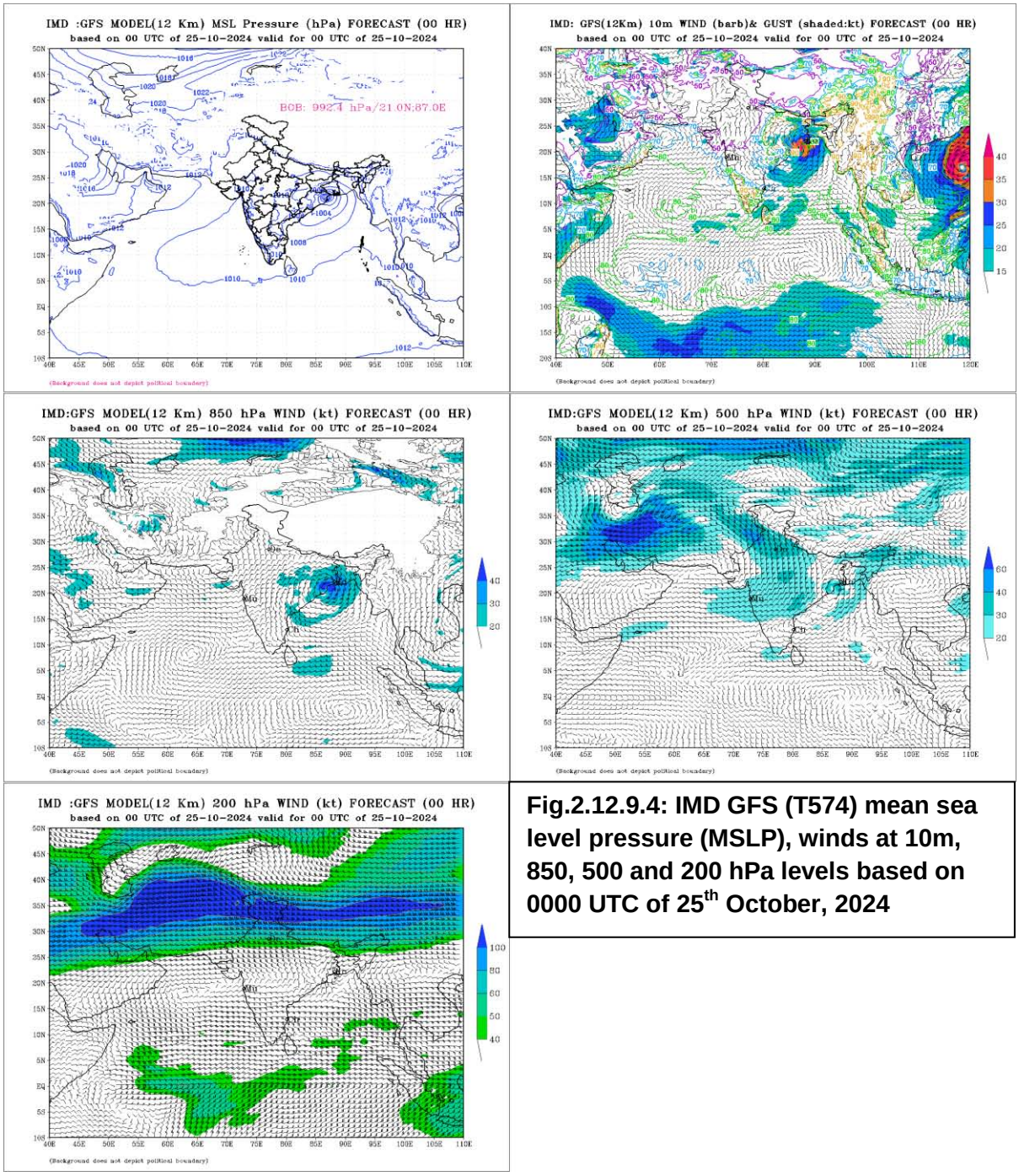


Fig.2.12.9.4: IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 25th October, 2024

The **Fig. 2.12.9.4** shows the analyses of the model at 0000 UTC of 25th October, 2025 when the system was over the north coastal Odisha and adjoining areas. The isobaric analysis at the top-left panels indicated that the system maintained the intensity of cyclonic storm along with maximum values of 10 m wind speed above 35 knots in top-right plot. The associated cyclonic circulations at 850 and 500 hPa pressure levels were indicating that the system had vertical extension up to 500 hPa. The upper-tropospheric outflow at the top of the system was still visible although weakened and gradually merged within the environmental westerlies.

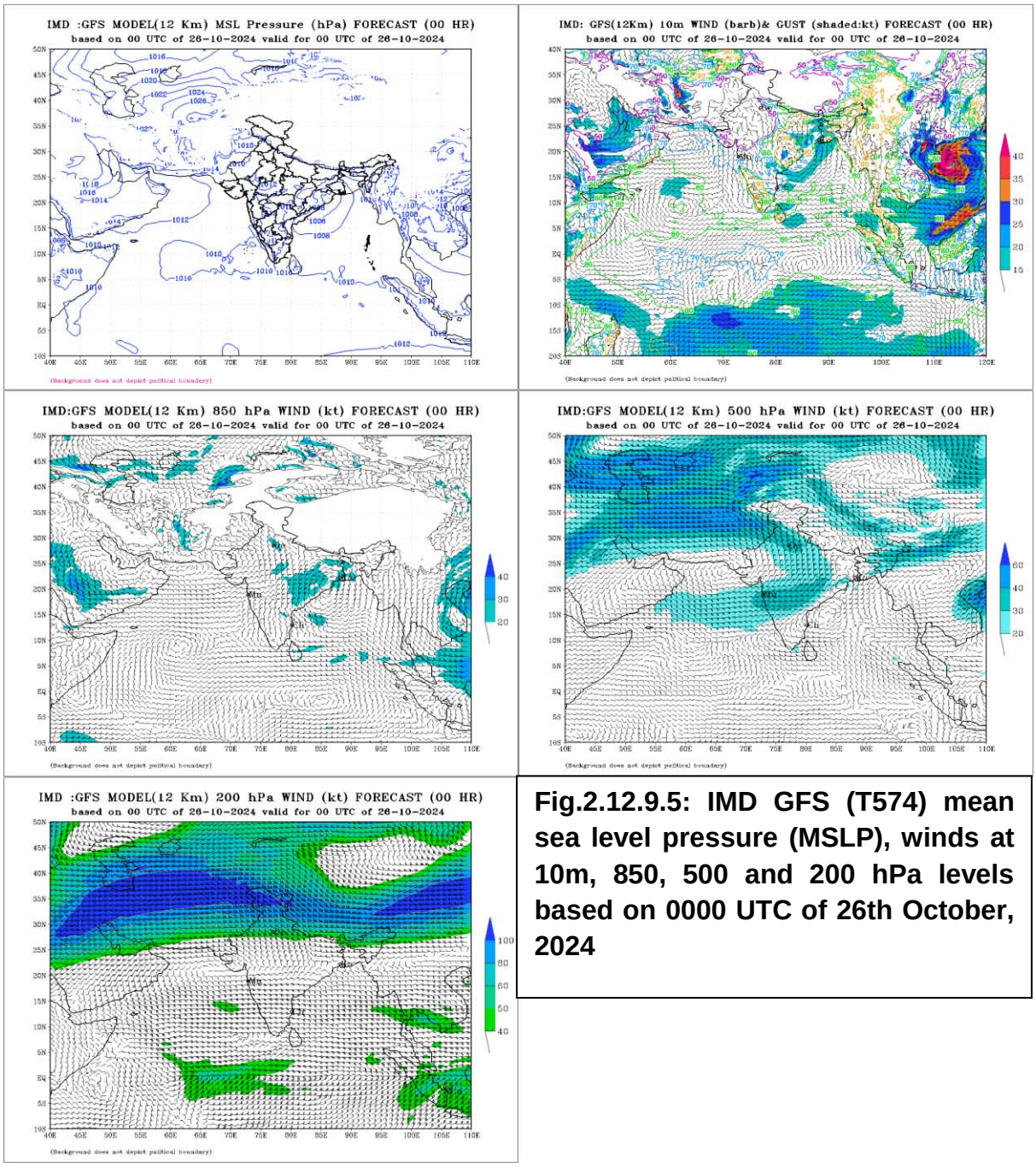


Fig.2.12.9.5: IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 26th October, 2024

The model analyses at 0000 UTC of 26th October are shown in Fig. 2.12.9.5. The surface features represented by the MSLP and 10 m winds indicated the weakening of the system with westward movement over interior Odisha. It was visible as a low pressure area over the region. Associated cyclonic circulation was still evident at 850 hPa pressure level but at 500 hPa pressure level it was hardly noticeable. The extension of the system in the upper-troposphere disappeared as it was fully dominated by the westerly winds at 200 hPa pressure level.

2.12.6 Realized Weather

2.12.6.1 Realized rainfall

24 hours accumulated realized rainfall based on NCMRWF-IMD satellite gauge merged data (Fig. 2.12.10) during the period from 21 to 27 October, 2024 indicated high rainfall over the

coastal regions of Odisha and West Bengal recorded on 24th, 25th and 26th October associated with the system.

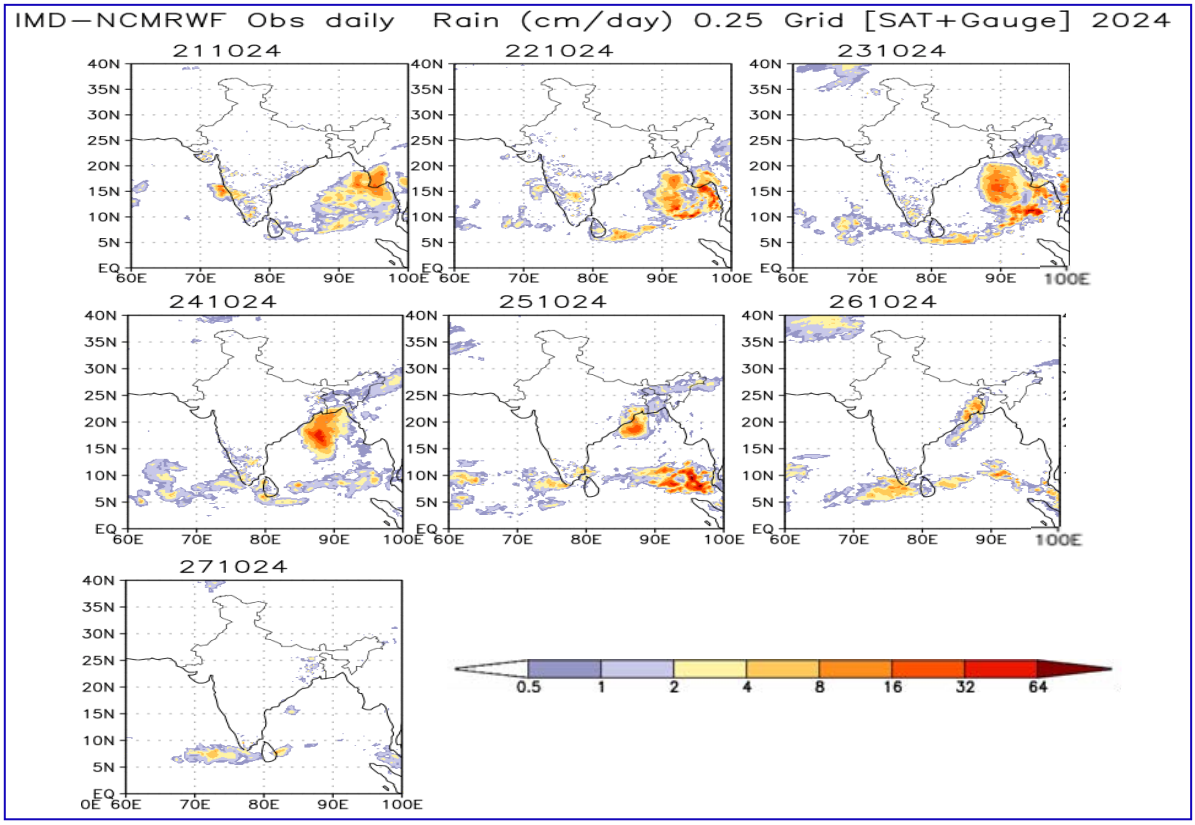


Fig. 2.12.10: NCMRWF-IMD satellite gauge merged data plots of 24 hours accumulated realized rainfall ending at 0830 IST of 21st to 27th October, 2024

2.12.6.2. Realised wind

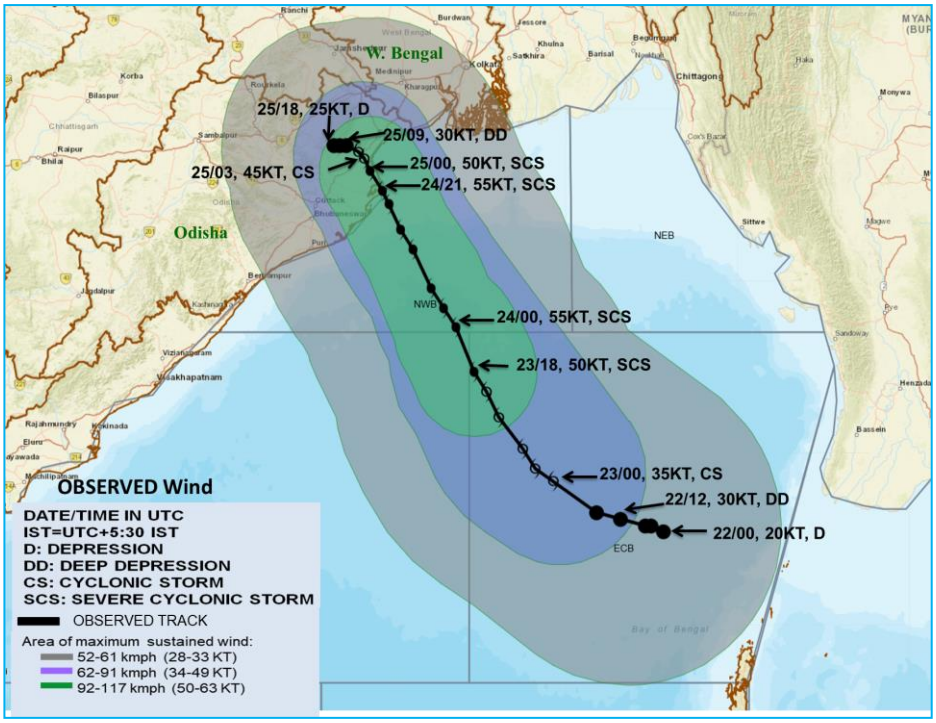


Fig. 2.12.11: Estimated maximum sustained wind during the life cycle of SCS DANA

2.12.6.3. Realised storm surge

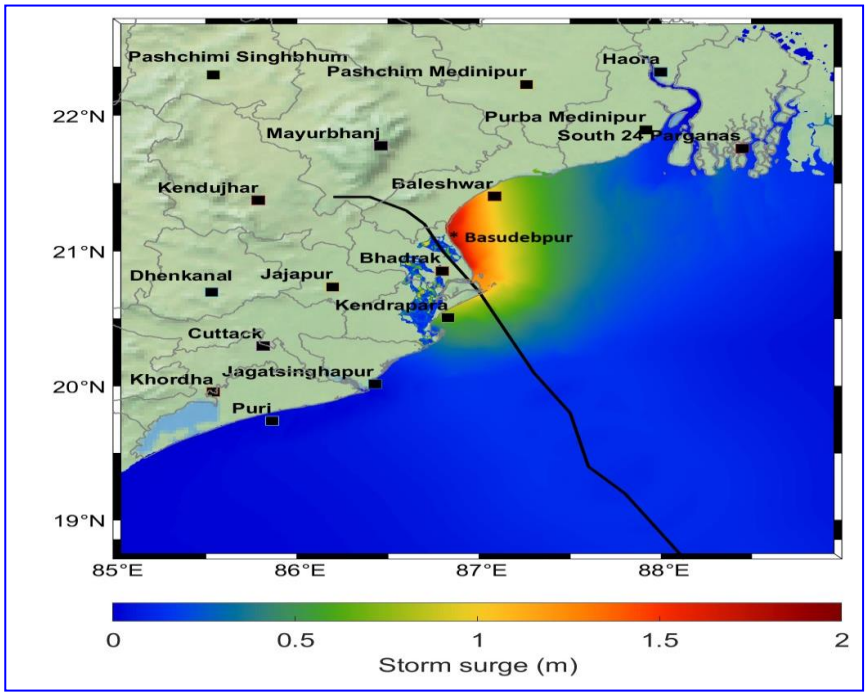


Fig.2.12.12: Estimated storm surge based on best track parameters of SCS DANA

2.12.7 Damage report:

As per media reports, no death was reported from Odisha due to cyclone. One died in West Bengal due to electrocution. In Bangladesh, 1 person died due to falling of tree and another due to drowning in a lake. About 5,800 homes were damaged due to Cyclone Dana, eight lakh people were evacuated to 6,210 cyclone relief centres in Odisha. A total of 35.95 lakh people in Odisha were impacted by cyclone Dana and subsequent flooding in 14 districts. The worst-hit districts were Kendrapara, Balasore and Bhadrak (PTI, 17 October).

Fig. 2.12.13(a) View of a jetty ahead of cyclone Dana landfall at Dhamra in Bhadrak district.(Hindustan Times, Oct 25, 2024 11:07 PM IST) (b) NDRF personnel clear a tree that fell on a house at Anantpur in Balasore(The New Indian Express 26 Oct 2024)

2.13 Cyclonic Storm "FENGAL" over the BoB (23rd November- 02th December, 2024):

2.13.1 Life History of "FENGAL":

- A low-pressure area formed over East Equatorial Indian Ocean (EEIO) and adjoining Southeast BoB (BoB) in the morning (0830 hours IST/0300 UTC) of 23rd November.
- Moving west-northwestwards, it became a well marked low pressure area in the morning (0830 hours IST/0300 UTC), of 24th November over southeast BoB and adjoining EEIO.
- It moved west-northwestwards, intensified into a depression in the morning (0830 hours IST/0300 UTC) of 25th November over central parts of south BoB and adjoining EEIO.
- Moving west-northwestwards, it intensified into a Deep Depression in the morning (0830 hours IST /0300 UTC), of 26th November over southwest BoB.
- Continuing to move west-northwestwards, it intensified into a cyclonic storm "FENGAL" [pronounced as FEINJAL] over southwest BoB in the afternoon (1430 hours IST/ 0900 UTC) of 29th November.
- It then moved initially westwards & then west-southwestwards and crossed North Tamil Nadu & Puducherry coasts close to Puducherry between 2230 hours IST/ 1700 UTC and 2330 hours IST/1800 UTC of 30th November as a cyclonic storm with wind speed of 70-80 kmph gusting to 90 kmph.
- Thereafter, it remained practically stationary for almost 12 hours and weakened into a deep depression in the forenoon (1130 hours IST/ 0600 UTC) of 1st December over north coastal Tamil Nadu.
- Continuing to move further west-northwestwards, it weakened into a depression over the same region in the evening (1730 hours IST/ 1200 UTC) of 1st December.
- Thereafter, it moved nearly westwards and weakened into a Well-Marked Low-Pressure Area over North Interior Tamil Nadu in the early morning (0530 hours IST/ 0000 UTC) of 2nd December.
- The best track parameters associated with cyclonic storm "FENGAL" are presented in Table 2.13.1. The observed track of the system is presented in **Fig.2.13.1.**

2.13.1 Salient Features

(i) Salient features compared to climatology:

It was the last cyclonic storm (CS) over the North Indian Ocean during 2024. During the last 59 years (1965-2023), out of 63 cyclones developed over BoB in the month of November and out of theses 15 crossed Tamil Nadu coast. (Fig.2.13.1). Thus, climatologically, there was 24% probability for the CS FENGAL to cross Tamil Nadu coast.

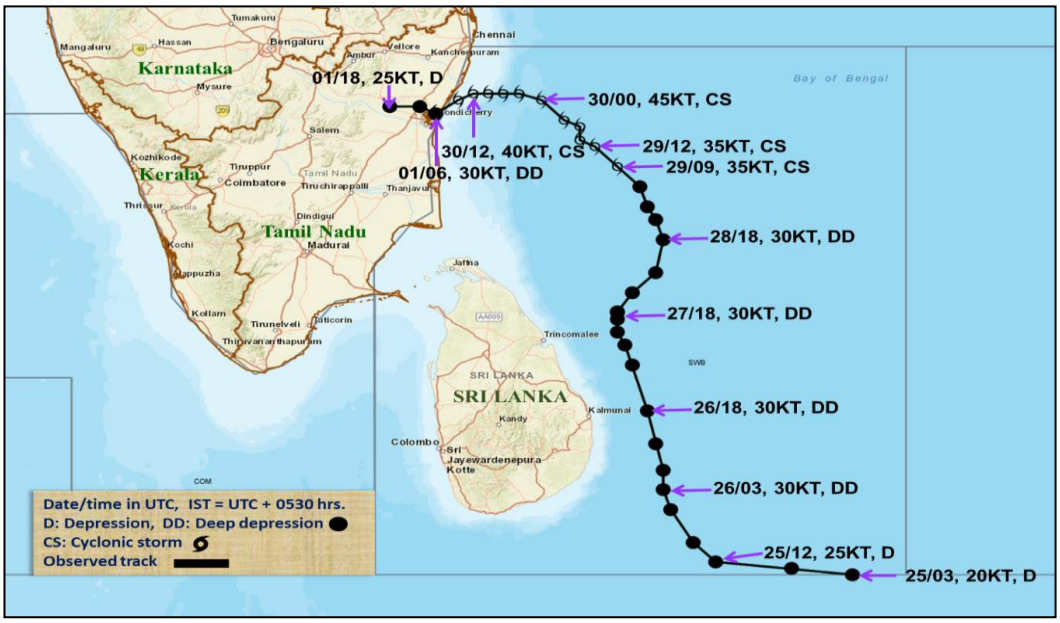


Fig. 2.13.1: Observed track of severe cyclonic storm "FENGAL" over Southwest BoB during 24th November- 02th December, 2024

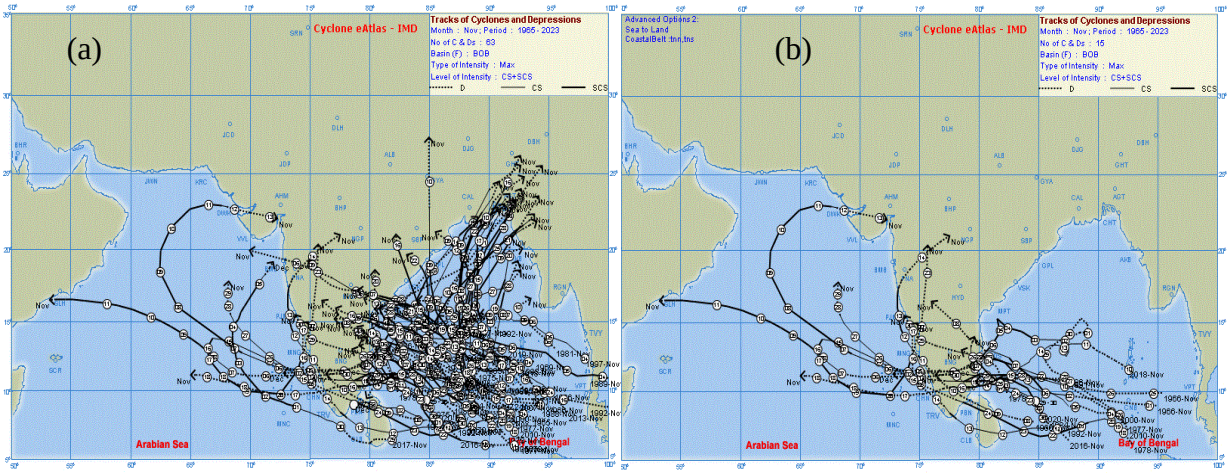


Fig. 2.13.2: Tracks of (a) all cyclones that developed over BoB during 1965-2023 in the month of November (b) that crossed Tamil Nadu coasts.

(ii) Movement :

Fengal had a recurving track. It changed its path 7 times during its life period. The six hourly average translational speed of "FENGAL" was 7.9 kmph against the normal speed of 12.9 kmph for CS category over the BoB during the post-monsoon season (October-December). It moved slower than the average translational speed during the entire life cycle (Fig. 2.13.3a). However, during landfall and particularly after landfall, on 30th November, it moved further slowly. As a result, the landfall process which commenced in the midnight (1900 hours IST) of 30th November, continued for 6.5 hours till morning (01:30 hours IST) of 1st December. After landfall, it remained practically stationary for almost 15 hours and then moved slowly west-northwestwards and weakened into a well-marked low pressure area over North Tamil Nadu by 0530 hrs IST.

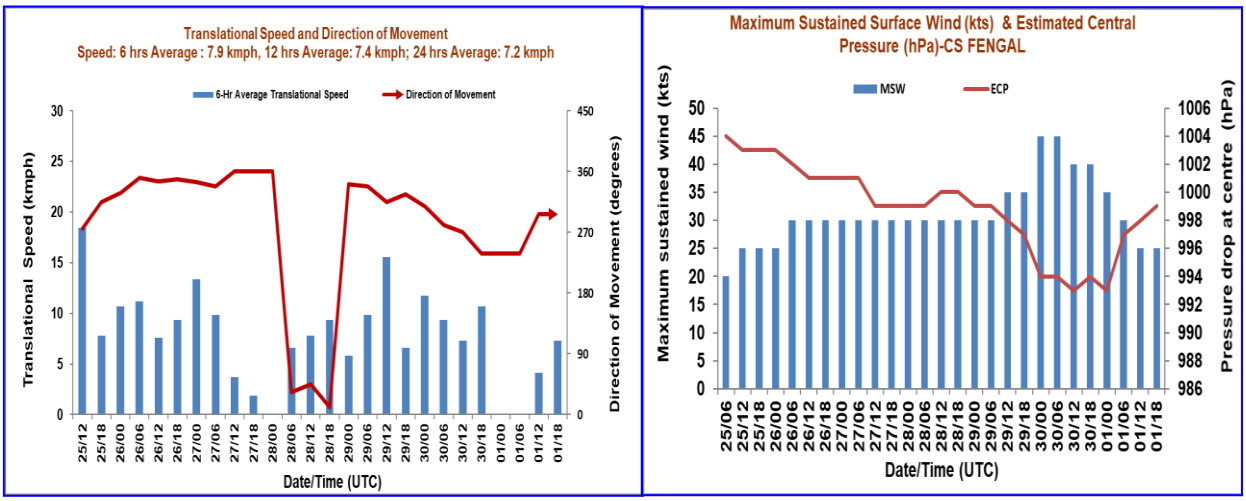


Fig. 2.13.3: (a) 6 hourly average translational speed and (b) maximum sustained wind speed with estimated central pressure during life cycle of FENGAL

(iii) Maximum sustained wind speed (MSW) and estimated central pressure(ECP):

The system intensified at the normal rate during early stages of its development i.e. from depression (1130 hours IST/0600 UTC of 25th November) to cyclonic storm stage(1430 hours IST/ 0900 UTC of 29th November). No rapid intensification (increase in intensity by at least 30 kt in 24 hours) was observed till landfall of the system. After landfall, the system weakened slowly, mainly because it remained practically stationary near coast and warm moist air incursion into the core region continued till 0300 UTC of 1st December. The system attained peak intensity of 45 kt in the early morning (0530 hrs IST/0000 UTC) of 30th November (Fig. 2.13.3(b)) over southwest BoB when the system entered into an area of high sea surface temperature (≥ 30^0C). Thereafter, from 1200 UTC of 30th November, it started weakening due to land interactions and cold dry air incursion from northwest and crossed coast with wind speed of 40 knots (70-80 gusting to 90 kmph). After landfall, it slowly weakened into a deep depression in the forenoon (1130 hours IST/ 0600 UTC) of 1st December and into a well-marked low pressure area over North Interior Tamil Nadu in the early morning (0530 hours IST/ 0000 UTC) of 2nd December. (Fig. 2.13.3b).

(iv) Track length:

The total track length of “FENGAL” was 1235 km from depression to depression stage.

(v) Life Period:

Fengal had an average life period longer than the normal, because it’s average translation speed was slower than the normal. The total life period (depression to depression) of “FENGAL” was 6 days and 6 hours against the normal of 3 days & 16 hours for cyclonic storm category over the BoB in post-monsoon season based on the data of 1990-2013.

(vi) Accumulated Cyclone Energy and Power Dissipation Index:

The Velocity Flux, Accumulated Cyclone Energy (a measure of damage potential) and Power Dissipation Index (a measure of loss) were 2.8×10^2 knots, 1.09×10^4 knots^2 and

0.44×10^6 knots^3 respectively against normal of 1.00×10^4 knots, 0.40×10^6 knots^3 for CS during post monsoon season over the BoB based on the data during 1990-2020.

Table 2.13.1: Best track positions and other parameters of the Cyclonic Storm "FENGAL" over Southwest BoB during 23rd November - 02th December, 2024

Date	Time	Latitude (N)	Longitude (E)	CI No.	Estimated Central Pressure(hPa)	Estimated Maximum Sustained surface wind (kt)	Estimated Pressure drop at the Centre (hPa)	Category
25.11.24	0300	5.0	85.3	1.5	1003	20	3	D
	0600	5.1	84.5	1.5	1003	20	3	D
	1200	5.2	83.5	1.5	1002	25	4	D
	1800	5.5	83.2	1.5	1002	25	4	D
26.11.24	0000	6.0	82.9	1.5	1002	25	4	D
	0300	6.3	82.8	2.0	1001	30	5	DD
	0600	6.6	82.8	2.0	1001	30	5	DD
	1200	7.0	82.7	2.0	1001	30	5	DD
	1800	7.5	82.6	2.0	1001	30	5	DD
27.11.24	0000	8.2	82.4	2.0	1001	30	5	DD
	0300	8.5	82.3	2.0	1001	30	5	DD
	0600	8.7	82.2	2.0	1001	30	5	DD
	1200	8.9	82.2	2.0	1000	30	6	DD
	1800	9.0	82.2	2.0	1000	30	6	DD
28.11.24	0000	9.0	82.2	2.0	1000	30	6	DD
	0300	9.1	82.3	2.0	1000	30	6	DD
	0600	9.3	82.4	2.0	1000	30	6	DD
	1200	9.6	82.7	2.0	1000	30	6	DD
	1800	10.1	82.8	2.0	1000	30	6	DD
29.11.24	0000	10.4	82.7	2.0	1000	30	6	DD
	0300	10.6	82.6	2.0	1000	30	6	DD
	0600	10.9	82.5	2.0	1000	30	6	DD
	0900	11.2	82.2	2.5	999	35	7	CS
	1200	11.5	81.9	2.5	999	35	7	CS
	1500	11.6	81.7	2.5	999	35	7	CS
	1800	11.8	81.7	2.5	999	35	7	CS
	2100	11.9	81.5	2.5	996	40	8	CS
30.11.24	0000	12.2	81.2	3.0	996	45	10	CS
	0300	12.3	80.9	3.0	996	45	10	CS
	0600	12.3	80.7	3.0	996	45	10	CS
	0900	12.3	80.5	3.0	996	45	12	CS
	1200	12.3	80.3	3.0	998	40	11	CS

30.11.24	1500	12.2	80.1	2.5	998	40	10	CS
	Crossed North Tamil Nadu and Puducherry coast near lat. 12.05N and long 79.9E close to Puducherry between 1700-1800 UTC of 30th November 2024.							
30.11.24	1800	12.0	79.8	-	998	40	10	CS
	2100	12.0	79.8	-	999	35	11	CS
01.12.24	0000	12.0	79.8	-	999	35	10	CS
	0300	12.0	79.8	-	999	35	7	CS
	0600	12.0	79.8	-	1000	30	6	DD
	1200	12.1	79.6	-	1001	25	4	D
	1800	12.1	79.2	-	1002	25	3	D
02.12.24	0000	Weaken into Well Marked low Pressure Area over North Interior Tamil Nadu						

MSW: Maximum sustained surface wind speed in knots (kt), 1 kt = 1.86 kmph, D: Depression, DD: Deep depression, CS: Cyclonic storm, SCS: Severe Cyclonic Storm, ECP: Estimated Central Pressure, CI No.: Current Intensity No., ΔP: Pressure drop at centre

2.13.2 Genesis, intensification and movement

2.5.3.1. Genesis

An upper air cyclonic circulation developed over the over East EIO off Sumatra coast and adjoining South Andaman Sea in the morning (0830 hours IST/0300 UTC) of 21st November, 2024. Under its influence, a low-pressure area formed over east Equatorial Indian Ocean (EIO) and adjoining Southeast Bay of Bengal (BoB) in the morning (0830 hours IST/0300 UTC) of 23rd November.

At 0300 UTC of 25th November, the sea surface temperature (SST) was more than 28-30^{0}C over south BoB. An intense patch of higher SST about 30^{0}C (6-10°N and 84-88°E) was seen over southwest BoB. It was indicating the system to show marginal intensification for a short period over southwest BoB. However, SST was relatively lesser along the coast and indicating slight weakening of the system before landfall. Tropical cyclone heat potential (TCHP) was more than 100 KJ/cm^2 over south BoB & adjoining Equatorial Indian Ocean (EIO). It was less than 40-60 KJ/cm^2 over southwest & adjoining eastcentral BoB and along & off Sri Lanka/Tamil Nadu/ Andhra Pradesh coasts. The barrier layer depth over the southwest BoB had increased upto 50m which was unfavorable for intensification. Total precipitable water (TPW) imagery indicated warm moist air incursion into the core. Near to coast it was indicating cold dry air incursion, suggesting weakening near coast. Madden Julian Oscillation (MJO) index was in phase 3 with amplitude more than 1 and it was likely to move across phase 3 & 4 during next 7 days with amplitude remaining more than 1. CFS-NCICS model forecast indicated presence of Equatorial Rossby Waves (ERW) over South Andaman Sea and south BoB during 25th-30th. Strong westerly winds anomaly over south BoB and easterly winds anomaly to its north over South & adjoining central BoB was also indicated during 25th - 30th November. During this period other waves including MJO, low frequency background waves, ERW were also indicated to prevail over south BoB. Low level winds indicated broad scale circulation over south and adjoining EIO. Low level positive relative vorticity at 850 hpa level was around 100-120x10^{-6}s^{-1} over southwest BoB & adjoining East EIO. The zone of the maximum vorticity indicated further organization and was extending upto 500 hPa level. The low-level convergence was around 30 x10^{-6}s $^{-1}$ over southwest BoB and adjoining East EIO to the west of system centre. Upper-level divergence was around 30x10^{-6}s^{-1} over the same region. The vertical wind shear (VWS) was low to moderate (10-15kt) over south BoB & adjoining EIO. Upper tropospheric ridge was near 10°N to the north of system. The southeasterly winds prevailing over the system steered the system northwesterly. Various environmental features (higher SST, warm moist air incursion

into the core, high ocean thermal energy) were indicating favorable environment for further intensification of system till 26th/1200 UTC. Under these features the well-marked low-pressure area over southeast BoB and adjoining EEIO moved west-northwestwards, and intensified into a depression on 25th November (0300 UTC) over central parts of south BoB and adjoining EEIO.

At 1200 UTC of 25th November, similar conditions prevailed and the system maintained its intensity.

2.5.3.2 Intensification:

At 0300 UTC of 26th November, the system was close to the intense patch of higher SST about 30^0C (6-10°N and 84-88°E) which caused warm moist air incursion into the core indicating marginal intensification into a cyclonic storm for a short period over southwest BoB. As the system was likely to track along Sri Lanka coast thus, land interactions may lead to slow intensification of system. Similar features wrt sea condition, MJO and equatorial waves prevailed. Low level positive relative vorticity at 850 hpa level was around 100-120x$10^{-6}s^{-1}$ over southwest BoB & adjoining East EIO. The zone of the maximum vorticity became more organized and was extending upto 500 hPa level. The low-level convergence had increased and was around 40 x$10^{-6}s^{-1}$ over southwest BoB to the west of system centre. Upper-level divergence was around 30x$10^{-6}s^{-1}$ over the same region. The system was not showing tilting with height. The system was being steered north-northwestwards along the periphery of upper tropospheric ridge near 10°N. Various environmental features (higher SST, warm moist air incursion into the core, high ocean thermal energy, moderate wind shear, favorable MJO & Equatorial Rossby Waves) indicated favorable environment for further intensification of system till 28th November. **Under these favorable conditions the depression over central parts of south BoB and adjoining EEIO intensified to deep depression over southwest BoB.**

At 0300 UT of 27th November, the system moved away from the intense patch of higher SST and was in area with relatively lower SST (29^0C). The sea conditions near coast indicated slight weakening before landfall. MJO and equatorial waves were in favourable phase. Low level positive relative vorticity at 850 hpa level was around 100x$10^{-6}s^{-1}$ over southwest BoB near system area and was extending upto 200 hPa level. The low-level convergence had increased and was around 60x$10^{-6}s^{-1}$ over system area. Upper-level divergence was same and around 40x$10^{-6}s^{-1}$ over system centre. VWS was moderate (15-20 kt) over the system area and was high to the north of 10°N. The system was showing no tilting with height. The system was being steered north-northwestwards along the periphery of upper tropospheric ridge near 13°N. Various environmental features (higher SST, warm moist air incursion into the core, high ocean thermal energy, moderate wind shear, favorable MJO & Equatorial Rossby Waves) were indicating favorable environment for marginal intensification of system till 28th November. However, all features indicate that system would show weakening trend as it moves towards Tamil Nadu coast (North of 11°N).

At 0300 UTC of 28th November, the area of higher SST lying to the eastern side of the system had relatively cooled down because of the continuous rainfall over the region, upwelling and very slow movement of the system. As a result, the system was not intensifying. The system was over an area with SST about 29^0C. The TPW imagery was indicating warm moist air around system area. However, colder air incursion was seen in the southwest sector. The TCHP was less than 40 KJ/cm^2 over southwest & adjoining westcentral BoB along & off Sri Lanka/Tamil Nadu/ Andhra Pradesh coasts. The increase in barrier layer depth over the southwest BoB was indicating marginal weakening near coast. The land interactions with Sri Lanka coast were also inhibiting intensification of system. MJO and equatorial waves were in favourable phase till 30th November. There was a trough in westerly over north and central India extending between 18°N/70°E to 35°N/82°E. In its association, there was a jet stream over central and northeast India. There was also an anticyclonic circulation over Myanmar. As a result, the upper level divergence was seen in northeast sector. It sheared the convective cloud mass to the northeast of system area. Low level positive relative vorticity at 850 hpa level was around 100x$10^{-6}s^{-1}$ over the system area

and was extending up to 500 hPa level. The low-level convergence was around $20x10^{-6}s^{-1}$ to the northeast of system area. Upper-level divergence was around $50x\ 10^{-6}s^{-1}$ to the northeast of system centre. VWS was moderate to high (20-25 kt) over the system area. However, as the system would move northwards, it would enter into a zone of low (5-10 kt) VWS during 28th/1200 UTC to 29th/0000 UTC. During this period the system was expected to show marginal intensification. Thereafter, VWS would become high to the north of 10°N and along the Tamil Nadu coast indicating weakening of the system near Tamil Nadu coast. The system was being steered north-northwestwards along the periphery of upper tropospheric ridge near 12°N in association with anticyclonic circulation over Myanmar. The trough in westerly was blocking further northwestwards movement of the system. Various environmental features were indicating favorable environment (high SST, low wind shear, convergence, divergence and vorticity) for marginal intensification of system during 28/1200 to 29/0000 November. However, various features like land interactions, high wind shear, lower SST, lower thermal energy, cold dry air incursion into the system area from Indian mainland were indicating gradual weakening near Tamil Nadu coast.

At 0900 UTC of 29th November, the system was over an area with SST about 29^0C. TPW imagery was indicating warm moist air around system area. However, colder air incursion was seen in the southwest sector. The TCHP was 40-50 KJ/cm^2 over southwest & adjoining westcentral BoB along & off Sri Lanka/Tamil Nadu/ Andhra Pradesh coasts MJO was in phase 4 with amplitude more than 1 and would move across phase 5 from 29th to 30th November onwards. Presence of ERW over south BoB, MJO, strong westerly wind anomaly over south BoB and easterly wind anomaly to its north over south & adjoining central BoB during 29th-30th November indicated a favorable environment for further intensification of system into a cyclonic storm. Low level positive relative vorticity at 850 hpa level increased and was around $150x10^{-6}s^{-1}$ over the system area with vertical extension upto 500 hpa level. The low level convergence was around $15\ x10^{-6}s^{-1}$ around system area. Upper level divergence was around $30x10^{-6}s^{-1}$ to the northeast of system centre. VWS was moderate (20 kt) over the system area. **Under these favorable conditions the deep depression intensified to Cyclonic Storm over southwest BoB.**

At 0300 UTC of 30th November, the system entered into an area with SST about 27^0C. The total precipitable water imagery was indicating warm moist air around system area. However, cold dry air incursion from southwest was reaching upto southeast sector. The TCHP was 40-50KJ/cm^2 over southwest & adjoining westcentral BoB along & off Sri Lanka/Tamil Nadu/Andhra Pradesh coasts MJO was in phase 5 with amplitude more than 1 and would move across phase 5 during next 5 days. Presence of ERW over south BoB, MJO, strong westerly wind anomaly over south BoB and easterly wind anomaly to its north over south & adjoining central BoB during 30th November to 1st December, indicated a favorable environment for maintenance of intensity of the system. Low level positive relative vorticity at 850 hpa level increased and was around $200x10^{-6}s^{-1}$ over the system area with vertical extension upto 200 hpa level and no tilting. The low level convergence was $30\ x10^{-6}s^{-1}$ to the southeast and another zone of $10\text{-}15\ x10^{-6}s^{-1}$ to the northwest of system area. Upper level divergence was around $30x10^{-6}s^{-1}$ and was north-south oriented. It was also indicating equatorward outflow. VWS was low to moderate (10-15kt) over the system area. The system was steered west-northwestwards under the influence of east-southeasterly winds prevailing in the western periphery of anticyclonic circulation over eastcentral BoB. Various environmental features were indicating favorable environment (high SST, low wind shear, convergence, divergence and positive vorticity, MJO & equatorial waves) for maintenance of intensity of the system.

2.13.3.3 Weakening

At 1200 UTC of 30th November, the system was over an area with SST about 27^0C. Cold dry air incursion from southwest was reaching upto southeast sector. The 40-50 KJ/cm^2 over southwest & adjoining westcentral BoB along & off Sri Lanka/Tamil Nadu/Andhra Pradesh coasts low level positive relative vorticity at 850 hpa level had decreased during past 3 hours and was around $150\ x\ 10^{-6}s^{-1}$ over the system area with vertical extension upto

200 hpa level. The area of positive vorticity also decreased. The low-level convergence was $20x10^{-6}s^{-1}$ around system area. Upper-level divergence decreased and was around $40x10^{-6}s^{-1}$ to the northeast of system area. VWS was moderate (15-20 kt) over the system area. The east northeasterly winds prevailing over system area were steering the system west-southwestwards. The system had started weakening due to land interactions, decrease in various environmental features like low level vorticity, low level convergence & upper-level divergence.

At 0600 UTC of 1st December, the system was over an area with SST about 27^0C. The total precipitable water imagery was indicating warm moist air around system area. However, cold dry air incursion from southwest was reaching upto southeast sector. TCHP was 40-50KJ/cm^2 over southwest & adjoining westcentral BoB along & off Sri Lanka/Tamil Nadu/Andhra Pradesh coasts low level positive relative vorticity at 850 hpa level was around $150x10^{-6}s^{-1}$ over south southeast of the system area with vertical extension upto 500 hpa level. The low-level convergence decreased to 10 x $10^{-6}s^{-1}$ to the south of system area. Upper-level divergence decreased to $10x10^{-6}s^{-1}$ to the south southwest of system area. VWS was moderate (10-15 kt) over the system area. The east northeasterly winds prevailing over system area were steering the system west-southwestwards. Under these conditions, the **cyclonic storm Fengal weakened into deep depression over north coastal Tamil Nadu.**

At 1200 UTC of 1st December, the system was mostly over the land. The total precipitable water imagery was indicating warm moist air around system area. However, cold dry air incursion from southwest was reaching upto southeast sector. Low level positive relative vorticity at 850 hpa level was around $100x10^{-6}s^{-1}$ over south of the system area with vertical extension upto 500 hpa level. The low-level convergence was $20x10^{-6}s^{-1}$ to the south west of system area. Upper level divergence was $10x10^{-6}s^{-1}$ to the southwest of system area. VWS was moderate (10-15 kt) over the system area. The east-northeasterly winds prevailing over system area were steering the system west-southwestwards. **Under these conditions the deep depression over north coastal Tamil Nadu moved west-southwestwards and weakened into a depression over north coastal Tamil Nadu.**

2.5.4 Monitoring of CS, "FENGAL"

India Meteorological Department (IMD) maintained round the clock watch over the north Indian Ocean (NIO) and the cyclone was monitored since 14th November. The extended range outlook (EROC) dated 14th November indicated low probability of cyclogenesis over southwest BoB about 11 days prior to formation of depression on 25th November. The EROC issued on 21st November (about 4 days ahead of formation of depression over the BoB and 9 days ahead of landfall) indicated with high confidence (67-100% probability) likelihood of the formation of a depression over the central parts of south BoB around 25th November and movement towards cross north Sri Lanka coast and south Tamil Nadu Coast. The cyclone was monitored with the help of available satellite observations from INSAT 3DR, SCAT SAT, OCEAN-SAT 3, ASCAT, microwave imageries, doppler weather Radar at Chennai and Visakhapatnam, available ships, buoys observations & coastal observations in the region. Various global models and dynamical-statistical models run by Ministry of Earth Sciences (MoES) institutions including IMD, NCMRWF, IITM & INCOIS and guidance from models from various international agencies under bilateral arrangement were utilized to predict the genesis, track and intensity of the cyclone as well as associated severe weather. The forecasts were mainly based on multi-model ensemble technique developed by IMD which was further modulated by analysis of observations and forecasters intervention at IMD through their knowledge, experience and expertise. An indigenously developed digitized forecasting system of IMD (Decision Support System) was utilized for analysis and comparison of various observations and numerical weather prediction models guidance, decision making process and warning products generation.

2.5.4.1 Features observed through satellite

The cyclone was monitored with the help of available satellite observations from INSAT 3D and 3DR, SCAT SAT, ASCAT, microwave imageries and available ships & buoy observations in the region. Various global models and dynamical-statistical models run by Ministry of Earth Sciences (MoES) institutions including IMD, NCMRWF, IITM & INCOIS and guidance from models from various international agencies under bilateral arrangement were utilized to predict the genesis, track, landfall and intensity of the cyclone as well as associated severe weather. The forecasts were mainly based on multi-model ensemble technique developed by IMD. which was further value added to arrive at consensus forecast by considering various prognostic & diagnostic features, observational features, initial conditions and consistency of individual models etc. A digitized forecasting system of IMD was utilized for analysis and comparison of various observations and numerical weather prediction models guidance, decision making process and warning products generation. Typical INSAT-3D visible/IR imageries, enhanced colored imageries and cloud top brightness temperature imageries and radar imageries from Doppler weather radar (DWR) Chennai & Karaikal are presented in Fig.5(a) – 5(e).

At 0300 UTC of 25th November, intensity of the system was characterized as **CI1.5**. It showed shear pattern. The convective cloud mass was sheared to the northwest of system area. Associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over south BoB and adjoining EIO between latitude 3.0°N to 12.0°N and longitude 80.0°E to 90.0°E. Minimum cloud top temperature (CTT) was minus 80°-93°C. The multi-satellite-based winds indicated stronger winds in the northeast sector.

At 1200 UTC of 25th November, intensity of the system was characterized as **CI1.5**. It showed shear pattern. The convective cloud mass was sheared to the northwest of system area. Associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over south BoB and adjoining EIO between latitude 3.0°N to 12.0°N and longitude 80.0°E to 90.0°E. Minimum CTT was minus 80°- 93°C. The multi-satellite-based winds indicated stronger winds in the northern sector.

At 0300 UTC of 26th November, intensity of the system was characterized as **CI2.0**. Cloud showed organization in curved band pattern. Associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over south BoB and adjoining EIO between latitude 4.0°N to 15.0°N and longitude 80.0°E to 92.0°E. Minimum CTT was minus 80°-93°C.

At 1200 UT of 26th November, intensity of the system was characterized as **CI2.0**. Cloud was organized in central dense overcast pattern. Intense cloud mass was seen to the northwest of system centre. Associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over south BoB and adjoining EIO between latitude 4.0°N to 15.0°N and longitude 80.0°E to 92.0°E. Minimum CTT was minus 80-93°C.

At 0300 UTC of 27th November, intensity of the system was characterized as **CI2.0**. Clouds were organized in shear pattern. Intense cloud mass was sheared to the north of

system area. Associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over southwest BoB and neighbourhood between latitude 7.0°N to 15.0°N and longitude 80.0°E to 92.0°E. Minimum CTT was minus 80-93°C.

At 1200 UTC of 27th November, intensity of the system was characterized as **CI2.0**. Clouds were organized in shear pattern. Intense cloud mass was sheared to the north of system area. Associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over south & adjoining central BoB and neighbourhood between latitude 8.0°N to 16.0°N and longitude 78.0°E to 90.0°E, Sri Lanka, Palk Strait, Gulf of Mannar, Tamil Nadu and Coastal Andhra Pradesh. Minimum CTT was minus 80-93°C.

At 0300 UTC of 28th November, intensity of the system was characterized as **CI2.0**. Associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over south & adjoining central BoB and neighborhood between latitude 7.0°N to 17.0°N and longitude 80.0°E to 92.0°E, Sri Lanka, Palk Strait, Gulf of Mannar, Coastal Tamil Nadu and Coastal Andhra Pradesh. Minimum CTT was minus 80-93°C.

At 1200 UTC of 28th November, intensity of the system was characterized as **CI2.0**. Associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over south & adjoining central BoB and neighborhood between latitude 7.0°N to 17.0°N and longitude 80.0°E to 92.0°E with minimum CTT as minus 80-93°C.Moderate to intense convection lay over Sri Lanka, Palk Strait, Gulf of Mannar, Coastal Tamil Nadu and Coastal Andhra Pradesh with minimum CTT as minus 40-70°C.

At 0300 UTC of 29th November, intensity of the system was characterized as **CI2.0**. Clouds were organised in shear pattern. Area of intense convection was seen to the north of system area. Associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over south & adjoining central BoB and neighborhood between latitude 7.0°N to 17.0°N and longitude 80.0°E to 90.0°E with minimum CTT as minus 80-93°C.

At 0900 UTC of 29th November, intensity of the system was characterized as **CI2.5**. Clouds were organised in shear pattern. Area of intense convection was seen to the north of system area. Associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over south & adjoining central BoB and neighborhood between latitude 7.0°N to 17.0°N and longitude 80.0°E to 90.0°E with minimum CTT as minus 80-93°C.

At 1200 UTC of 29th November, intensity of the system was characterized as **CI2.5**. Clouds are organised in irregular CDO pattern. Area of intense convection was seen to the north of system area. Associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over south & adjoining central BoB and neighborhood between latitude 7.0°N to 16.0°N and longitude 80.0°E to 90.0°E with minimum CTT as minus 80-93°C.

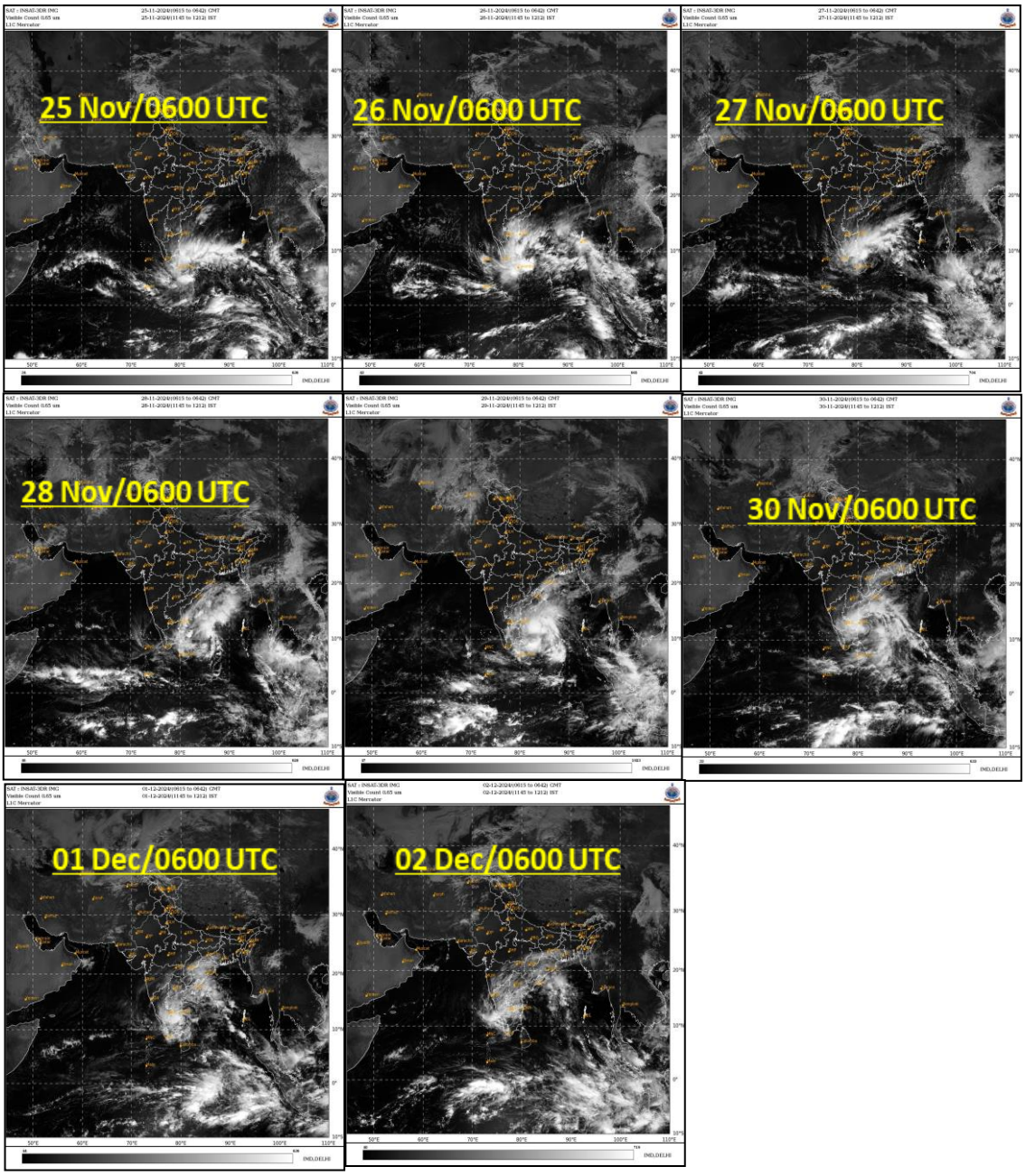


Fig. 2.13.4(a): INSAT-3D visible imageries during life cycle of CS FENGAL (23rd November-02nd December, 2024)

At 0300 UTC of 30th November, intensity of the system was characterized as **CI3.0**. Clouds are organised in irregular CDO pattern. Area of intense convection was seen to the northwest of system area. Associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over south & adjoining central BoB and neighborhood between latitude 8.0N to 18.0N and longitude 80.0E to 90.0E with minimum CTT as minus 80-93°C.

At 1200 UTC of 30th November, intensity of the system was characterized as **CI3.0**. Area of intense convection was seen to the northwest of system area. Associated scattered to broken low and medium clouds with embedded intense to very intense convection lay

over south & adjoining central BoB and neighborhood between latitude 8.0°N to 18.0°N and longitude 80.0°E to 90.0°E with minimum CTT as minus 80-93°C. Moderate to intense convection lay over coastal Andhra Pradesh, Telangana, Karnataka, central Tamil Nadu.

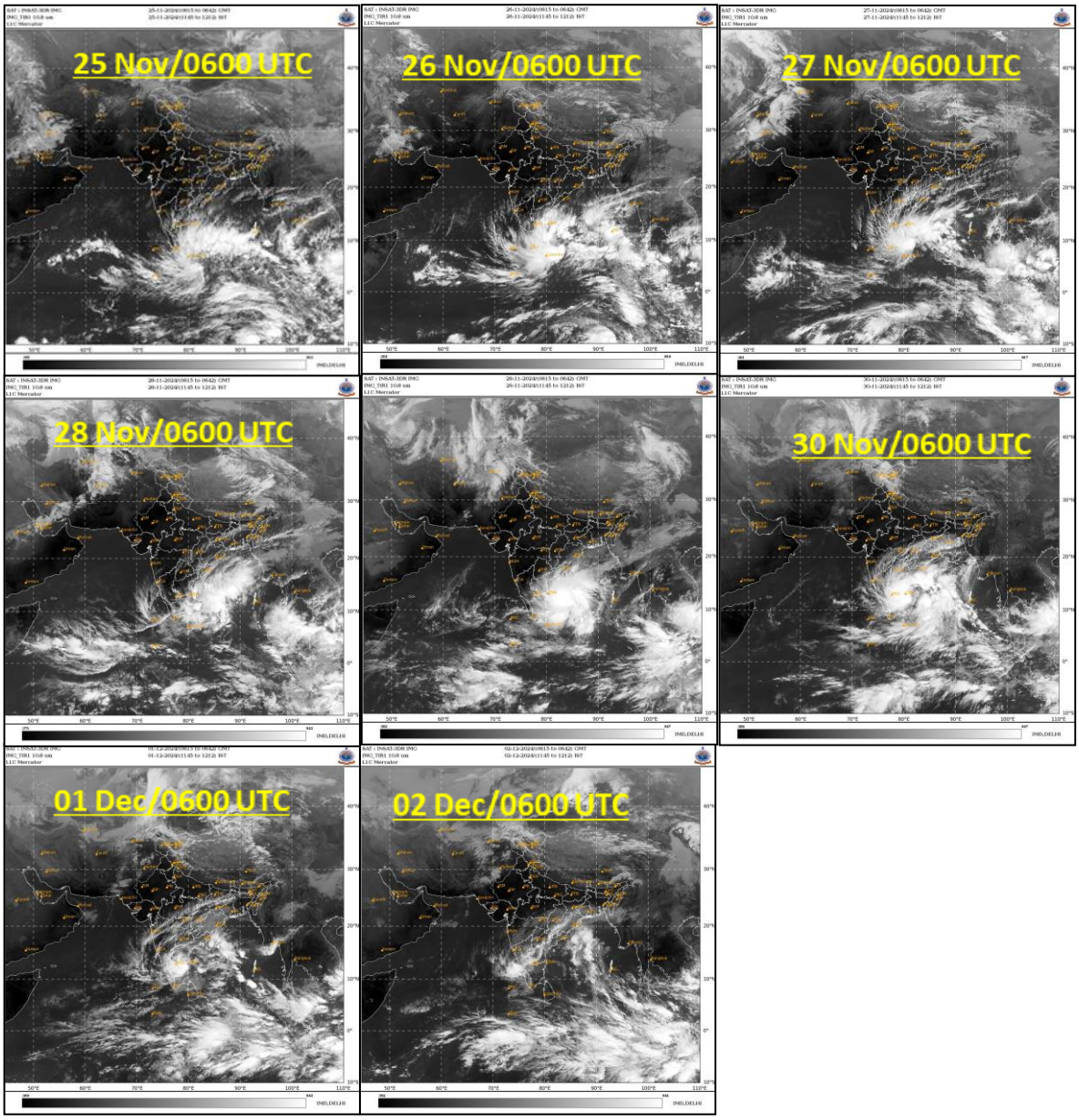


Fig. 2.13.4(b): INSAT-3D IR imageries during life cycle of CS FENGAL (23 November-02 December)

AT 0300 UTC of 1st December, associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over west central and adjoining southwest BoB, south coastal Andhra Pradesh, Rayalaseema, Tamil Nadu and south interior Karnataka with minimum CTT as minus 70-90°C.

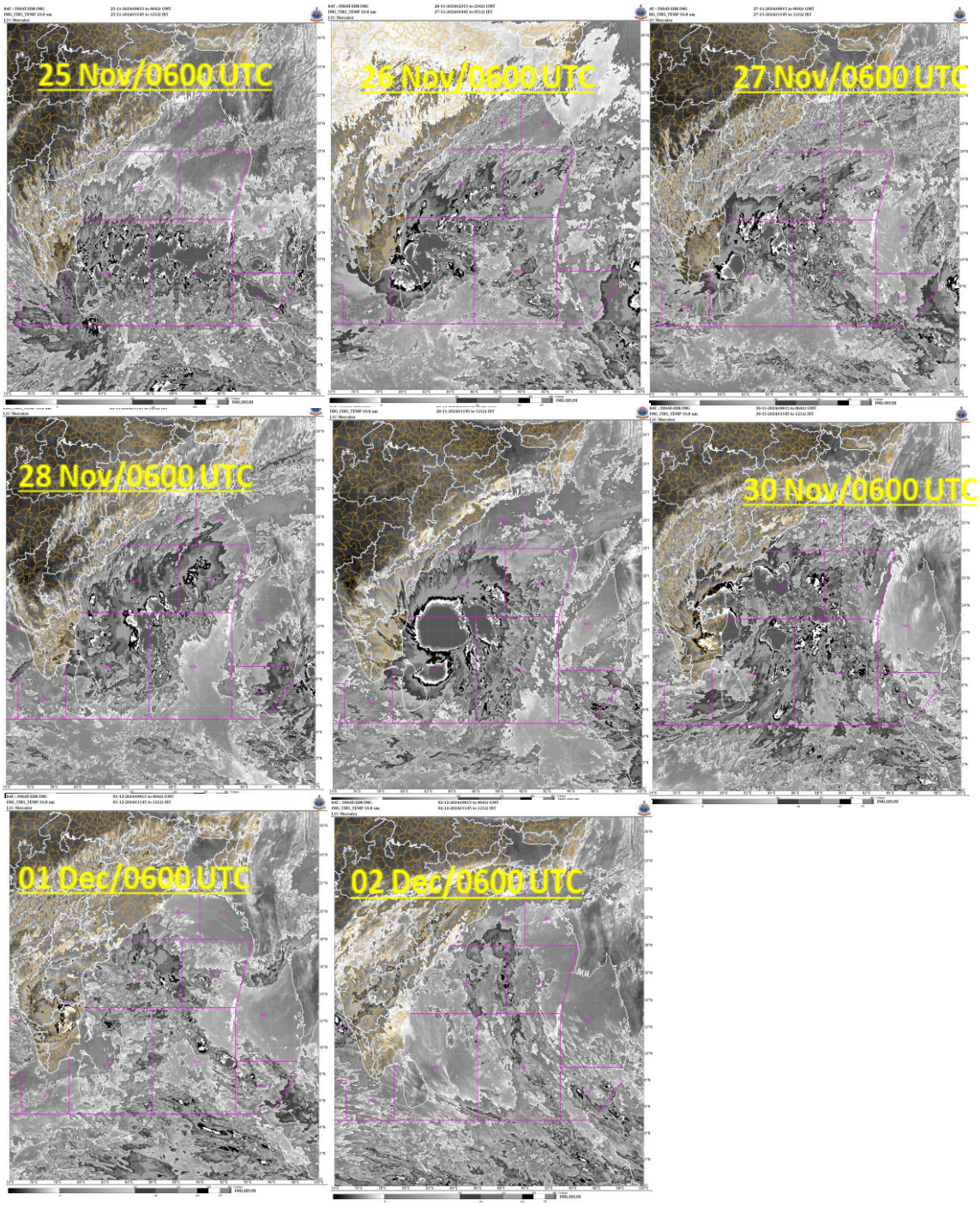


Fig. 2.13.4(c): INSAT-3D enhanced IR imageries during life cycle of CS FENGAL (23 November- 02 December)

AT 1200 UTC of 1st December, associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over north Tamil Nadu and adjoining Rayalaseema, south Kerala with minimum CTT as minus 70-80°C and moderate to intense convection over south coastal Andhra Pradesh, north Rayalaseema, south interior Karnataka, south Tamil Nadu, north Kerala and also over southwest and adjoining west

central BoB off north Tamil Nadu coasts adjoining south Andhra Pradesh coast and neighbourhood with minimum CTT as minus 60-70°C.

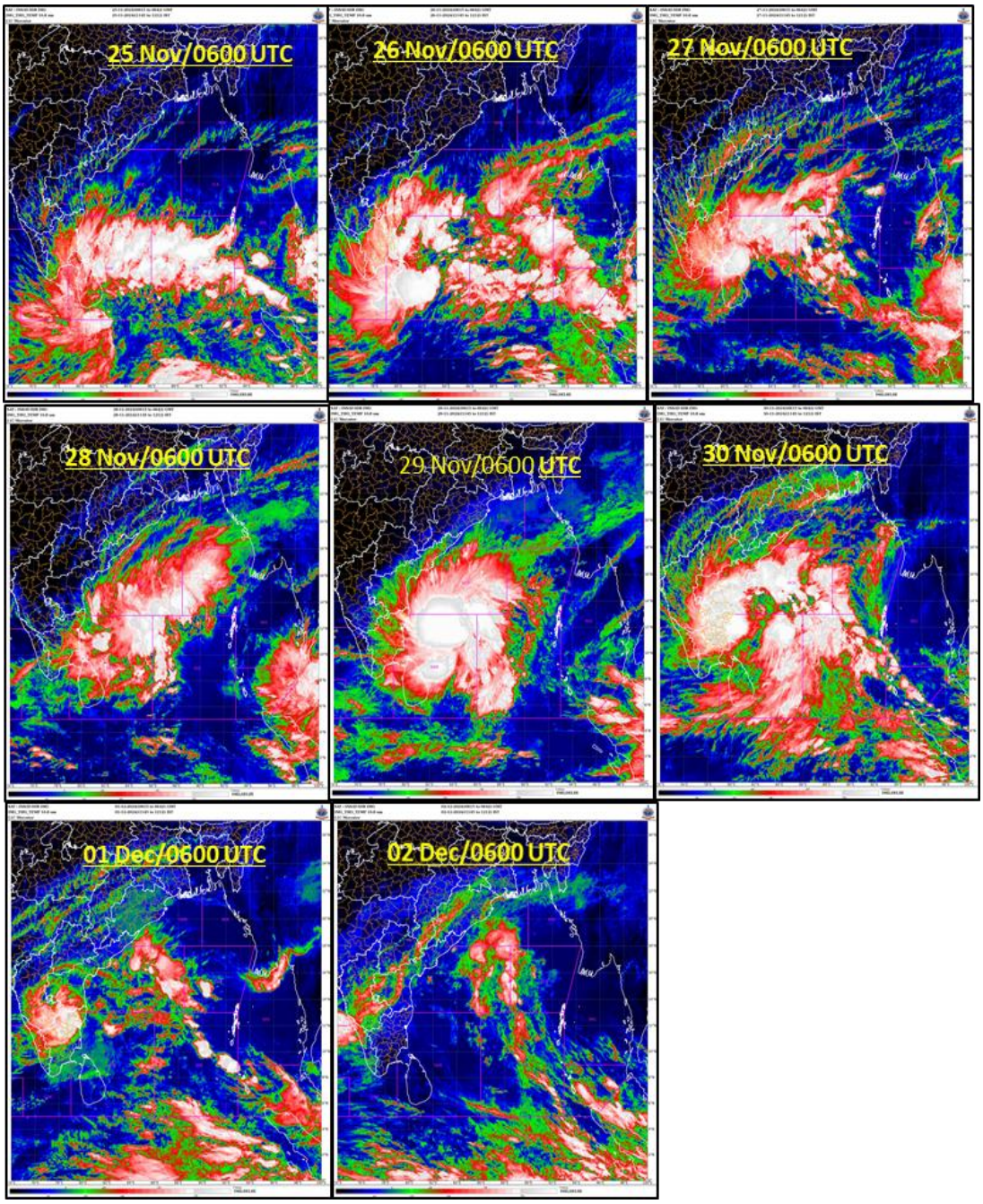


Fig. 2.13.4(d): INSAT-3D enhanced color imageries during life cycle of CS FENGAL (23 November- 02 December)

Typical reflectivity imageries from DWR Karaikal and Chennai are presented in Fig. 2.13.4 (e).

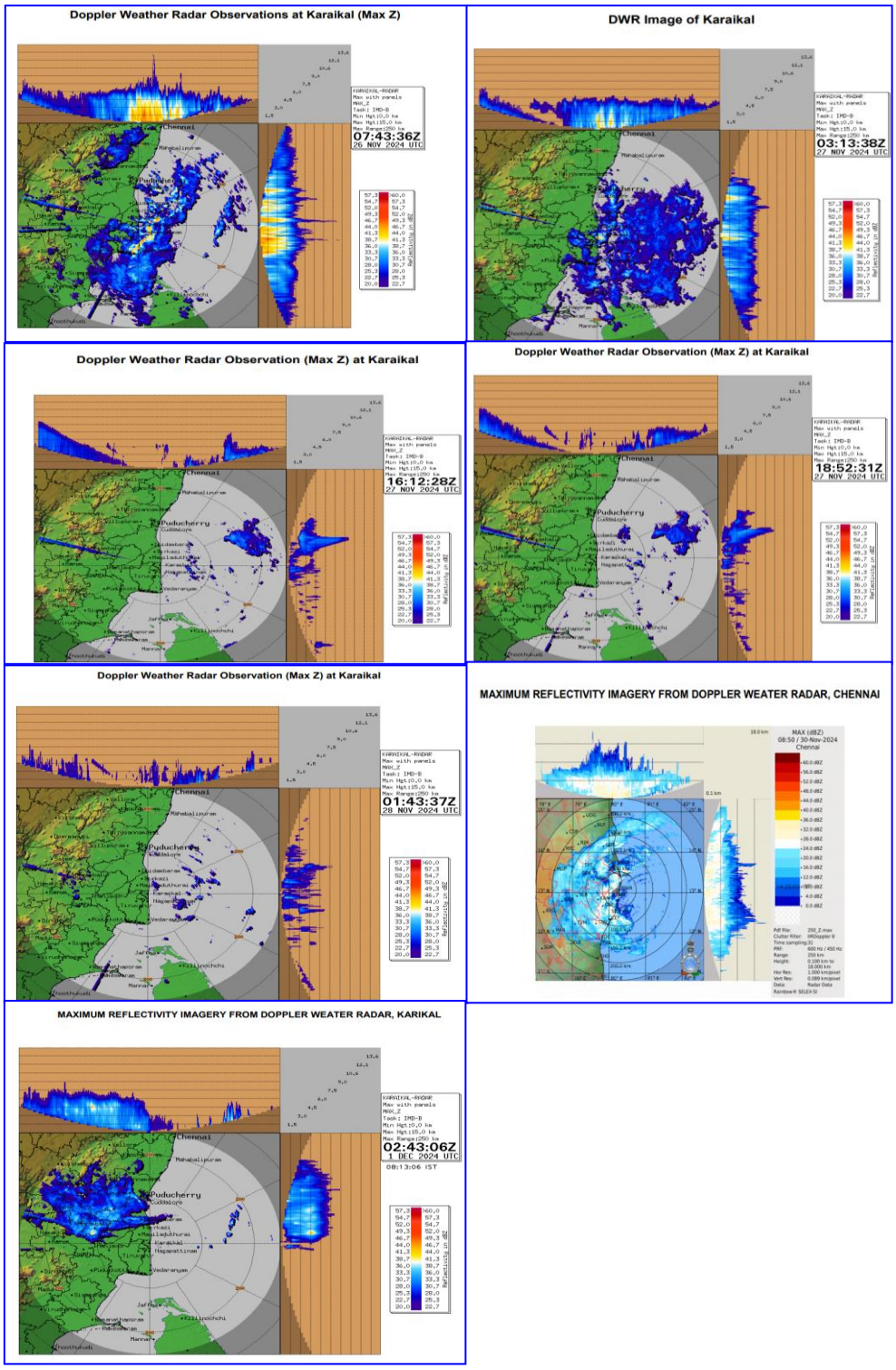


Fig. 2.13.4(e): Typical Radar imagery from DWR Karikal and Chennai during life cycle of CS FENGAL (27 November- 01 December)

2.5.5 Dynamical features

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels during 23rd November – 02nd November are presented in **Fig. 2.13.6.1 – 2.13.6.9.**

At 0000 UTC of 23rd November, the MSLP analysis field indicated a well marked low pressure area/depression over south Andaman Sea. Actually, at that time it was a low-pressure area. The model over estimated the intensity of system.

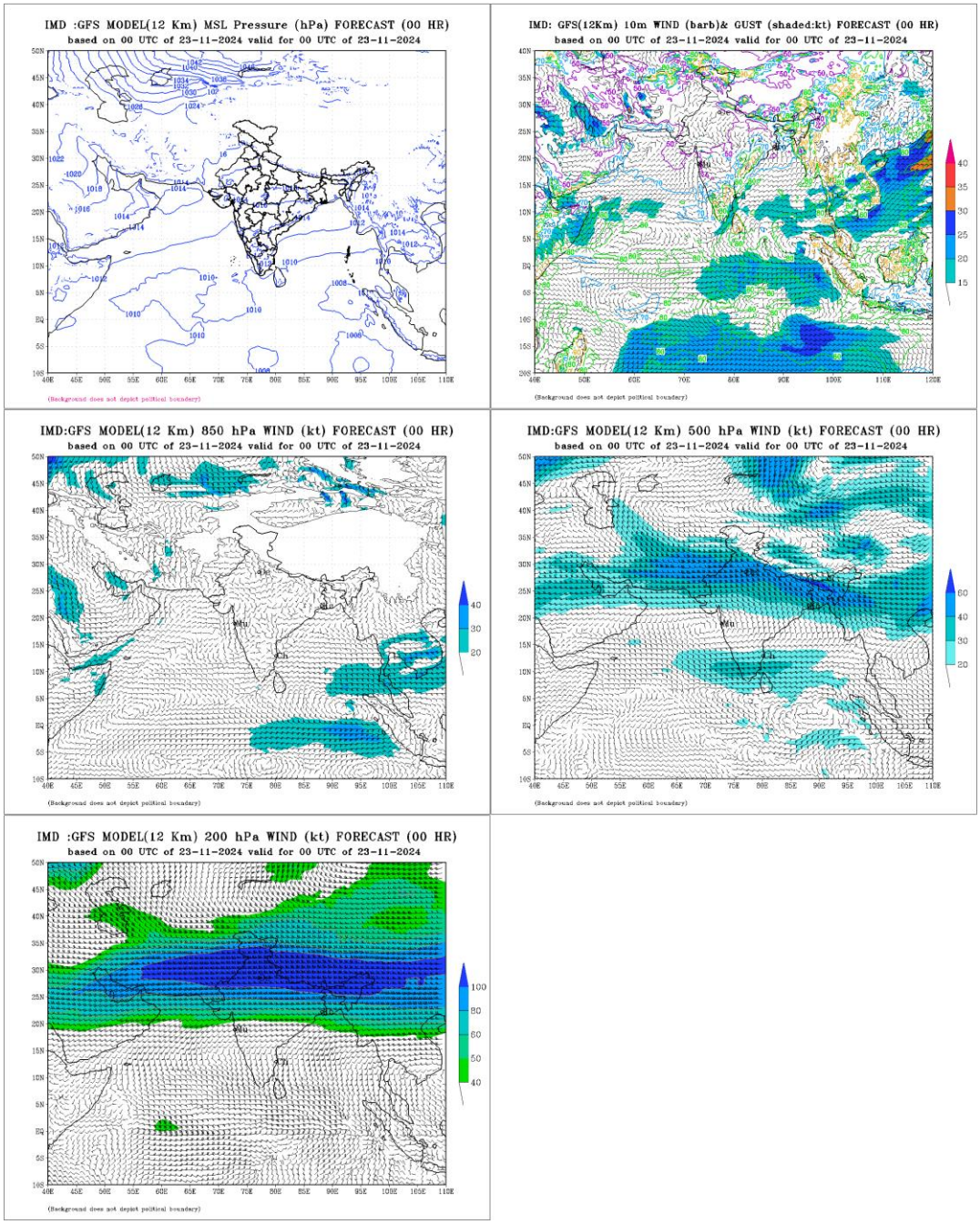


Fig.2.13.6.1: IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 23rd November, 2024

At 0000 UTC of 24th November, the MSLP analysis field indicated weakening of the system. It indicated an extended low pressure area over southeast BoB and adjoining east Equatorial Indian Ocean (EIO). Actually, at that time it lay as a well marked low pressure area over southeast BoB & adjoining east EIO.

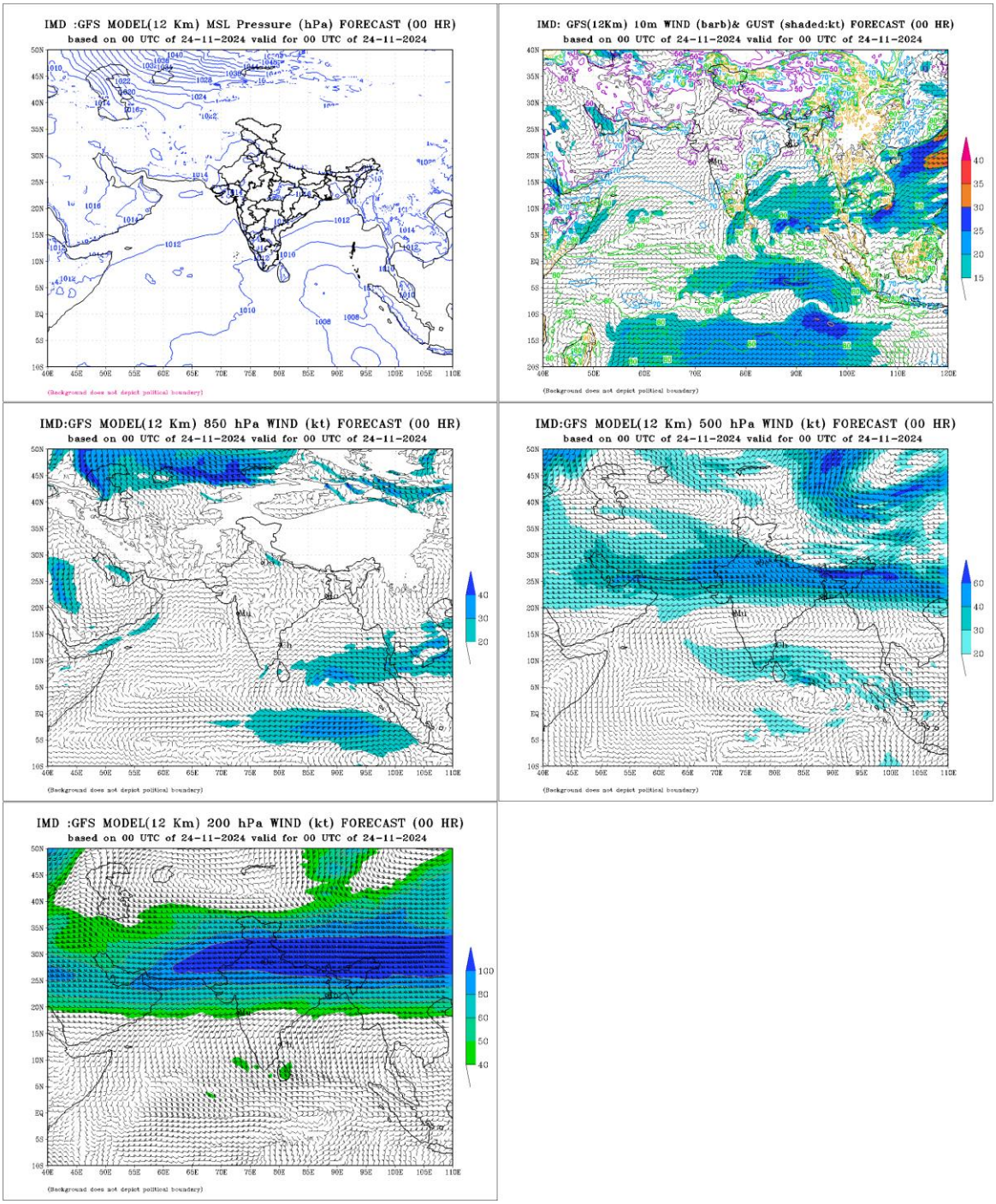


Fig.2.13.6.2: IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 24th November, 2024

At 0000 UTC of 25th November, the MSLP analysis field indicated a deep depression over southwest BoB & adjoining east EIO near 4.8°N/84.0°E. Actually, the system was located as a depression over southwest BoB & adjoining east EIO near 5.0°N/85.3°E at 0000 UTC of

25th November, 2024. The model showed that vertically, the system extended upto 500 hpa level tilting southwestwards with height. Upper tropospheric Ridge was seen near 14°N. Thus, GFS was capturing the location on 25th November. However, the model overestimated the intensity of the system.

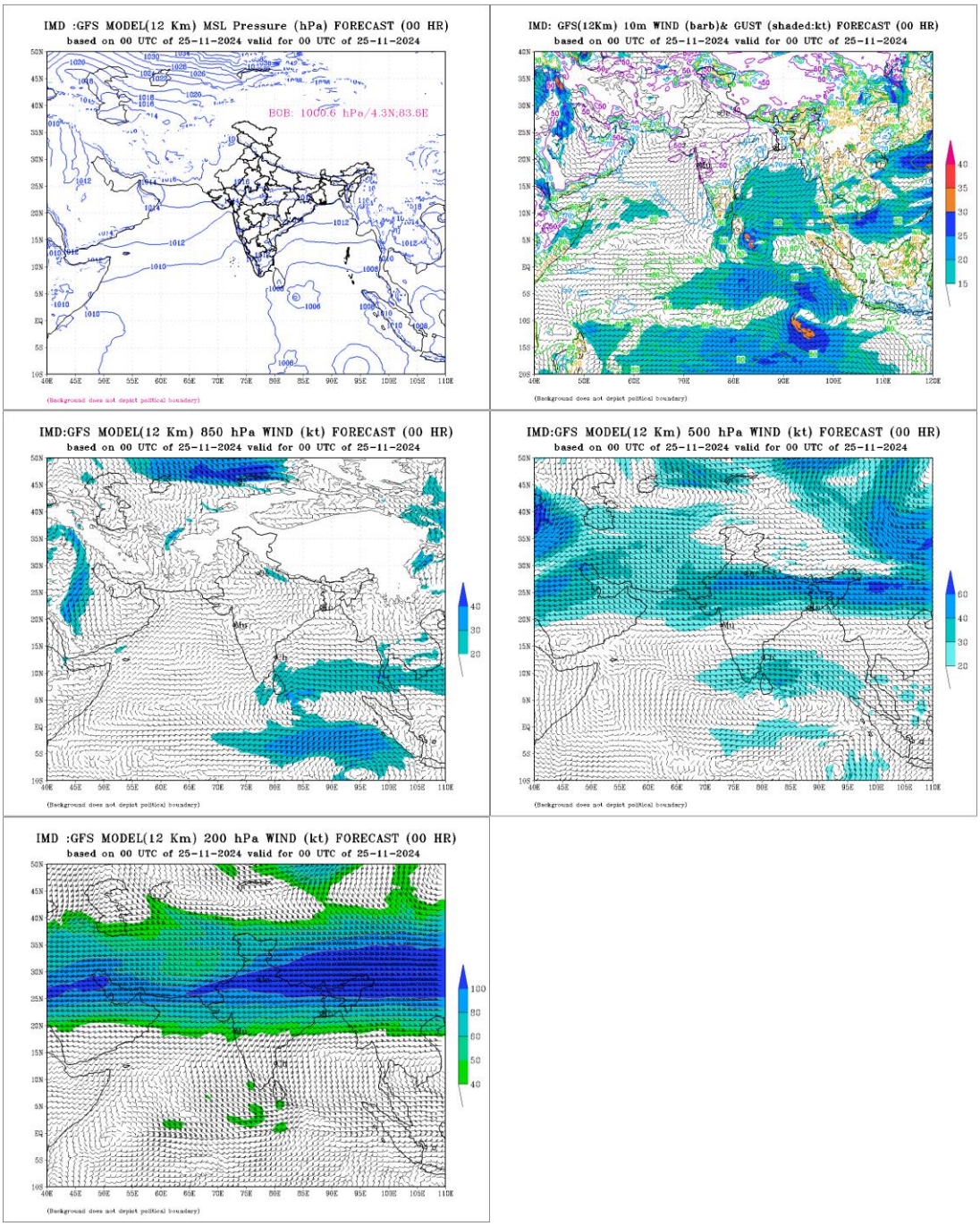


Fig.2.13.6.3: IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 25th November,2024

At 0000 UTC of 26th November, the MSLP analysis field indicated a deep depression over southwest BoB off southeast Sri Lanka coast near 5.7°N/82.3°E. Actually, the system was located as a depression over southwest BoB near 6.0°N/82.9°E at 0000 UTC of 26th November, 2024. The model showed that vertically, the system extended upto 500 hpa level

tilting southwestwards with height. Upper tropospheric Ridge was seen near 14°N. Thus, GFS was capturing the location on 26th November. However, the model overestimated the intensity of the system.

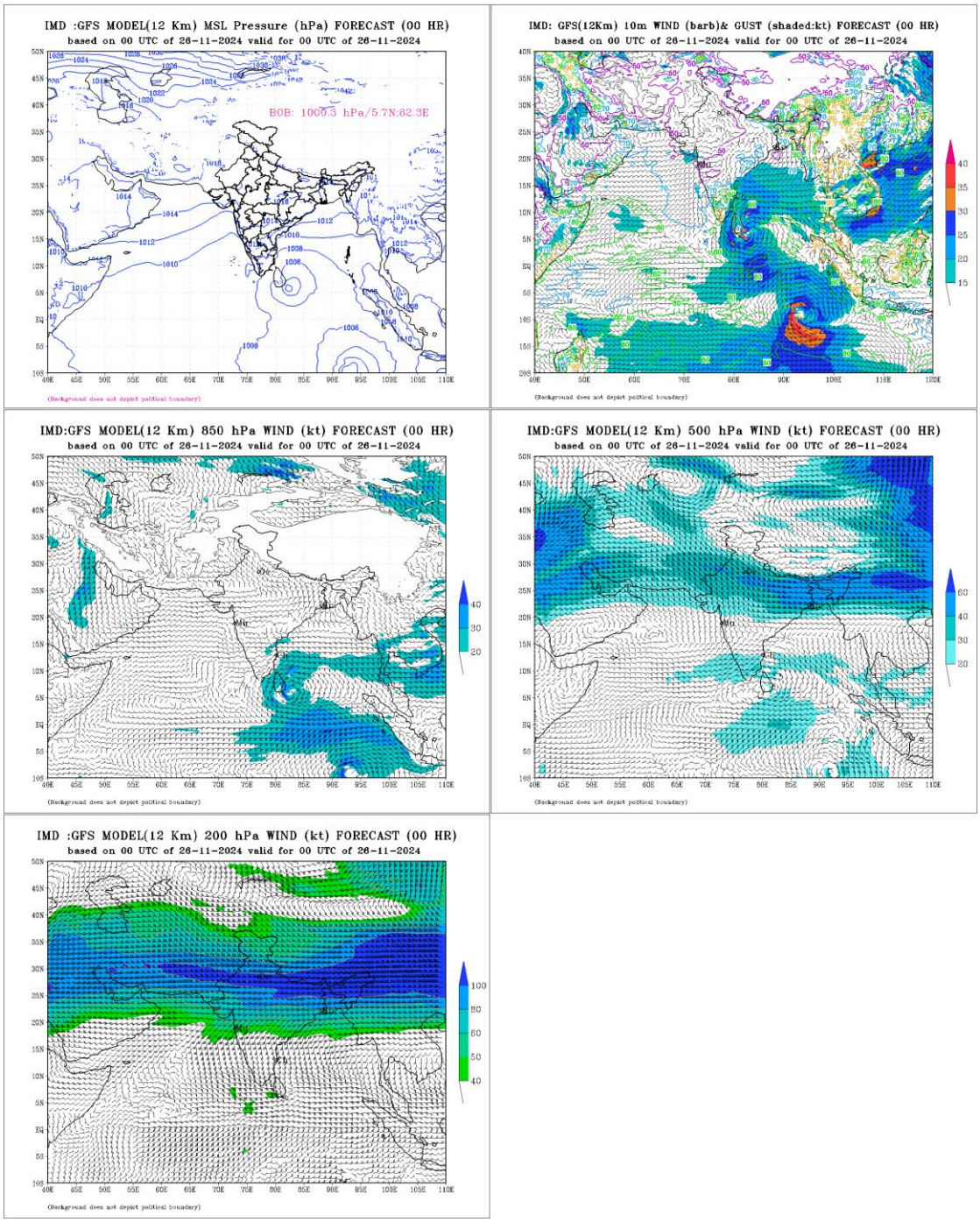


Fig.2.13.6.4: IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 26th November, 2024

At 0000 UTC of 27th November, the MSLP analysis field indicated further intensification of system over southwest BoB very close to Sri Lanka coast near 8.3°N/81.7°E. Actually, the system was located as a deep depression over southwest BoB near 8.2°N/82.4°E at 0000 UTC of 27th November, 2024. The model showed that vertically, the system extended upto

500 hpa level tilting southwestwards with height. Upper tropospheric Ridge was seen near 14°N. Thus, GFS was capturing the location on 27th November. However, the model overestimated the intensity of the system.

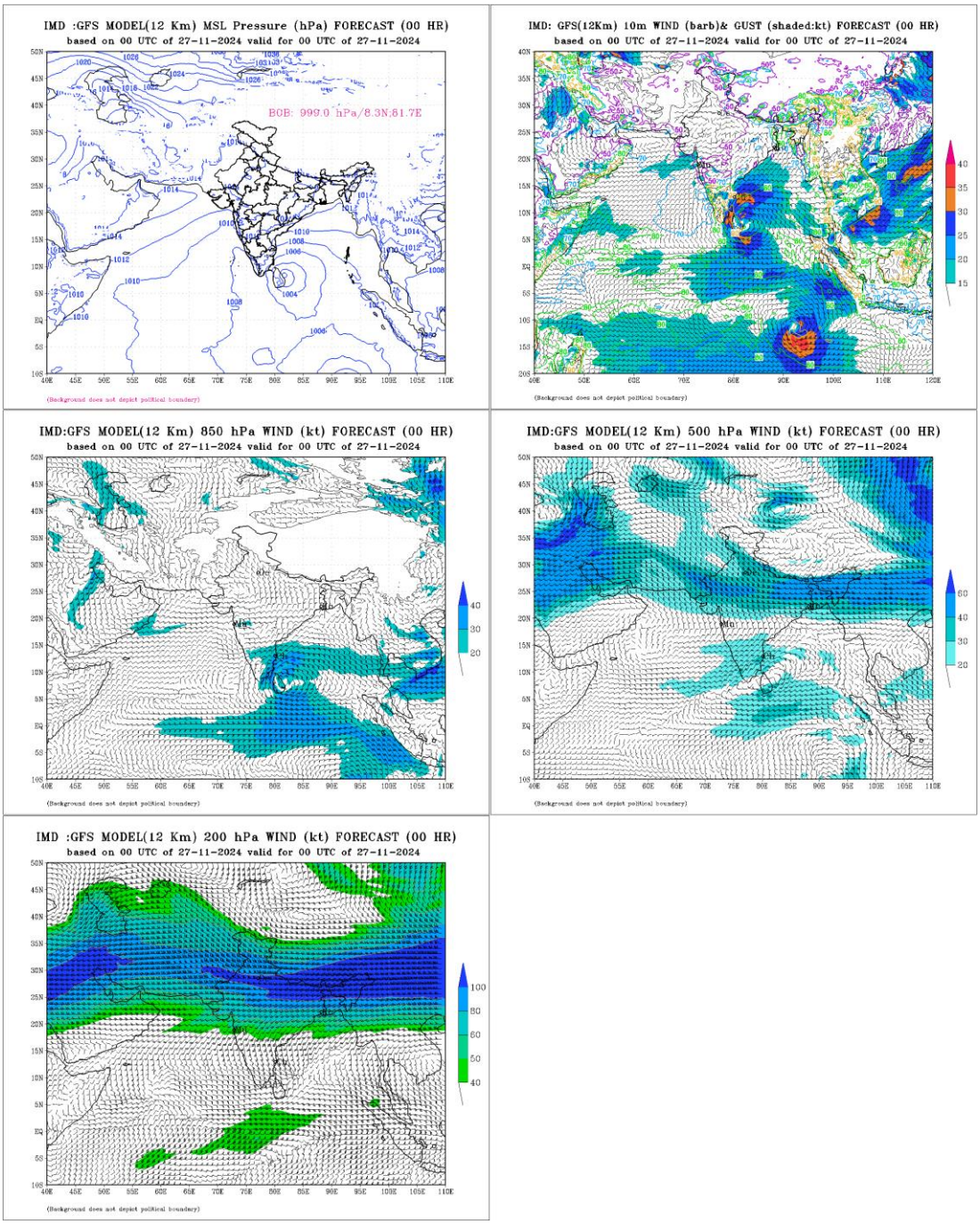


Fig.2.13.6.5: IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 27th November, 2024

At 0000 UTC of 28th November, the MSLP analysis field indicated deep depression/cyclonic storm over southwest BoB near 9.2°N/82.7°E. Actually, the system was located as a deep depression over southwest BoB near 9.0°N/82.2°E at 0000 UTC of 28th November, 2024. The model indicated northeastwards movement in past 24 hours The model showed that

vertically, the system extended upto 500 hpa level tilting southwestwards with height. Upper tropospheric Ridge was seen near 14°N. Thus, GFS was capturing the location on 28th November. However, the model overestimated the intensity of the system.

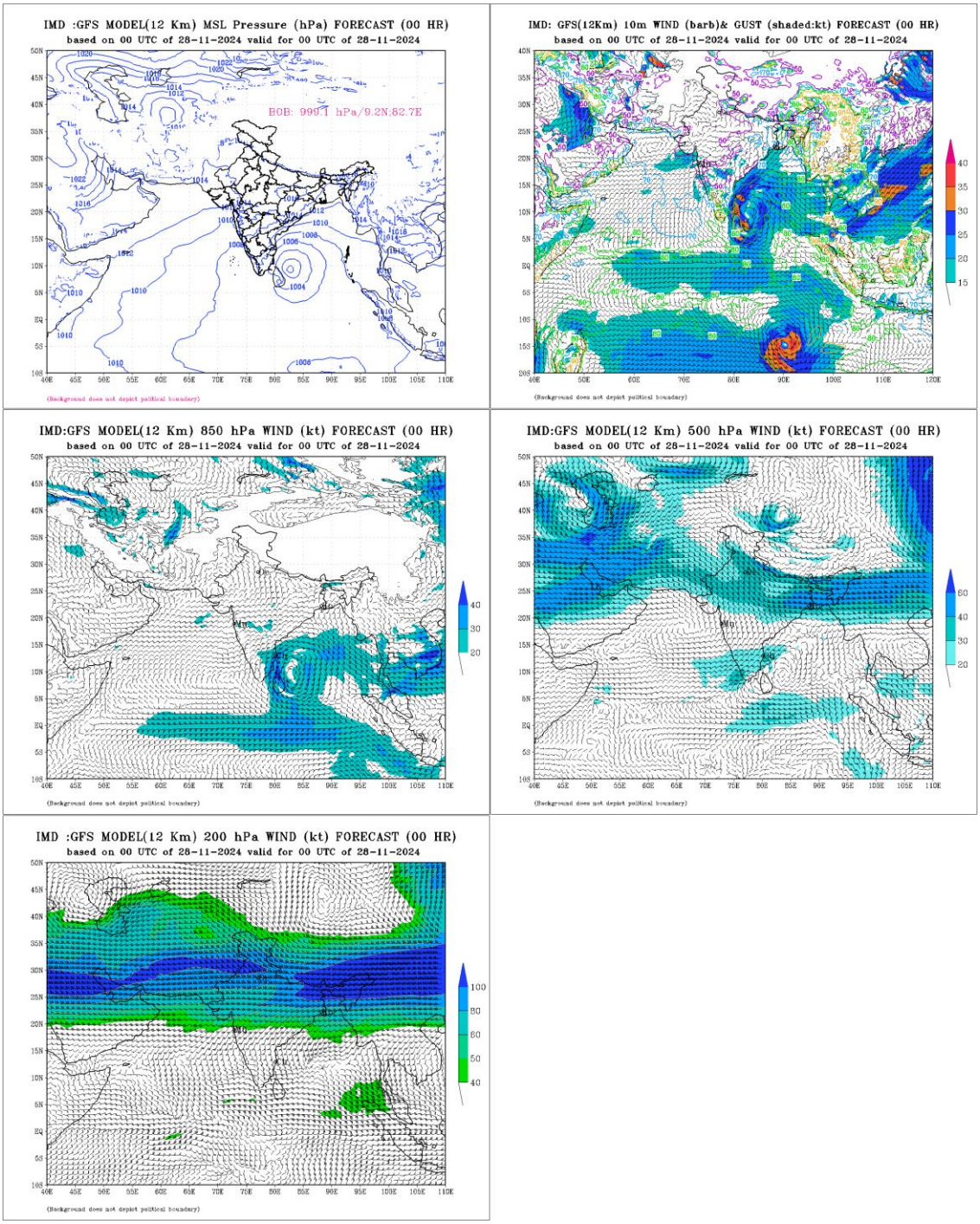


Fig.2.13.6.6: IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 28th November, 2024

At 0000 UTC of 29th November, the MSLP analysis field indicated further intensification into a cyclonic storm over southwest BoB near 10.6°N/83.6°E. Actually, the system was located as a deep depression over southwest BoB near 10.4°N/82.7°E at 0000 UTC of 29th November, 2024. The model indicated more eastwards movement which was not realized.

Also it intensified into a cyclonic storm at 0900 UTC of 29th November,2024. The model showed that vertically, the system extended upto 500 hpa level tilting southwestwards with height. Upper tropospheric Ridge was seen near 14°N. Thus, GFS was capturing the location on 29th November. However, the model overestimated the intensity of the system.

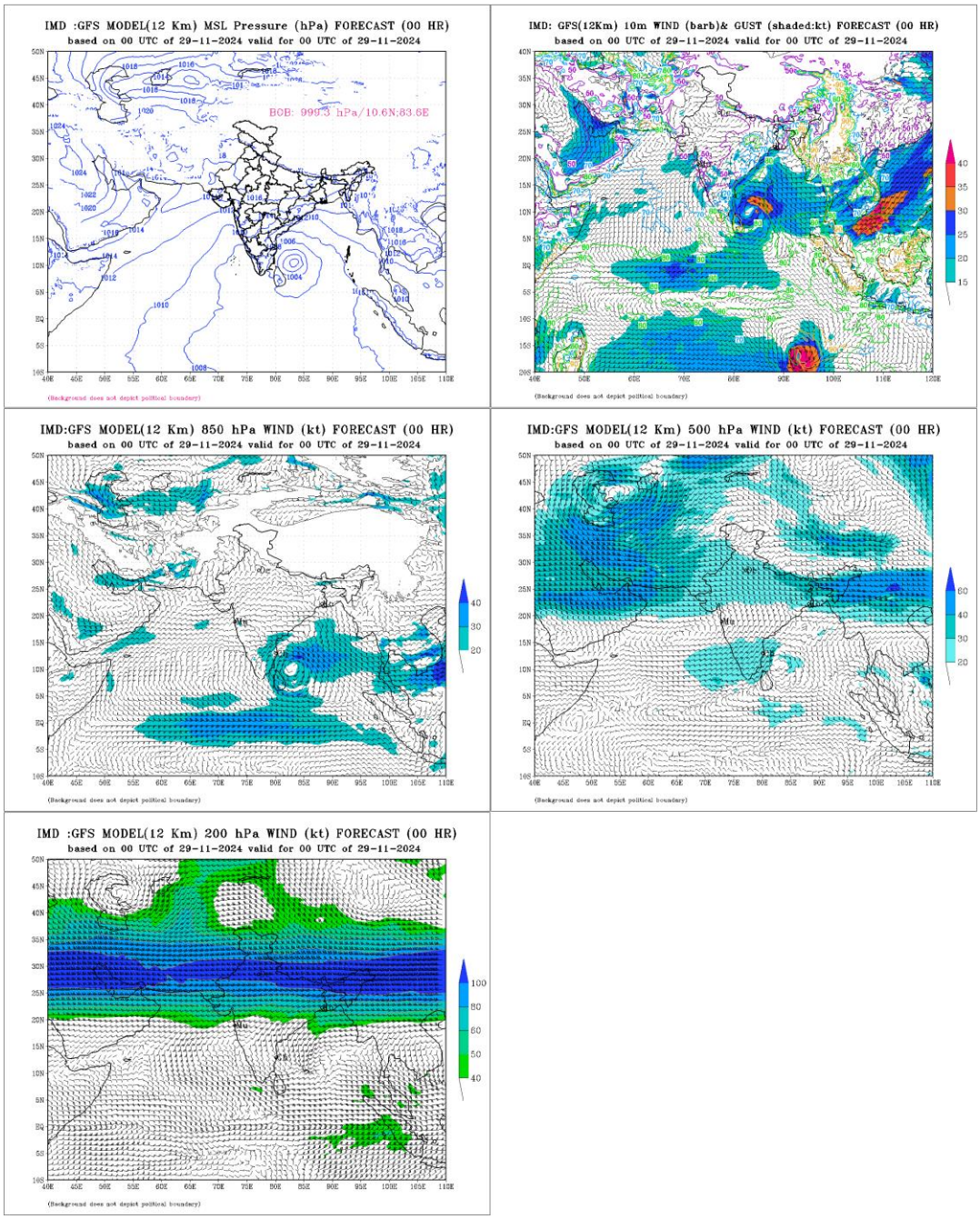


Fig.2.13.6.7: IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 29th November, 2024

At 0000 UTC of 30th November, the MSLP analysis field indicated further intensification into a severe cyclonic storm over westcentral & adjoining southwest BoB near 12.5°N/81.4°E. Actually, the system was located as a cyclonic storm over westcentral & adjoining southwest BoB near 12.2°N/81.2°E at 0000 UTC of 30th November, 2024. The model showed that

vertically, the system extended upto 500 hpa level tilting southwestwards with height. Upper tropospheric Ridge was seen near 14°N. Thus, GFS was capturing the location correctly on 29th November. However, the model overestimated the intensity of the system.

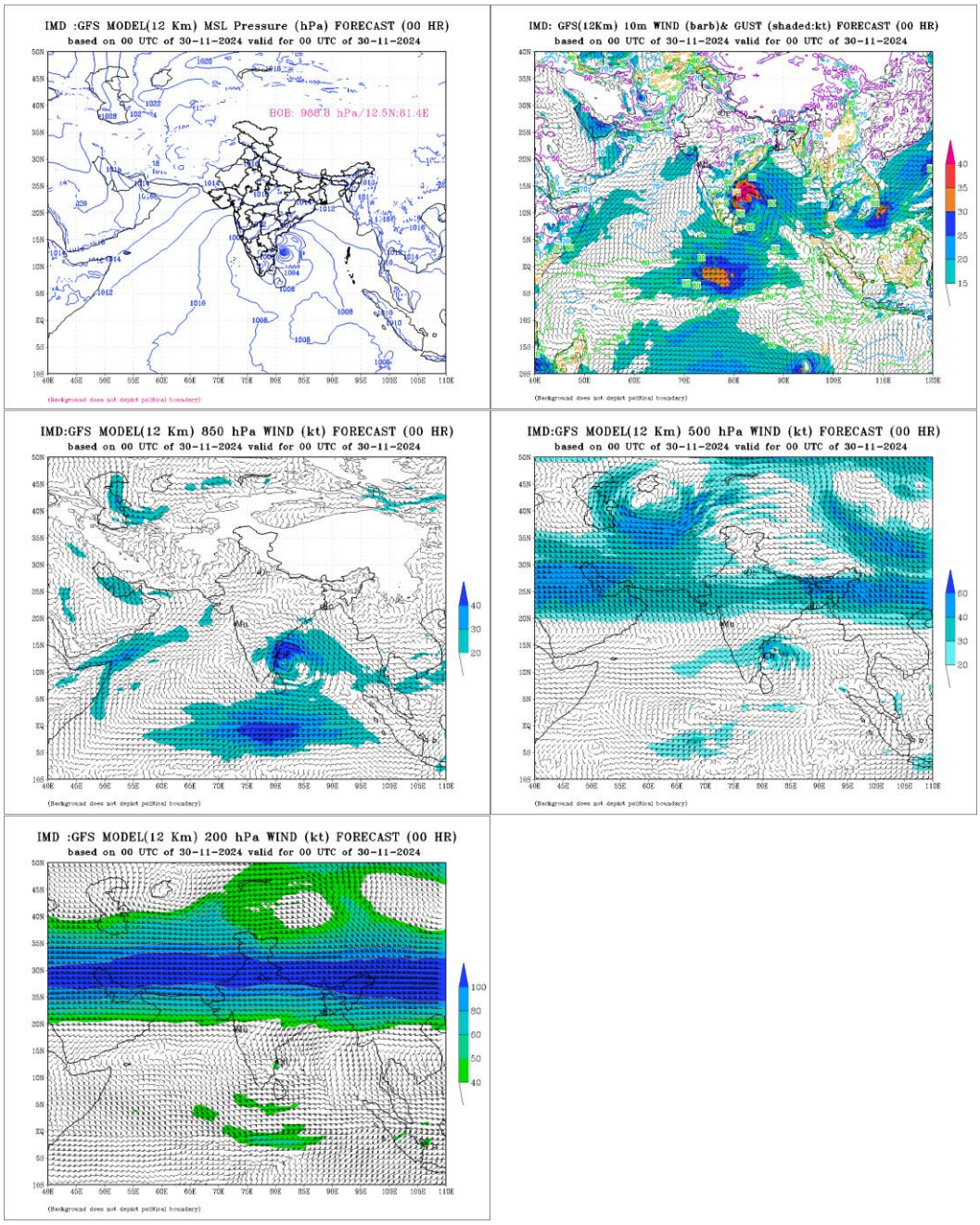


Fig.2.13.6.8: IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 30th November, 2024

At 0000 UTC of 1st December, the MSLP analysis field indicated the system over north Tamil Nadu coast near 12.1°N/80.0°E as a cyclonic storm. Actually, the system was located as a cyclonic storm over north Tamil Nadu coast near 12.0°N/79.8°E at 0000 UTC of 1st December, 2024. The model showed that vertically, the system extended upto 500 hpa level tilting southwestwards with height. Thus, GFS was capturing the location as well as intensity correctly on 1st December.

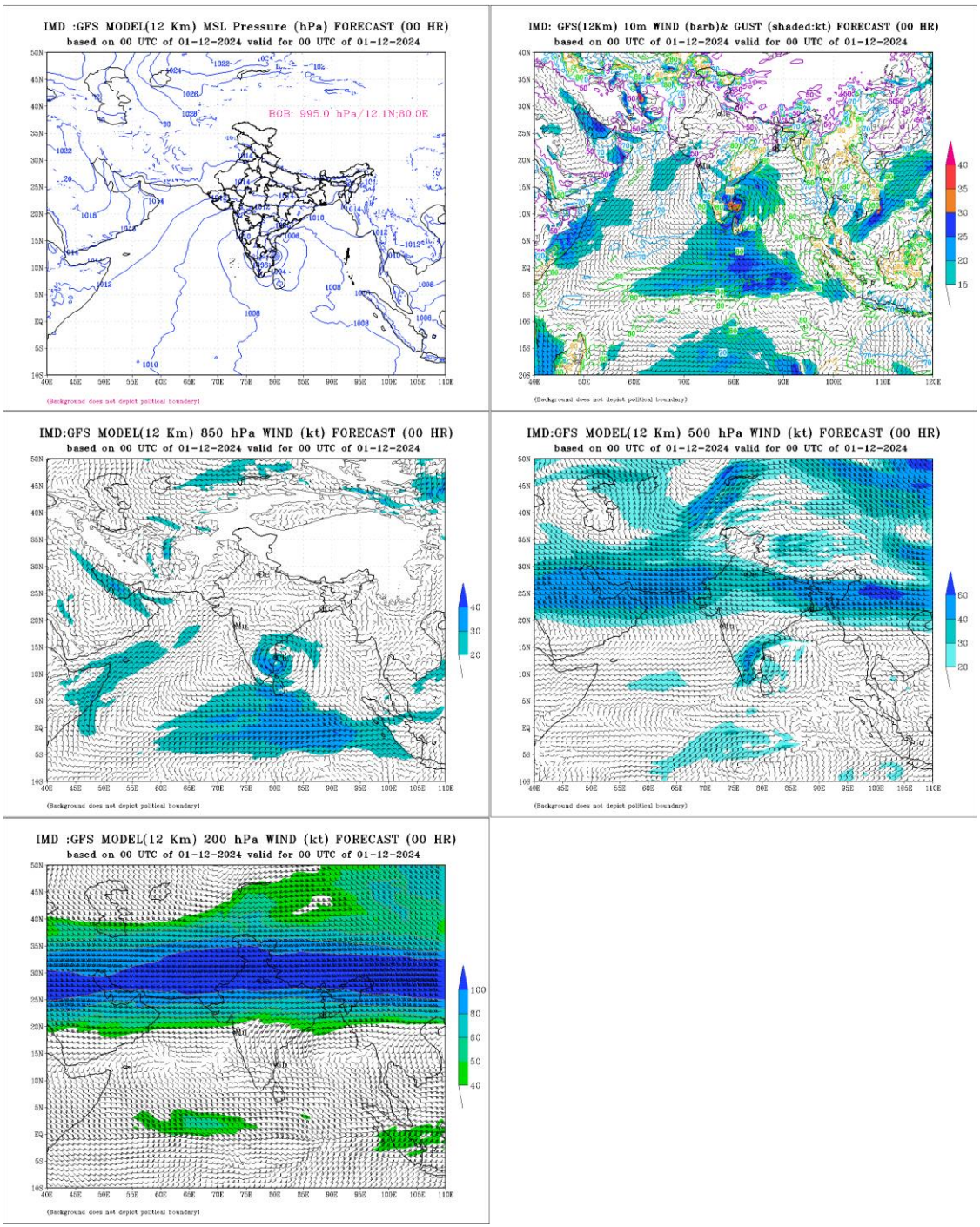


Fig.2.13.6.9: IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 01st December, 2024

At 0000 UTC of 2nd December, the MSLP analysis field indicated well marked low pressure area over north interior Tamil Nadu coast near 11.8°N/79.3°E. Actually, the system weakened into a well-marked low pressure area over north interior Tamil Nadu near 12.2°N/79.0°E at 0000 UTC of 2nd December, 2024. The model showed that vertically, the system extended upto 500 hpa level tilting southwestwards with height. Thus, GFS was capturing the location as well as intensity correctly on 2nd December.

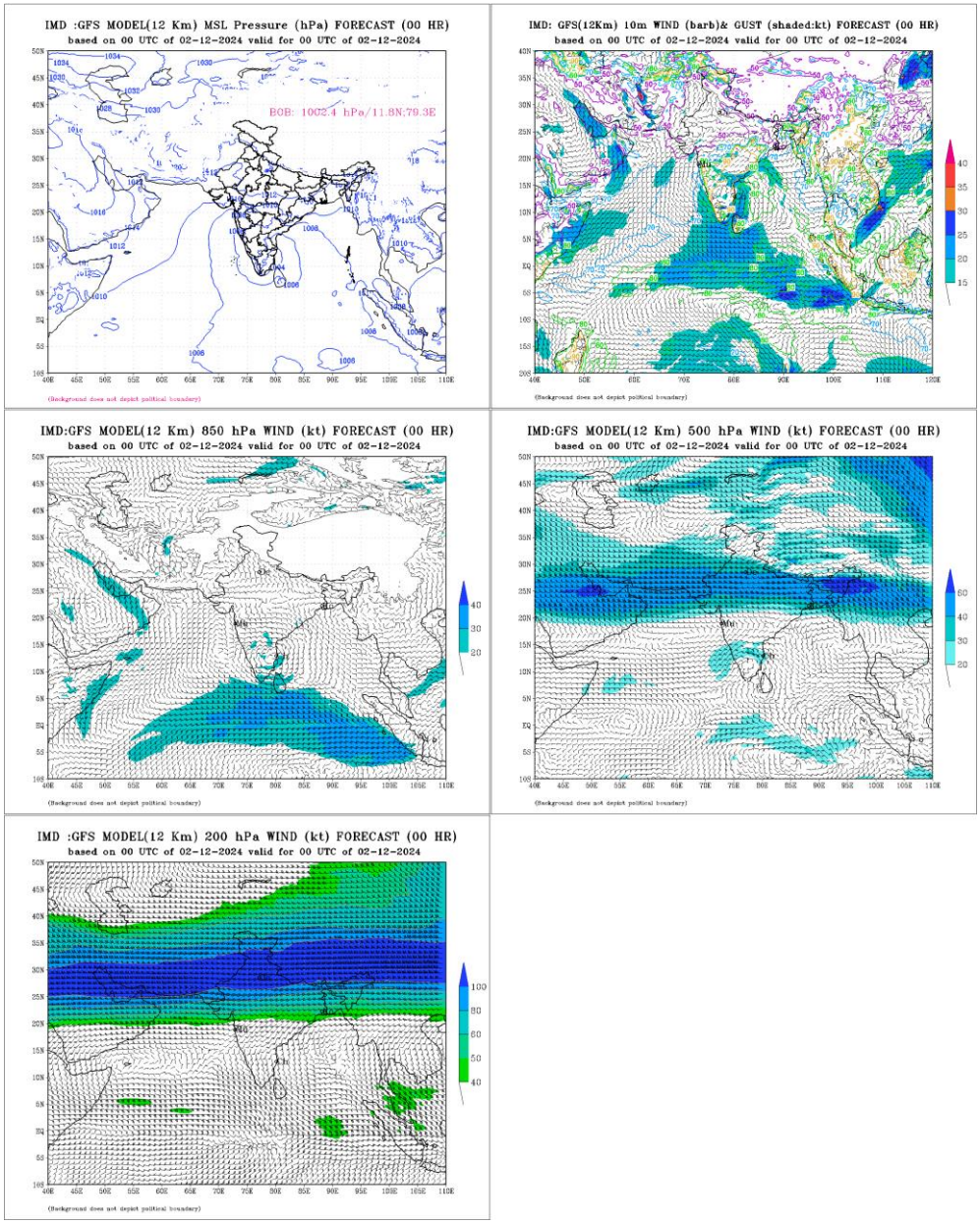


Fig.2.13.6.10: IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 02nd December, 2024

Hence IMD GFS could correctly capture the location and movement of the system. However, the intensity was over estimated till landfall. Landfall point and time was correctly captured.

2.5.6 Realized Weather

2.13.6.1. Realised rainfall

The system caused heavy to extremely heavy rainfall activity over Tamil Nadu, Puducherry & Karaikal southern states of India including Kerala. It is seen that light to moderate rainfall occurred at many places over Tamil Nadu, Puducherry & Karaikal with heavy rainfall at isolated places over Andaman & Nicobar Islands on 26th November.

Light to moderate rainfall occurred at many places with heavy to very heavy rainfall at isolated places on 27th November and heavy rainfall at a few places over on 30th November over Tamil Nadu, Puducherry & Karaikal.

Light to moderate rainfall occurred at most places with extremely heavy rainfall at many places over Tamil Nadu, Puducherry & Karaikal and heavy rainfall at isolated places over Kerala on 01st December.

Light to moderate rainfall occurred at most places with extremely heavy rainfall at many places over Tamil Nadu, Puducherry & Karaikal, heavy to very rainfall at a few places over Kerala and heavy rainfall at isolated places over Coastal Andhra Pradesh & Yanam on 02nd December.

NCMRWF IMD satellite gauge merged data plot showing 24 hours accumulated rainfall ending at 0300 UTC of dates during 21st – 27th November presented in **Fig. 2.13.7**.

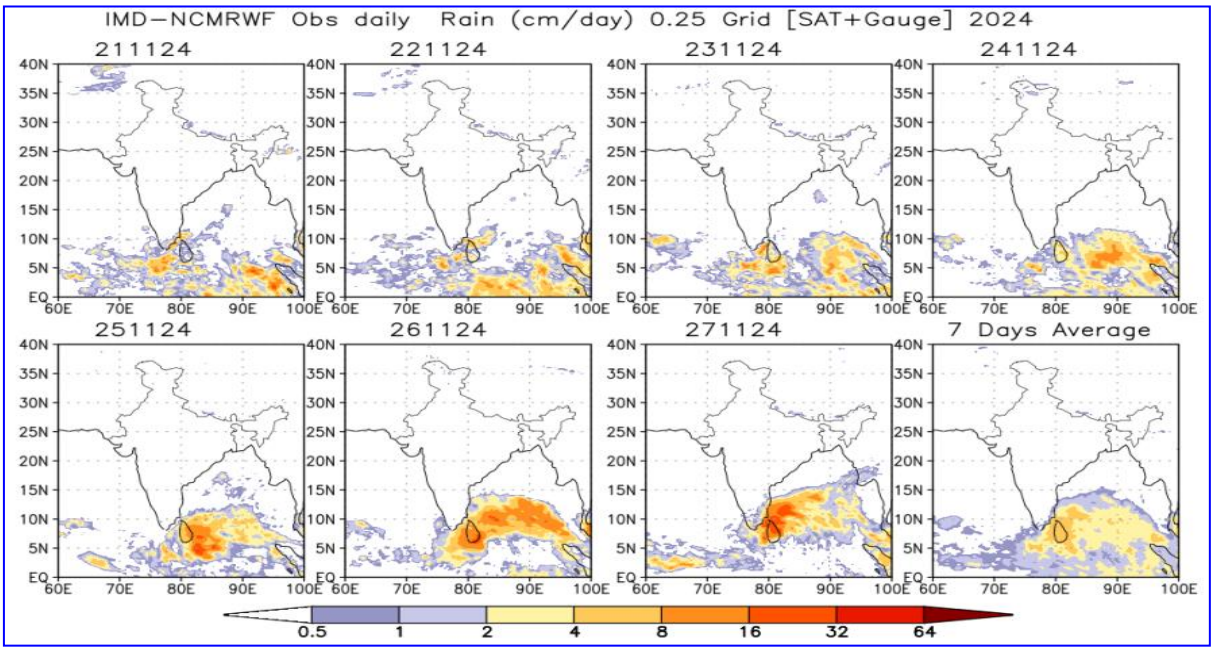


Fig. 2.13.7(a): NCMRWF-IMD satellite gauge merged data plots of 24 hours accumulated realized rainfall during 21st November to 27th November, 2024

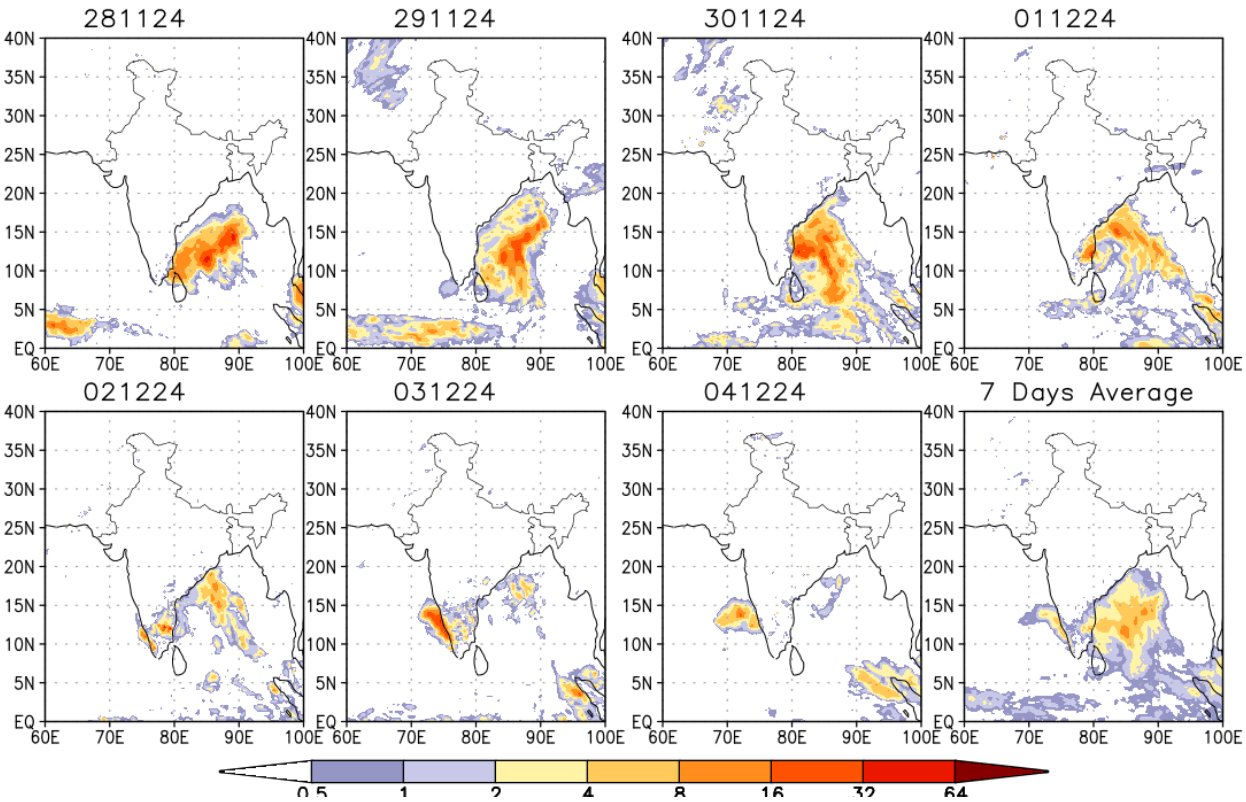


Fig.2.13.7 (b): NCMRWF-IMD satellite gauge merged data plots of realized 24 hours accumulated rainfall from 28th November – 04th December, 2024.

24 hours cumulative rainfall (≥ 7 cm) ending at 0830 hours IST of date:

<u>26th November, 2024</u>:

Andaman & Nicobar Islands: Car Nicobar (Nicobar) 7,

<u>27th November, 2024</u>

Tamil Nadu, Puducherry & Karaikal: Nagapattinam (Nagapattinam) 19, Kodiayakarai (Nagapattinam), Nagapattinam (Nagapattinam) & Velankanni (Nagapattinam) 18 each, Tirupoondi (Nagapattinam) 14, Manali (Chennai), Thirukuvalai (Nagapattinam) 13 each, Tiruvarur (Thiruvarur), Vedaranyam (Nagapattinam) 12 each, Mahabalipuram (Chengalpattu), Cheyyur (Chengalpattu), Thalaignayer (Nagapattinam), Sirkali (Mayiladuthurai), Kathivakkam (Chennai), Marakkanam (Villupuram), Vadakuthu (Cuddalore), Mahabalipuram (Chengalpattu) & Tarangambadi (Mayiladuthurai) 11 each, Mayiladuthurai (Mayiladuthurai), Thiruthuraipoondi (Thiruvarur), Kollidam (Mayiladuthurai), Tiruvarur (Thiruvarur), Cuddalore Collector Office (Cuddalore), Cuddalore (Cuddalore) & Karaikal (Karaikal), Nannilam (Thiruvarur) 10 each, Muthupet (Thiruvarur), Mannudi (Thiruvarur), Ayyampettai (Thanjavur), Needamangalam (Thiruvarur), Karaikal (Karaikal), Madukkur (Thanjavur) & NIOT_Pallikaranai (Chennai) 9 each, Bahour (Puducherry), Manalmedu (Mayiladuthurai), Nctpl M ECR (Chengalpattu), Mayiladuthurai (Mayiladuthurai), Manalmedu (Mayiladuthurai), Adiramapattinam (Thanjavur), Ayinkudi (Pudukkottai), Red Hills (Tiruvallur), Pattukottai (Thanjavur), Mylam (Villupuram), Thirukalukundram (Chengalpattu), Puducherry (Puducherry), Vettikadu (Thanjavur), Ennore (Tiruvallur), Orthanad (Thanjavur), Annamalai Nagar (Cuddalore) &

Puducherry Town (Puducherry) 8 each and Chidambaram (Cuddalore), Puducherry (Puducherry), Puzhal (Chennai), Kodavasal (Thiruvarur), Valangaiman (Thiruvarur), Neivasal Thenpathi (Thanjavur), Lower Anaicut (Thanjavur), Manjalaru (Thanjavur), Perungudi (Chennai), Taramani (Chennai), Puzhal (Tiruvallur), Nagudi (Pudukkottai), Madhavaram (Chennai), Thirukkanur (Puducherry), Thiruvottiyur (Chennai), Parangipettai (Cuddalore), Vanamadevi (Cuddalore), Royapuram (Chennai), Adyar Eco Park (Chennai), Adyar (Chennai), Vilupuram (Villupuram), Sholinganallur (Chennai), Peravurani (Thanjavur), Pandavaiyar Head (Thiruvarur), Avadi (Tiruvallur) & Sembanarkoil (Mayiladuthurai) 7 each;

30th November, 2024

Tamil Nadu, Puducherry &Karaikal: Ennore AWS (Tiruvallur) 13, Kathivakkam (Chennai) 12, Thiruvottiyur (Chennai), Tondiarpet (Chennai), Sholinganallur (Chennai), CD Hospital Tondiarpet (Chennai) & Basin Bridge (Chennai) 9 each, Ponneri (Tiruvallur), Manali (Chennai), Ice House (Chennai), Chennai (N) (Chennai) & Chennai Central (Chennai) 8 each and Adyar (Chennai), Alandhur (Chennai), Kolathur (Chennai), YMCA Nandnam (Chennai), Madhavaram (Chennai), Anna University ARG (Chennai), Chennai Collector Office (Chennai), DGP Office (Chennai), Sholinganallur (Chennai), Puzhal (Chennai), Hindustan_University (Chengalpattu), Manali New Town (Chennai) & Vadapalani (Chennai) 7 each;

1st December, 2024

Tamil Nadu: Mylam (Villupuram) 51, Puducherry (Puducherry) 49, Puducherry (Puducherry) 48, Patthukannu (Puducherry) 45, Thirukkanur(Puducherry) 43, Puducherry Town (Puducherry) 40, Tindivanam (Villupuram) 37, Nemoor (Villupuram) 35, Bahour (Puducherry) & Vallam (Villupuram) 32 each, Semmedu (Villupuram) 31, Valavanur (Villupuram) & Koliyanur (Villupuram) 28 each, Vilupuram (Villupuram) 27, Gingee (Villupuram) & Kedar (Villupuram) 25 each, Valathy (Villupuram), Vanur (Villupuram), Soorapattu (Villupuram) & Marakkanam (Villupuram) 24 each, Cuddalore (Cuddalore) & Avalurpettai (Villupuram) 23 each, Tiruvannamalai (Tiruvannamalai) & Chetpet (Tiruvannamalai) 22 each, Jamunamarathur (Tiruvannamalai), Cuddalore Collector Office (Cuddalore), Anandhapuram (Villupuram) & Uthiramerur (Kancheepuram) 21 each, Maduranthagam (Chengalpattu), Keelpennathur (Tiruvannamalai), Gummidipoondi(Tiruvallur) & Chengalpattu Chengalpattu) 20 each, Avadi (Tiruvallur), Thirukalukundram (Chengalpattu) & Vanamadevi (Cuddalore) 19 each, Tiruttani (Tiruvallur), Arani (Tiruvannamalai), Mugaiyur (Villupuram) & Arcot(Ranipet) 18 each, Kudithangi (Cuddalore) & Cheyyar (Tiruvannamalai) 17 each, Thirukoilur (Kallakurichi), Vandavasi (Tiruvannamalai), Thamaraipakkam (Tiruvallur), Kalasapakkam (Tiruvannamalai) & Kanjanur (Villupuram),Tambaram (Chengalpattu) 16 each, Thandarampettai (Tiruvannamalai), Kallakurichi (Kallakurichi), Kancheepuram (Kancheepuram), Wallajah (Ranipet), Cheyyur (Chengalpattu), MGR Nagar (Chennai), Ayanavaram Taluk Office (Chennai), Mundiyampakkam (Villupuram) & Kalavai PWD (Ranipet) 15 each, Yercaud (Salem), Cheyyar (Tiruvannamalai), Arakonam (Ranipet), Sholingur(distRanipet), Vembakkam (Tiruvannamalai), Panruti (Cuddalore), Pallipattu (Tiruvallur), Kallakurichi (Kallakurichi), Mahabalipuram (dist Chengalpattu) & Jaya Engg College (Tiruvallur) 14 each, Koratur (Tiruvallur), PalarAnicut (Ranipet), Uthukottai (Tiruvallur), Chembarabakkam (Tiruvallur), Kaveripakkam (Ranipet), R.K.Pet (Tiruvallur), DSCL Madampoondi (Kallakurichi), Sriperumbudur (Kancheepuram), Panapakkam

(Ranipet), Walajabad (Kancheepuram), Red Hills (Tiruvallur),Poondi (Tiruvallur), BASL Manampoondi (Villupuram), R.K.Pet (Tiruvallur), Minnal (Ranipet) & Tiruvallur (Tiruvallur) 13 each, Meenambakkam (Chennai), Ambathur Rev (Chennai), Valasaravakkam(Chennai), Cholavaram (Tiruvallur), Thirupalapandal (Kallakurichi), Kalayanallur (dist Kallakurichi), Kolapakkam (Chengalpattu), Ayapakkam (Chennai), Ranipet (Ranipet), Tirukoilur (Kallakurichi), Maduravoyal (Chennai), Tiruttani (Tiruvallur) & Ambattur MW (Chennai) 12 each, Chennai (AP) (Chennai), Tiruttani (dist Tiruvallur), Alandur (dist Chennai), BASLManalurpet (Kallakurichi), Mill-1 Ariyalur (Kallakurichi), Vengur (Kallakurichi), Meenambakkam (Chennai), Valasaravakkam (Chennai), Anna Nagar (Chennai), Ammoor (Walajah Railway) (Ranipet), Marg (Chengalpattu), Vellore (Vellore), Thiru-Vi-Ka Nagar (Chennai),Ponneri (Tiruvallur), Chennai Collector Office (Chennai), Kattumayilur (Cuddalore), Sankarapuram (distKallakurichi), Perambur (dist Chennai), Chennai(N) AWS(dist Chennai), Kundrathur (dist Kancheepuram), Vadapalani (dist Chennai), ACS Medical College ARG (Kancheepuram), Ulundurpet (Kallakurichi), Sholinganallur(Chennai), Kodambakkam (Chennai), Virugavoor (Kallakurichi) & Chennai(N) (Chennai) 11 each and Alangayam (Tirupathur), DGP Office (Chennai), Poonamallee (Tiruvallur), Ponnai Dam (Vellore), Tondiarpet (Chennai), Thiruvalangadu (Tiruvallur), Mugalivakkam (Chennai), Ariyalur Camp Area (Kallakurichi), DSCL Sulangurichi (Kallakurichi), Aminjikarai (Chennai), L Thiyagadurgam (Kallakurichi), Keelpadi (Kallakurichi), Basinbridge (Chennai), Ammundi (dist Vellore) & Madipakkam (Chennai) 10 each.

Kerala: Ulanad (Pathanamthitta) 9 and Enadimangalam (Pathanamthitta) 7

2nd December, 2024

Tamilnadu, Puducherry & Karaikal: Uthangarai (Krishnagiri) 50, Kedar (Villupuram) 42, Soorapattu (Villupuram) 38, Vilupuram (Villupuram) 35, Harur (Dharmapuri) 33, Mundiyampakkam (Villupuram), Koliyanur (Villupuram) & Thirupalapandal (Kallakurichi) 32 each, Madampoondi (Kallakurichi) 31, Mugaiyur (Villupuram) & Valavanur (Villupuram) 30 each, Nemoor (Villupuram), Manampoondi (Villupuram) & Kanjanur (Villupuram) 29 each, Vengur (Kallakurichi) 27, Tirukoilur (Kallakurichi) 26, Jambukuttapatti (Krishnagiri) & Pochampalli (Krishnagiri) 25 each, Yercaud (Salem) 24, Eraiyur (Kallakurichi) & Jamunamarathur (Tiruvannamalai) 23 each, Pambar (Krishnagiri), Manalurpet (Kallakurichi) 21 each, Thandarampettai (Tiruvannamalai), Barur (Krishnagiri) & Pappireddipatti (Dharmapuri) 20 each, Penucondapuram (Krishnagiri), Sankarapuram (Kallakurichi) 19 each, Kallakurichi (Kallakurichi) 18, Anandhapuram (Villupuram) & Kalayanallur (Kallakurichi) 17 each, Tiruvannamalai (Tiruvannamalai), Panruti (Cuddalore) & Dharmapuri (Dharmapuri) 16 each, Moorarpalayam (Kallakurichi), Vanamadevi (Cuddalore), Keelpennathur (Tiruvannamalai), Moongilthuraipattu (Kallakurichi), Ulundurpet (Kallakurichi), Kariyakovil Dam (Salem), Sulangurichi (Kallakurichi), Rishivandhiyam (Kallakurichi), SCS Mill Pillaiyarkuppam (Kallakurichi) & Keelpadi (Kallakurichi) 15 each, Virugavoor (Kallakurichi), Nedungal (Krishnagiri) & Kattumayilur (Cuddalore) 14 each, Ariyalur (Kallakurichi), Ariyalur Camp Area (Kallakurichi), Kadavanur (Kallakurichi) 13 each, Vepur (Cuddalore) & Me Mathur (Cuddalore) 12 each, Thiyagadurgam (Kallakurichi), Pennagaram (Dharmapuri), Semmedu (Villupuram), Manimutharu Dam PWD (Kallakurichi), SRC Kudithangi (Cuddalore), Krishnagiri (Krishnagiri), Kachirayaopalayam (Kallakurichi), Thirukkanur (Puducherry) & Paiyur (Krishnagiri) 11 each, Sethiathope (Cuddalore), Anaimaduvu Dam (Salem), Omalur (Salem), Dam (Krishnagiri) & Danishpet (Salem) 10 each, Kallakurichi

(Kallakurichi), Gomugi Dam (Kallakurichi), Palacode (Dharmapuri), Pelandurai (Cuddalore), Hogenekal (Dharmapuri) 9 each, Vadapudupattu (Tirupathur), Bhuvanagiri (Cuddalore), Bahour (Puducherry), Palacode (Dharmapuri), Denkanikottai (Krishnagiri), TNAU CRI Yethapur (Salem) & Vaniyambadi (Tirupathur) 8 each and Dharamapuri (Dharmapuri), Arasoor (Villupuram), Kuppanatham (Cuddalore), Gudalur Bazar (The Nilgiris), Thiruvennainal (Villupuram), Tirupattur (Tirupathur), Natrampalli (Tirupathur), Ambur (Tirupathur), Lakkur (Cuddalore), Kodanad (The Nilgiris), Tirupattur (Tirupathur), Avalurpettai (Villupuram), Mangalapuram (Namakkal), Kilacheruvai (Cuddalore), Kethandapatti (Tirupathur), Chengam(Tiruvannamalai), Chidambaram(Cuddalore) & Vridhachalam (Cuddalore) 7 each,

Kerala: Kodungallur (Thrissur) 19, Kottayam18,Kurudamannil (Pathanamthitta)17, Konni (Pathanamthitta), Kanjirappally (Kottayam district) & Ranni (Pathanamthitta) 16 each, Kochi (Ernakulam), Haripad (Alappuzha) & Peerumedu (Idukki) 15 each, Perumbavur (Ernakulam) 14, Aluva (Ernakulam), Laha (Pathanamthitta) & Aluva (Ernakulam) 13 each, Cherthala (Alappuzha),Kunnathanam (Pathanamthitta) & Thycauttussery (Alapuzha) 12 each, Kalamassery (Ernakulam) 11, Kumarakom (Kottayam) & Konni(Pathanamthitta district) 8 each and Kozhikode, Vaikom (Kottayam) & Piravam (Ernakulam) 7 each.

Coastal Andhra Pradesh &Yanam: Yanam (Yanam) 8

2.13.6.2. Realized wind

At the time of landfall, the estimated maximum sustained wind speed was about 70-80 kmph gusting to 90 kmph over Puducherry. Realised estimated wind distribution in the tropical cyclone field during its life cycle is presented in **Fig.2.13.8.**

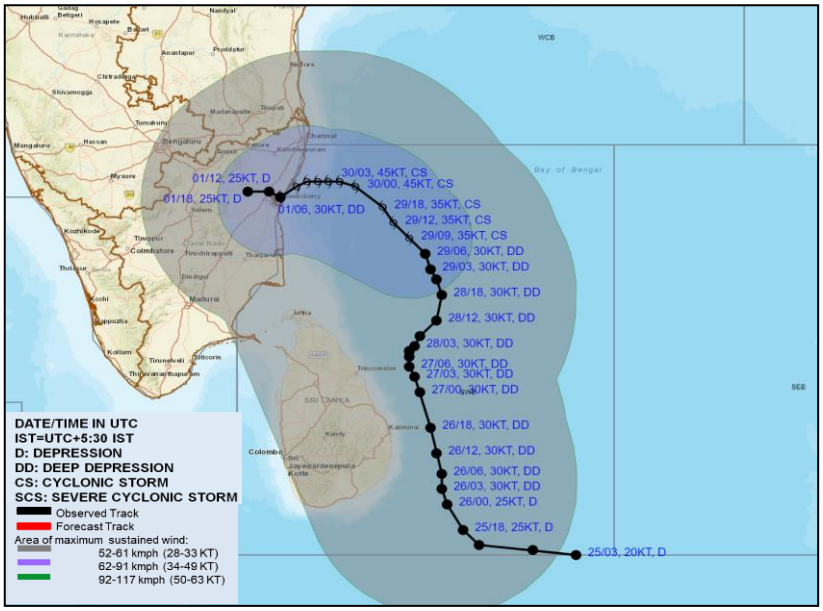


Fig. 2.13.8: Estimated maximum sustained wind during the life cycle of CS FENGAL

2.13.6.3. Realized storm surge

Storm surge of about 1-1.5-meter height above the astronomical tide inundated the low-lying areas of the coastal districts of north Tamil Nadu, Puducherry and adjoining south Andhra Pradesh during the time of landfall.

2.13.7. Damage report

As per media reports, in Tamil Nadu, 10 persons lost their lives, seven from a landslide, two from drowning and another due to electrocution. Heavy rains of up to 130 mm (5.1 in) also caused severe flooding in Chennai, resulting in four deaths from electrocution. In Ooty, heavy rains caused a house to collapse, killing a 45-year-old man, 4 people were killed in Pondicherry and another in Vellore. Flooding inundated around 800 acres of farmland in Nagapattinam. Damage report due to CS Fengal is shown in **Fig 2.13.9.**

As Fengal skirted along Sri Lanka coast during 26th -28th November, it caused significant damage. Nearly 480,000 people were displaced, 17 were killed and 20 were injured, with 103 homes destroyed and 2,635 others damaged (Source: Sinhala Adaderna https://sinhala.adaderana.lk/news/203904)

Fig. 2.13.9(a): Cyclone Fengal damage report: MHA's figures stand in stark contrast with Tamil Nadu govt data (DTNEXT Bureau 6Dec2024) **(b)** Cyclone FENGAL: incessant downpour breaks 30-year record in Puducherry (livemint.com, 01st December, 2024), **(c)** Cyclone Fengal: Buses Swept Away by Floodwaters as Storm Wreaks Havoc in Tamil Nadu (News18.com 02th December, 2024), **(d)** Cyclone Fengal: Flood leaves Villupuram battered (thehindu.com, 09th December, 2024).

2.14. Depression over westcentral Bay of Bengal off Andhra Pradesh coast during 20th - 21st December, 2024

2.14.1. Life History

- Under the influence of an upper air cyclonic circulation over south Andaman Sea and adjoining southeast Bay of Bengal (BoB), a low-pressure area formed over central parts of south BoB in the morning (0830 hours IST/0300 UTC) of the 16th December, 2024.
- It lay as a well-marked low-pressure area over southwest BoB in the morning (0830 hours IST/0300 UTC) of the 18th December, 2024.
- It moved southwestwards and lay over southwest and adjoining westcentral BoB in the morning (0830 hours IST/0300 UTC) of 19th December, 2024.
- Thereafter, it moved nearly northwards and lay over westcentral and adjoining southwest BoB in the morning (0830 hours IST/0300 UTC) of 20th December, 2024.
- Further moving northwards, it concentrated into a depression over westcentral BoB off Andhra Pradesh coast in the evening (1730 hours IST/1200 UTC) of 20th December, 2024.
- It moved east-northeastwards and lay over westcentral BoB in the morning (0830 hours IST/0300 UTC) of the 21st December, 2024.
- It moved east-northeastwards and weakened into a well-marked low-pressure area over the same region in the evening (1730 hours IST/1200 UTC) of 21st December, 2024.

The Observed track of the system is presented in **Fig. 2.14.1**. The best track parameters associated with the system are given in **Table 2.14.1.**

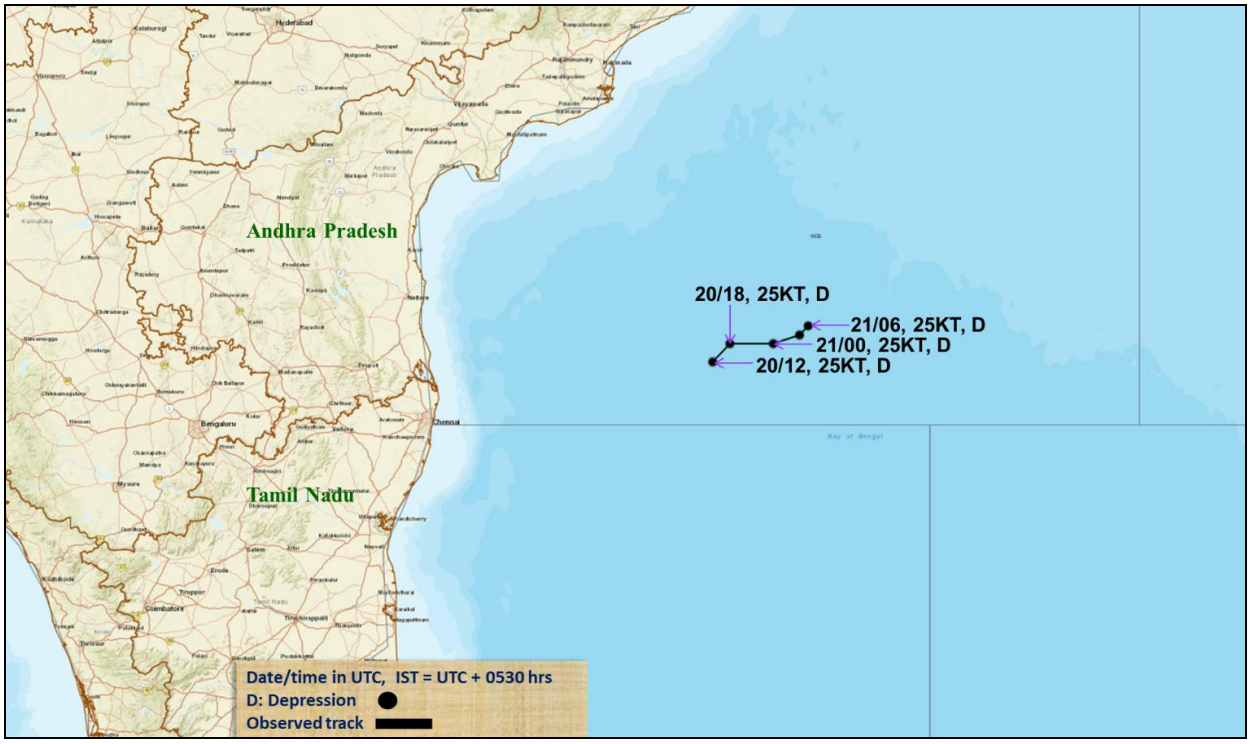


Fig. 2.14. 1: Observed track of Depression over westcentral BoB off Andhra Pradesh coast

Table 2.14.1: Best track positions and other parameters of the Depression over westcentral BoB off Andhra Pradesh coast during 20th– 21st December, 2024

Date	Time (UTC)	Lat.	Long.	C.I no	ECP	ΔP	MSW (kt)	Category
20.12.24	1200	13.7	83.5	1.5	1003	3	20	D
	1800	13.9	83.7	1.5	1003	3	25	D
21.12.24	0000	13.9	84.2	1.5	1002	4	25	D
	0300	14.0	84.5	1.5	1002	4	25	D
	0600	14.1	84.6	1.5	1003	3	20	D
	1200	Weakened into a well-marked low-pressure area over westcentral BoB.						

kt: Knot (nautical mile per hour), 1 kt =1.85 kmph, D: Depression

2.14.2. Genesis, Intensification and movement

At 1200 UTC of 20th December, a well-marked low-pressure area was over the sea area with warm sea surface temperature (SST) around 28°C and tropical cyclone heat potential (TCHP) was around 70 KJ/cm^2 over southwest and adjoining westcentral BoB. The total precipitable water imagery (TPW) was indicating warm moist air incursion into the system core with feeding from southeast sector. However, cold dry air was also entering into the core from southwest sector. Low level positive relative vorticity at 850 hpa level was around 80x10^{-6}s^{-1} to the south of the system area over southwest BoB with vertical extension upto 500 hpa level. The low-level convergence was around 10 x10^{-6}s^{-1} to the north of system centre. Upper-level divergence was around 10 x 10^{-6}s^{-1} over an elongated region extending over southwest to northeast sectors. The vertical wind shear (VWS) was moderate (15-20 kt) over the system area. The ridge was lying near 12°N latitude to the south of system area. The southwesterly winds to the north of ridge steered the system north-northeastwards. Under these favorable conditions, the well-marked low-pressure area over southwest BoB concentrated into a depression over the same region.

At 0300 UTC of 21st December, there was prevalence of westerly wind anomaly and Madden Julian Oscillation (MJO) over south BoB and easterly wind anomaly over central parts of BoB along with Kelvin wave to the south. These equatorial waves supported the system to maintain its intensity. However, the low level positive relative vorticity at 850 hpa level decreased significantly and was around 50x10^{-6}s^{-1} to the north-northeast of system centre with vertical extension upto 500 hpa level. The low-level convergence had increased and was around 30x10^{-6}s^{-1} to the north-northeast of system centre and the upper-level divergence was fragmented and was around 10x10^{-6}s^{-1} to the southeast and another zone to northeast sector of system. Divergence was significantly less than the convergence indicating no further intensification of the system. The mid-level VWS was moderate (10-20 kt) over the system area, which supported the system to maintain its intensity. The west-southwesterly winds prevailing in the mid-tropospheric levels were steering the system east-northeastwards. Further, the presence of convergence zone to the southeast of system area indicated vorticity advection towards southeast sector. While the vorticity advection suggested southeastwards movement of the system, the mid-level flow suggested east-northeastwards movement of the system. Due to these diverging forces, the system moved slowly in east-northeastwards. At that time, the system was in a moderately favorable

environment (SST 27-28^{0}C, moderate VWS and poleward outflow) and thus maintained its intensity.

At 1200 UTC of 21st December, the system was over the sea area with warm SST (27-29°C) and TCHP around 70 KJ/cm^2. The total precipitable water imagery was indicating significant decrease in warm moist air around system area and cold and dry air incursion was also seen from southwest sector. Low level positive relative vorticity at 850 hpa level was around 50x10^{-6}s^{-1} to the north-northeast of the system centre with vertical extension upto 700 hpa level. Vertical extension of the system decreased. The low-level convergence was same and was around 20x10^{-6}s^{-1} to the north-northeast of system centre. At the same time, the upper-level divergence decreased significantly with emergence of a large convergence zone to the northeast of system centre. The mid-level VWS was moderate (15-20 kt) over the system area. All these features led to weakening of the system into a well-marked low pressure area over westcentral BoB.

2.14.3. Monitoring

India Meteorological Department (IMD) maintained round the clock watch over the north Indian Ocean (NIO) and the system was monitored well in advance since 16th December. IMD utilized all available data sources including satellite observations from INSAT 3D and 3DR, polar orbiting satellites, available ships & buoy observations in the region and coastal observations on the day of landfall. 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 system. A digitized forecasting system of IMD was utilized for analysis and comparison of various models' guidance, decision making process and warning products generation.

2.14.3.1. Features observed through satellite

Satellite monitoring of the system was mainly done by using half hourly INSAT-3D and 3DR imageries. Satellite imageries of other international geostationary satellites, high resolution polar orbiting satellites and scatterometer imageries from ASCAT were also considered for monitoring of the system. Typical INSAT-3D enhanced colored imageries, visible/ IR, brightness temperature and water vapour imageries are presented in **Fig. 2.14.2(a) to (d)**. During the entire life cycle, the clouds were organized in shear pattern. The detailed features based on satellite imageries are discussed in this section.

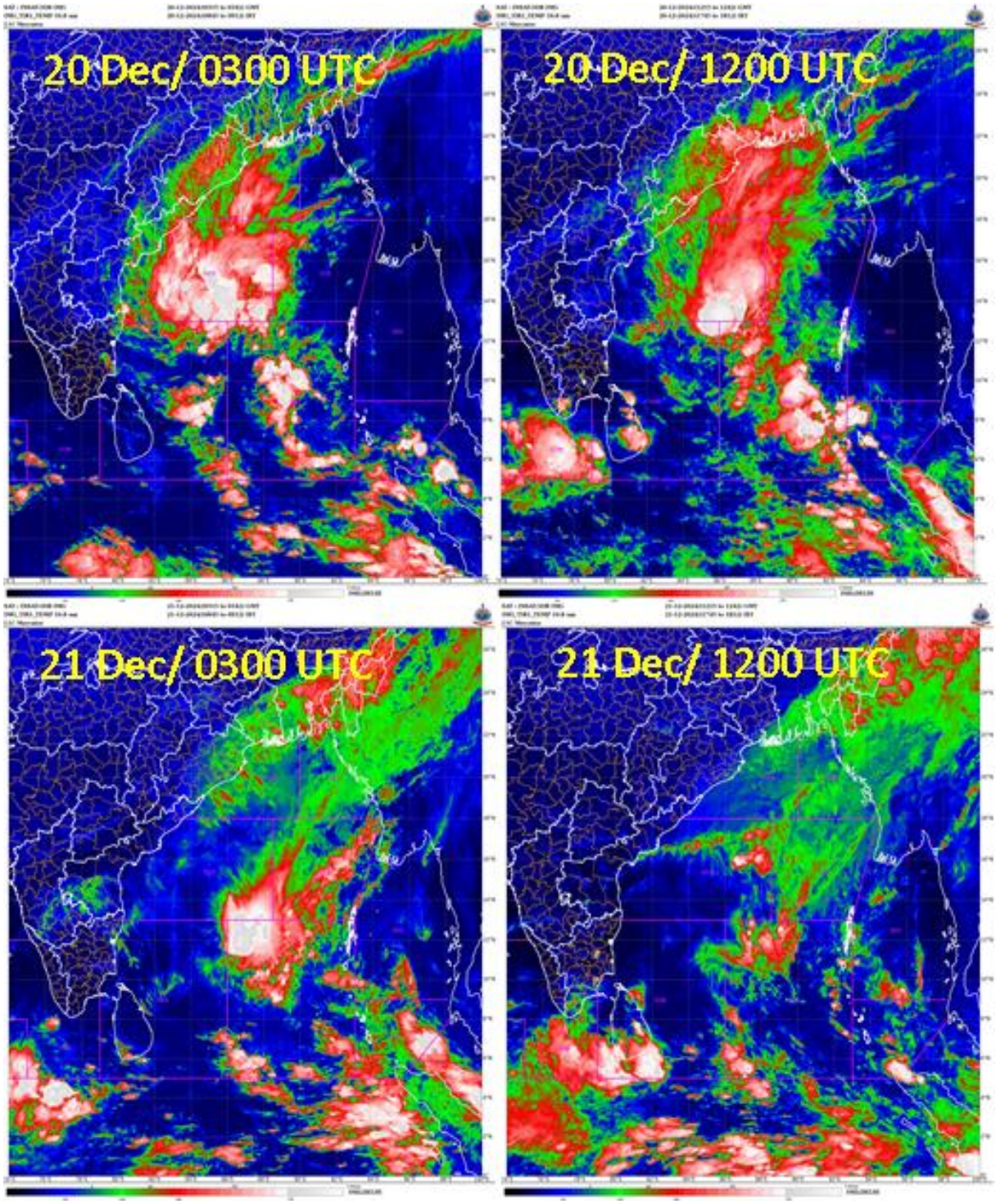


Fig. 2.14.2(a): INSAT-3D enhanced colored imageries during life cycle of Depression over westcentral BoB off Andhra Pradesh coast during 20th - 21st December, 2024

At 0300 UTC of 20th December scattered to broken low and medium clouds with embedded intense to very intense convection lay over westcentral, adjoining eastcentral & South BoB (minimum cloud top temperature (CTT) -70 to -80^{0}C). Scattered low and medium clouds with embedded moderate to intense convection lay over north BoB and south Andaman Sea.

At 1200 UTC of 20th December, associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over BoB between latitude 12.0°N to 18.0°N and longitude 82.0°E to 87.0°E with minimum CTT as -80 to -90°C and moderate to intense convection over south Gangetic West Bengal, Odisha and north coastal Andhra Pradesh.

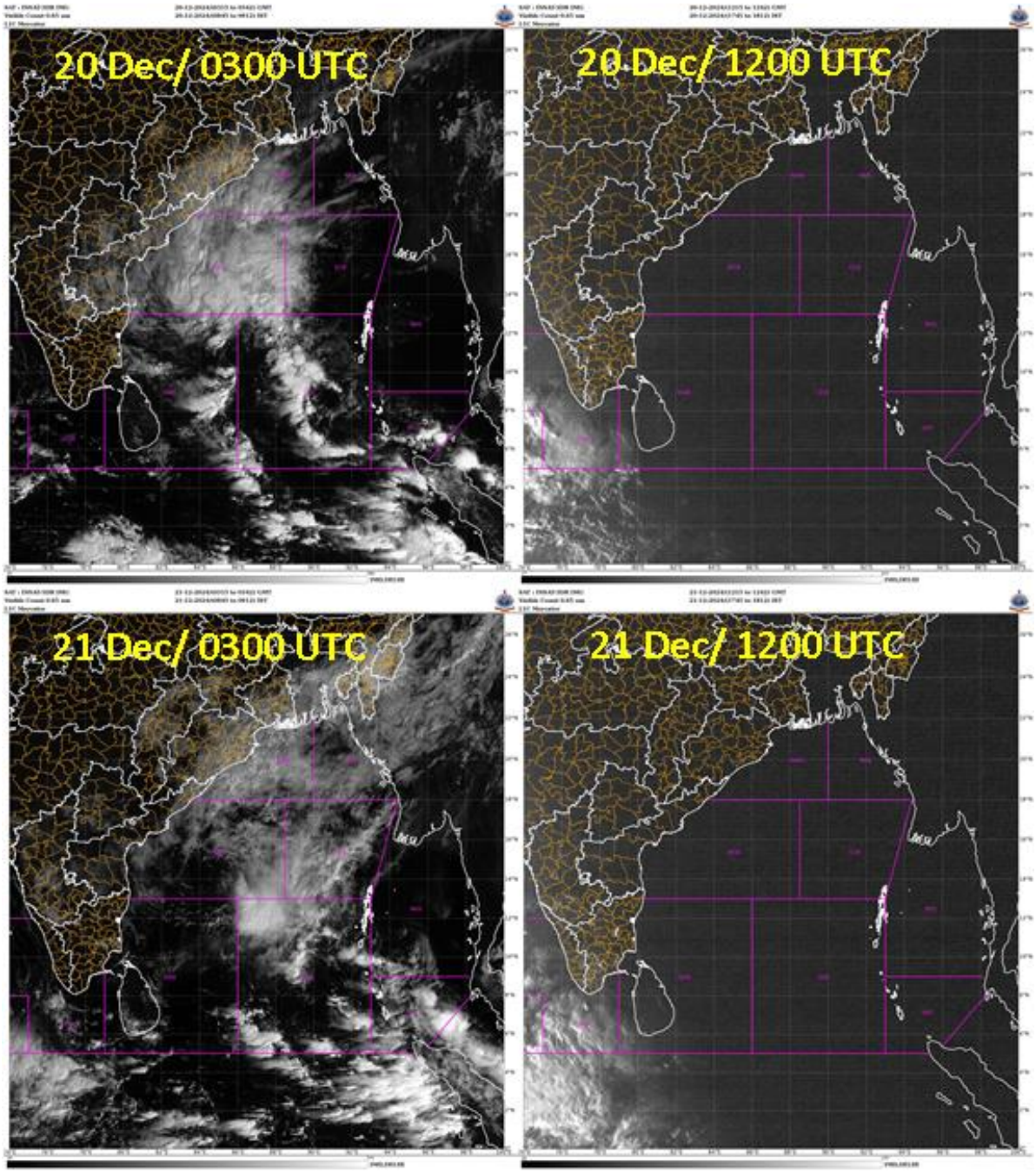


Fig. 2.14.2 (b): INSAT-3D Visible imageries during life cycle of Depression over westcentral BoB off Andhra Pradesh coast during 20th - 21st December, 2024

At 0300 UTC of 21st December, intensity of system was T1.5. Clouds were organised in shear pattern. Associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over BoB between latitude 8.0°N to 15.0°N and longitude 82.0°E to 90.0°E with minimum CTT as -82 to -90°C and moderate convection lay over Mizoram, Tripura and adjoining areas and low/medium clouds over south Gangetic West Bengal, Odisha, north coastal Andhra Pradesh and north eastern states. As per the ASCAT imagery at 0344 UTC, broad scale circulation prevailed over west & adjoining south BoB.

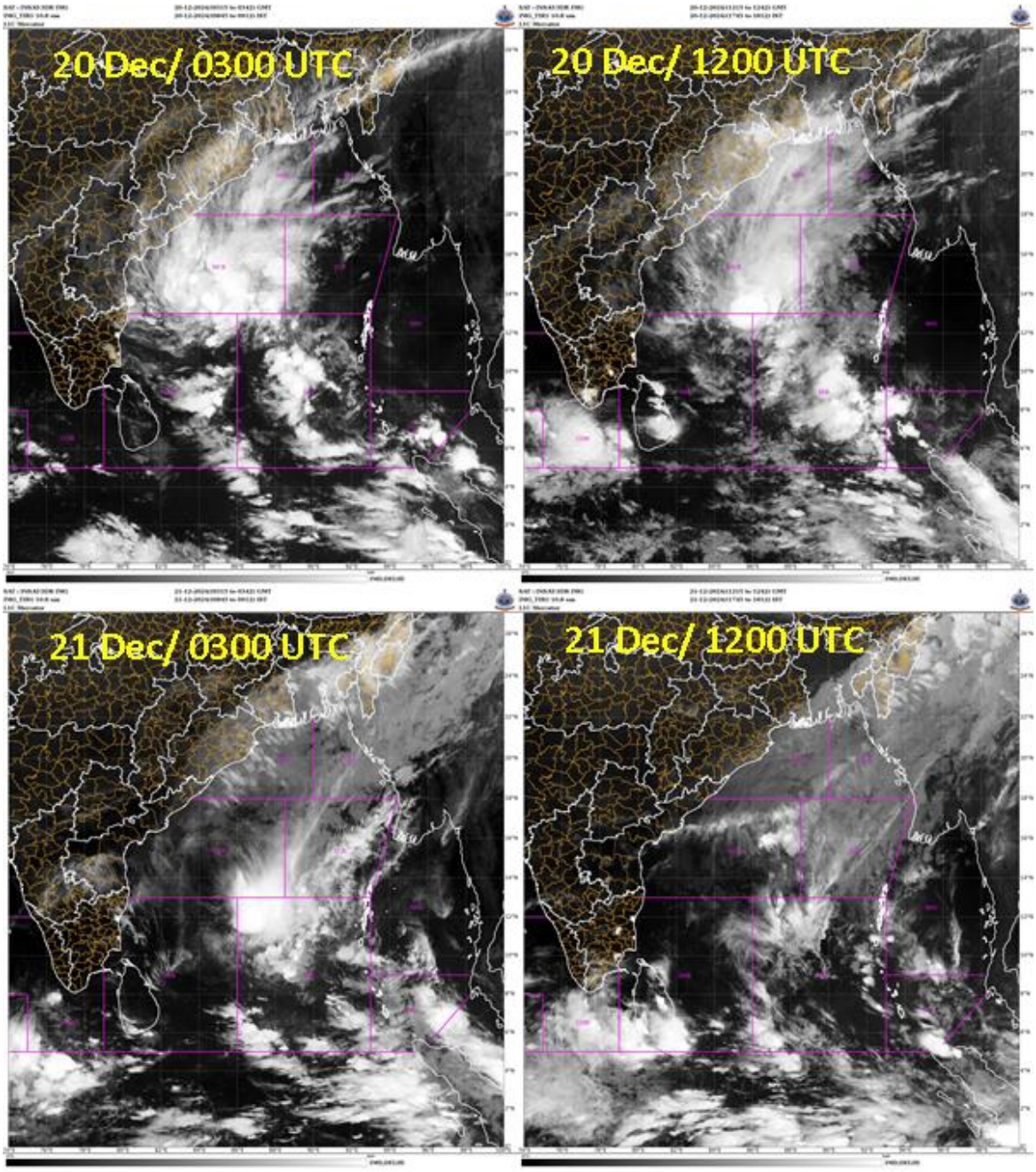


Fig. 2.14.2(c): INSAT-3D IR imageries during life cycle of Depression over westcentral BoB off Andhra Pradesh coast during 20th - 21st December, 2024

At 1200 UTC of 21st December, intensity of the system was T1.5. Clouds were organised in shear pattern. Associated scattered to broken low and medium clouds with embedded intense to very intense convection lay over BoB between latitude 8.0°N to 15.0°N and longitude 82.0°E to 90.0°E with minimum CTT as -82 to -90°C and moderate convection lay over Mizoram, Tripura and adjoining areas and low/medium clouds over south Gangetic West Bengal, Odisha, north coastal Andhra Pradesh and northeastern states.

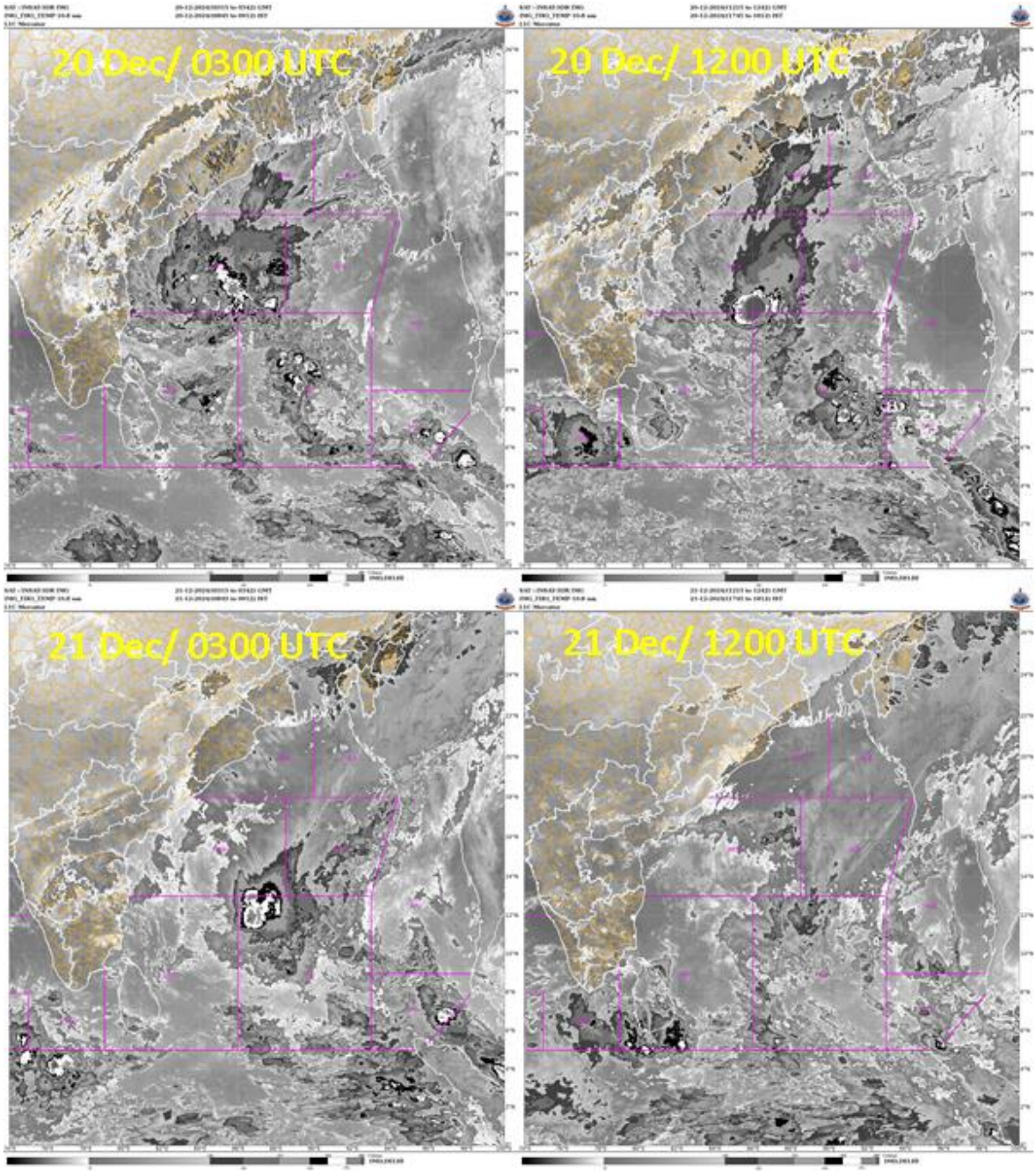


Fig. 2.14.2(d): INSAT-3D IR enhanced imageries during life cycle of Depression over westcentral BoB off Andhra Pradesh coast during 20th - 21st December, 2024

2.14.4. Dynamical Features

IMD GFS (T1534) daily analyses at 0000 UTC of mean sea level pressure (MSLP), winds at 10 m, 850, 500 and 200 hPa levels on 20th Dec to 21st Dec are presented in **Fig. 2.14.3(a) to (b)** respectively.

At 0000 UTC of 20th December, the model indicated a depression over southwest & adjoining westcentral BoB near 13.2^0 N/83.8^0 E. At that time, it lay as a depression over westcentral BoB near 13.7^{0}N/83.5^{0}E. Vertically, the system extended upto 500 hPa level. Thus, the model could correctly capture the genesis and intensity of the system.

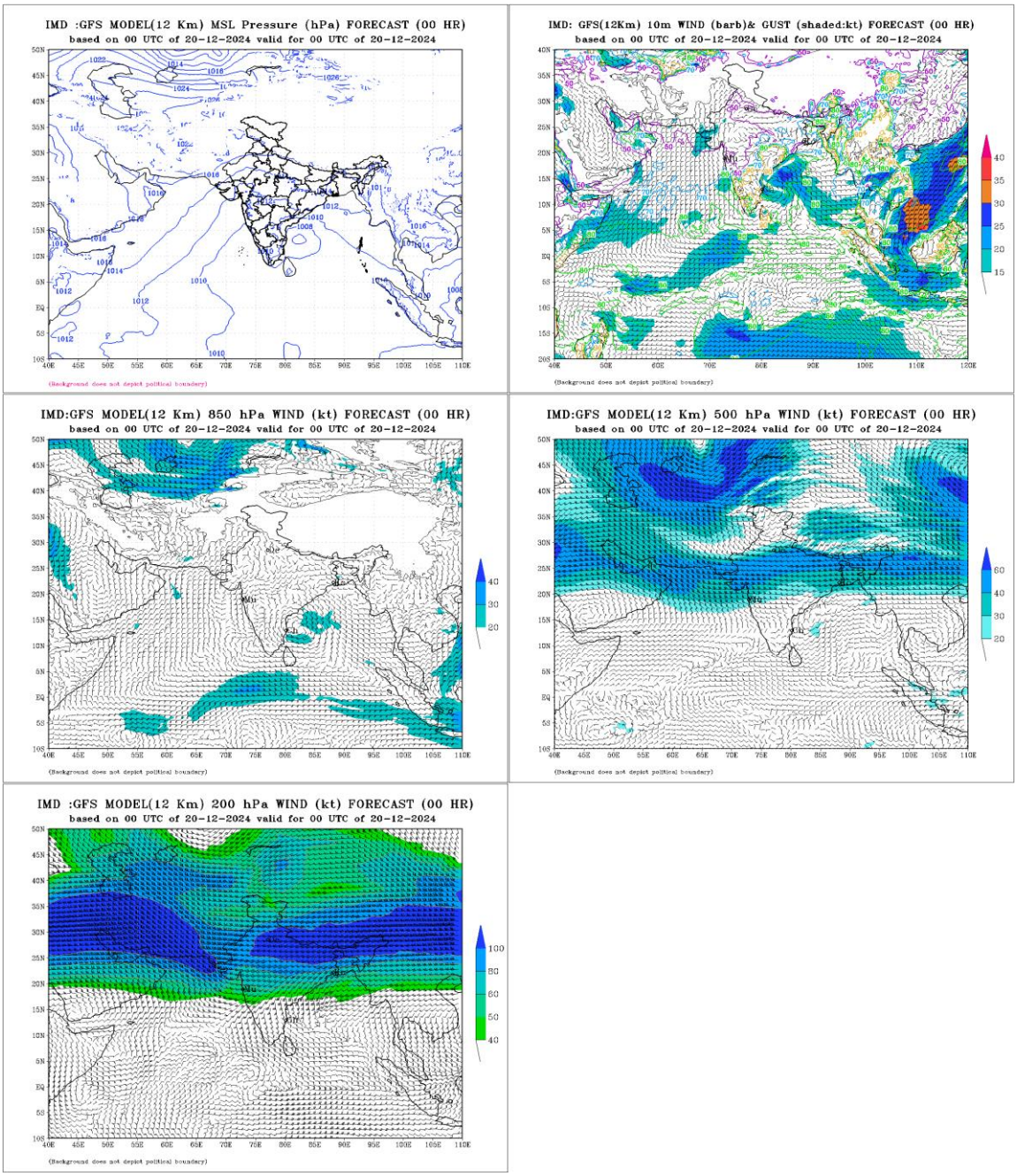


Fig. 2.14.3(a): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 20th December 2024

At 0000 UTC of 21st December, the model indicated a low pressure area over westcentral & adjoining southwest BoB off South Andhra Pradesh-North Tamil Nadu coasts. At 0000 UTC of 21st December, the system moved nearly northeastwards and lay as a depression over westcentral BoB. Thus, the model could not capture the movement and intensity of the system.

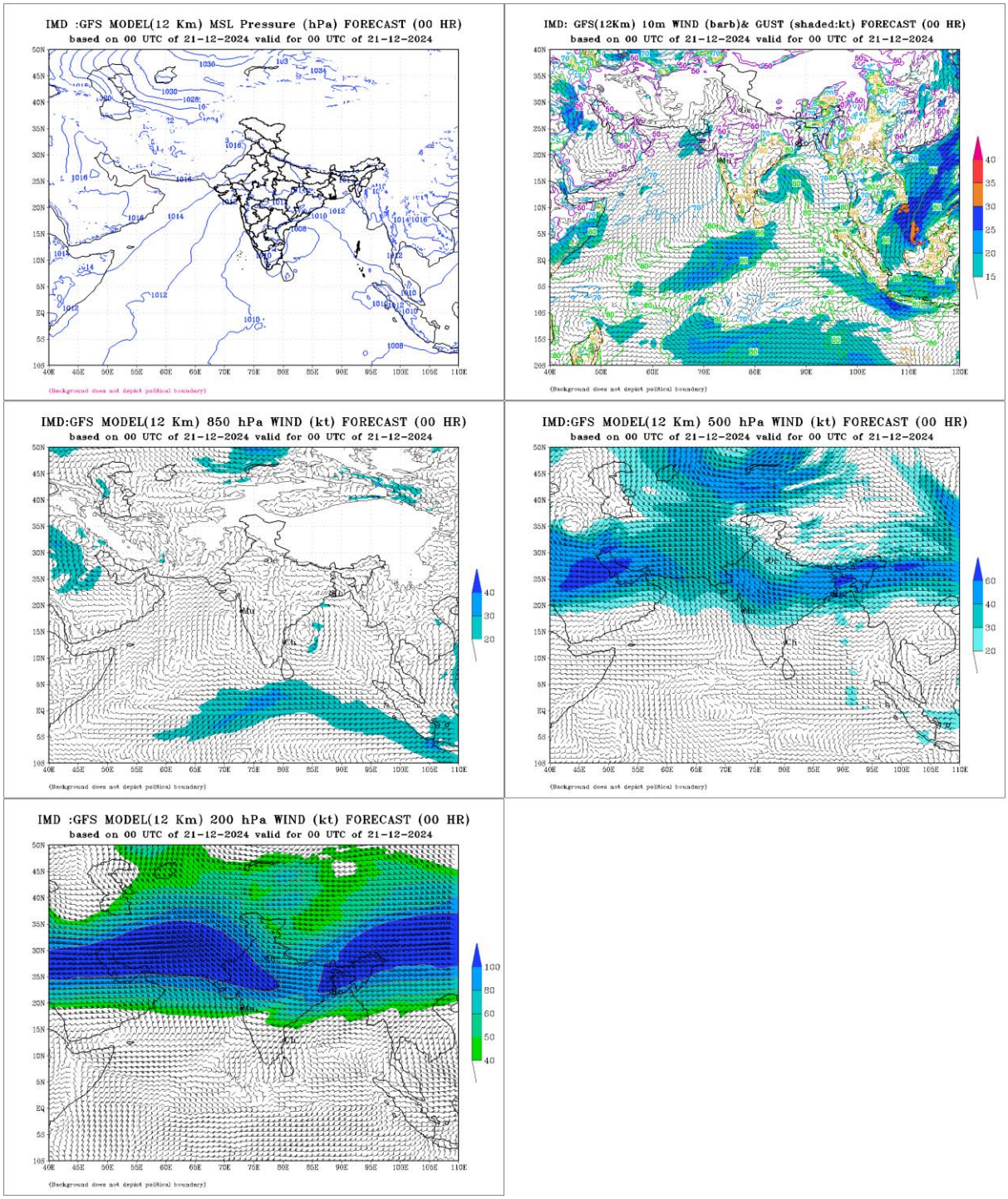


Fig. 2.14.3(b): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 21st December 2024

Though IMD GFS correctly captured the genesis of the system, its further movement and intensity was not correctly captured.

2.14.5. Realized Weather

Rainfall associated with the depression based on IMD-NCMRWF satellite gauge merged data are depicted in **Fig 2.14.4**. It is seen that light to moderate rainfall occurred at isolated places with heavy to very heavy rainfall at isolated places over coastal areas of Tamil Nadu, Puducherry & Karaikal, South Odisha and Andhra Pradesh & Yanam on 19th December. Light to moderate rainfall occurred at isolated places with heavy rainfall at isolated places over coastal areas of Odisha and Gangetic West Bengal on 20th December.

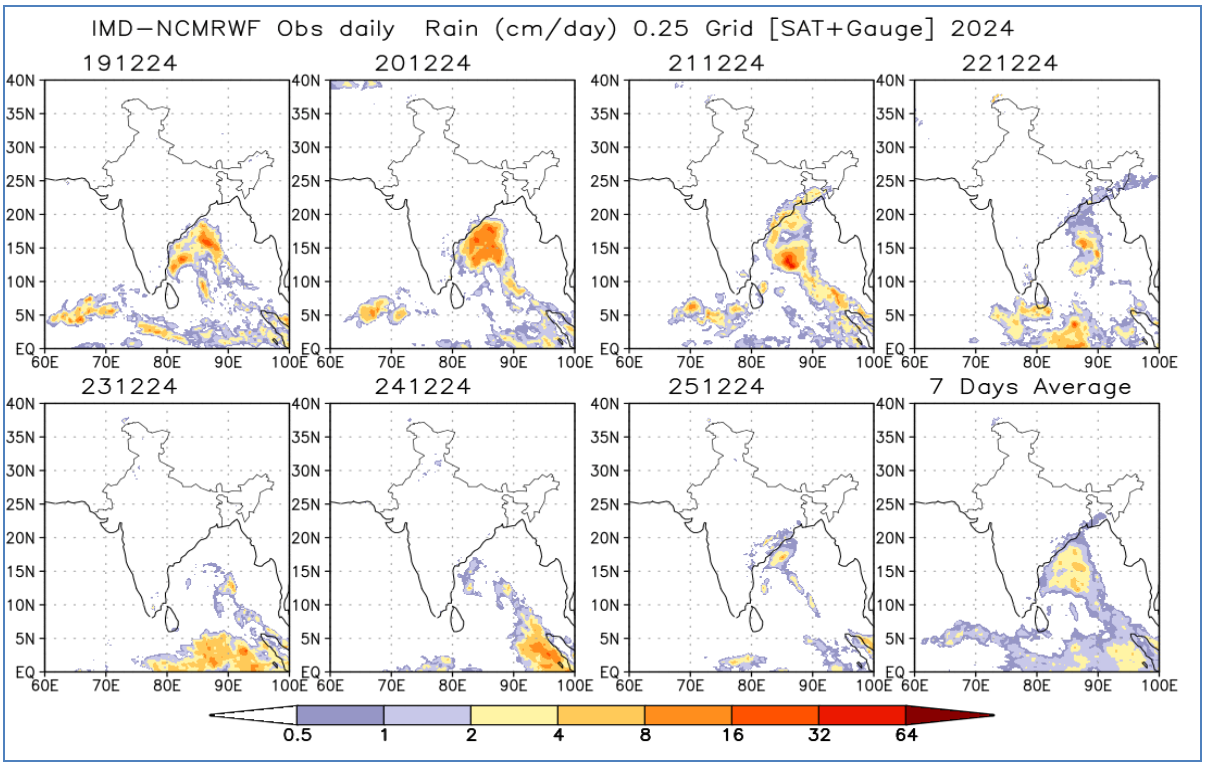


Fig. 2.14.4: NCMRWF-IMD satellite gauge merged data plots of realized 24 hours accumulated rainfall from 20th to 21st December, 2024.

2.14.5.1 Rainfall forecast verification

The forecast for heavy rainfall in association with the system are verified with the 24 hours accumulated rainfall realized at various stations ending at 0830 IST of date. The details of the day-wise verification are given in **Table - 2.14.2.**

Table 2.14.2: Heavy rainfall forecast verification

Date/Base Time of observation	24 hr Heavy rainfall warning ending at 0300 UTC of next day	Realised 24-hour heavy rainfall (≥ 7 cm) ending at 0300 UTC of date
20.12.2024 / 0830 IST	**Coastal Andhra Pradesh**: Heavy rainfall at isolated places is very likely over coastal Andhra Pradesh on 20th December and over north coastal Andhra Pradesh on 21st December 2024.	**20th December:** **Tamil Nadu, Puducherry & Karaikal: Needamangalam (dist Thiruvarur) 7** **21st December:** **Tamil Nadu, Puducherry & Karaikal**: Sandhiyur (dist Salem) 8 and Kodumudiyaru Dam (dist Tirunelveli), Balamore (dist Kanyakumari), Oothu (dist Tirunelveli) and Nandhiyar Head (dist Thiruchirappalli) 7 each. **Coastal Andhra Pradesh & Yanam**: Bondapalle (dist Vizianagaram) 9, Merakamudidam (dist Vizianagaram) 8, Bobbili (dist Vizianagaram), Therlam (dist Vizianagaram), Mentada (dist Vizianagaram), Bheemunipatnam (dist ishakhapatnam) 8 each and Nellimarla (dist Vizianagaram), Garividi (dist Vizianagaram), Cheepurupalle (dist Vizianagaram), Gajapathinagaram(dist Vizianagaram) 7 each. **Odisha**: Ranpur (dist Nayagarh) 11, Begunia (dist Khurda) 8, Berhampur (dist Ganjam) 8 each and Jatni (dist Khurda), Khordha (dist Khurda), Pipili (dist Puri), Naugaon (dist Jagatsinghpur), Banpur (dist Khurda), Belaguntha (dist Ganjam), Krishnaprasad (dist Puri), Gop (dist Puri), Purushottampur (dist Ganjam) 7 each.

CHAPTER-III

3.1. NWP Models in operational use during the year 2023

3.1.1. Global Models

Global Forecast System (GFS):

The Global Forecast System (GFS), adopted from National Centre for Environmental Prediction (NCEP) was implemented at India Meteorological Department (IMD), New Delhi on Mihir 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).

Global ensemble Forecast Systems (GEFS):

A very high resolution (12 km grid scale) state-of-the-art global Ensemble Prediction Systems (EPS) developed at IITM, Pune based on GFS model of IMD are operational for generating operational 10-days probabilistic forecasts of weather with 21 members. The EPS involves the generation of multiple forecasts using slightly varying initial conditions.

NCMRWF Unified Model (NCUM):

The global unified model NCUM adapted from the UK Met Office and assimilation system of GFS model adapted from NCEP GFS. The observations from various in-situ and remote sensing platforms (e.g., satellites and radars) are assimilated to generate initial condition at NCMRWF using hybrid 4D-Var data assimilation system. It uses “ENDGame” dynamical core, which provides improved accuracy of the solution of primitive model equations and reduced damping. NCUM is a grid point model which has a non-hydrostatic dynamics with a deep atmosphere suitable for all scales. It has semi-implicit time integration with 3D semi-Lagrangian advection, terrain following height coordinates and high order advection. NCUM has the model physics configuration of GA7.2 (Global Atmosphere version 7.2) and a land surface model configuration of GL 8.1 which is based on JULES land surface scheme.

NCMRWF Ensemble Prediction System (NEPS-G):

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 ~12km. The NCUM model analysis is used as the initial condition for the control model forecast from NCUM model.

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

The THORPEX Interactive Grand Global Ensemble (TIGGE) is an implementation of ensemble forecasting for global weather forecasting and is part of THORPEX, an international research programme of World Meteorological Organization (WMO) which 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) to generate products e.g., deterministic and Ensemble TC track forecasts, Strike Probability Maps, Strike probability of cities within the range of 120 kms 4 days in advance. The forecast products are made available in real time.

Forecasts from other GDPFS centers:

The forecast products and guidance from other Global Data Processing and Forecasting System (GDPFS) centers. Some of them are European Centre for Medium-Range Weather Forecasts (ECMWF), India Meteorological Department (IMD), Japan Meteorological Agency (JMA), Korea Meteorological Administration (KMA), Met Office - UK (UKMO), and National Centers for Environmental Prediction, USA (NCEP).

3.1.2. Regional Forecast System

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

The mesoscale forecast system Weather Research and Forecast WRFDA (version 3.9.1) with regional GSI data assimilation is being operated daily twice to generate mesoscale analysis at 3 km horizontal resolution using IMD GFS initial and boundary conditions. The WRF (ARW) is run 4 times a day at 06 hourly interval.

Coupled Hurricane WRF- Hybrid Coordinate Ocean Model (HWRF-HYCOM):

The coupled HWRF -HYCOM is operational with triple nested (18x6x2 km) atmospheric component for tropical cyclone forecasting includes vortex initialization and correction, GSI based regional data assimilation, coupler for two-way coupling between atmosphere and ocean components and fine-tuned physical parameterization schemes. The model utilized ocean initial state from the ITOPSI (INCOIS Tendral Ocean Prediction System – Indian Ocean Model) during each cycle to initialize the HYCOM ocean component. This model is customized specifically to forecast the track, intensity and structure of tropical cyclones. It is run 4 times a day in cyclic mode with 6 hourly cycles.

High Resolution Rapid Refresh Modeling System (HRRR):

The High-Resolution Rapid Refresh system based on Weather Research and Forecast (WRF-ARW) model with WRFDA (3DVAR-FGAT) data assimilation is experimentally operationalized in IMD with horizontal resolution of 2km. The model uses forecast of IMD-GFS (T1534L64) model as first guess and forecast as boundary during cold start and is then cycled providing hourly updates based on Radar Data. The HRRR is run to produce forecasts up to 12 hours and forecasts are made available after every two hours on NWP website. The model is run in three different domains covering Indian mainland. The three domains are North-West domain, East & North-East domain and South-Peninsular domain.

NCMRWF Unified Model -Regional (NCUM-R):

It is a regional model having a horizontal grid resolution of ~4km with 90 vertical levels reaching up to 40 km height. NCUM-R uses the high-resolution analysis prepared by the regional 4D-Var system. In addition to most of the in-situ and satellite observation types used in the global NCUM, Indian DWR observations of radial wind and rainfall intensity estimates are also used in the regional NCUM DA.

3.1.3. 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.

Genesis Potential Parameter (GPP):

A cyclone genesis parameter, termed the genesis potential parameter (GPP), for the North Indian Sea. 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 grid point analysis and forecast of the genesis parameter up to seven days is also generated on real time for cyclogenesis over the North Indian Ocean.

Multi-model ensemble (MME) technique:

The multi model ensemble (MME) technique 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. 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 based on the past data. These coefficients are then used as weights for the ensemble forecasts A collective bias correction is applied in the MME by applying multiple linear regression-based minimization principle for the member models GFS(IMD), GFS(NCEP), ECMWF, UKMO and JMA. ECMWF data are available at 24h intervals.

Since 2021, IMD has also implemented IFS TC Tracker (available from ECMWF) for all available Tropical Cyclone Ensemble Forecast based on Global Models Ensemble (TIGGE) models (9 in numbers). These 9 models are from Bureau of Meteorology, Australia (BoM), Environment and Climate Change Canada (ECCC), ECMWF, IMD-GFS, JMA, KMA, UKMO, NCEP-GFS and NCMRWF-NCUM are nine International Institutes model outputs (contributing to the TIGGE) are chosen based on availability at the ECMWF-TIGGE

Statistical Dynamical model for Cyclone Intensity Prediction (SCIP):

A statistical-dynamical model (SCIP) has been implemented for real time forecasting of 12 hourly intensities up to 120 hours. The model parameters are derived based on model analysis fields of past cyclones. For the real-time forecasting, model parameters are derived based on the forecast fields of IMD-GFS model.

Rapid Intensification (RI) Index:

A rapid intensification index (RII) is developed for tropical cyclones over the Bay of Bengal. The RII uses large-scale characteristics of tropical cyclones to estimate the probability of rapid intensification (RI) over the subsequent 24-h. The forecasts are made available in real time since 2013.

Decay of Intensity after the landfall:

The decay model has been used for real time forecasting of decaying intensity (after landfall) of TCs.

3.2 Performance of NWP models during SCS REMAL

3.2.1 Cyclogenesis prediction (Genesis Potential Parameter) for REMAL

The Fig. 3.2.1 is showing the GPP analysis and forecasts during the initial stage of the Cyclone Remal using GFS model analysis and forecasts. The panels in the figure starting from top-left corner to bottom-right corner represent the analysis and forecasts of GPP after 24, 72 and 120 hours respective based on at 1200 UTC on 22nd May, 2024.

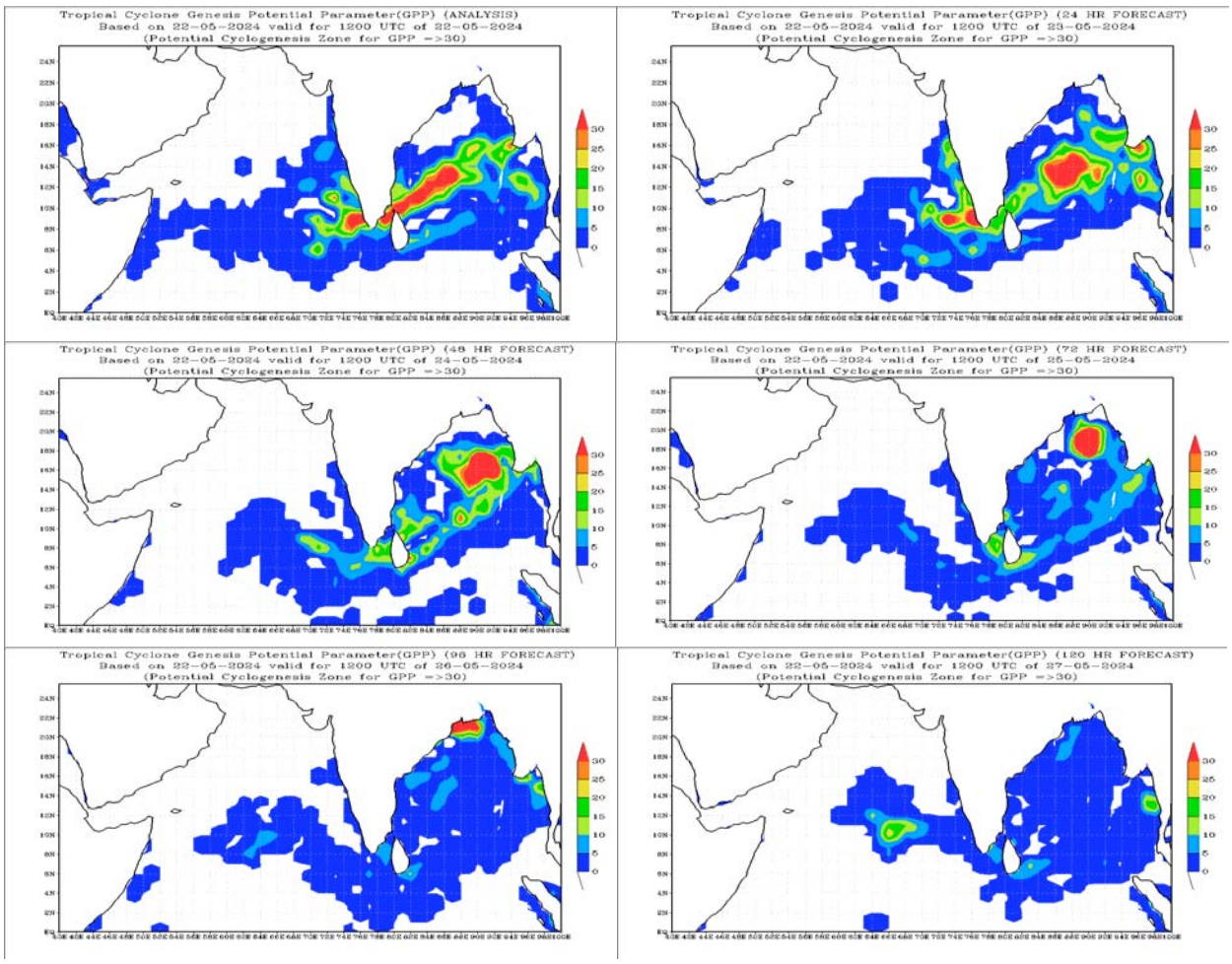


Fig. 3.2.1 Predicted zone of Cyclogenesis based on 0000 UTC of 22nd May -27th May 2024 valid for 0000 UTC of 22nd May, 2024

In the analysis on 22nd May, the zone significant GPP was found to be elongated in southwest-northeast direction extending from Gulf of Munnar to eastcentral BoB. During this stage the system was in a stage of low pressure area. As the system intensified gradually the prominent GPP zone became isolated and moved northeastwards initially and then northwards gradually with increasing forecast hours. An area of with GPP crossing necessary threshold was found to be existed up to 96 hours forecast valid till 1200 UTC of 26th May, 2024. Therefore, the cyclogenesis of the and its intensification to a cyclonic storm was well predicted at 1200 UTC of 22nd May, 2025. Moreover, although the predicted track of the IMD GFS model had as eastward bias, the trajectory of the significant GPP zone nearly followed the best estimated track of the cyclonic storm Remal. Another feature may be noted that the spatial coverage of the GPP zone gradually decreased as the system moved northwards before it reaches over northwest BoB near Bangladesh-West Bengal coasts on 26th May, 2024.

3.2.2 Track prediction by NWP models

In the Fig. 3.2.2 (a), the tracks of various models and members along with control model of the IMD Global Ensemble Forecast System (GEFS) and NCMRWF ensemble prediction systems (NEPS) at 0000 UTC of 24th May, 2024 are plotted in the different panels.

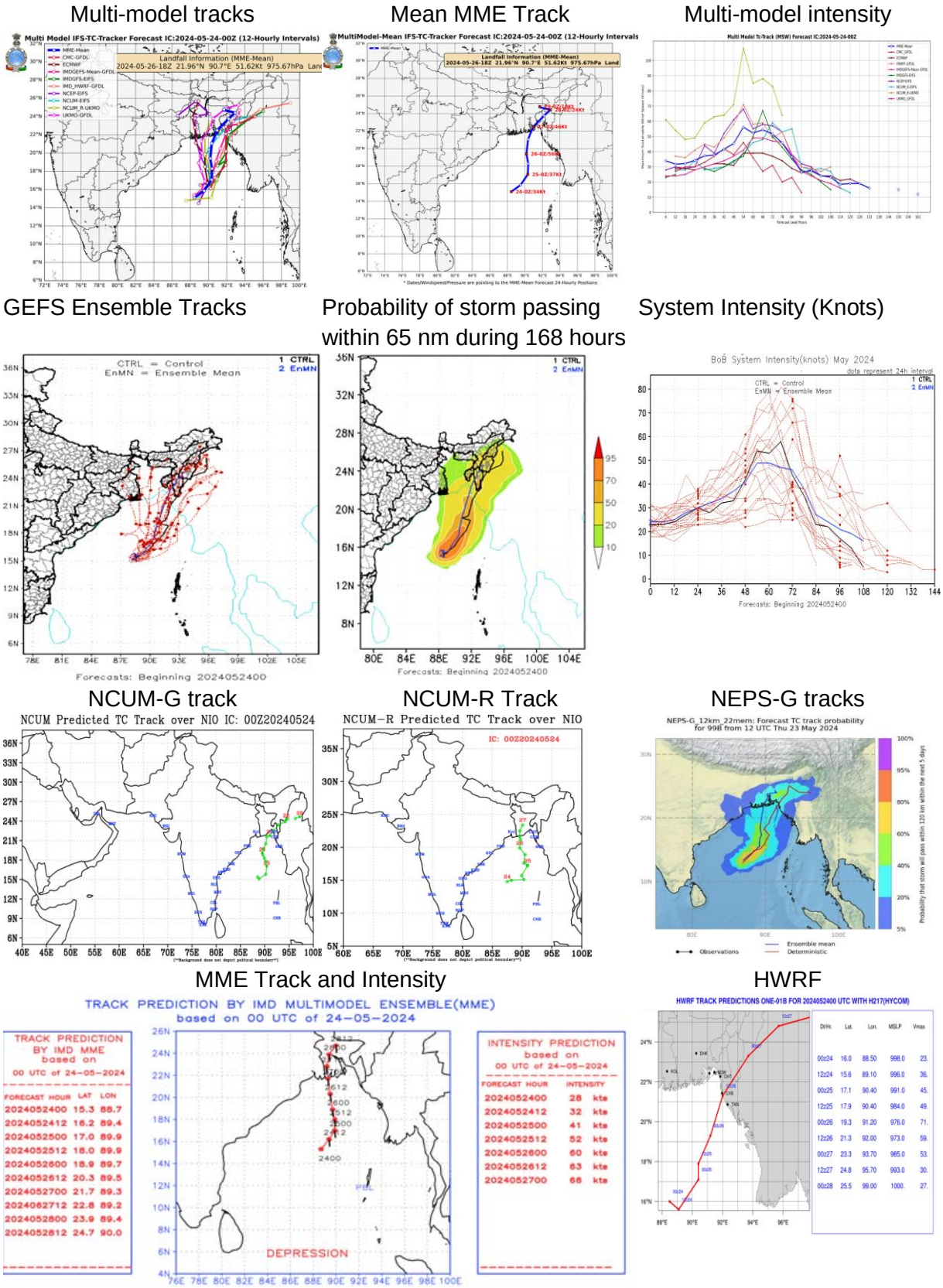
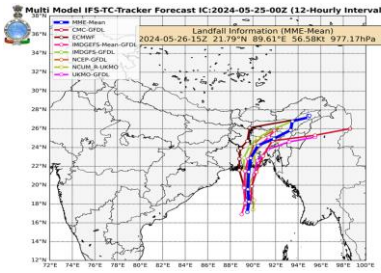


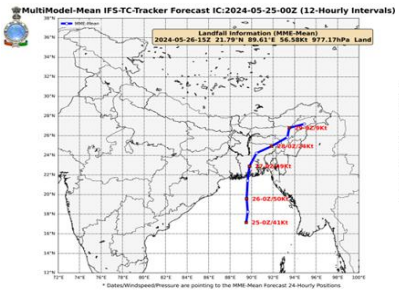
Fig. 3.2.2 (a) NWP model track and intensity forecasts based on 0000 UTC of 24.05.2024

Most of the members GEFS including control model track indicated north-northeastward movement crossing at south Bangladesh-Myanmar coasts. The range of wind speed forecasts for maximum MSW was 30-80 knots just before landfall. The NCUM-G and NEPS predicted the landfall over south Bangladesh coasts but far from the landfall location. On the other hand, the landfall point from NCUM-R model track was close to the observed landfall location. The HWRF model track was biased towards east and nearly followed the ensemble mean track GEFS model with a highest value of MSW of 70 knots. The individual model tracks (top-left panel) were showing a spread regarding the landfall point starting from West Bengal to south Bangladesh-Myanmar coasts

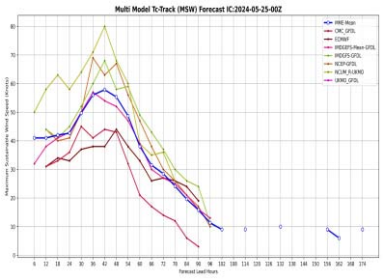
Multi-model tracks



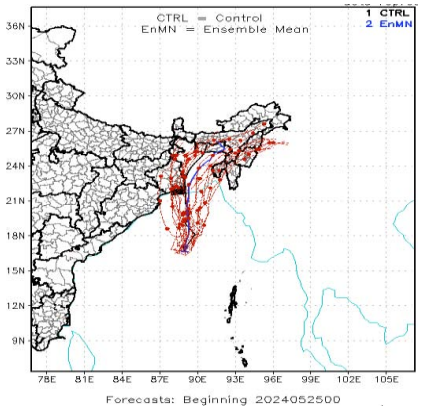
Mean MME Track



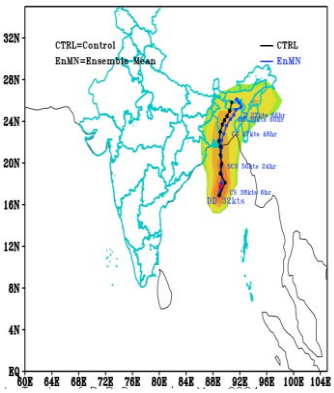
Multi-model intensity



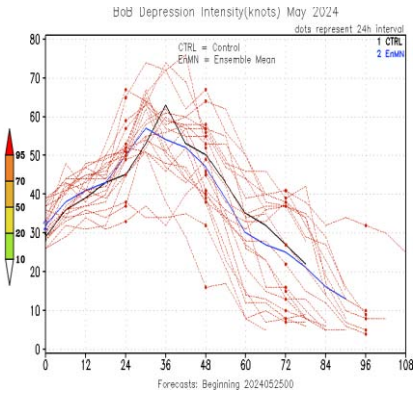
GEFS Ensemble Tracks



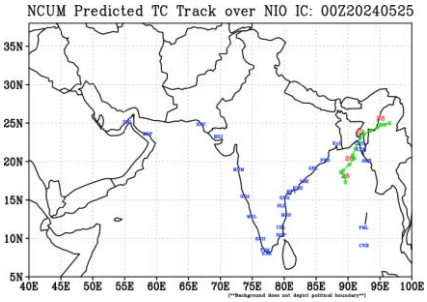
Probability of storm passing within 65 nm during 168 hours



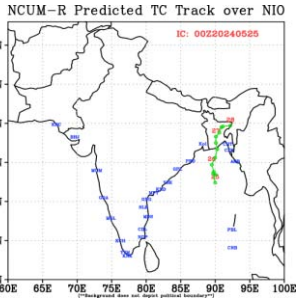
System Intensity (Knots)



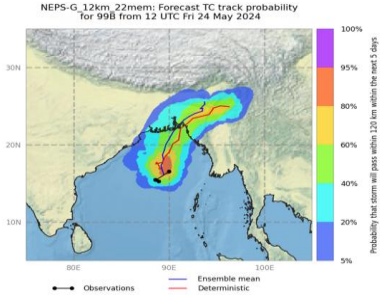
NCUM-G track



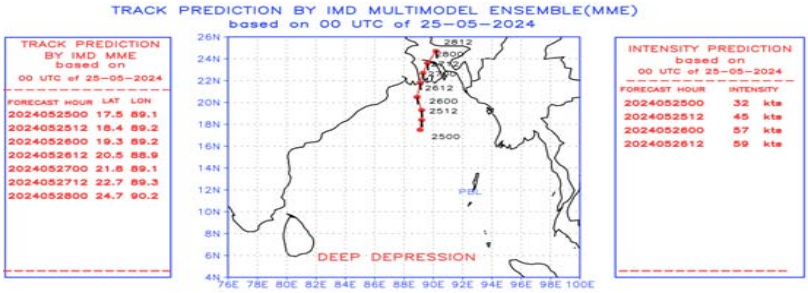
NCUM-R Track



NEPS-G Track



MME Track and Intensity



HWRF

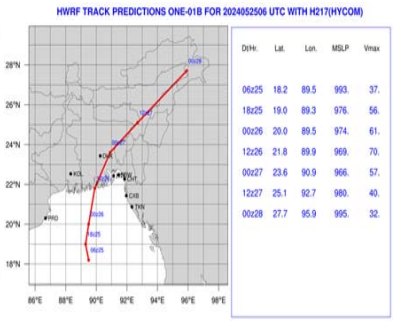


Fig. 3.2.2 (b) NWP model track and intensity forecasts based on 0000 UTC of 25.05.2024

The mean MME track (top-middle) at the same time showed initial northeastwards movement followed by north-northeastward movement crossing south Bangladesh coast around 0000 UTC of 27th May, 2024. Although the regression-based MME notified as MME forecasts indicated a very accurate track. However, the track after the landfall has as more northward movement compared to westward.

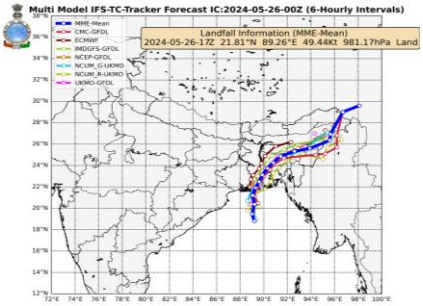
The Fig 3.2.2 (b) describes the track prediction by various NWP models at 0000 UTC of 25th May, 2024. The GEFS along with control GFS model, NCUM global and regional models, NEPS, HWRF and mean MME and regression-based MME tracks were available for comparison.

The GEFS members and control model along with mean track forecasts at 0000 UTC of 25th were found to be more accurate compared to the forecasts on 24th May. The tracks forecasts by control model and ensemble mean were very close to the best track estimate and the same followed even after landfall up to 12 UTC of 27th May. The recurvature towards northeast direction after the landfall was better predicted by the mean ensemble track. The peak intensity of the storm although overestimated by the many members of the GEFS, the range of wind speed (50-70 Knots) and ensemble mean captured the MSW during landfall time. The HWRF model track forecast also became closer to the best estimate tracks till landfall. The peak intensity of the storm before landfall predicted by the model was 58 knots. The recurvature in the model track after the landfall showed more northward bias against larger eastwards component in the movement. The NCUM group of models including NEPS members still had eastward bias with their landfall points over south Bangladesh near Chittagong. The both mean MME and regression-based MME produced very accurate forecasts of landfall and also fairly the eastwards recurvature after the landfall. Although a few individual models had overestimated intensity prediction, both MMEs predicted peak intensity before landfall around 60 knots.

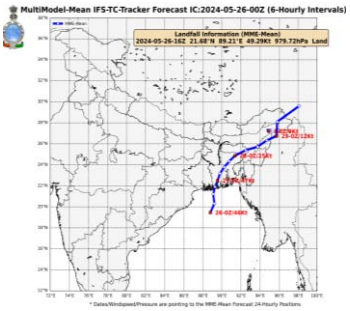
The forecasts of tracks all model along with intensity based on 0000 UTC of 26th May with a lead time less than 24 hours before landfall are plotted in Fig. 14(c). Due to shorter lead period before landfall, most of the models predicted very accurate tracks till landfall along with better timings of the event. The spread of the members for the MME or even for single model ensembles e.g., GEFS and NEPS were very less compared to the forecasts of the previous cycles. However, the regional models NCUM-R and HWRF predicted landfall point a little east of the observed location as the eastward component of storm movement acted early in both the models. In this cycle, the NCUM-G and NCUM-R models corrected their eastward bias in their forecasts and forecast tracks were very close to the best estimate. The intensity of the storm was underestimated by the GEFS model. Both the MMEs indicated marginally weaker MSW compared to the observed estimate. The HWRF predicted intensity of 58 knots around landfall time.

As the severe cyclone Remal made landfall crossing West-Bengal-Bangladesh coasts during 1700-1900 UTC of 26th May, the storm location at 0000 UTC 27th May was over coastal Bangladesh. Based on the initial condition at this time, the forecast tracks of all models based are shown in Fig. 3.2.2 (d). The GFS and members of GEFS model along with mean ensemble tracks produced very good forecast after the landfall. However, the forecast track by these models were biased towards more northward movement after the landfall although observed best estimate track had more eastward component in the storm movement. Due to these models the mean MME track also had a fair amount of northward bias although weakening of the storm was predicted well.

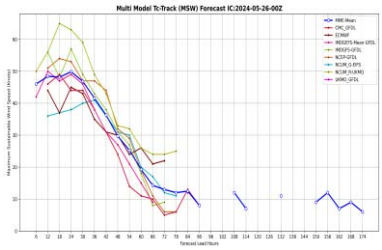
Multi-model tracks



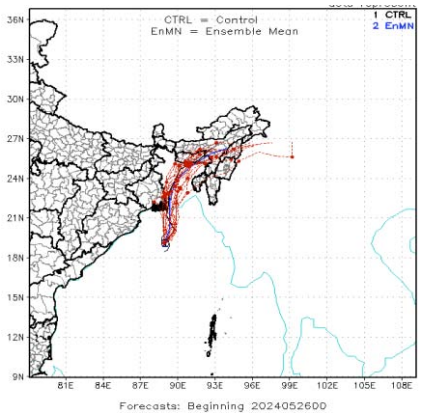
Mean MME Track



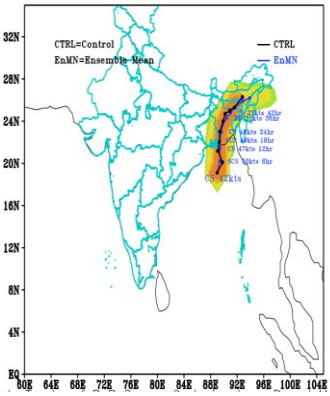
Multi-model intensity



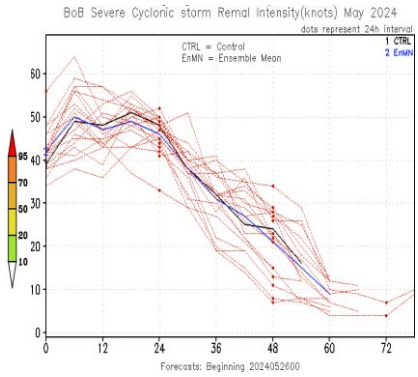
GEFS Ensemble Tracks



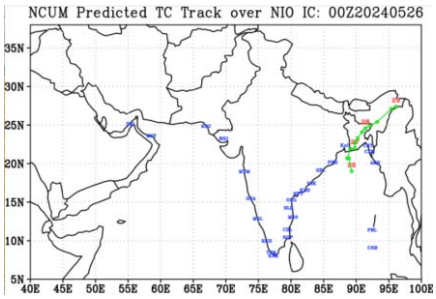
Probability of storm passing within 65 nm during 168 hours



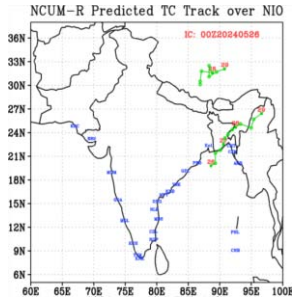
System Intensity (Knots)



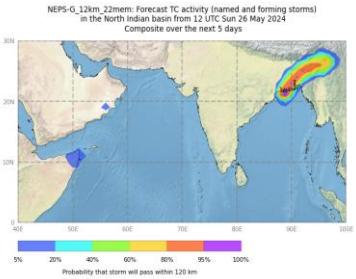
NCUM-G track



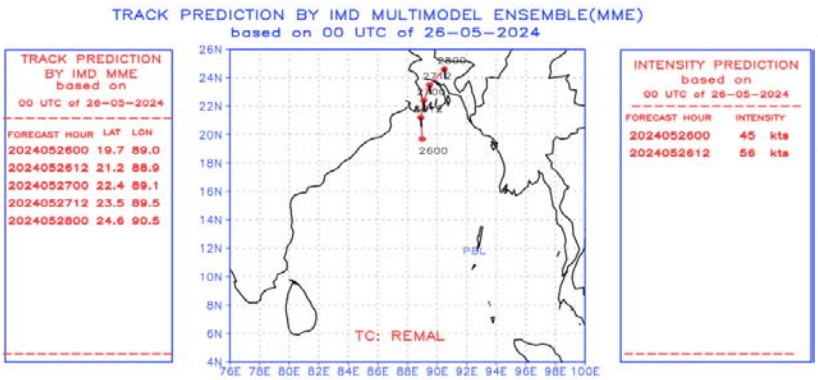
NCUM-R Track



NEPS-G Track



MME Track and Intensity



HWRF

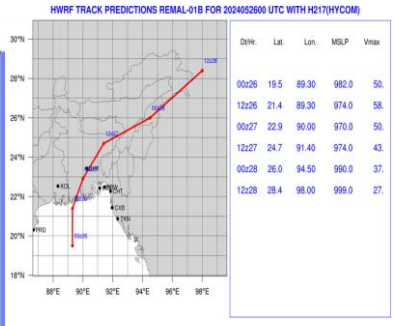
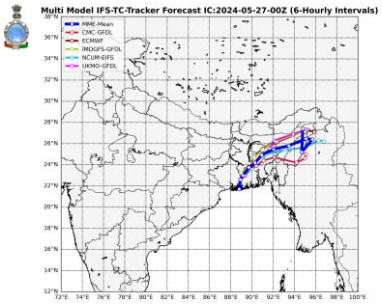


Fig. 3.2.2 (c) NWP model track and intensity forecasts based on 0000 UTC of 26.05.2024

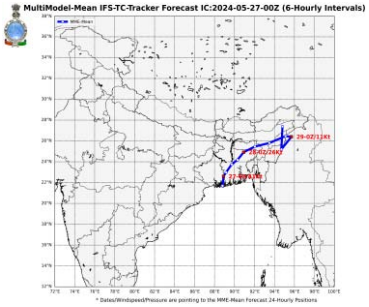
The NCUM group of models and HWRF suggested very accurate track compared to GFS group of models. The steady weakening of the storm was captured by all models.

The comparative verification of different models are described in the next sub-section with tables and figures.

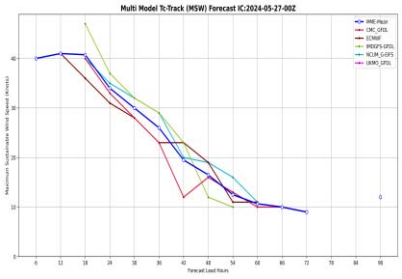
Multi-model tracks



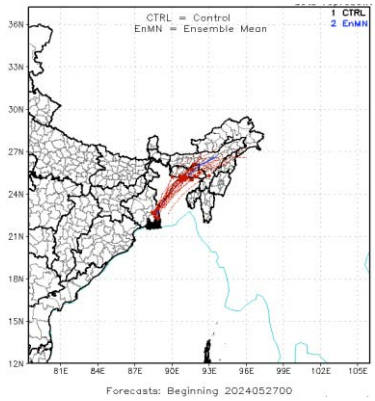
Mean MME Track



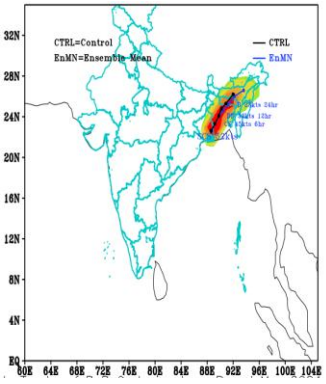
Multi-model intensity



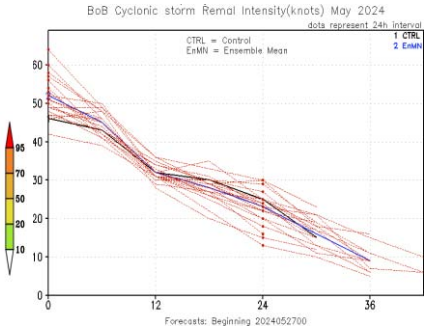
GEFS Ensemble Tracks



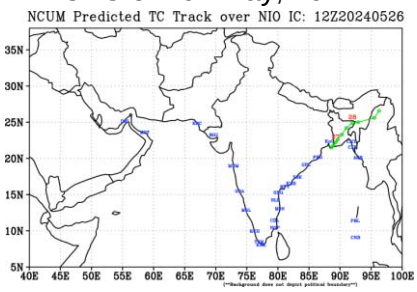
Probability of storm passing within 65 nm during 168 hours



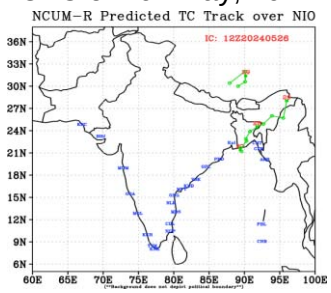
System Intensity (Knots)



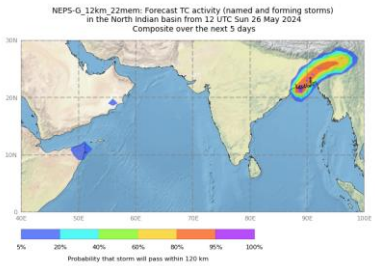
NCUM-G track based on 12 UTC of 26th May, 2024



NCUM-R Track based on 12 UTC of 26th May, 2024



NEPS-G Tracks based on 12 UTC of 26th May, 2024



HWRF

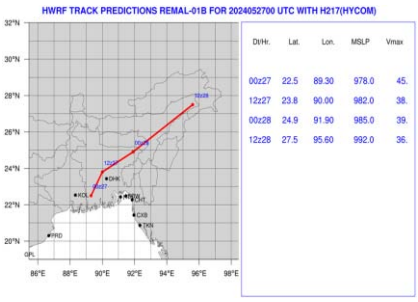


Fig. 3.2.2 (d) NWP model track and intensity forecasts based on 0000 UTC of 27.05.2024 (the models from NCMRWF based on 1200 UTC of 26th May)

3.2.3 Track forecast errors by various NWP Models

In this section, various tables are prepared to compare the errors of different models. The models are indicated with in the table with their short names as described in the annexure-1 of the document.

The average track forecast errors (Direct Position Error) in km at different lead period (hr) of various models are presented in **Table 3.2.1**. From the verification of the forecast guidance available from various NWP models, it is found that the average track forecast errors of both mean MME and regression-based MME were minimum for 24 and 48 hr and 72 hours forecasts. The ECMWF and both MMEs had DPE less than 100 km up to 48 hours. The IMD operational forecasts had DPE less than 100 km even in 84 hours forecast. As expected, GFS group of models had smaller errors for shorter lead time but it increased rapidly after 60 hours. The comparison of track errors of the global models can also be seen in **Fig. 3.2.3 (a)**. The regional models also furnished larger track errors for the severe cyclonic storm Remal.

Table 3.2.1. Average track forecast errors (Direct Position Error (DPE)) 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	120H
IMD-MME	40(3)	39(3)	65(3)	72(3)	101(2)	93(2)	103(1)	181(1)		
HWRF	57 (14)	85 (13)	158 (11)	224 (9)	351 (7)	392 (5)	461 (3)			
GEFS (CNTL)	67(8)	69(7)	102(6)	100(5)	167(4)	255(3)	371(2)	495(1)		
GEFS (ENS_MEAN)	56(8)	69(7)	89(6)	112(5)	166(4)	187(3)	237(2)	244(1)		
NCUM-R	100(9)	125(9)	129(8)	145(7)	175(6)	147(5)				
NUCM-G	73(10)	89(9)	102(8)	143(8)	200(7)	214(8)	171()7	180(7)	180()6	203(5)
NEPS-G	43(8)	61(8)	96(7)	146(6)	189(5)	195(4)	173(3)	101(2)	54(1)	NA(0)
NCUM_R-UKMO	83 (5)	133 (5)	152 (5)	166 (5)	183 (4)	112 (3)	nan (0)	nan (0)		
NCEP-GFDL	60 (6)	48 (5)	26 (5)	37 (4)	64 (3)	83 (2)	126 (1)	nan (0)		
HWRF-GFDL	67 (1)	93 (1)	138 (1)	190 (1)	291 (1)	469 (1)	623 (1)	805 (1)		
ECMWF-EIFS	62 (8)	59 (7)	57 (6)	73 (5)	85 (4)	127 (3)	186 (2)	259 (1)		
IMDGFS-EIFS	nan (0)	144 (1)	256 (1)	196 (1)	307 (1)	314 (1)	479 (1)	496 (1)		
IMDGFS-GFDL	65 (7)	76 (6)	70 (5)	92 (4)	110 (3)	177 (2)	271 (1)	nan (0)		
NCEP-EIFS	92 (1)	54 (1)	39 (1)	39 (1)	83 (1)	63 (1)	124 (1)	256 (1)		
NCUM_G-EIFS	60 (4)	82 (4)	114 (4)	112 (3)	239 (2)	201 (1)	316 (1)	338 (1)		
CMC_GFDL	45 (7)	60 (6)	103 (6)	160 (5)	208 (4)	344 (3)	437 (2)	nan (0)		
MMEM	40 (8)	51 (7)	65 (6)	81 (5)	106 (4)	118 (3)	163 (2)	183 (1)		
IMDOPER	44 (8)	72 (7)	62 (6)	54 (5)	61 (4)	62 (3)	81 (2)	143 (1)		

Table 3.2.2. Average Intensity Forecast Errors of maximum sustained wind in knots (Number of forecasts verified is given in the parentheses). Negative sign indicates underestimation of intensity and vice versa

Lead Time	12 Hr	24 Hr	36 Hr	48 Hr	60 Hr	72 Hr	84 hr	96 hr
IMD-SCIP (AAE)	7.0(3)	9.0(2)	9.0(2)	10.0(1)	3.0(1)			
HWRF	10.9 (14)	15.2 (13)	12.8 (11)	11.9 (9)	10.7 (7)	8.1 (5)	8.3 (3)	
CTRL	-1(8)	-2(7)	-1(6)	-4(5)	-3(4)	-1(3)	-12(2)	-3(1)
EnMN	0(8)	-2(7)	-3(6)	-5(5)	-4(4)	-1(3)	-5(2)	1(1)
NCUM_R-UKMO	15 (5)	17 (5)	19 (5)	22 (5)	12 (4)	12 (3)	nan (0)	nan (0)
NCEP-GFDL	10 (6)	4 (5)	9 (5)	7 (4)	5 (3)	6 (2)	17 (1)	nan (0)
HWRF-GFDL	11 (1)	15 (1)	14 (1)	21 (1)	1 (1)	8 (1)	5 (1)	7 (1)
ECMWF-EIFS	7 (8)	7 (7)	9 (6)	10 (5)	12 (4)	9 (3)	7 (2)	4 (1)
IMDGFS-EIFS	nan (0)	1 (1)	5 (1)	13 (1)	7 (1)	2 (1)	7 (1)	0 (1)
IMDGFS-GFDL	5 (7)	4 (6)	7 (5)	11 (4)	6 (3)	7 (2)	7 (1)	nan (0)
IMDGEFS_mean_GFDL	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)
NCEP-EIFS	4 (1)	14 (1)	17 (1)	18 (1)	2 (1)	8 (1)	3 (1)	4 (1)
NCUM_G-EIFS	11 (4)	8 (4)	3 (4)	10 (3)	7 (2)	8 (1)	5 (1)	9 (1)
NCUM_G-UKMO	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)
UKMO_GFDL	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)
CMC_GFDL	4 (7)	5 (6)	8 (6)	10 (5)	18 (4)	16 (3)	14 (2)	nan (0)
MMEM	6 (8)	5 (7)	3 (6)	5 (5)	3 (4)	3 (3)	5 (2)	4 (1)
IMDOPER	3 (8)	5 (7)	5 (6)	2 (5)	1 (4)	7 (3)	5 (2)	5 (1)

The Table 3.2.2 and 3.2.3 described the comparison of errors of various models in predicting the intensity of Remal during its lifetime. The average Intensity forecast errors of maximum sustained wind (MSW) in knots were represented in Table 3.2.2 whereas RMSE of MSW in Table 3.2.3. The mean MME along with a few global models e.g., ECMWF, NCEP-GFS and IMD-GFS had lesser intensity errors compared to SCIP model. However, the IMD operational forecast had the least errors compared to other forecasts in predicting the intensity of Remal irrespective of lead time. The comparison of errors in intensity prediction in terms of MSW (knots) and central pressure (hPa) are also described in the Fig. 3.2.3(b) & (c).

Table 3.2.3. Root Mean Square (RMSE) errors of maximum sustained wind in knots of CNTL and ENS_MEAN from GEFS model (Number of forecasts verified is given in the parentheses)

Lead Time	12 Hr	24 Hr	36 Hr	48 Hr	60 Hr	72 Hr	84 hr	96 hr
IMD-SCIP(AAE)	7.0(3)	9.0(2)	9.0(2)	10.0(1)	3.0(1)			
HWRF	11.7 (14)	17.8 (13)	15.0 (11)	15.7 (9)	14.1 (7)	12.2 (5)	8.0 (3)	
GEFS CNTL	5(8)	5(7)	6(6)	10(5)	4(4)	7(3)	12(2)	3(1)
GEFS ENS_MEAN	6(8)	4(7)	4(6)	7(5)	6(4)	6(3)	6(2)	1(1)

Table 3.2.4 LANDFALL POINT Error (in Km)

	Lead Time	00 Hr	12 Hr	24 Hr	36 Hr	48 Hr	60 Hr	72 Hr	84 Hr	96 Hr	108 Hr	120 Hr
LANDFALL POINT	**HWRF**		41	68	89	133	245					
	CTRL	327	88	20	44	11	37					
	EnMN	298	148	12	33	22	37					
	MME	12		12		12						
	NCUMG	50	210	58	86	218	277	270	270	260	20	30
	NCUM-R					240	35	35	110	270	95	20
	NEPS-G					50	105	130	160	140	60	40

(+ indicates delay landfall, - indicates early landfall)

Table 3.2.5 LANDFALL TIME Error (in hrs)

	Lead Time	00 Hr	12 Hr	24 Hr	36 Hr	48 Hr	60 Hr	72 Hr	84 Hr	96 Hr	108 Hr	120 Hr
LANDFALL TIME	**HWRF**		-3	+3	-3	-12	-6					
	CTRL	0	-6	-6	-6	-6	-6					
	EnMN	0	0	-6	-12	-6	-6					
	MME	6		6		-1						
	NCUMG	-6	0	3	0	3	12	6	3	9	0	0
	NCUM-R					-6	-6	-3	-6	3	0	0
	NEPS-G					-3	0	0	0	0	0	0

The landfall point (direct position) errors and landfall time errors of various models are illustrated in table 2.4 and 2.5 respectively. The comparison of errors during landfall time along with operational forecast are also described in Fig. 16.

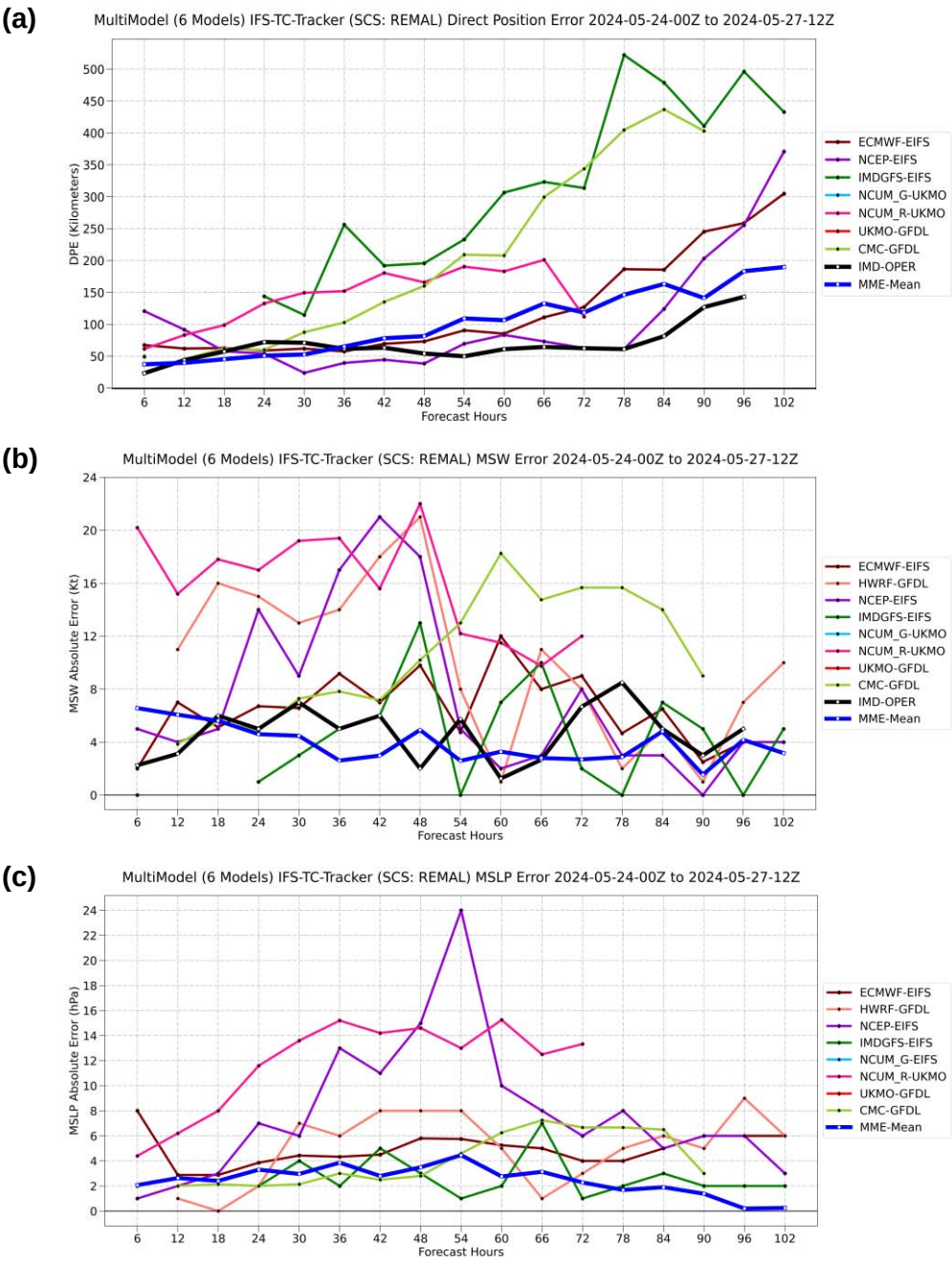


Fig. 3.2.3. Track and intensity errors of various Global models. (a) Direct Position Error(DPE) in km, (b) MSW mean absolute errors in knots and (c) mean errors of the central MSLP in hPa.

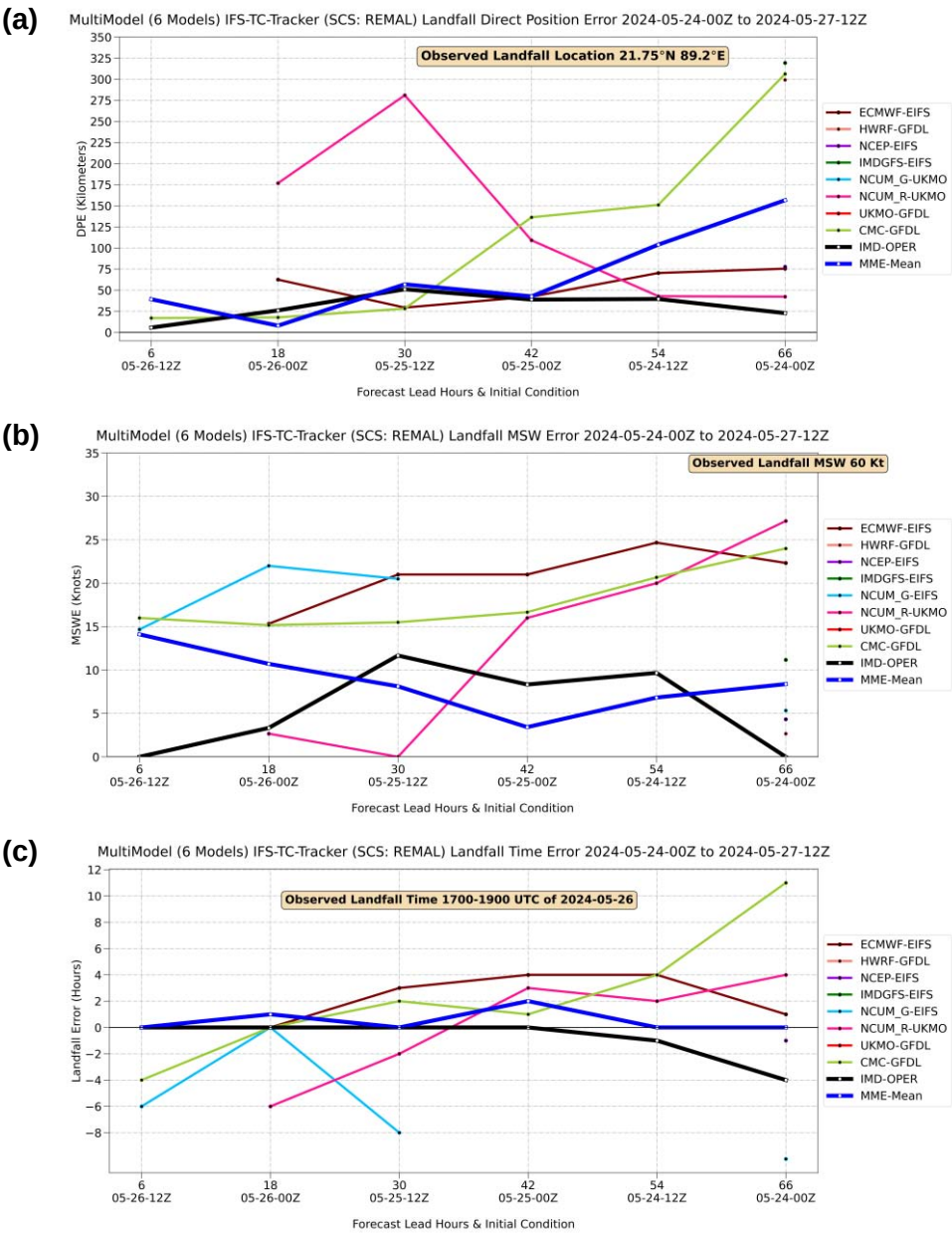


Fig. 3.2.4 Landfall position, intensity and time errors of various Global models. (a) Direct Position Errors (DPE) in km, (b) Landfall MSW mean absolute errors in knots and (c) landfall time errors in hours.

Annexure-1

Description of Models

Model Mnemonic	Model Name
IMD-MME	IMD Multi-Model Ensemble
HWRF	Hurricane WRF
GEFS (CNTL)	Global Ensemble Forecast System (Control)
GEFS (ENS_MEAN)	Global Ensemble Forecast System (Ensemble Mean)
NCUM-R	NCMRWF Unified Model - regional
NUCM-G	NCMRWF Unified Model - Global
NEPS-G	NCMRWF Ensemble Prediction System - Global
NCUM_R-UKMO	NCMRWF Unified Model – regional (UK Met. Office Configuration)
NCEP-GFDL	National Centers for Environmental Prediction – with

	Geophysical Fluid Dynamics Laboratory (GFDL) tracker
HWRF-GFDL	**HWRF with GFDL tracker**
ECMWF-EIFS	**European Centre for Medium-Range Weather Prediction – with ECMWF Integrated Forecast System (EIFS) tracker**
IMDGFS-EIFS	**IMD Global Forecast System – with ECMWF Integrated Forecast System tracker**
IMDGFS-GFDL	**IMD Global Forecast System – with GFDL tracker**
NCEP-EIFS	**NCEP with EIFS tracker**
NCUM_G-EIFS	**NCUM-Global with EIFS tracker**
CMC_GFDL	**Canadian Meteorological Centre model – with GFDL tracker**
MMEM	**Mean Multi-Model Ensemble**
IMDOPER	**IMD operational forecasts**

3.3 Performance of operational NWP models during CS ASNA

3.3.1 Track and intensity prediction by NWP models: -

At 0000 UTC of 28th September, 2024, the Fig. 3.3.1 (a) displayed the GEFS track & intensity forecasts, which indicated initial west-southwestwards movement till 0000 UTC of 1st September and then nearly southwestwards. In Fig. 3.3.1(b) MME mean track was very much close to the best track as it was very close to Saurashtra & Kachchh before likely to move slowly west-southwestwards across Saurashtra & Kachchh region and reach Saurashtra & Kachchh coast & adjoining areas of Pakistan after the system emerged over the sea while moving from land over northeast Arabian Sea around 0000 UTC of 29th august. The MME forecast was closer to the best estimate track information. The intensity forecasts of the cyclone in the MME forecast indicated maximum sustained wind of 36.5 kts at 0600 UTC of 30th August 2024.

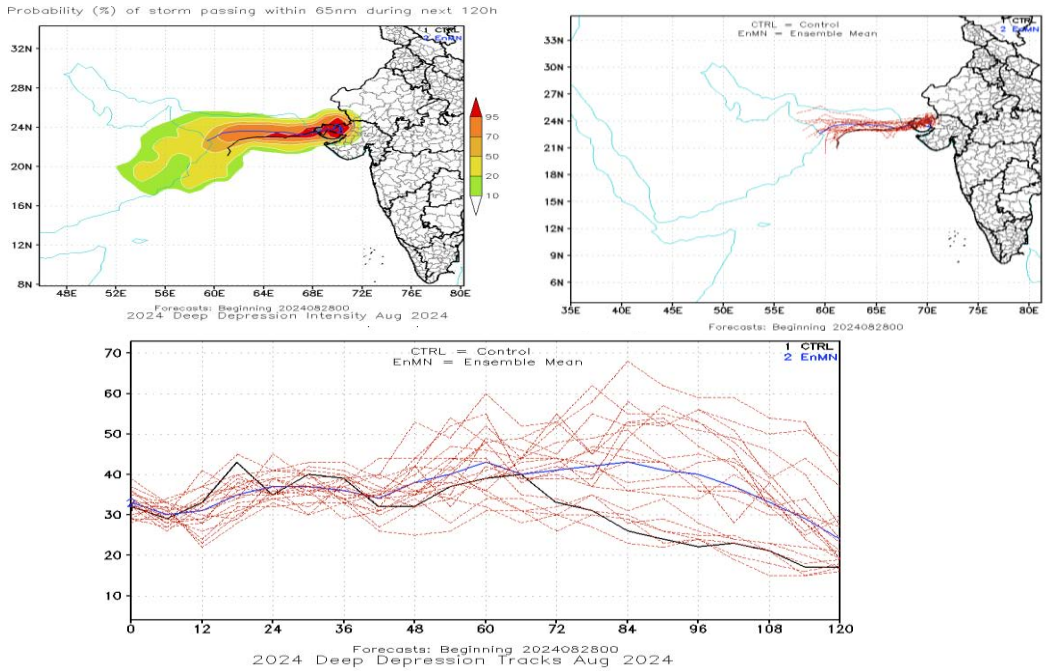


Fig. 3.3.1 (a): NWP (GEFS) model track forecast based on 0000 UTC of 28.08.2024

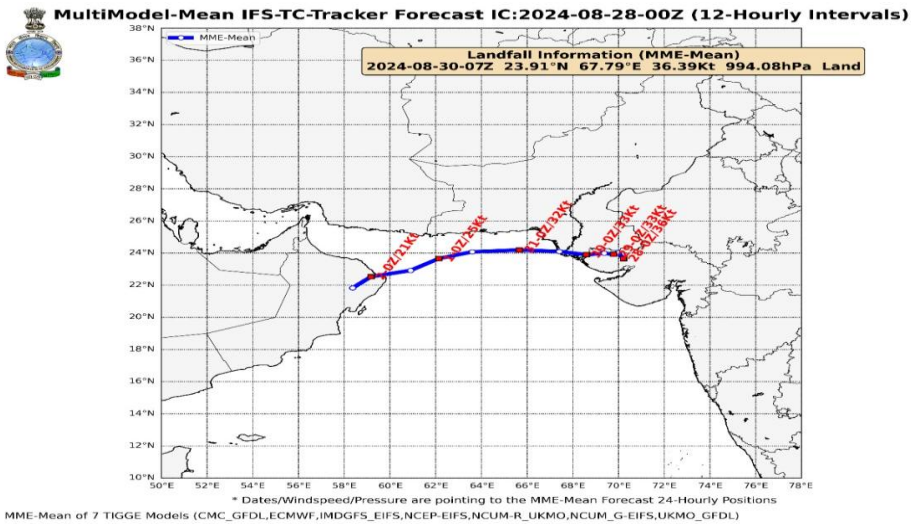


Fig. 3.3.1 (b): MME model track forecast based on 0000 UTC of 28.08.2024

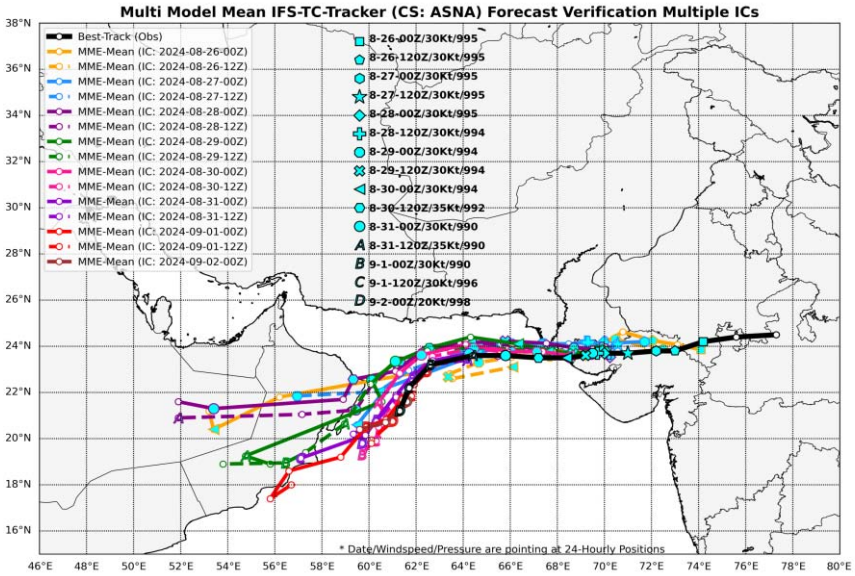


Fig. 3.3.1 (c): MME-based track forecasts based on 00 UTC of 26th Aug.- 2nd Sep.

MME-based track forecasts based on ICs from 26th August 0000 UTC to 2nd Sep 0000 UTC along with the best track shown in Fig. 3.3.1c indicated a broad temporal consistency with respect to the forecast tracks with all ICs indicating initial westward and subsequent west-southwestward movement like the observed track.

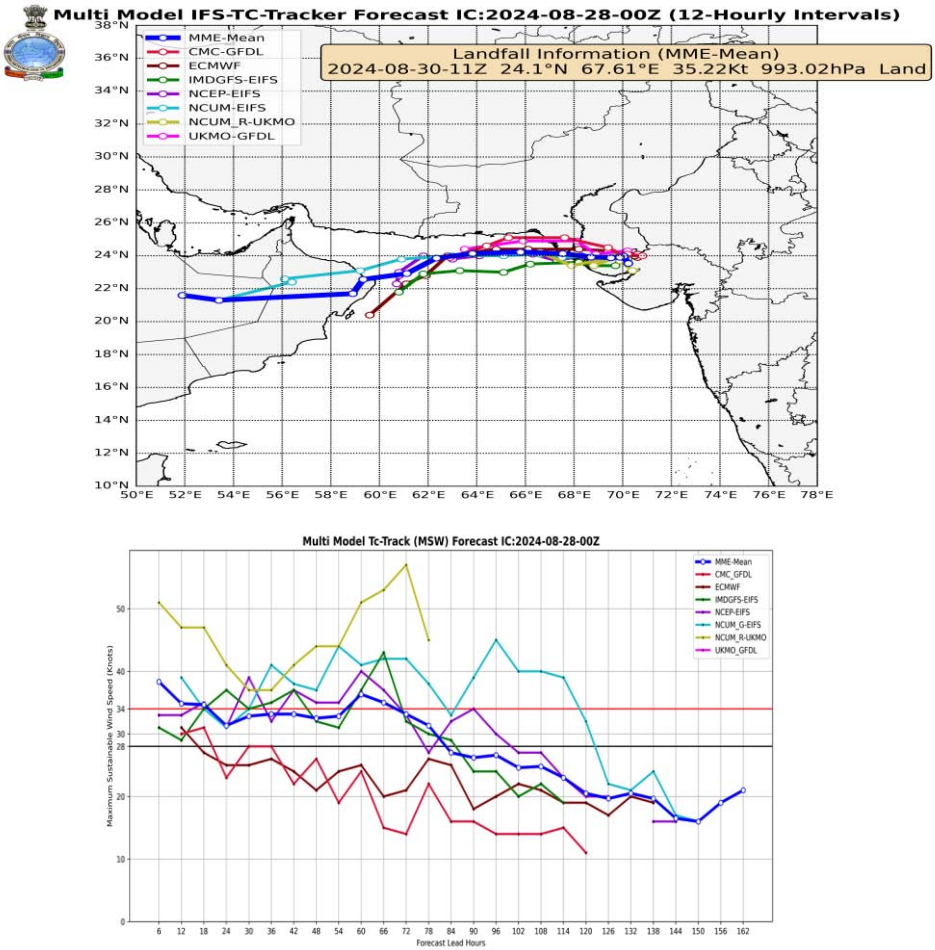
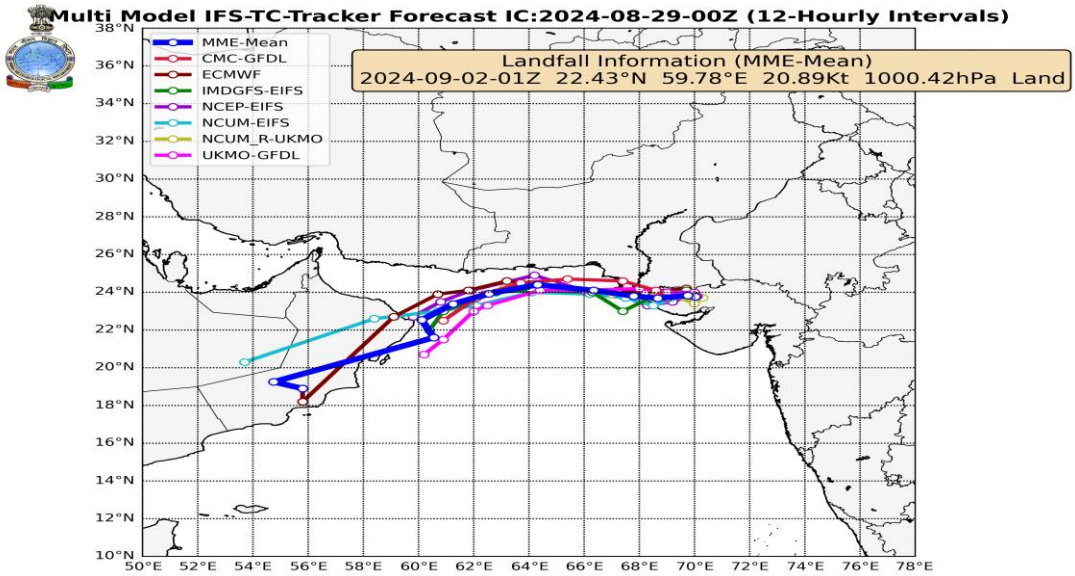


Fig. 3.3.1 (d) shows the track and intensity forecasts based on 28th August 0000 UTC.

Fig. 3.3.1 d shows the track and intensity forecasts based on the IC of 28th August 0000 UTC. As can be seen, there is a broad consensus among individual models regarding the predicted tracks of the system, which are similar to the observed track. However, with respect to the intensity of the system, the model differs from each other with NCUM-R indicating a much stronger system with maximum sustained wind speed exceeding 50 knots. The NCUM-G also slightly over-predicted. The other models like CMC-GFDL and ECMWF under-predicted the intensity as it didn't show the intensity of tropical cyclones reaching MSW of 34 knots.



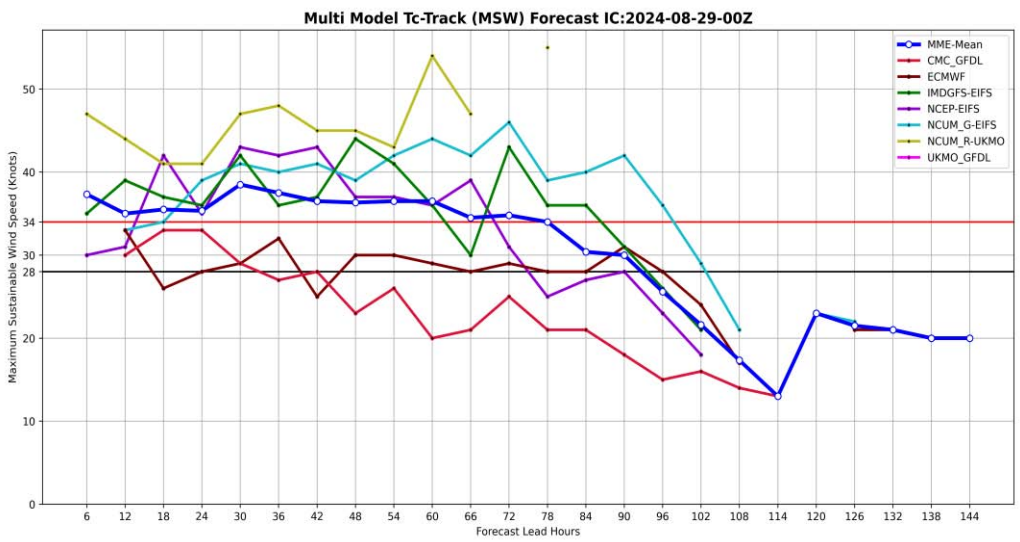
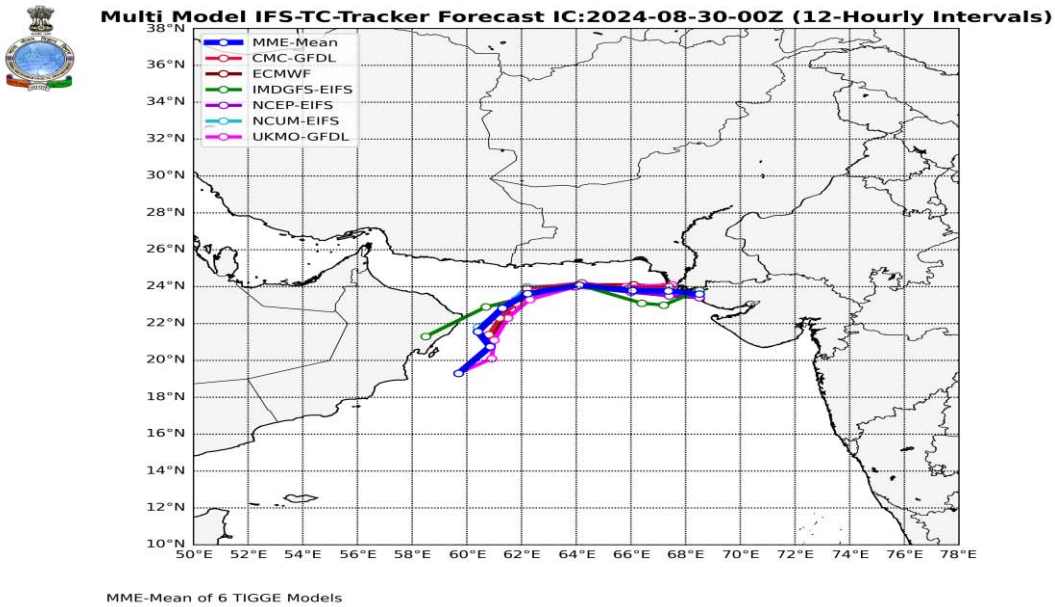


Fig. 3.3.1 (e) shows the track and intensity forecasts based on the IC of 29th August 0000 UTC.

Fig. 3.3.1 (e) shows the track and intensity forecasts based on the IC of 29th August 0000 UTC. It shows similar patterns like that seen with respect to the IC of 28th August shown in Fig. 10d. As can be seen in Fig. 10e, there is a broad consensus among individual models regarding the predicted tracks of the system with initial westward movement over the northeast Arabian Sea followed by west-southwestward movement over the northwest Arabian Sea. With respect to the intensity of the system, the model varies with NCUM-R indicating a much stronger system with maximum sustained wind speed exceeding 50 knots.

The NCUM-G is also slightly over-predicted. The other models like CMC-GFDL and ECMWF under-predicted the intensity as it didn't show the intensity of tropical cyclones reaching MSW of 34 knots.



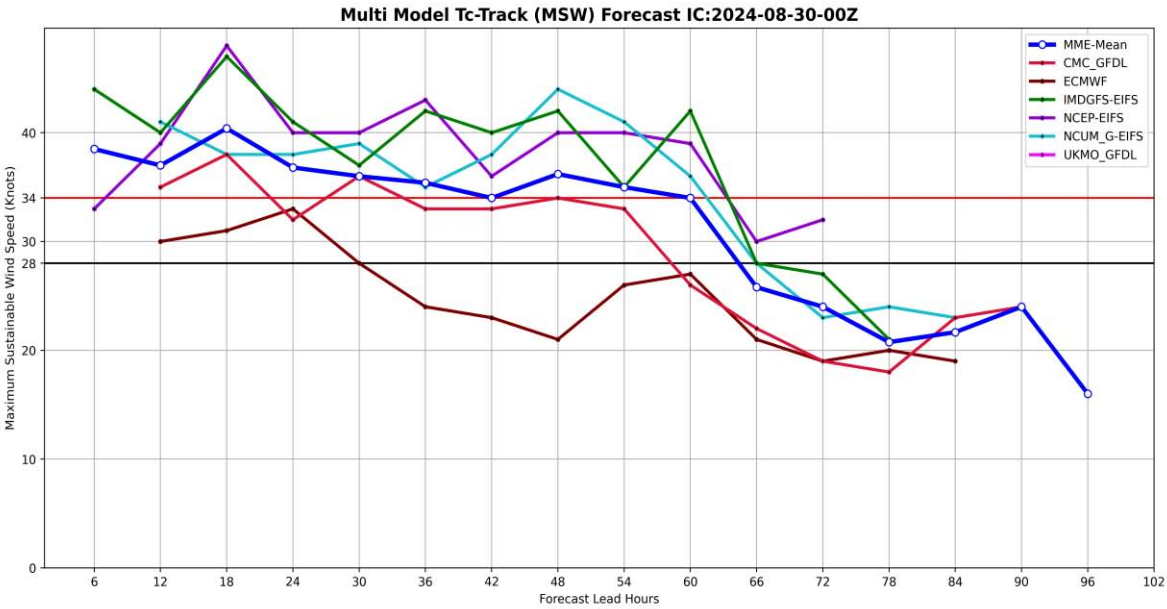
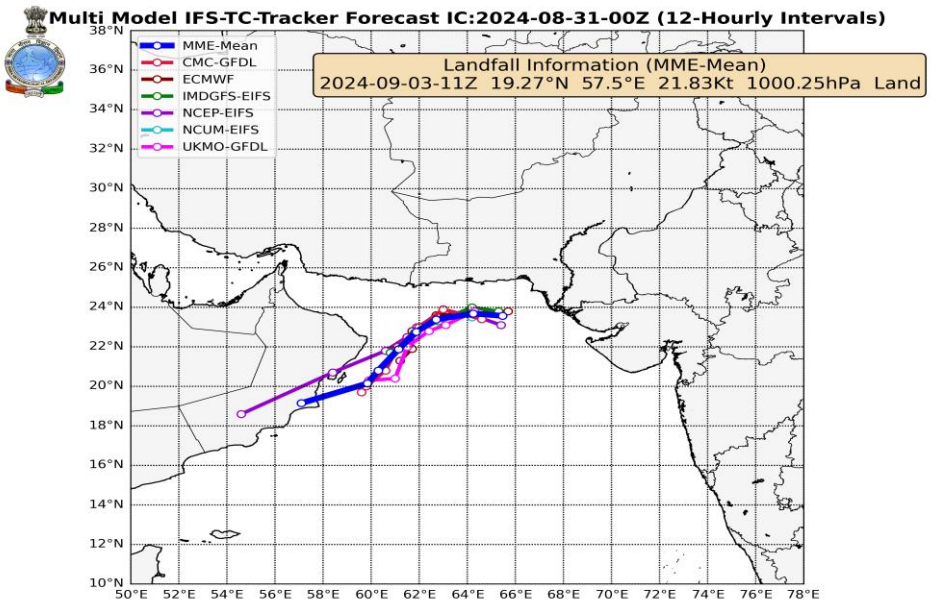


Fig. 3.3.1 (f) shows the track and intensity forecasts based on the IC of 30th August 0000 UTC.



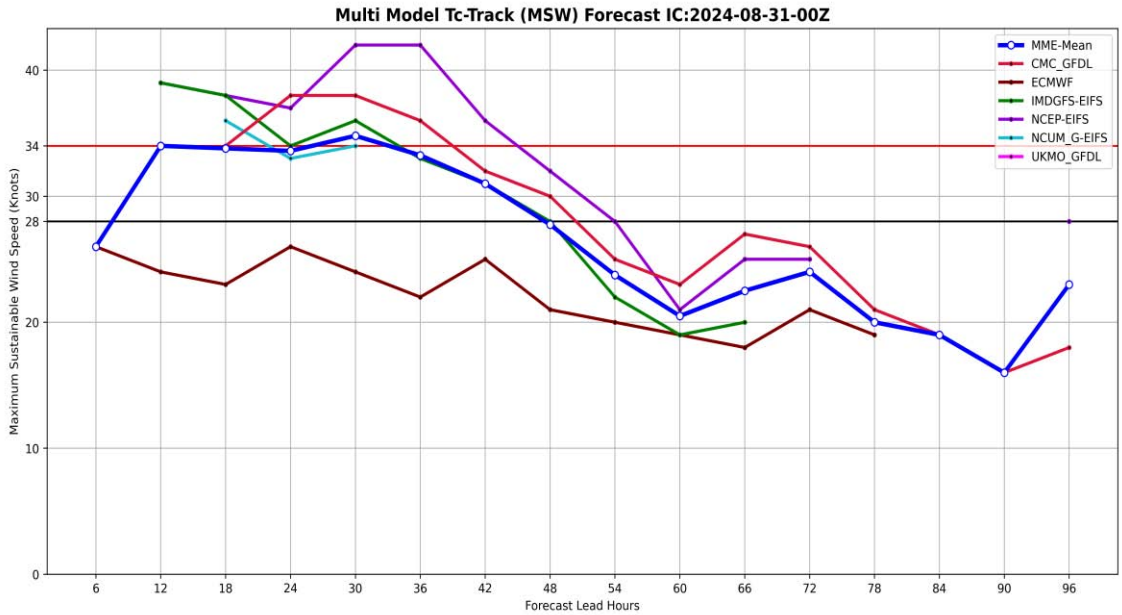


Fig. 3.3.1 (g) shows the track and intensity forecasts based on the IC of 31st August 0000 UTC.

Fig. 3.3.1 (f) and Fig. 3.3.1 (g) show the track and intensity forecasts based on the IC of 30th 0000 and 31st August 0000 UTC respectively. It may be mentioned here that on 30th August it was having the intensity of Deep Depression and on 31st August it had already reached to the cyclone stage. As seen in Fig. 3.3.1 (f), there is a broad consensus among individual models regarding the predicted tracks of the system with initial westward movement followed by southwestward movement over the northwest Arabian Sea except the IMD GFS model which indicated initial westward and subsequent west-southwestward movement over the northwest Arabian Sea. Based on 31st August all models show southwestward movement.

With respect to the intensity, the ECMWF model under-predicted the intensity as it didn't show the intensity of tropical cyclones reaching MSW of 34 knots (Fig. 3.3.1 f and 3.3.1 g).

3.3.2. Track forecast errors by various NWP Models

The average track forecast errors (Direct Position Error) in km at different lead periods (hr) of various models are presented in Table 3.3.1. As it is seen, the MME performed better than the individual model and is very close to or better than IMD's operational forecasts.

Table 3.3.1. Average track forecast errors (Direct Position Error) in km at different lead periods (Number of forecasts verified is given in parentheses).

Lead Time	12 Hr	24 Hr	36 Hr	48 Hr	60 Hr	72 Hr	84 Hr	96 Hr	108 Hr	120 H
NCUM_R-UKMO	58.17 (8)	72.7 (7)	84.18 (7)	74.42 (6)	73.4 (6)	80.57 (5)	nan (0)	nan (0)	nan (0)	nan (0)
NCEP-GFDL	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)
HWRF-GFDL	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)
ECMWF-EIFS	54.52 (11)	75.91 (11)	78.31 (11)	98.16 (10)	100.63 (9)	101.67 (8)	130.23 (7)	135.4 (6)	116.24 (5)	160.79 (4)
IMDGFS-EIFS	52.64 (13)	60.44 (12)	69.58 (11)	48.39 (10)	74.66 (9)	104.47 (8)	122.47 (7)	99.23 (7)	85.14 (5)	123.14 (4)
IMDGFS-GFDL	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)
IMDGEFS_mean_GFDL	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)
NCEP-EIFS	40.76 (14)	55.32 (13)	75.94 (12)	80.67 (11)	103.41 (10)	116.19 (8)	125.92 (8)	156.42 (6)	138.65 (3)	123.26 (2)
NCUM_G-EIFS	51.24 (7)	49.14 (7)	54.25 (7)	73.31 (7)	76.61 (7)	86.41 (7)	130.09 (6)	228.03 (5)	238.54 (4)	332.52 (3)
NCUM_G-UKMO	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)
UKMO_GFDL	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)
CMC_GFDL	54.78 (14)	81.96 (13)	115.28 (12)	127.14 (11)	158.0 (10)	189.75 (9)	215.98 (8)	295.95 (7)	344.16 (5)	546.42 (3)
MMEM	33.91 (14)	44.25 (13)	50.97 (12)	51.93 (11)	62.24 (10)	80.95 (9)	100.2 (8)	106.99 (7)	124.03 (6)	163.09 (5)
IMDOPER	24.52 (7)	48.02 (6)	69.22 (5)	99.43 (4)	162.08 (3)	173.1 (2)	nan (0)	nan (0)	nan (0)	nan (0)

Table 3.3.2. Average Intensity Forecast Errors of maximum sustained wind in knots (Number of forecasts verified is given in parentheses). The negative sign indicates an underestimation of intensity and vice versa.

Lead Time	06 Hr	18 Hr	30 Hr	42 Hr	54 Hr	66 Hr	78 hr
NCUM_R-UKMO	12.86 (7)	10.71 (7)	19.33 (6)	18.67 (6)	22.33 (6)	23.2 (5)	nan (0)
NCEP-GFDL	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)
HWRF-GFDL	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)
ECMWF-EIFS	3.91 (11)	4.36 (11)	6.09 (11)	4.8 (10)	5.89 (9)	5.5 (8)	5.57 (7)
IMDGFS-EIFS	4.54 (13)	3.75 (12)	4.64 (11)	5.6 (10)	4.44 (9)	3.88 (8)	4.14 (7)
IMDGFS-GFDL	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)
IMDGEFS_mean _GFDL	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)
NCEP-EIFS	5.36 (14)	6.46 (13)	5.5 (12)	5.09 (11)	3.4 (10)	5.0 (8)	4.5 (8)
NCUM_G-EIFS	4.43 (7)	5.29 (7)	5.43 (7)	7.86 (7)	7.71 (7)	4.57 (7)	8.67 (6)
NCUM_G-UKMO	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)
UKMO_GFDL	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)
CMC_GFDL	5.21 (14)	4.38 (13)	6.58 (12)	4.73 (11)	7.4 (10)	10.0 (9)	11.12 (8)
MMEM	4.43 (14)	3.46 (13)	4.09 (12)	3.8 (11)	3.53 (10)	2.02 (9)	3.88 (8)
IMDOPER	2.86 (7)	3.33 (6)	3.0 (5)	3.75 (4)	3.33 (3)	2.5 (2)	nan (0)

3.4 Performance of operational NWP models during SCS DANA

3.4.1 Prediction of Cyclogenesis (Genesis Potential Parameter (GPP) for DANA

Grid point analysis and forecast of GPP is used to identify potential zone of cyclogenesis. **Fig 3.4.1** below shows the predicted zone of cyclogenesis.

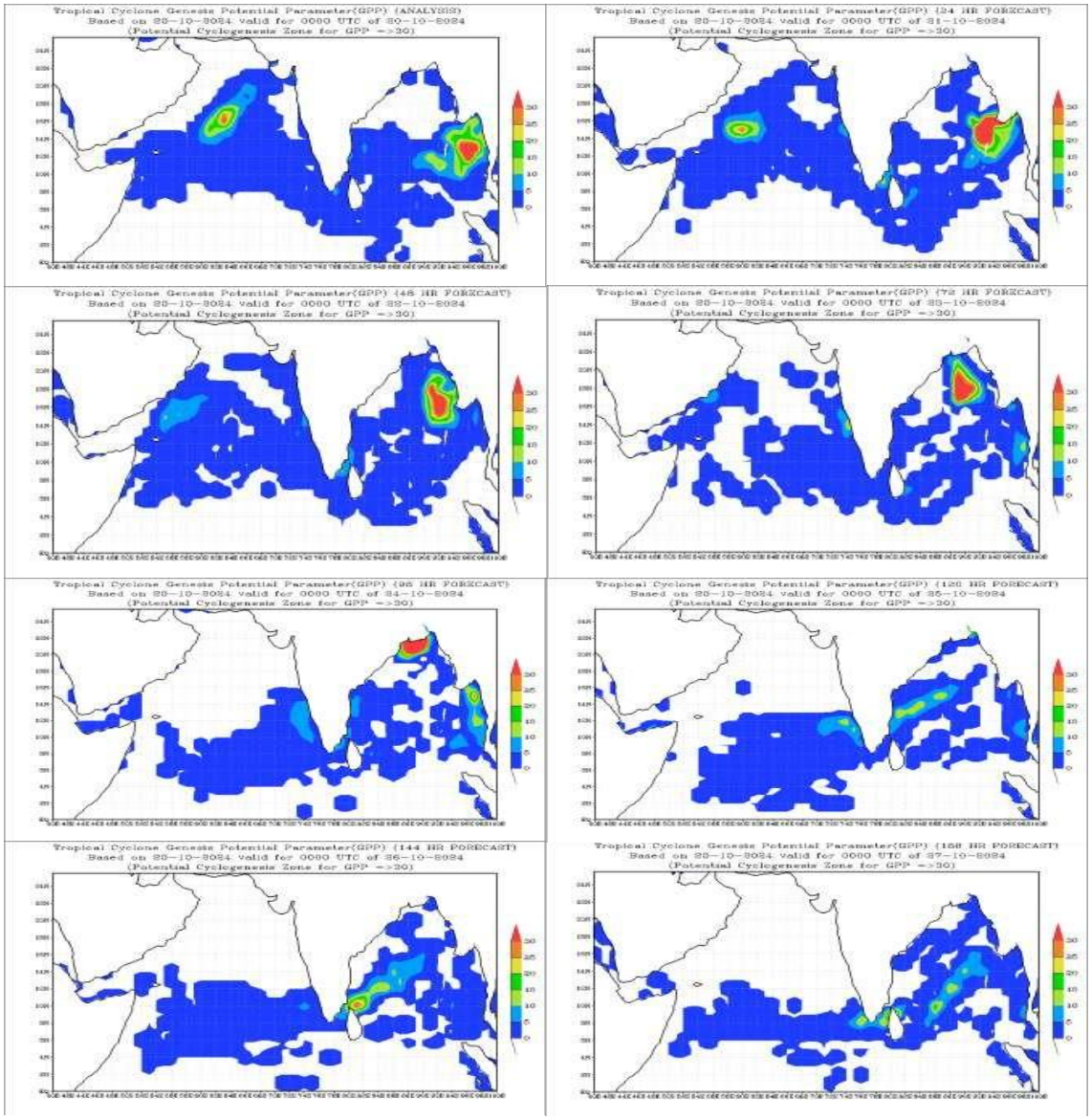


Fig.3.4.1: Predicted zone of Cyclogenesis based on 0000 UTC of 20th October, 2024

3.4.2 Track and intensity prediction by NWP models

The fig **3.4.2 to 3.4.4** are representing track and intensity predictions by different NWP models. In general, all of them indicated initial northwestwards movement till 0000 UTC of 23rd October then nearly north-northwestward movement till 0000 UTC of 25th October and further west-northwestwards movement after landfall. The mean track of GEFS also showed similar track. In general MME mean track was very much close to the best track as it was very close to north Odisha. The verification of MME mean track with respect to the Best Track is presented in **Fig.3.4.5**.

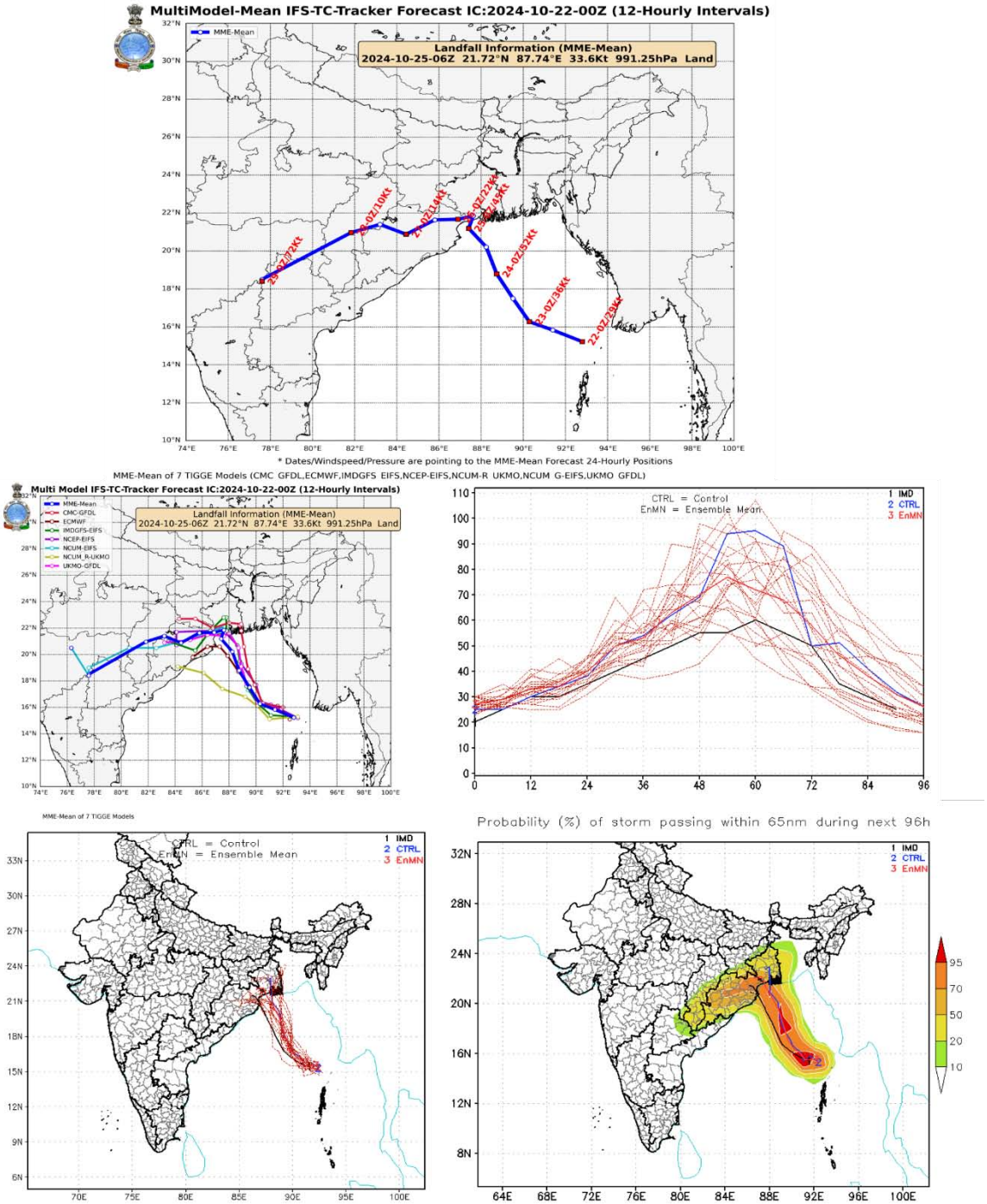


Fig. 3.4.2: NWP model track forecast based on 0000 UTC of 22.10.2024

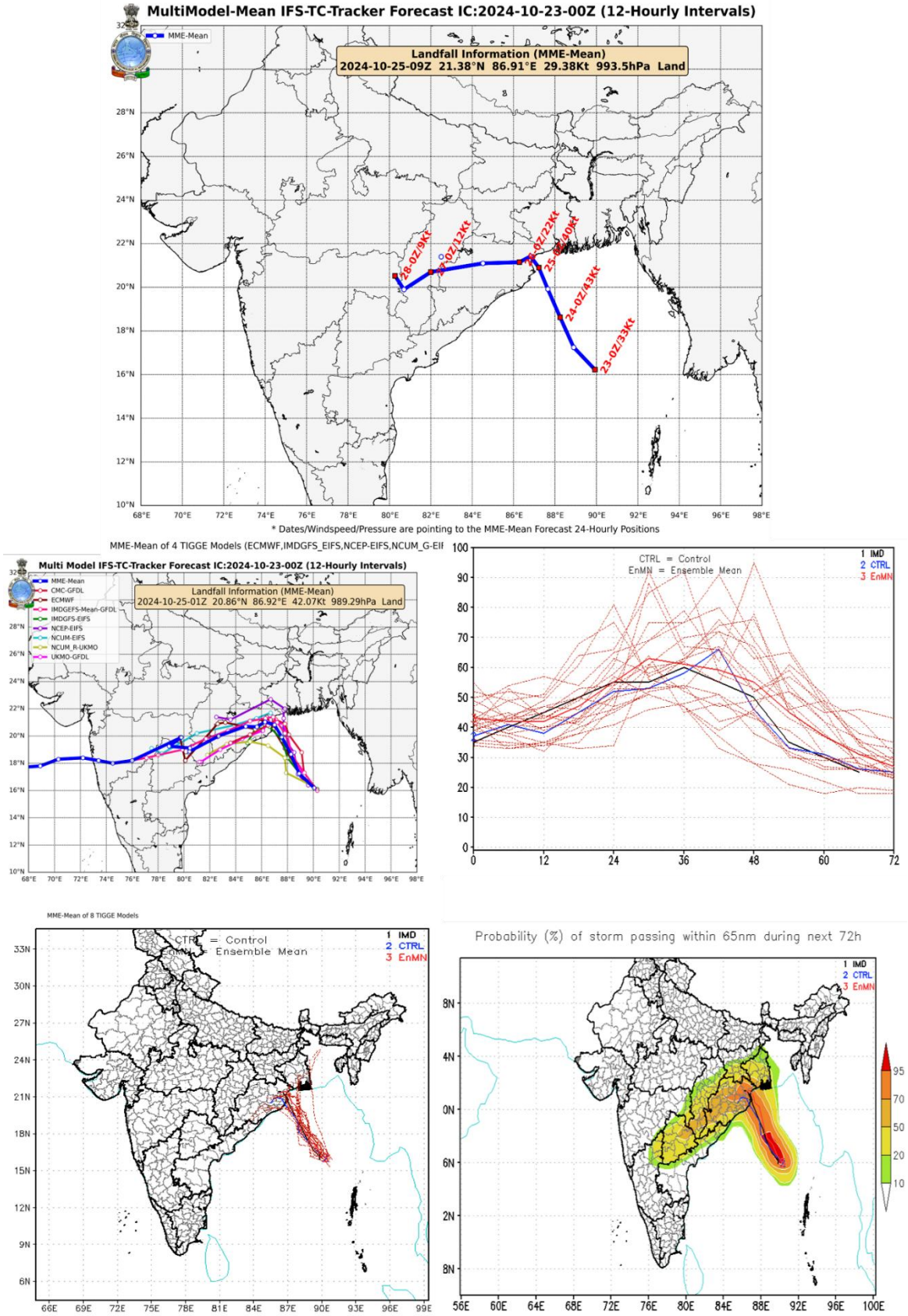


Fig. 3.4.3: NWP model track forecast based on 0000 UTC of 23.10.2024

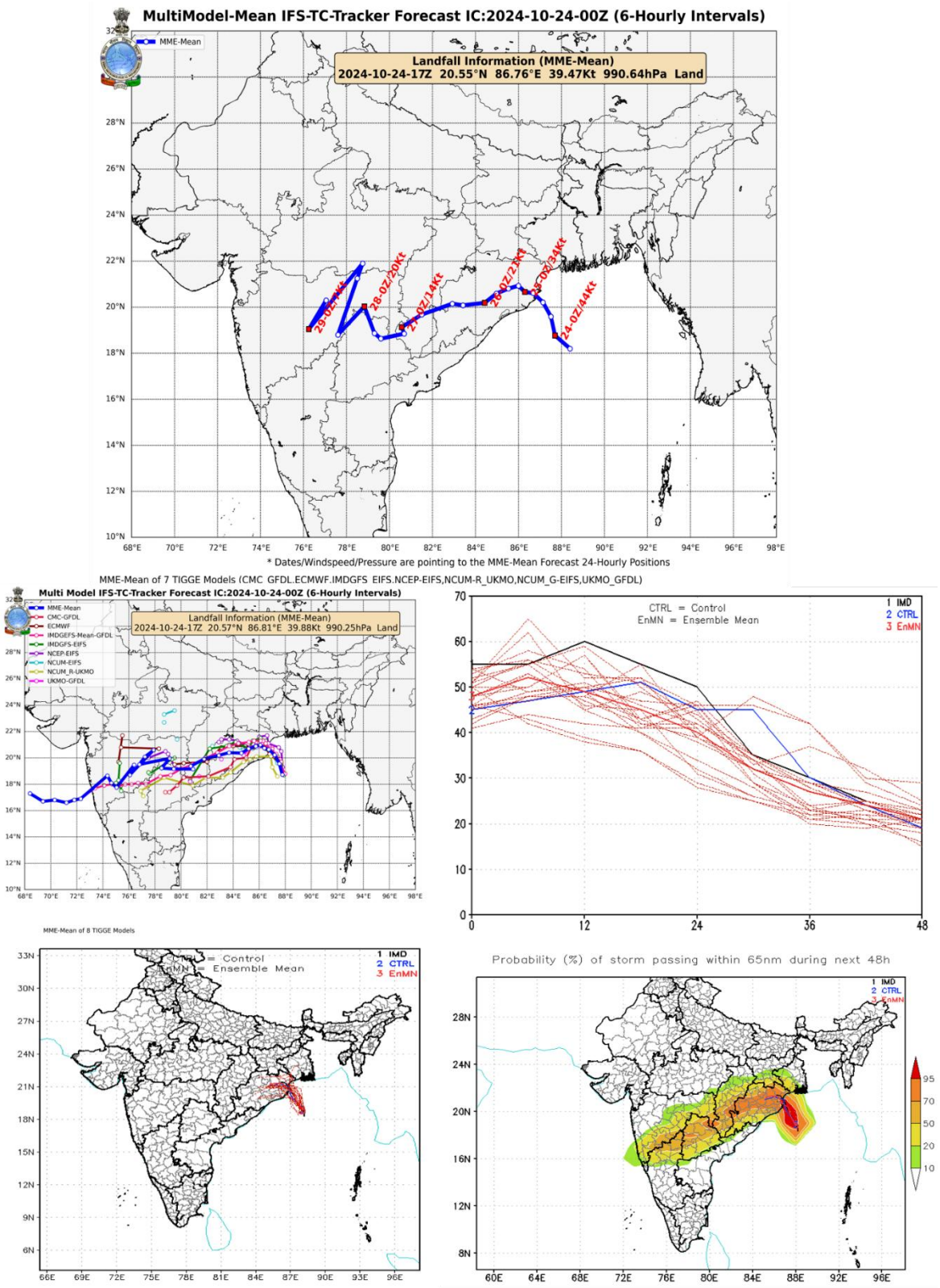


Fig. 3.4.4: NWP model track forecast based on 0000 UTC of 24.10.2024

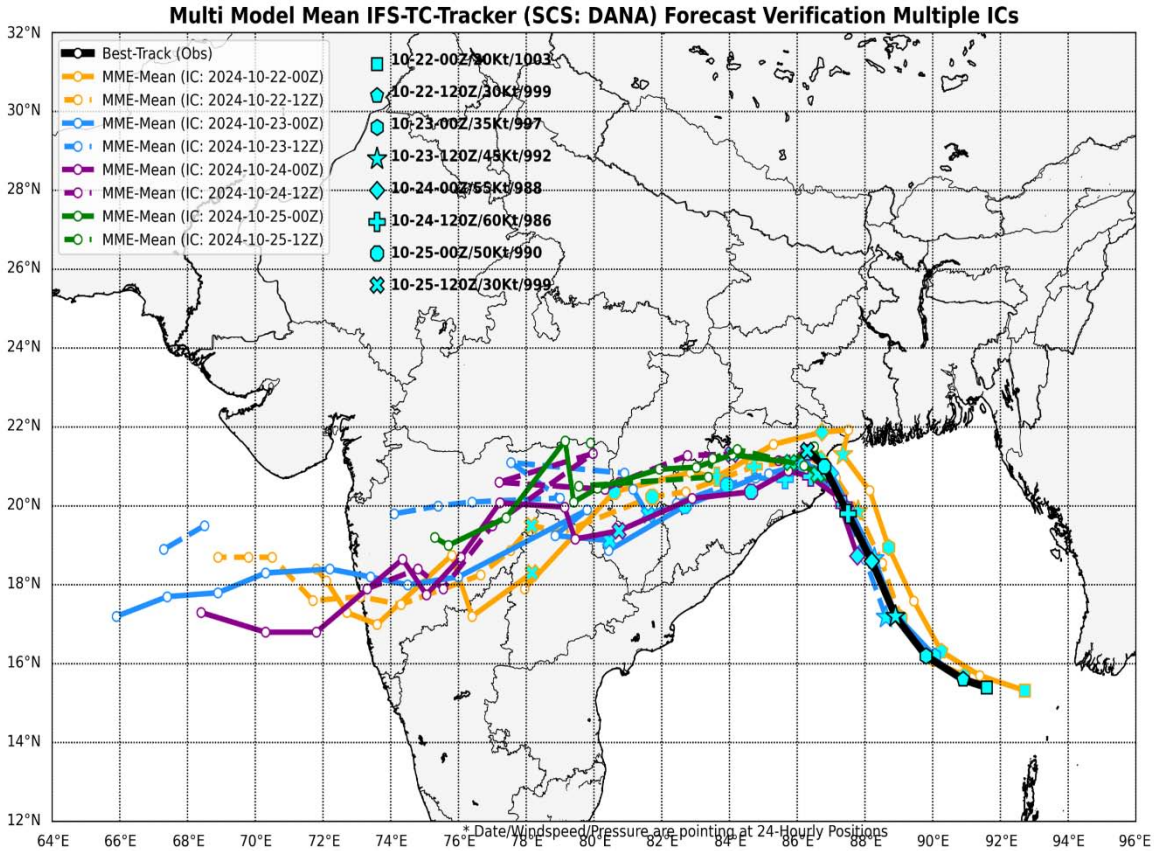


Fig. 3.4.5: Verification of MME mean track with respect to the Best Track

3.4.3Track 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 to 3.4.5**. From the verification of the forecast guidance available from various NWP models, it is found that the average track forecast errors of ECMWF model were minimum for 24 and 48 hr and 72 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	12Hr	24Hr	36Hr	48Hr	60Hr	72Hr	84Hr
HWRF	32	40	51	55	118		
GEFS (CNTL)	22(7)	49(6)	83(5)	97(4)	109(3)	192(2)	249(1)
GEFS (ENS_MEAN)	30(7)	40(6)	62(5)	94(4)	100(3)	128(2)	134(1)
NCUM_R-UKMO	73.31 (7)	83.33 (6)	158.63 (5)	196.63 (4)	282.84 (3)	396.0 (2)	nan (0)
NCEP-GFDL	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)
ECMWF-EIFS	51.13 (6)	58.43 (6)	89.26 (5)	98.98 (4)	63.49 (3)	36.25 (2)	63.71 (1)
IMDGFS-	19.45	35.52	63.29 (5)	103.08	122.93	175.18	219.34

EIFS	(7)	(6)		(4)	(3)	(2)	(1)
IMDGFS-GFDL	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)
IMDGEFS_mean_GFDL	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)
NCEP-EIFS	31.67 (7)	40.65 (6)	53.21 (5)	80.7 (4)	134.45 (3)	136.43 (2)	131.78 (1)
NCUM_G-EIFS	50.32 (6)	47.21 (6)	60.01 (5)	66.78 (4)	94.83 (3)	112.58 (2)	164.2 (1)
NCUM_G-UKMO	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)
IMDOPER	27.19 (7)	38.45 (6)	34.45 (5)	21.3 (4)	18.95 (3)	16.49 (2)	52.93 (1)
MMEM	29.48 (7)	26.02 (6)	46.07 (5)	42.45 (4)	60.33 (3)	57.1 (2)	138.23 (1)
HWRF-GFDL	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)
CMC_GFDL	49.96 (6)	61.13 (6)	82.79 (5)	117.61 (4)	137.28 (3)	203.3 (2)	272.98 (1)

Table 3.4.2. Average Intensity Forecast Errors of maximum sustained wind in knots (Number of forecasts verified is given in the parentheses).

Lead Time	12Hr	24Hr	36Hr	48Hr	60Hr	72Hr	84Hr
HWRF	9	8	6	14	12		
CTRL	-7(7)	-2(6)	1(5)	8(4)	9(3)	-2(2)	11(1)
EnMN	-5(7)	-3(6)	0(5)	7(4)	6(3)	5(2)	8(1)
NCUM_R-UKMO	16.14(7)	15.0(6)	11.8 (5)	10.25(4)	10.0 (3)	6.0 (2)	nan (0)
NCEP-GFDL	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)
ECMWF-EIFS	11.83(6)	14.3(6)	16.8 (5)	19.75(4)	19.0 (3)	16.0(2)	11.0 (1)
IMDGFS-EIFS	8.71 (7)	5.5 (6)	9.0 (5)	8.0 (4)	17.0 (3)	9.0 (2)	10.0 (1)
IMDGFS-GFDL	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)
IMDGEFS_mean_GFDL	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)
NCEP-EIFS	9.43 (7)	10.3(6)	12.2 (5)	9.25 (4)	10.3 (3)	8.5 (2)	8.0 (1)
NCUM_G-EIFS	14.17(6)	12.7(6)	13.8 (5)	9.25 (4)	6.0 (3)	7.0 (2)	2.0 (1)
NCUM_G-UKMO	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)
IMDOPER	1.43 (7)	2.5 (6)	6.0 (5)	6.25 (4)	8.33 (3)	2.5 (2)	10.0 (1)
MMEM	6.77 (7)	7.22(6)	6.06 (5)	4.5 (4)	2.72 (3)	2.78(2)	0.83(1)
HWRF-GFDL	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)
UKMO_GFDL	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)	nan (0)
CMC_GFDL	9.17 (6)	7.836)	7.0 (5)	7.5 (4)	5.33 (3)	14.5(2)	2.0 (1)

Table 3.4.3. Root Mean Square (RMSE) errors of maximum sustained wind in knots of CNTL and ENS_MEAN from GEFS model (Number of forecasts verified is given in the parentheses)

Lead Time	12Hr	24Hr	36Hr	48Hr	60Hr	72Hr	84Hr
HWRF	11	8	8	19	16		
GEFS CNTL	11(7)	5(6)	7(5)	14(4)	21(3)	3(2)	11(1)
GEFS MEAN	8(7)	8(6)	6(5)	9(4)	8(3)	6(2)	8(1)

Table 3.4.4 Landfall Point forecast error (in Km)

Lead Time	6 Hr	18Hr	30 Hr	42 Hr	54 Hr	66 Hr
Initial Condition	1200 UTC 24 Oct	0000 UTC 24 Oct	1200 UTC 23 Oct	0000 UTC 23 Oct	1200 UTC 22 Oct	0000 UTC 22 Oct
HWRF	33	44	46	16		
GEFS CNTL	8	16	98	43	108	150
GEFS ENS_MEAN	0	16	83	66	108	113
NCUM_R-UKMO	15.25	83.47	82.6	203.37	235.09	293.87
ECMWF-EIFS	8.76	34.6	49.59	13.3	83.76	11.83
IMDGFS-EIFS	3.42	21.04	127.96	26.27	137.0	157.81
NCEP-EIFS	20.34	44.99	19.39	145.33	143.52	143.52
NCUM_G-EIFS	357.31	23.65	26.38	83.4	15.76	160.38
CMC_GFDL	47.73	12.26	28.75	24.73	11.13	243.99
MMEM	9.45	12.55	4.48	23.5	62.89	128.81
IMDOPER	2.28	20.34	35.59	12.26	5.72	12.5

Table 3.4.5 Landfall Time forecast error (in hrs)

(+ indicates delay landfall, - indicates early landfall)

Lead Time	6 Hr	18Hr	30 Hr	42 Hr	54 Hr	66 Hr
Initial Condition	1200 UTC 24 Oct	0000 UTC 24 Oct	1200 UTC 23 Oct	0000 UTC 23 Oct	1200 UTC 22 Oct	0000 UTC 22 Oct
HWRF	-1	-2	-2	-3		
GEFS CNTL	0	-6	6	0	-6	0
GEFS ENS_MEAN	0	-6	12	12	0	0
NCUM_R-UKMO	3	5	4	0	-1	0
ECMWF-EIFS	0	7	8	6	-12	4
IMDGFS-EIFS	1	2	-8	2	3	-1
NCEP-EIFS	0	-1	-2	-7	-8	-2
NCUM_G-EIFS	-51	3	3	-8	-6	-6
CMC_GFDL	-4	2	-1	-19	-29	-2
MMEM	2	3	0	-3	-8	-6
IMDOPER	0	-3	-4	0	0	0

3.5 Performance of operational NWP models during CS FENGAL

3.5.1 Prediction of Cyclogenesis (Genesis Potential Parameter (GPP) for FENGAL

Grid point analysis and forecast of GPP is used to identify potential zone of cyclogenesis. Fig 3.5.1 below shows the predicted zone of cyclogenesis. The GPP could correctly predict the Gensis of depression over southwest Bay of Bengal near (5.0N, 83.5E) since 18th November.

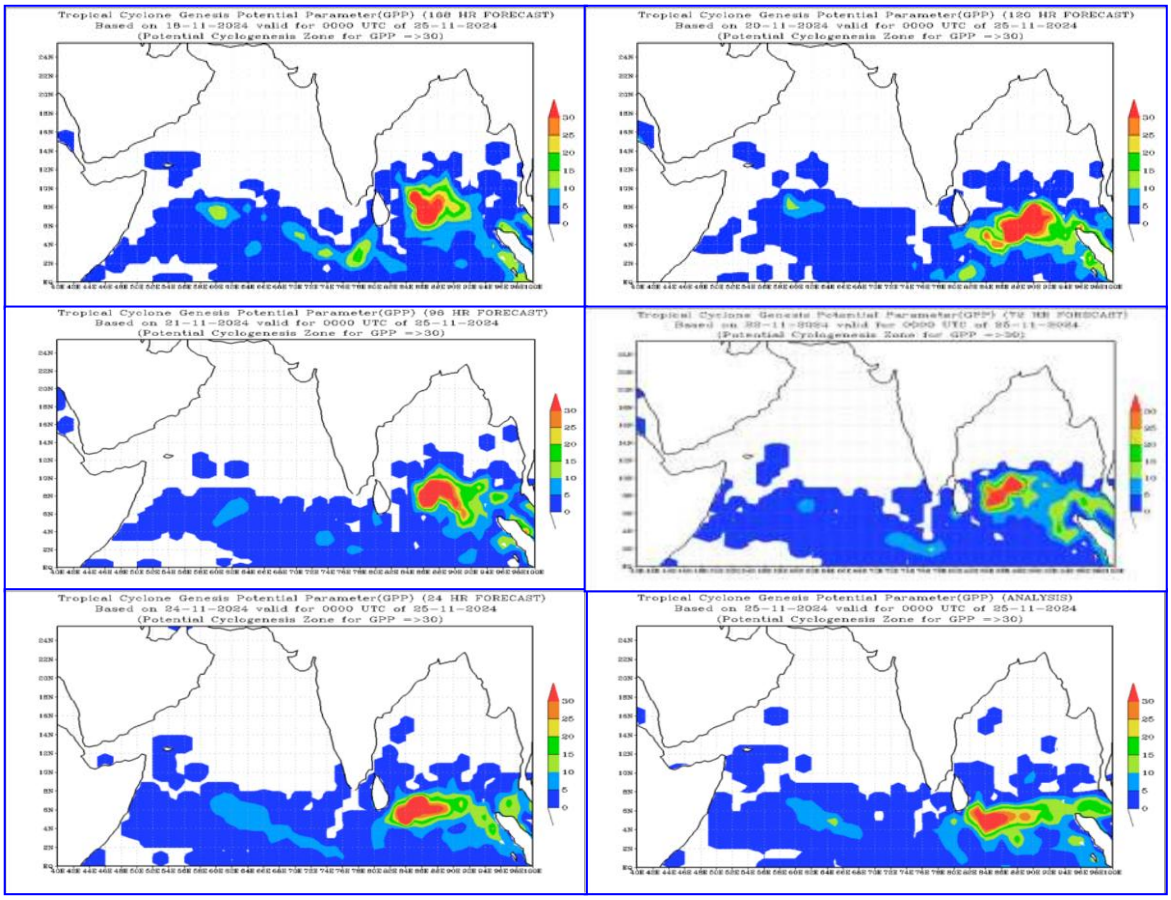


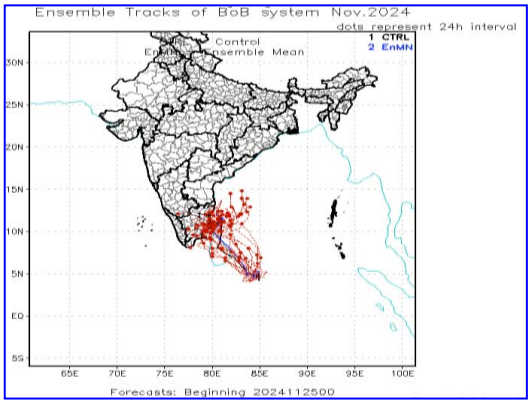
Fig.3.5.1: Predicted zone of Cyclogenesis based on 0000 UTC of 18th-25th November 2024 valid for 0000 UTC of 25th November, 2024

3.5.2 Track prediction by NWP models

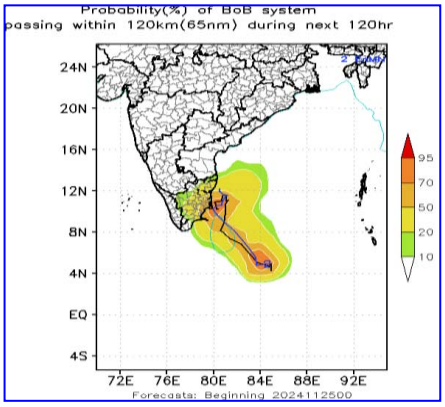
At 0000 UTC of 25th November, there was large variation among various models wrt. track, intensification and landfall of system. Peak intensification was varying from depression to marginal cyclonic storm stage. There was large variation among various models wrt landfall. NCUM and CMC were indicating landfall over North Tamil Nadu. ECMWF, UKMO, IMD GFS, IMD GEFS were indicating initial north-northwestwards movement followed with north-northeastwards movement beyond 10^0N. IMD MME indicated intensification of the system into a marginal cyclonic storm. IMD MME was indicating crossing over Andhra Pradesh coast around 1300 UTC of 2nd December near 15.0N/79.8E.

Based on 0000 UTC of 26th November, there was large variation among various models wrt landfall. GFS group of models (NCEP, IMD GEFS, IMD GFS) were indicating north-northeastwards recurvature towards central BoB beyond 10^0N. GEFS ensemble tracks indicated large spread among various members. NCUM & ECMWF were indicating landfall over North Tamil Nadu coast. IMD MME indicated landfall over North Tamil Nadu coast near 14.0N/80.2E as a depression around 2200 UTC of 1st December.

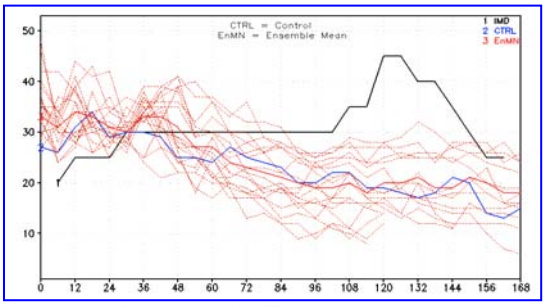
Ensemble Tracks



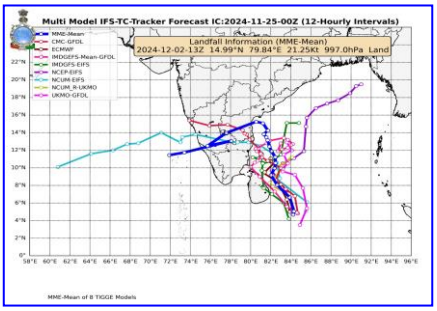
GEFS Strike Probability



GFS Intensity Forecast



Multi Model Track



Mean MME

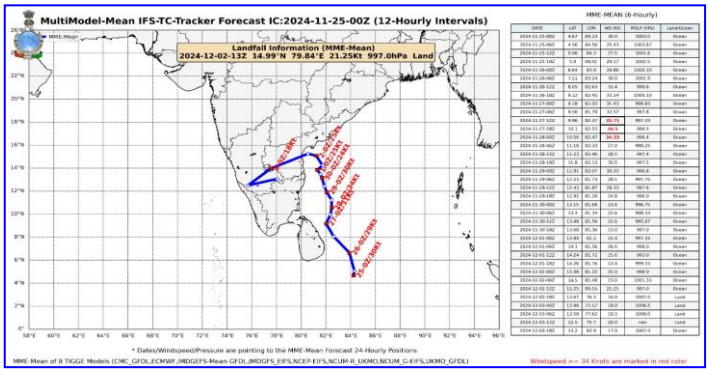
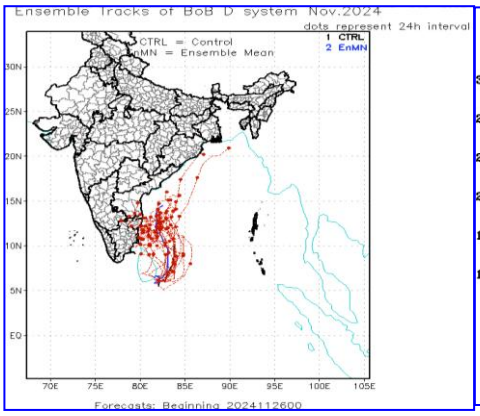


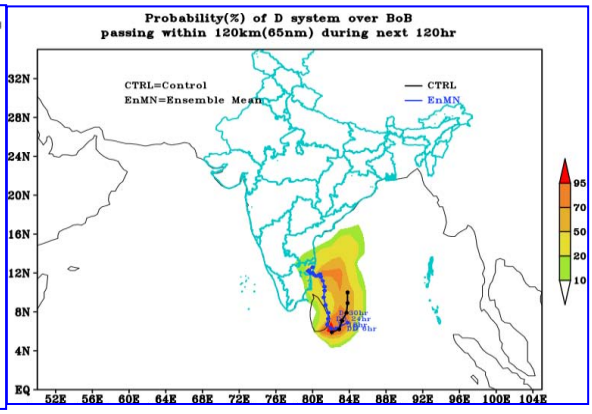
Fig. 3.5.2. (a): NWP model track forecast based on 0000 UTC of 25.11.2024

Based on 0000 UTC of 27th November, still there was large variation among various models wrt landfall. Most of the models were indicating looping, recurving tracks over westcentral bob only. IMD MME, UKMO and CMC were indicating landfall over Tamil Nadu with IMD MME & UKMO over North Tamil Nadu and CMC over South Tamil Nadu. Most of the member models track in GEFS were indicating north-northeastwards recurvature and weakening over westcentral BoB. GEFS ensemble tracks indicated large spread among various members. IMD MME indicated landfallover North Tamil Nadu coast near 12.6N/80.2E as a depression around 0500 UTC of 1st December. Thus, the models couldn't predict the landfall point and time on 27th Nov

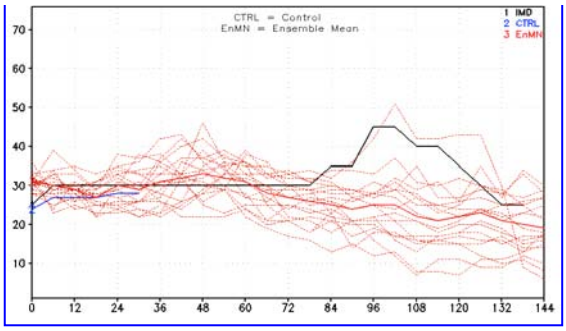
Ensemble Tracks



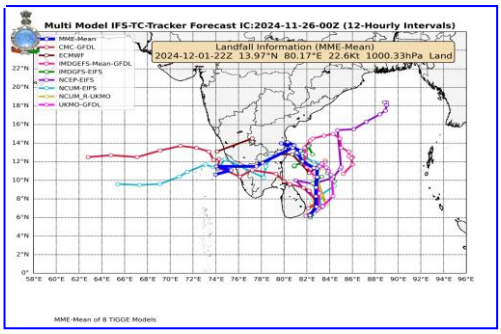
GEFS Strike Probability



GFS Intensity Forecast



Multi Model Track



Mean MME

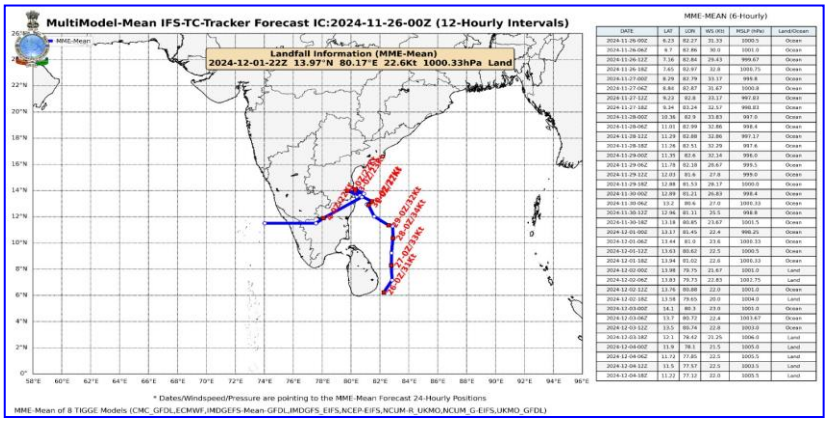
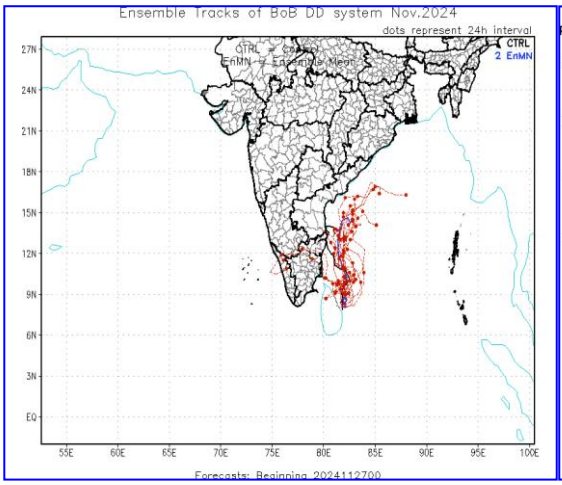


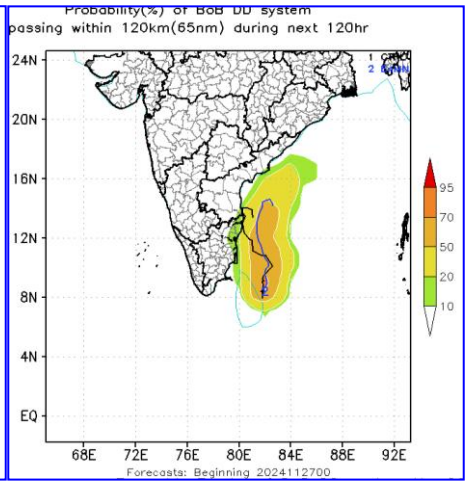
Fig. 3.5.2. (b): NWP model track forecast based on 0000 UTC of 26.11.2024

Based on 0000 UTC of 28th November, consensus developed among various models. Most of them indicated landfall over North Tamil Nadu. GEFS members also converged and indicated landfall over North Tamil Nadu. IMD MME indicated landfall over North Tamil Nadu coast near 11.9N/79.8E as a deep depression around 0500 UTC of 30th November (against previous run indicating landfall as a depression around 0500 UTC of 1st December).

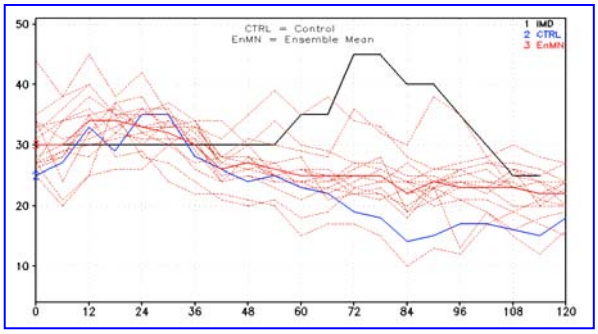
Ensemble Track



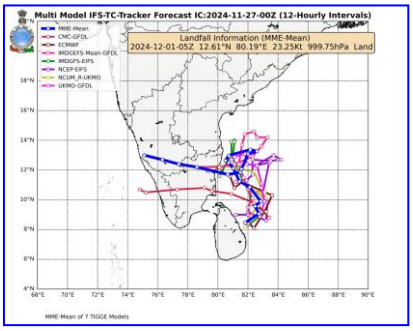
GEFS Strike



GFS Intensity Forcast



Multi Model Track



Mean MME

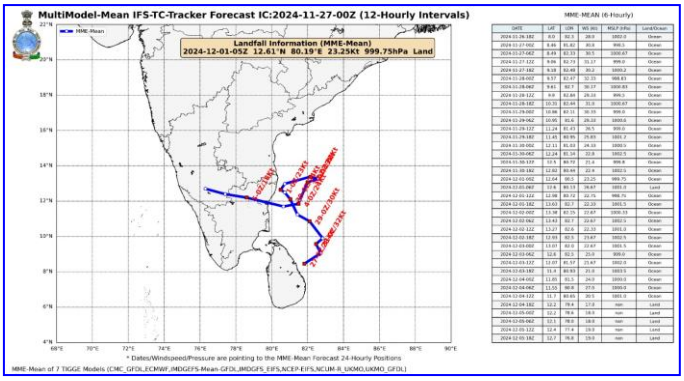
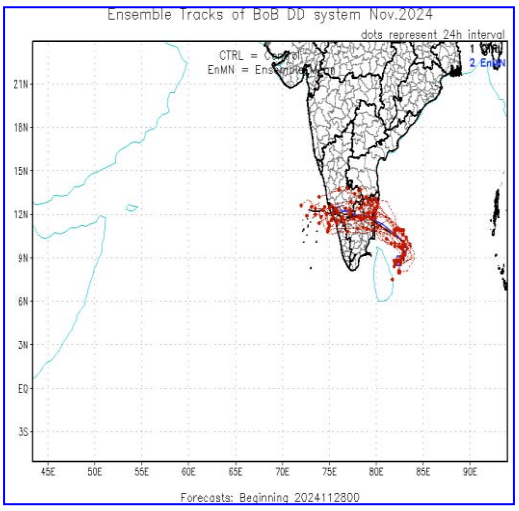


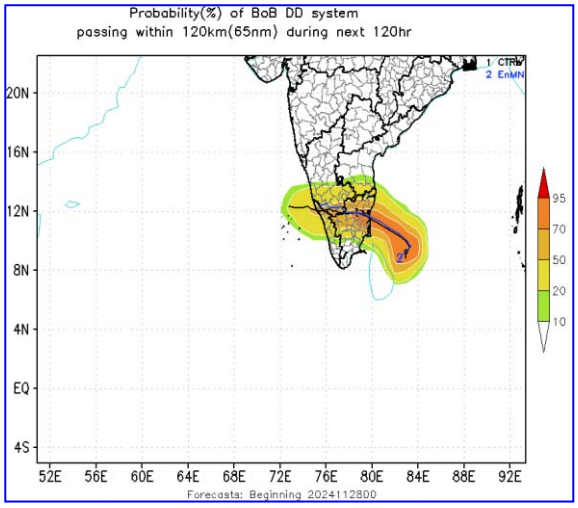
Fig. 3.5.2. (c): NWP model track forecast based on 0000 UTC of 27.11.2024

Based on 0000 UTC of 29th November, most of the models were indicating initial northwestwards movement followed by southwestwards movement near the coast. Models were also indicating the emergence of the system into Arabian Sea. The MME indicated landfall over North Tamil Nadu coast near 12.0N/79.9E as a deep depression around 1800 UTC of 30th November (against previous run indicating landfall as a deep depression around 0500 UTC of 30th November).

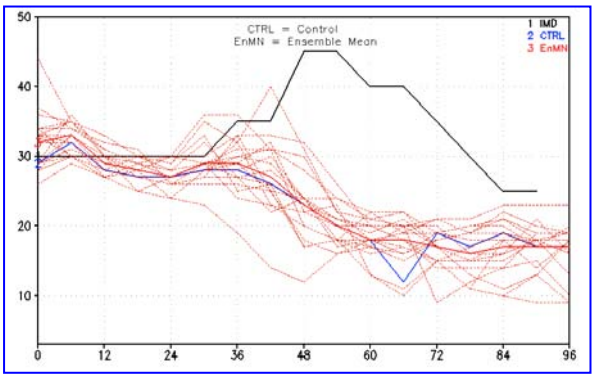
Ensemble Track



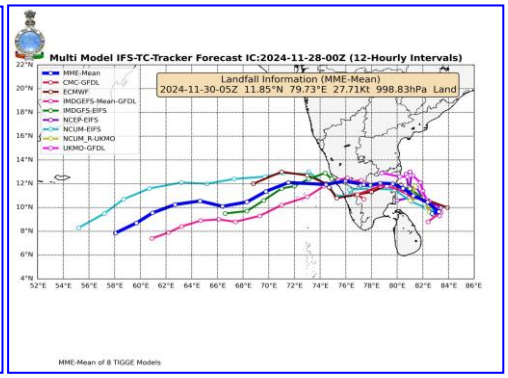
GEFS Strike Probability



GFS Intensity Forcast



Multi Model Track



Mean MME

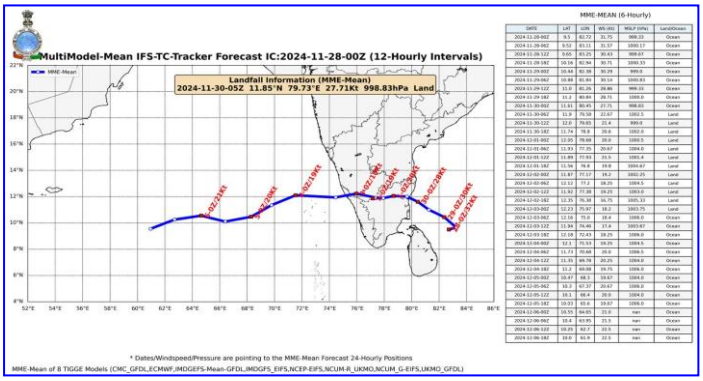
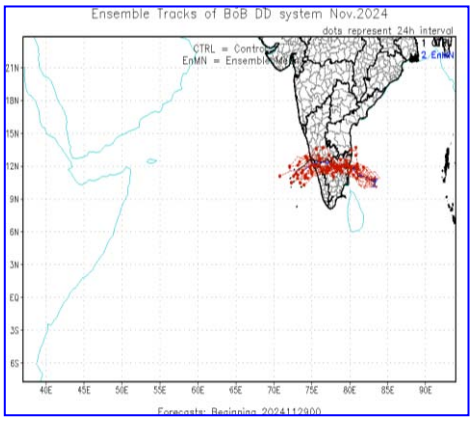
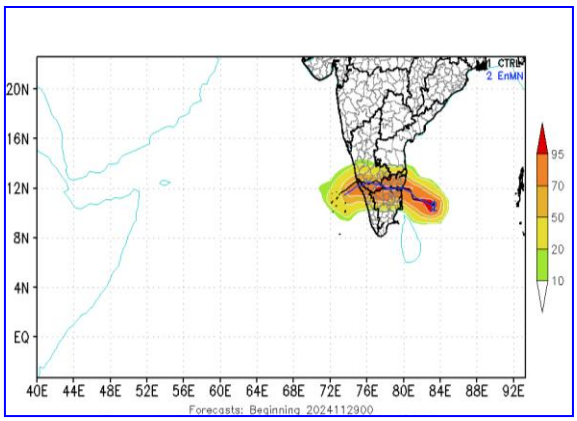


Fig. 3.5.2. (d): NWP model track forecast based on 0000 UTC of 28.11.2024

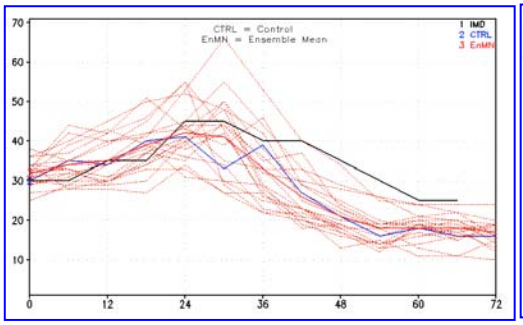
Ensemble Track



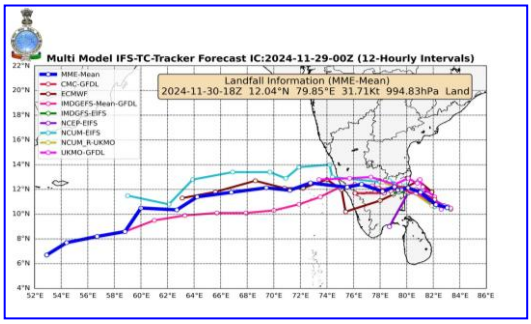
GEFS Strike Probability



GFS Intensity Forcast



Multi Model Track



Mean MME

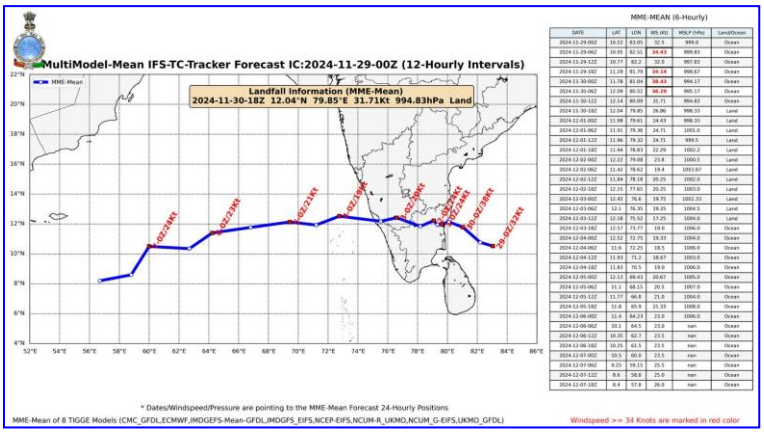
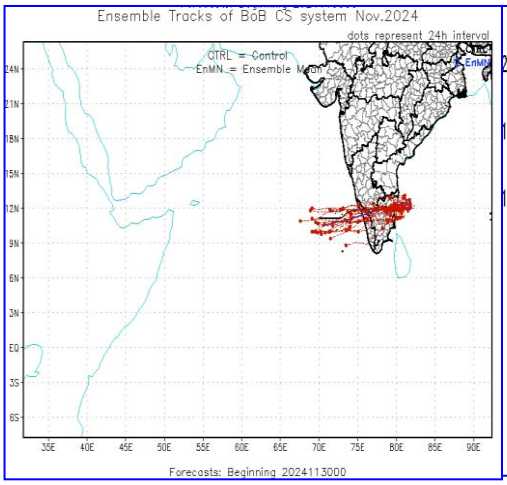


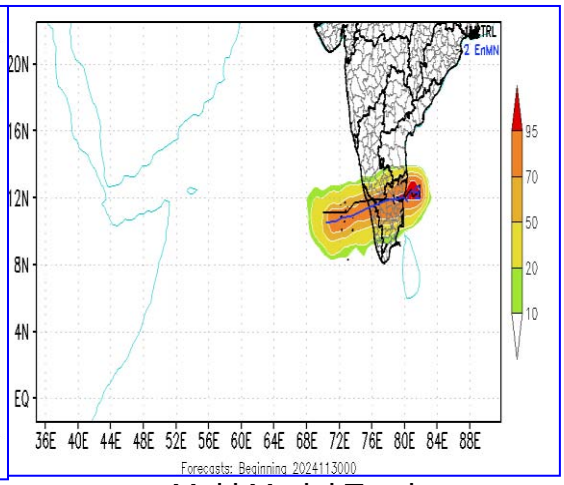
Fig. 3.5.2. (e): NWP model track forecast based on 0000 UTC of 29.11.2024

Based on 0000 UTC of 30th November, there was large variation among models with respect to intensity and landfall time. Most of the models were indicating crossing over North Tamil Nadu initial northwestwards movement followed by southwestwards movement near the coast. Models were also indicating the emergence of the system into Arabian Sea. The MME indicated landfall over North Tamil Nadu coast near 12.0N/79.9E as a deep depression around 1800 UTC of 30th November (against previous run indicating landfall as a deep depression around 0500 UTC of 30th November).

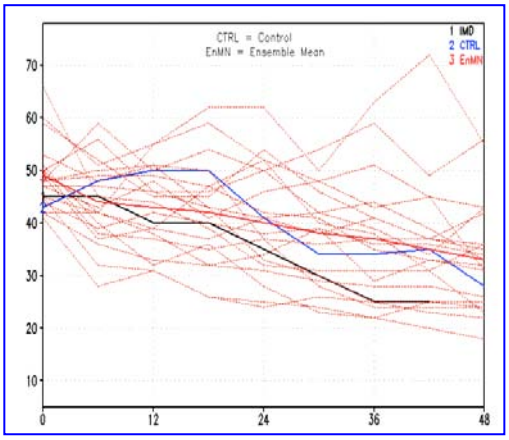
Ensemble Track



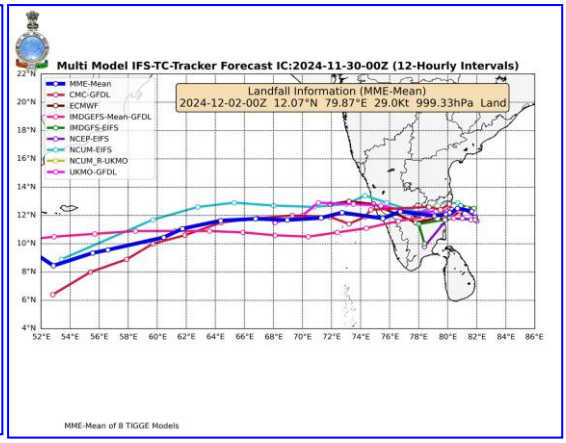
GEFS Strike Probability



GFS Intensity Forcast



Multi Model Track



Mean MME

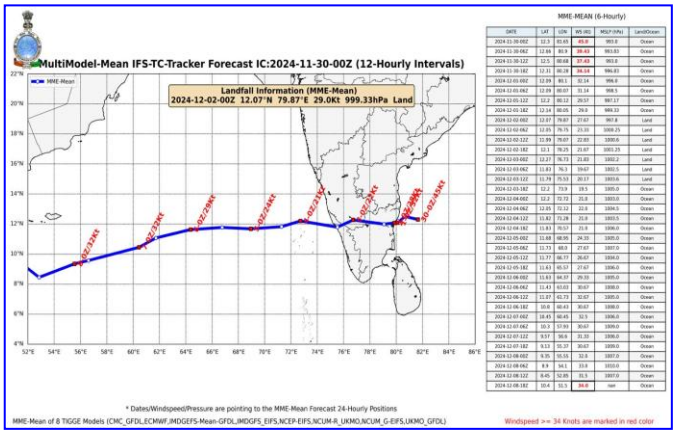


Fig. 3.5.2. (f): NWP model track forecast based on 0000 UTC of 30.11.2024

3.5.4 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 3.5.1 and Fig 3.5.3(a-b).** From the verification of the forecast guidance available from various NWP models, it is found that the average

track forecast errors of IMD MMME model were the minimum upto 60 hrs lead period and beyond that ECMWF performed better. Overall, MMME and ECMWF performed better than operational forecast for all lead periods.

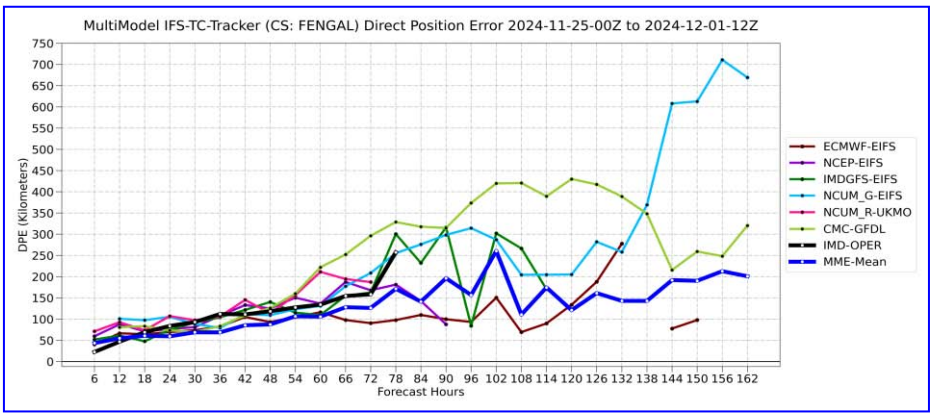


Fig.3.5.3(a): Comparative track forecast errors errors during Fengal

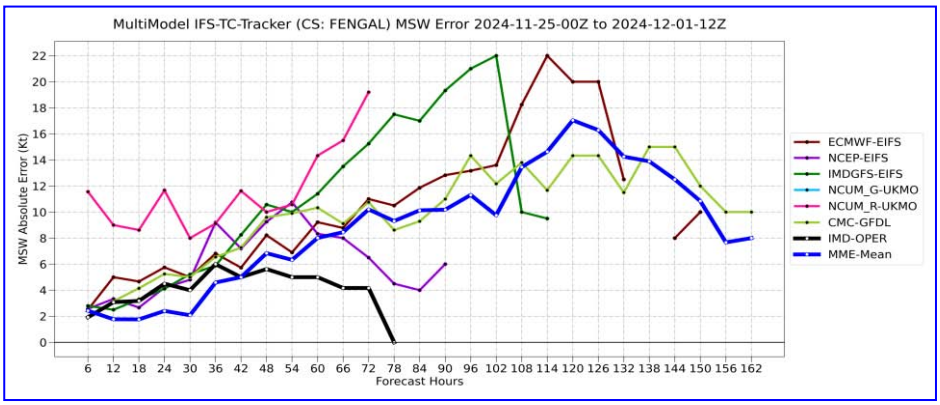


Fig.3.5.3(b):Comparative analysis of intensity forecast errors in terms of mean absolute errors during Fengal

Comparative analysis of landfall point forecast accuracy is presented in Fig.3.5.3(c). It is seen that MMME performed better than operational or any of the individual models in prediction of landfall point and time.

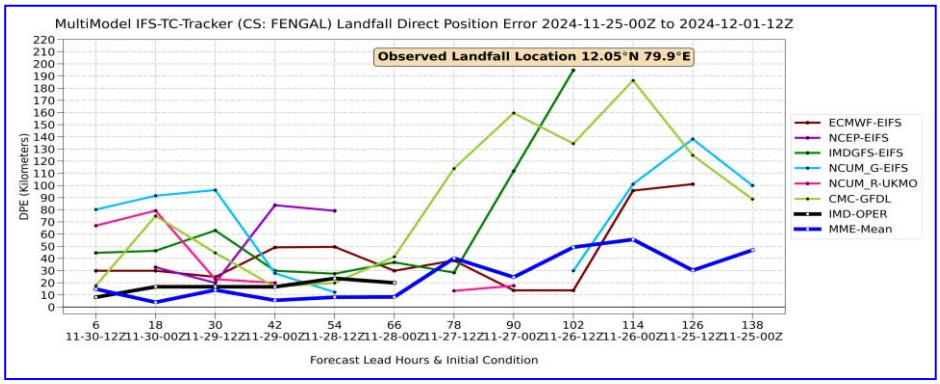


Fig.3.5.3(c): Comparative analysis of landfall point forecast errors during Fengal.

Comparative analysis of landfall time forecast accuracy is presented in Fig.3.5.3(d). It is seen that even MMME had large error in prediction of landfall time, for all lead periods upto 42 hours. Among all the models utilized for predicting cyclone Fengal, the landfall time prediction error, the least was by NCUM regional model, even better than IMD operational forecast error. The comparative performance of various NWP models vis-à-vis the operational forecast performance for prediction of intensity in terms of MSW is presented in

Table 3.5.2. The mean absolute errors in intensity forecast indicate that IMD-MMME performed better than operational intensity forecast upto 60 hrs lead period. Beyond that operational forecast had better accuracy.

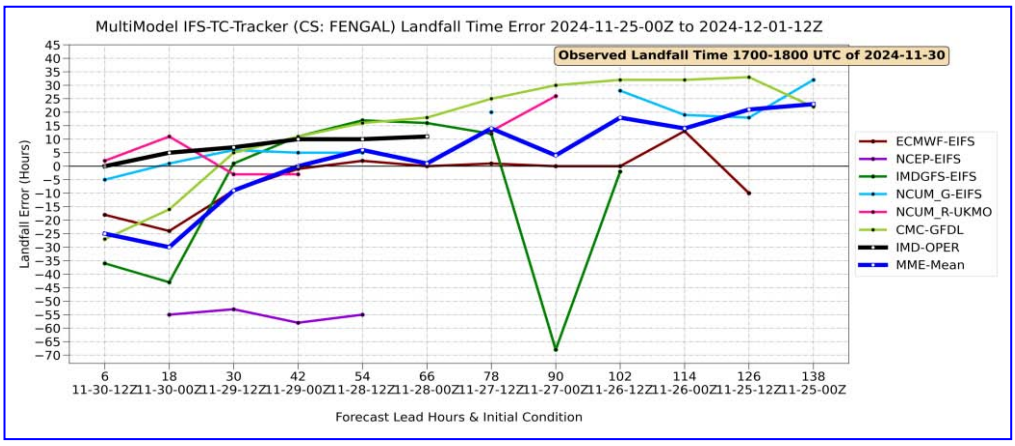


Fig.3.5.3(d):Comparative analysis of landfall time forecast errors in terms of mean absolute errors vis-à-vis operational forecast errors during Fengal.

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	12 Hr	24 Hr	36 Hr	48 Hr	60 Hr	72 Hr	84 Hr	96 Hr	108Hr	120Hr
GEFS (CNTL)	55 (13)	99 (12)	116 (10)	152 (9)	221 (8)	233 (7)	257 (6)	214 (5)	254 (4)	287 (3)
GEFS (ENS_MEAN)	44 (13)	74 (12)	134 (11)	170 (10)	189 (9)	180 (8)	208 (7)	187 (6)	224 (5)	147 (4)
NCUM_R-UKMO	92.6 (9)	106.9 (9)	106.2 (8)	113.7 (7)	211.3 (6)	187.3 (5)	-	-	-	-
ECMWF-EIFS	66.5 (13)	69.4 (12)	82.2 (11)	93.1 (9)	116.1 (9)	90.5 (7)	109.8 (7)	93.3 (6)	69.4 (4)	133.8 (1)
IMDGFS-EIFS	61.3 (10)	74.7 (9)	104.3 (8)	140.4 (7)	109.7 (5)	162.7 (4)	232.3 (4)	84.4 (1)	266.5 (1)	-
NCEP-EIFS	87.6 (6)	76.4 (5)	107.7 (5)	124.9 (4)	136.5 (3)	167.9 (2)	142.5 (1)	-	-	-
NCUM_G-EIFS	100.7 (8)	105.4 (9)	79.3 (6)	109.2 (8)	131.1 (7)	208.7 (6)	276.1 (5)	314.4 (5)	204.4 (3)	205.1 (3)
IMOPER		43 (13)	86 (10)	112.0 (10)	124 (8)	142 (7)	151 (6)	-	-	-
IMD MMME	54.8 (13)	59.5 (12)	68.7 (11)	87.5 (10)	105.7 (9)	126.4 (8)	141.1 (7)	156.6 (6)	110.6 (5)	121.0 (4)

Table 3.5.2: Average Intensity Forecast Errors of maximum sustained wind in knots (Number of forecasts verified is given in the parentheses). Negative sign indicates underestimation of intensity and vice versa

Lead Time	12 Hr	24 Hr	36 Hr	48 Hr	60 Hr	72 Hr
GEFS CNTL	2 (13)	2 (12)	-3 (10)	-9 (9)	-12 (8)	-15 (7)
GEFS ENS_MEAN	2 (13)	2 (12)	-1 (11)	-7 (10)	-10 (9)	-12 (8)
NCUM_R-UKMO	2.56 (9)	3.0 (9)	3.0 (8)	3.14 (7)	4.5 (6)	9.4 (5)
ECMWF-EIFS	1.0 (13)	1.1 (12)	1.2 11)	2.0 (9)	2.7 (9)	4.0 (7)
IMDGFS-EIFS	1.8 (10)	1.2 (9)	1.5 (8)	3.4 (7)	4.6 (5)	6.3 (4)
NCEP-EIFS	1.0 (6)	1.2 (5)	1.4 (5)	3.3 (4)	4.0 (3)	3.5 (2)
IMD OPER		2.6	4.2	6.4	7.3	5.0
IMD MMME	0.9 (13)	1.1 (12)	1.6 11)	2.6 (10)	3.3 (9)	5.0 (8)

CHAPTER-IV
PERFORMANCE OF RSMC, NEW DELHI
Prediction of cyclonic disturbances and associated adverse weather during 2024

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 2024. It issued pre-genesis forecast once daily from the stage of low-pressure area. It was followed by 6 hourly forecast and warning/advisory bulletins in the stage of depression/deep depression, 3 hourly advisories from the stage of cyclonic storm and hourly advisories on the day of landfall to various national disaster management agencies including National Disaster Management Authority (NDMA), Ministry of Home Affairs (MHA), concerned state Govts. and other users. It also issued advisories to World Meteorological Organization (WMO)/Economic and Social Cooperation for Asia and the Pacific (ESCAP) Panel member countries including Bangladesh, Myanmar, Thailand, Sri Lanka and Maldives during cyclone period. As tropical cyclone advisory centre (TCAC), it also issued tropical cyclone advisories with effect from the stage of deep depression for international civil aviation purpose as per the requirement of international civil aviation organization (ICAO) to the Meteorological watch offices of Asia Pacific region and middle east countries. The TCAC bulletin was also sent to Aviation Disaster Risk Reduction (ADRR) centre of WMO at Hong Kong like previous years.

IMD continuously monitored, predicted cyclogenesis, track, intensity and structure of cyclones. The genesis forecast in probabilistic terms in medium range forecast was issued from 01 June 2015 for a lead period of 72 hours and was extended to 120 hours in 2018 and 168 hours in 2023. Extended range outlook for next two weeks in probabilistic terms commenced in 2018. Pre-genesis forecast for track, intensity, landfall and structure commenced in March, 2022. 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 were issued regularly. The above structured track and intensity forecasts were issued from the stage of well marked low pressure area onwards. The cone of uncertainty in the track forecast was also given for all deep depressions and cyclones. The radius of maximum wind and radius of ≥28 kts, ≥ 34 kts, ≥ 50 kts and ≥ 64 kts wind in four quadrants of deep depression and cyclones was also issued every six hourly. 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 website regularly. The storm surge guidance and coastal inundation was provided as and when required to the member countries of WMO/ESCAP Panel based on IMD's statistical model, IITD model and INCOIS ADCirc Model. The prognosis and diagnosis of the systems have been 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 2024 are analysed and discussed in sec.4.3.

4.2 Bulletins issued by IMD

The following are the statistics of bulletins issued by IMD in association with the cyclonic disturbances during 2024

Bulletins issued during ‘REMAL’

Bulletins for national disaster management agencies	:	34
Bulletin for WMO/ESCAP Panel counties		34
(Special Tropical Weather Outlook and Tropical Cyclone Advisory)	:	
Hourly Bulletins		12
Tropical cyclone advisory for international civil aviation	:	14

Bulletins issued during ‘ASNA

Bulletins for national disaster management agencies	:	51
Bulletin for WMO/ESCAP Panel counties		
(Special Tropical Weather Outlook and Tropical Cyclone Advisory)	:	51
Tropical cyclone advisory for international civil aviation	:	13

Bulletins issued during 'DANA'

Bulletins for national disaster management agencies	:	28
Bulletin for WMO/ESCAP Panel counties		
(Special Tropical Weather Outlook and Tropical Cyclone Advisory)	:	28
Hourly Bulletins		21
Tropical cyclone advisory for international civil aviation	:	11

Bulletins issued during 'FENGAL'

Bulletins for national disaster management agencies	:	39
Bulletin for WMO/ESCAP Panel counties		
(Special Tropical Weather Outlook and Tropical Cyclone Advisory)	:	40
Tropical cyclone advisory for international civil aviation	:	8
Hourly Bulletins	:	8

Bulletins issued for all cyclones during 2024

Bulletins for national disaster management agencies	:	269
RSMC bulletin for WMO/ESCAP Panel member countries		272
(Special Tropical Weather Outlook and Tropical Cyclone Advisory)	:	
TCAC bulletin for international civil aviation	:	116
Hourly bulletins on the day of landfall	:	41

The number of bulletins issued during 2009-2024 for all cyclones over the NIO is shown in Fig.**4.2.1**.

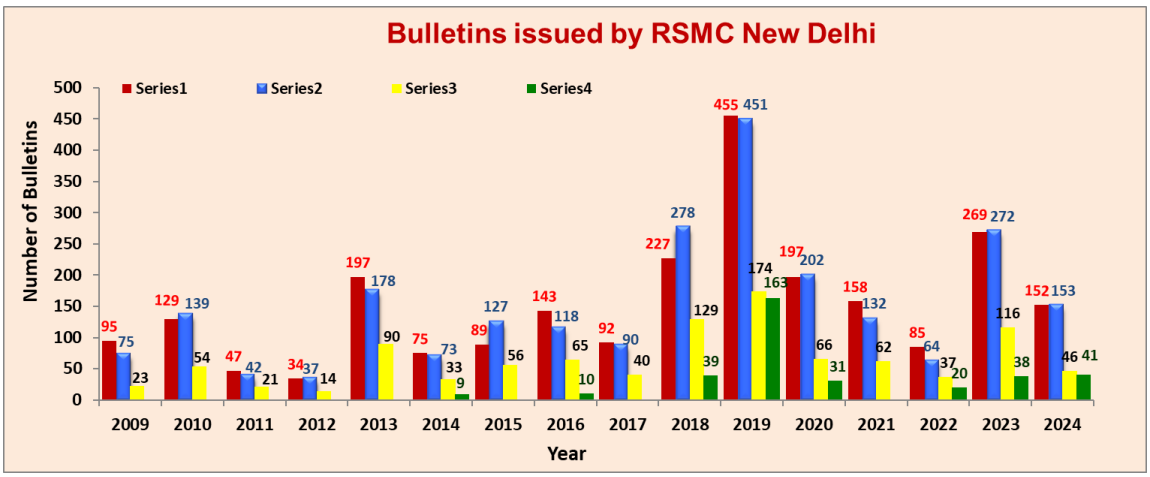


Fig.4.2.1: Total Number of bulletins issued by RSMC, New Delhi for all cyclones during 2009-2024

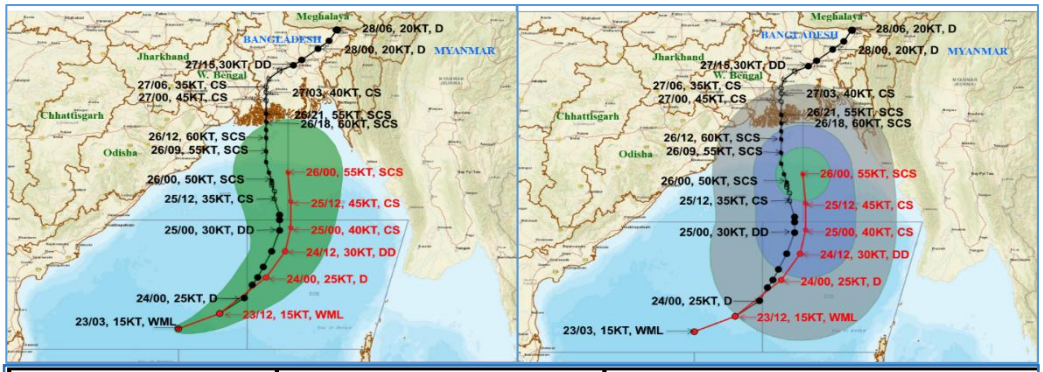
4.3 Performance of Operational Genesis, Track, intensity and landfall forecast

The performance of operational genesis, track, landfall and intensity forecasts issued by IMD, New Delhi for the three cyclones during 2024 is described in following sections:

4.3.1 Severe Cyclonic Storm REMAL over Bay of Bengal during 24th – 28th May, 2024

4.3.1.1 Genesis Forecast

- First information about likely cyclogenesis (formation of depression) over Bay of Bengal (BoB) during end of the week (17th-23rd May) was issued in the extended range outlook issued on 9th May (about 15 days ahead of formation of depression on 24th May).
- The extended range outlook was further updated on 16th May. It indicated likely formation of depression over central BoB with moderate confidence (34-67%) (about 8 days ahead of formation of depression and 11 days ahead of landfall over Bangladesh).
- Daily tropical weather outlook issued since 19th May indicated moderate probability of formation of depression during 24th – 25th (about 5 days ahead). The graphical tropical weather outlooks issued during 19th-22nd May indicated area of genesis from 5 days ahead of cyclogenesis.
- It was followed by extended range outlook issued in the evening of 23rd May indicating high confidence of genesis with the area of genesis over central BoB and movement towards Bangladesh-West Bengal coasts.
- The Pre-genesis track, intensity and structure forecast issued on 23rd May on formation of well-marked low-pressure area over westcentral BoB indicated the genesis over central BoB on 24th, initial north-northeastwards movement followed by nearly northwards movement towards north BoB and intensification upto severe cyclonic storm stage (Fig. 4.3.1.1).



MSW(knot)/kmph)	Impact	Action
28-33 /(52–61)	Very rough seas.	Total suspension of fishing operations
34-40/(62-74)	High to very high seas	Total suspension of fishing operations
41-63/(75-117)	Very High seas	Total suspension of fishing operations

WML: WELL MARKED LOW
D: DEPRESSION,
DD: DEEP DEPRESSION,

OBSERVED TRACK
FORECAST TRACK
CONE OF UNCERTAINTY

Fig. 4.3.1.1: Observed track & intensity along with predicted Pre-genesis track and intensity forecast issued at the stage of well-marked low-pressure area on 23rd May 2024 about 3 days and 12 hours ahead of landfall on 26th May demonstrating accuracy in track and intensity forecast

4.3.1.2. Track forecast error and skill

The track forecast errors for 24, 48 and 72 hrs lead period were 71, 48 and 63 km respectively against the long period average (LPA) errors of 72, 112 and 156 km respectively based on data of 2019-23 (Fig. 4.3.1.2a). The track forecast skills calculated against Climatology & Persistence (CLIPER) forecast for 24, 48 and 72 hrs lead period were 51, 86 and 90 km respectively against the long period average (LPA) skill of 66, 75 and 76% respectively based on data of 2019-23 (Fig. 4.3.1.2b). The operational track forecast errors were less than the LPA errors for all lead periods.

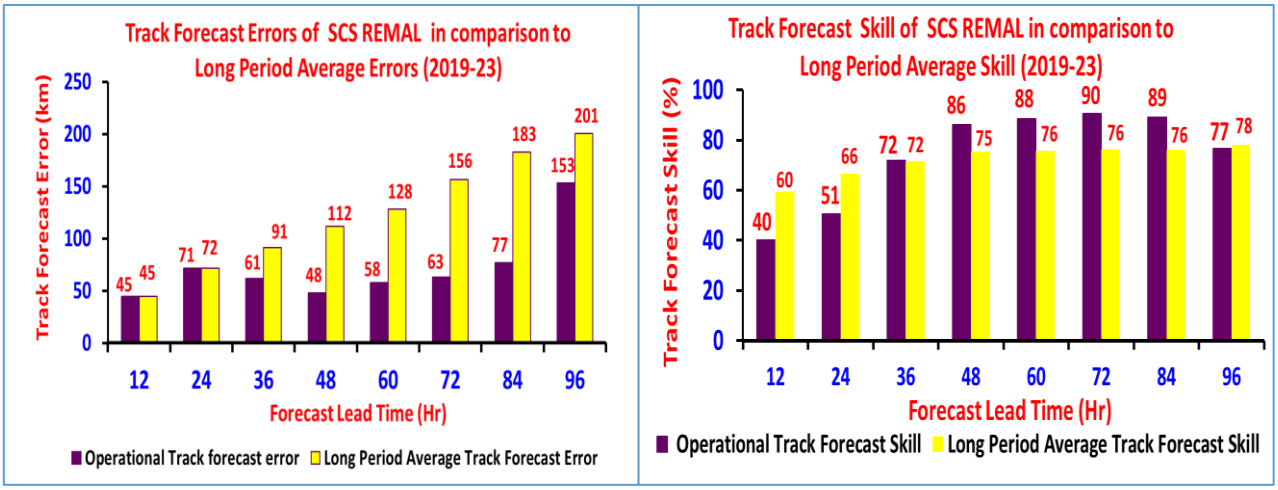


Fig. 4.3.1.2: (a) Track forecast errors and (b) skills against Climatology & Persistence (CLIPER) compared to long period average (LPA of 2019-2023) errors & skills respectively

Table 4.3.1.1: Operational Track forecast errors and skill as compared to long period average (2019-23)

Lead Period (hrs)	N	Operational Track forecast error (km)	Operational Track Forecast Skill (%)	Long Period Average (2019-23)	
				Track Forecast Error (km)	Track Forecast Skill (%)
12	16	45	40	45	60
24	14	71	51	72	66
36	11	61	72	91	72
48	9	48	86	112	75
60	7	58	88	128	76
72	5	63	90	156	76
84	3	77	89	183	76
96	1	153	77	201	78

4.3.1.3. Intensity forecast error and skill

The absolute errors (AE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 5.7, 2.2 and 7.0 knots against the LPA errors of 7.1, 10.3 and 13.8 knots based on data of 2019-23 respectively (**Fig. 4.3.1.3a**). The Root mean square error (RMSE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 7.6, 3.3 and 8.7 knots against the LPA errors

of 9.2, 12.8 and 16.5 knots during 2019-23 respectively (**Fig. 4.3.1.3b). The** skills in intensity forecast based on AE calculated against persistence-based forecast for 24, 48 and 72 hrs lead period were 73, 93 and 76% against the LPA skills of 57, 71 and 77% based on data of 2019-23 respectively (**Fig.4.3.1.4a**). The skill based on RMSE in intensity forecast for 24, 48 and 72 hrs lead period were 70.9%, 91.6% and 74.6% against the LPA skill of 62.9%, 73.4% and 80.6% during 2019-23 respectively (**Fig.4.3.1.4b**). For all lead periods, the operational intensity forecast errors were less and skills were more than the LPA

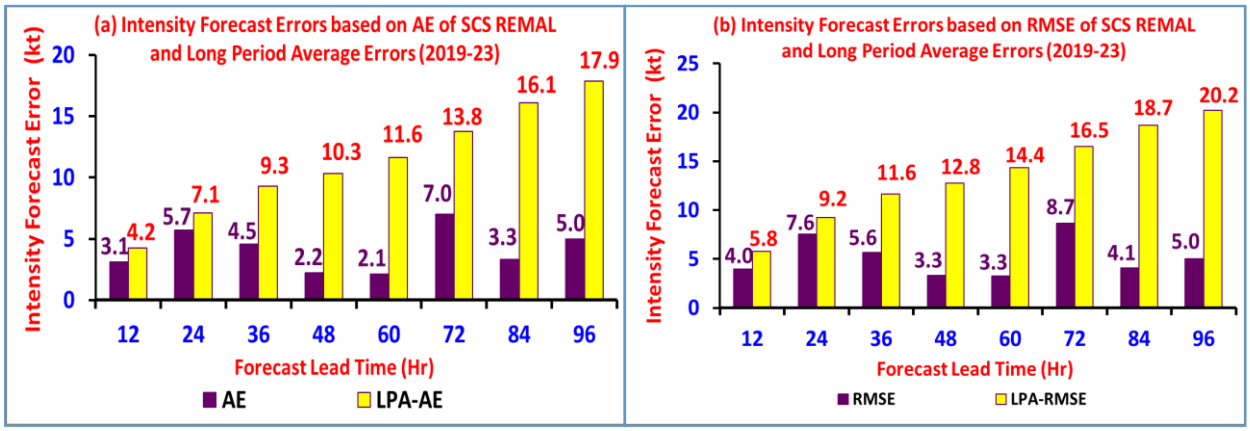


Fig. 4.3.1.3: (a) Absolute errors (AE) and (b) Root Mean Square errors (RMSE) in intensity forecast (winds in knots) as compared to long period average (2019-23)

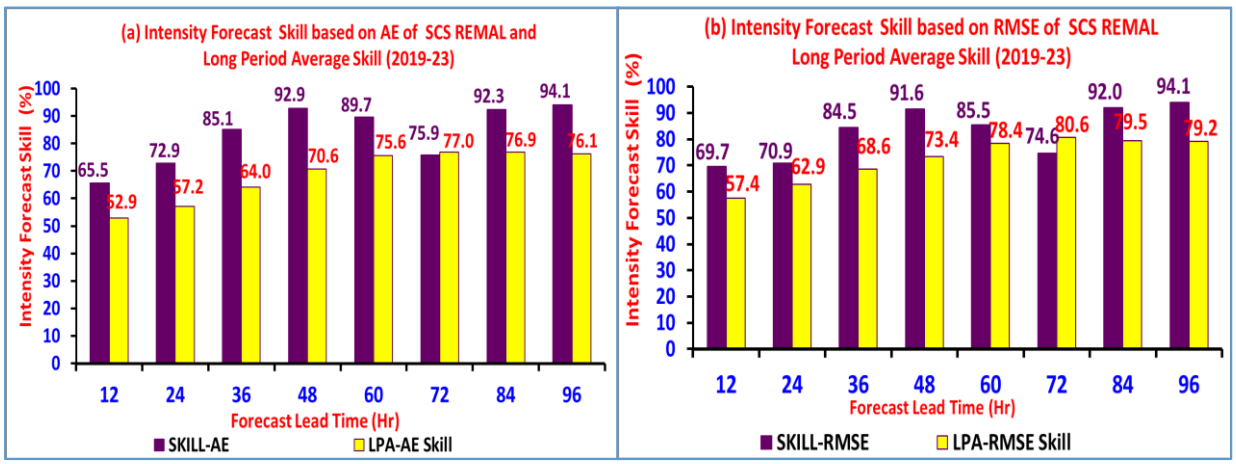


Fig. 4.3.1.4: Skill (%) in intensity forecast based on (a) Absolute errors (AE) and (b) Root Mean Square errors (RMSE) as compared to long period average (2019-23)

Table 4.3.1.2: Operational Absolute errors (AE) and Root Mean Square errors (RMSE) and corresponding skill in intensity forecast as compared to long period average (2019-23)

Lead Period	N	AE	RMSE	Skill-AE	Skill-RMSE	Long Period Average (2019-23)			
						AE	RMSE	Skill-AE	Skill-RMSE
12	16	3.1	4.0	65.5	69.7	4.2	5.8	52.9	57.4
24	14	5.7	7.6	72.9	70.9	7.1	9.2	57.2	62.9
36	11	4.5	5.6	85.1	84.5	9.3	11.6	64.0	68.6
48	9	2.2	3.3	92.9	91.6	10.3	12.8	70.6	73.4

60	7	2.1	3.3	89.7	85.5	11.6	14.4	75.6	78.4
72	5	7.0	8.7	75.9	74.6	13.8	16.5	77.0	80.6
84	3	3.3	4.1	92.3	92.0	16.1	18.7	76.9	79.5
96	1	5.0	5.0	94.1	94.1	17.9	20.2	76.1	79.2

N: No. of observations verified, AE: Absolute error, RMSE: Root Mean Square Error, LPA: Long Period Average

4.3.1.4: Landfall point and time errors

The landfall points forecast errors for 12, 24, 48 and 60 hrs lead period were Zero, 20, and 25 km respectively against the LPA errors of 11, 18, and 56 km based on data of 2019-23 respectively (Fig.4.3.1.5a). The landfall time forecast errors for 12, 24, 48 and 60 hrs lead period were Zero, 1.0, and 2.0 hours respectively against the LPA errors (2019-23) of 1.9, 2.8, and 7.7 hours based on data of 2019-23 respectively (Fig.4.3.1.5b). For all lead periods, the landfall time errors were appreciably less than LPA errors.

Fig. 4.3.1.5: (a) Operational landfall point and (b) time forecast errors compared to long period average during 2019-23.

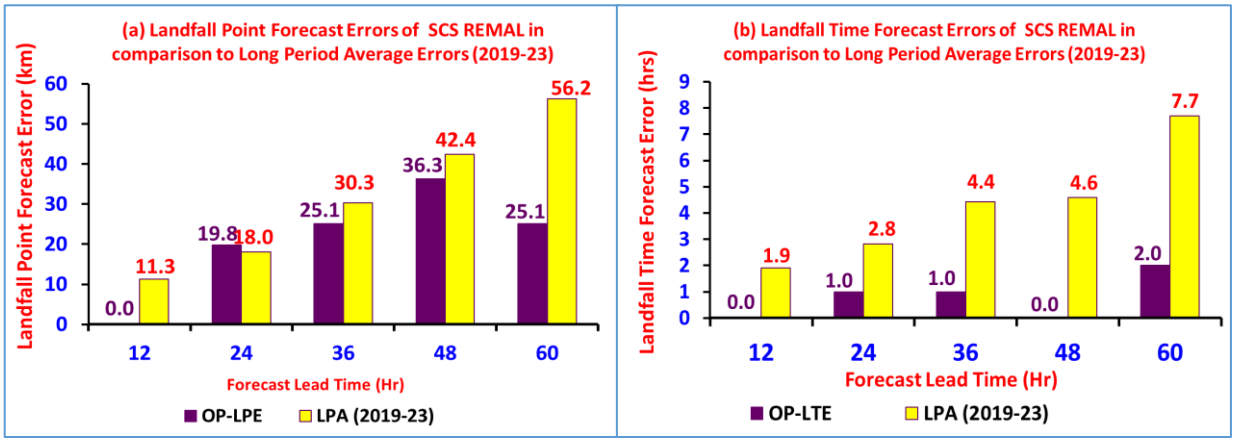


Table 4.3.1.3: Landfall point and time errors as compared to long period average (2019-23)

Lead Period	Base Time	Landfall Point		Landfall Time		Landfall Point and Time errors			
						LPE (km)		LTE (hrs)	
		Forecast	Actual	Forecast	Actual	Op.	LPA	Op.	LPA
12	24/00	21.7/89.2	21.7/89.2	26/1800	26/1800	0.0	11.3	0.0	1.9
24	24/06	21.85/89.3	21.7/89.2	26/1700	26/1800	19.8	18.0	1.0	2.8
36	24/18	21.81/89.4	21.7/89.2	26/1700	26/1800	25.1	30.3	1.0	4.4
48	25/06	21.89/89.4	21.7/89.2	26/1800	26/1800	36.3	42.4	0.0	4.6
60	25/18	21.81/89.4	21.7/89.2	26/2000	26/1800	25.1	56.2	2.0	7.7

Op.: Operational Error, LPA: Long period Average, LPE: Landfall point Erro, LTE: Landfall time Error

4.3.1.5. Adverse weather forecast performance:

Table 4.3.1.4: Verification of Heavy Rainfall Forecast

Date	Forecast of Heavy Rainfall based on 0300 UTC of date H: Heavy, VH: Very Heavy, EH: Extremely Heavy	Realized Rainfall at 0300 UTC of date
23rd May, 2024 /0300UTC	➢ H-VH rainfall at isolated places over coastal districts of West Bengal and adjoining districts of North Odisha on 26th and 27th May. ➢ H-VH rainfall at isolated places over Mizoram, Tripura and South Manipur on 26th and 27th May.	**26 May 2024:** **Tripura:** Manughat (Dholai) 8, Secretariat (West Tripura) 7 **27 May 2024** **Arunachal Pradesh :** Hollongi (Papumpara) 7 **Assam :** Beki Mathungari (Barpeta), N.lakhimpur/Lilabari (Lakhimpur) 10 each, Majuli (Jorhat), Tezpur (Shonitpur) 7 each **Meghalaya :** Shella (East Khasi Hills) 17, Mynram (East Khasi Hills) 8, Cherrapunji (East Khasi Hills), Cherrapunji (East Khasi Hills) & Sohra (East Khasi Hills) 7 each. **Manipur :** Ukhrul (Ukhrul) & Chandel (Chandel) 7 each **Mizoram :** Mizoram University (Aizawal), Kolasib (Kolasib), Kolasib (Kolasib), Aizwal (Aizawl) & 8 each. **Odisha :** Ranpur 9, Rajnagar 8, Bhapur, Aul & Nawana 7 each **Gangetic West Bengal:** Tarakeshwar 30, Sagar Island 18, Alipore 15, Durgachack 14, Contai & Uluberia 13 each, Diamond Harbour 12, Amta 11, Saltlake & Canning 10 each, Dum Dum, Kakdwip & Kalyani S 9 each, Rajnagar, Barrackpur & Basirhat 8 each, Champasari, Barobhisha, Bagati & Digha 7 each **28 May 2024** **Arunachal Pradesh:** Nari (Lower Siang) 13, Basar (West Siang) & Basar (West Siang) 8 each, Huri (KurungKumey) 7. **Assam :** Umrangso (Dima Hasao) 24, Karimganj (Karimganj) 22, Silchar (Cachar) 17, Karimganj (Karimganj), Matijuri
24th May, 2024 /0300UTC	➢ H-VH rainfall at isolated places over coastal districts of West Bengal on 26th & 27th and isolated heavy rainfall over North Coastal Odisha on 25th & 26th May and isolated EH rainfall over coastal districts of West Bengal on 26th May. H-VH rainfall at isolated places over eastern districts of Sub-Himalayan West Bengal on 27th and 28th May. ➢ H-VH rainfall at isolated places over Mizoram, Tripura & South Manipur on 26th and over Assam & Meghalaya, Arunachal Pradesh, Nagaland, Mizoram, Manipur & Tripura on 27th & 28th May. ➢ Isolated EH rainfall over Assam & Meghalaya on 27th & 28th May, Arunachal Pradesh on 28th May and Mizoram & Tripura on 27th May. ➢ H-VH rainfall at isolated places over Andaman Islands on 24th May and heavy rainfall at isolated	

	places over north Andaman Islands on 25th May.	(Hailakandi), B P Ghat (Karimganj) & Lala (Hailakandi) 16 each, Hailakandi (Hailakandi), Silchar (Cachar), Udalguri (Udalguri) & Badarpur (Karimganj) 15 each, Lkhep (KarbiAnglong) & A P Ghat (Cachar) 14 each, Gharmura (Hailakandi) 13, Halflong (Dima Hasao) 11, Lakhipur (Cachar) & Dholai (Cachar) 9 each, Kheronighat (KarbiAnglong), Lakhipur (Cachar), Amraghat (Cachar) & Amraghat (Cachar) 8 each, Harinagar (Karimganj) & Cachar (Cachar) 7 each **Meghalaya:** Cherrapunji (East Khasi Hills) 59, Mawphlang (East Khasi Hills) & Cherrapunji (East Khasi Hills) 39 each, Mynram (East Khasi Hills) 36, Jowai (West Jaintia Hills) 27, Rattacherra (East Jaintia Hills) 26, Shillong C.S.O. (East Khasi Hills) & Shillong (East Khasi Hills) 24 each, Mawkyrwat (South West Khasi Hills) & Williamnagar (East Garo Hills) 23 each, Mawkyrwat (South West Khasi Hills) 22, Khliehriat (East Jaintia Hills) 18, Barapani (RiBhoi) 17, Nongpuh (RiBhoi) 7 **Manipur:** Ukhrul (Ukhrul) & Jiribam (Imphal East) 9 each, Bishnupur (Bishnupur), Chandel (Chandel) & Thoubal (Thoubal) 7 each. **Mizoram:** Mizoram University (Aizawl) 20, Thingsulthiah (Aizawl) 17, Vairengte (Kolasib) 12, Kolasib (Kolasib) & Mamit (Mamit) 10 each, Lunglei (Lunglei) & Kolasib (Kolasib) 9 each. **Tripura:** Kailashashar (Unakoti),Kumhat (Unakoti) & Kumhat (Unakoti) 25 each, Nutanbazar (North Tripura) & Dhalai (Dhalai) 24 each, DM Office (West Tripura) 23, Kailashahar (Unakoti) & Secretariat (West Tripura) 22 each, Agartala (West Tripura), Budhjongnagar (West Tripura), Kadamtala (North Tripura) & Manughat (Dhalai) 21 each, Amarpur (Gomati) & Khowai (Khowai) 20 each, Nagicherra (West Tripura), Khowai (Khowai), Lembuchhera (West Tripura), Gajaria (Sipahijhala) & Arundhutinagar (West Tripura) 19 each, Ashapara (North Tripura) &
25th May, 2024 /0300UTC	➢ **West Bengal:** H-VH rainfall at a few places over coastal districts of West Bengal and eastern districts of Gangetic West Bengal adjacent to Bangladesh on 26th & 27th with isolated EH rainfall over these districts on 26th May. H-VH rainfall at isolated places over eastern districts of Sub-Himalayan West Bengal on 27th and 28th May. ➢ **Odisha:** Isolated heavy rainfall over North Coastal Odisha on 25th & 26th May. ➢ **Northeastern States:** H-VH rainfall at isolated places over Mizoram, Tripura and South Manipur on 26th and over Assam, Meghalaya, Arunachal Pradesh, Nagaland, Mizoram, Manipur & Tripura on 27th & 28th May. Isolated EH rainfall over Assam, Meghalaya on 27th & 28th May, Arunachal Pradesh on 28th May and Mizoram & Tripura on 27th May. ➢ **Andaman Islands:** Isolated H rainfall over north Andaman Islands on 25th May.	
26th May, 2024 /0300UTC	➢ **West Bengal:** H-VH rainfall at a few places over coastal districts of West Bengal and eastern districts of Gangetic West Bengal adjacent to Bangladesh on 26th & 27th with isolated EH rainfall (≥ 20 cm) over these districts on 26th May. The peak rainfall activity during noon of 26th to noon of 27th May. H-VH rainfall at isolated places over eastern	

	districts of Sub-Himalayan West Bengal on 27th and 28th May. ➢ **Odisha:** Isolated H rainfall over North Coastal Odisha on 26th May. ➢ **Northeastern States:** H-VH rainfall at isolated places over Mizoram, Tripura and South Manipur on 26th and over Assam, Meghalaya, Arunachal Pradesh, Nagaland, Mizoram, Manipur & Tripura on 27th & 28th May. Isolated EH rainfall (≥ 20 cm) over Assam, Meghalaya on 27th & 28th May, Arunachal Pradesh on 28th May and Mizoram & Tripura on 27th May.	Dharmanagar/ Panisagar (North Tripura) 18 each, Gandachara (Dhalai), Houra (West Tripura), Kadamtala (North Tripura), Sabroom (South Tripura) & Amarpur (Gomati) 17 each, Sipahijhala (Sipahijhala) & Kamalpur (Dhalai) 16 each, Udaipur (Gomati) & Sonamurahanbhog (Sipahlijhala) 15 each, South (South Tripura), Lengpui (Aizawl) & Amarpur (Gomati) 14 each, Kanchanpur (North Tripura) 13, Kamalpur (Dhalai) 12, Cti (Sipahijala), Belonia (South Tripura), Sabroom (South Tripura), Gokulpur (Gomati), Gandacherra (Dhalai) & Bishalgarh (Sipahijala) 11 each, Belonia (South Tripura) & Karbook (Gomati) 10 each, Chhanu (Dhalai) 9, Bagafa (South Tripura) 8, Eden Launge (North Tripura) 7. **29 May 2024** **Arunachal Pradesh:** Bomdila (West Kameng) 19, Miao (Changlang) 12, Miao (Changlang) 11, Namsai (Lohit) & Kalaktang (West Kameng) 7 each**.** **Assam :** Cachar (Cachar) & Lala (Hailakandi) 18 each, Lakhipur (cachar) 17, Hailakandi (Hailakandi), Amraghat (Cachar) & Haflong (Dima Hasao) 15 each, Dholai (Cachar) & Silchar (Cachar) 14 each, Amraghat (Cachar) 13, A.PGhat (Cachar) & Kokrajhar (Kokrajhar) 11 each, Silchar (Cachar) & Harinagar (Karimganj) 10 each, Gossaigaon (Kokrajhar), Fakiragram (Kokrajhar), Lakhipur (cachar), Goalpara (Goalpara) & Karimganj (Karimganj) 9 each, Karimganj (Karimganj), Karimganj (Karimganj), Badarpur (Karimganj) & Bilasipara (Dhubri) 8 each,Baithlghanso (KarbiAnglong), Hazuwa (Barpeta), Dhemaji (Dhemaji), B.P.Ghat (Karimganj) & Beki Mathanguri (Barpeta) 7 each. **Meghalaya:** Pynursula (East Khasi Hills) 31, Cherrapunji (East Khasi Hills) 28, Khliehriat (East Jaintia Hills) & Cherrapunji (East Khasi Hills) 18 each, Secretariat Hills (East Khasi Hills) 7. **Nagaland :** Tening (Peren) 10
27th May, 2024 /0300UTC	➢ **West Bengal:** H-VH rainfall at a few places over coastal and eastern districts of Gangetic West Bengal adjacent to Bangladesh on 27th May. H-VH rainfall at a few places likely over eastern districts of Sub-Himalayan West Bengal on 27th and 28th May. ➢ **Northeastern States:** H-VH rainfall at a few places over Assam, Meghalaya, Arunachal Pradesh, Nagaland, Mizoram, Manipur & Tripura on 27th & 28th May. Isolated EH rainfall (≥ 20 cm) over Assam, Meghalaya, Mizoram & Tripura on 27th and Arunachal Pradesh on 28th May.	
28th May, 2024 /0300UTC	➢ **Northeastern States:** H-VH rainfall at a few places is very likely over Eastern Assam, Meghalaya, Mizoram & Tripura and at isolated places over Arunachal	

	Pradesh, Nagaland, Manipur on 28th May. Isolated EH rainfall (≥ 20 cm) over south & East Assam, Meghalaya & Tripura on 28th May.	**Manipur :** Ukhrul (Ukhrul) 11, Imphal (ImphalEast) 9, Jiribam (Imphal East) 7, **Mizoram :** Lawngtlai (Lawngtlai) 15, Chawnhu (Lawngtlai) 13, Lawngtlai (Lawngtlai) 12, Vairengte (Kolasib) 10, Saiha (Saiha) 9 . **Tripura :** Kadamtala (North Tripura) 11, Nutan Bazar (North Tripura) 8. **Sub-Himalayan West Bengal :** Kumargram & Hasimara 19 each, Buxaduar 16, Barobhisha & Champasari 11 each, Chengmari/Diana 10 **Sikkim :** Chepan 12 .
29th May, 2024 /0300UTC	➢ **Northeastern States:** Isolated H-VH rainfall over Arunachal Pradesh, Assam & Meghalaya and isolated heavy rainfall over Nagaland, Manipur, Mizoram & Tripura on 29th and 30th May, 2024. Isolated EH falls over Meghalaya on 29th May, 2024.	

Table 4.3.1.5 Verification of Gale/Squally Wind Forecast issued by IMD

Date/ Base Time of observation	Gale/ Squally wind Forecast	Realised 24- hour Gale/ Squally wind Forecast till 0830 hours IST of date
24.05.2024 /0300UTC	40-50 gusting to 60 kmph along & off Bangladesh, West Bengal and adjoining north Odisha coasts from 12 UTC of 25th May. To increase becoming 60-70 gusting to 80 kmph from 00 UTC of 26th May and 100-120 gusting to 135 kmph along & off Bangladesh and adjoining west Bengal coasts from evening of 26th for subsequent 12 hours.	Bangladesh: Khepupara and Patuakhali stations in Bangladesh reported highest wind speed of 111 kmph during landfall on 26th midnight. West Bengal: Highest wind speed of 91 kmph was reported at Dum Dum followed by 78 kmph at Canning during landfall on 26th midnight. Northeastern states of India: Assam (Guwahati University) reported maximum of 65 kmph, Meghalaya (Mawkyrwat) reported 76 kmph, Mizoram (Mizoram University) 57 kmph, Tripura (A D Nagar) 63 kmph in 24 hours till
25.05.2024 /0300UTC	(A) along & off Bangladesh and west Bengal coasts: • 100-120 gusting to 135 kmph along & off Bangladesh and adjoining West Bengal coasts from 1200 UTC of 26th May for subsequent 6 hours. (B) North-eastern states: • 50-60 gusting to 70 kmph over Mizoram Tripura & south Manipur on 26th & 27th May and 40-50 gusting to 60 kmph over south Assam and Meghalaya on 27th May	
26.05.2024 /0300UTC	(A) along & off Bangladesh and West Bengal coasts: • 100-120 gusting to 135 kmph along & off Bangladesh and adjoining west Bengal coasts from 1200 UTC of 26th May till 0000 UTC of 27th May. (B) Northeastern states: • 50-60 gusting to 70 kmph over Mizoram Tripura south Manipur on 26th & 27th May and 40-50 gusting to 60 kmph over south Assam and Meghalaya on 27th May.	
27.05.2024 /0300UTC	(A) Along & off Bangladesh and west Bengal coasts	

	• 80-90 gusting to 100 kmph along & off Bangladesh and adjoining west Bengal coasts during next 3 hours. (B) Northeastern states: • 50-60 gusting to 70 kmph over Mizoram Tripura & south Manipur on 27th May and 40-50 gusting to 60 kmph over & Mizoram, Manipur and remaining parts of Assam on 27th May. To reduce to 40-50 gusting to 60 kmph over Assam & Meghalaya till noon of 28th May.	0830 hours IST of 27th May. Assam (Guwahati Observatory) reported 70 kmph, Meghalaya (Nongstonin) 48 kmph, Mizoram (Champai) 81 kmph and Tripura (Ashapara) 59 kmph in 24 hours till 0830 hours IST of 28th May.
28.05.2024 /0300UTC	(A)Northeastern States: • 40-50 gusting to 60 kmph over Eastern Assam and Meghalaya, Mizoram, Tripura and 35-45 gusting to 55 kmph over Nagaland, Manipur and remaining parts of Assam till evening of 28th May.	

Table 4.3.1.6 Verification of storm surge warning issued for West Bengal and Bangladesh

Date/ Base Time of observation	Storm Surge Forecast at 0300 UTC of date	Realised Storm Surge at the time of landfall
24.05.2024 /0300UTC	Storm surge of about 1 meter height above astronomical tide is likely to inundate low lying areas of coastal West Bengal and 3-4 m height above astronomical tide likely to inundate low lying areas of coastal Bangladesh around the time of landfall.	➢ Storm surge of about 1.0 m height above astronomical tide was observed over North & South 24 Parganas districts of West Bengal during landfall ➢ Storm surge of about 3.8 m height inside the creeks of Balaswar river close to Sapleja, Bangladesh occurred during landfall.
25.05.2024 /0300UTC	-do-	
26.05.2024 /0300UTC	-do-	

4.3.2 Cyclonic Storm "ASNA" over the Arabian Sea (25th Aug - 2nd Sep, 2024)

4.3.2.1 Genesis Forecast

- First information about likelihood of cyclogenesis (formation of Depression) with moderate confidence (34-67%) was issued in the extended range outlook issued on 15th August (about 10 days ahead of formation of depression on 25th August).
- The extended range outlook was further updated on 24th August. It indicated likely formation of depression over Northwest Madhya Pradesh with high confidence (68-100%) (about 1 day ahead of formation of depression) and probable emergence of system into the northeast Arabian Sea.
- Daily tropical weather outlook issued since 24th August indicated probability of formation of depression over land around 26th Aug.

4.3.2.2. Track forecast error and skill

The track forecast errors for 24, 48 and 72 hrs lead period were 56, 110 and 174 km respectively against the long period average (LPA) errors of 72, 112 and 156 km respectively based on data of 2019-23 (**Fig. 4.3.2.2a**). The track forecast skills calculated against Climatology & Persistence (CLIPER) forecast for 24, 48 and 72 hrs lead period were 51, 53 and 70 km respectively against the long period average (LPA) skill of 66, 75 and 76% respectively based on data of 2019-23 (Fig. 2.2.2b). (**Fig.4.3.2.2b**).

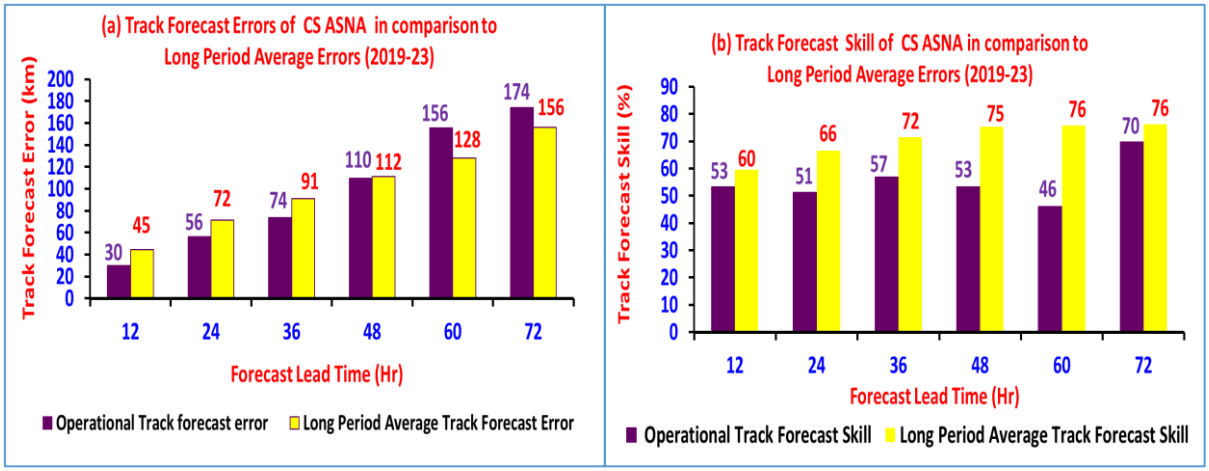


Fig. 4.3.2.2: (a) Operational track forecast errors and (b) skill compared to long period average during 2019-23

Table 4.3.2.1: Operational Track forecast errors and skill of CS "ASNA" as compared to long period average (2019-23) N: no. of observations verified

Lead Period (hrs)	N	Operational Track forecast error (km)	Operational Track Forecast Skill (%)	Long Period Average (2019-23)	
				Track Forecast Error (km)	Track Forecast Skill (%)
12	13	30	53	45	60
24	11	56	51	72	66
36	9	74	57	91	72
48	7	110	53	112	75
60	5	156	46	128	76
72	3	174	70	156	76

4.3.2.3. Intensity forecast error and skill

The absolute error (AE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 3.2, 5.0 and 1.7 knots against the LPA errors of 7.1, 10.3 and 13.8 knots during 2019-23 respectively (**Fig. 4.3.2.3a**). The Root mean square error (RMSE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 4.0, 5.0 and 2.9 knots against the LPA errors of 9.2, 12.8 and 16.5 knots during 2019-23 respectively (**Fig. 4.3.2.3b**).

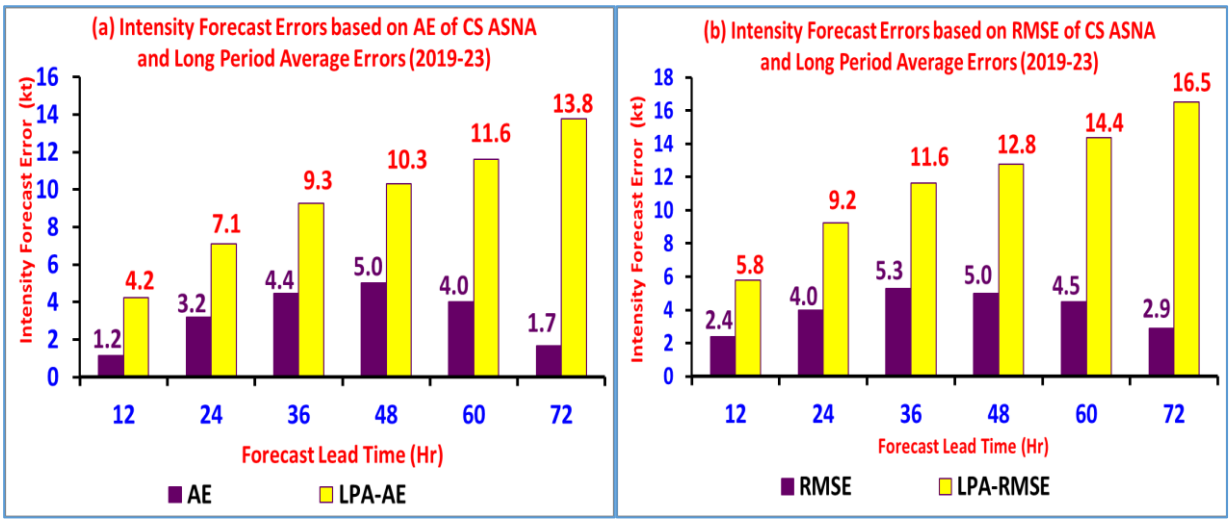


Fig. 4.3.2.3: (a) Absolute errors (AE) and (b) Root Mean Square errors (RMSE) in intensity forecast (winds in knots) as compared to long period average (2018-22)

The skill based on AE in intensity forecast for 24, 48 and 72 hrs lead period were 65.0%, 70.8% and 50.0% against the LPA skill of 57.2%, 70.6% and 77.0% during 2019-23 respectively (**Fig.4.3.2.4a**). The skill based on RMSE in intensity forecast for 24, 48 and 72 hrs lead period were 61.0%, 75.6% and 50.0% against the LPA skill of 62.9%, 73.4% and 80.6% during 2019-23 respectively (**Fig.4.3.2.4b**).

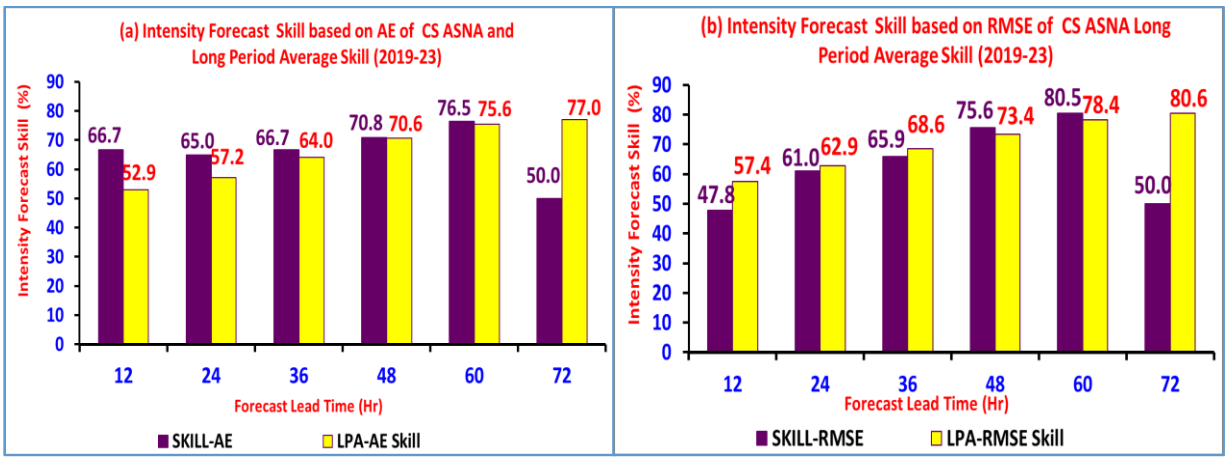


Fig. 4.3.2.4: Skill (%) in intensity forecast based on (a) Absolute errors (AE) and (b) Root Mean Square errors (RMSE) as compared to long period average (2019-23)

Table 4.3.2.2: Operational Absolute errors (AE) and Root Mean Square errors (RMSE) and corresponding skill in intensity forecast of CS "ASNA" as compared to long period average (2019-23)

Lead Period	N	AE	RMSE	Skill-AE	Skill-RMSE	Long Period Average (2018-22)			
						AE	RMSE	Skill-AE	Skill-RMSE
12	13	1.2	2.4	84.2	80.8	4.2	5.8	52.9	57.4
24	11	3.2	4.0	70.8	72.4	7.1	9.2	57.2	62.9
36	9	4.4	5.3	71.4	70.4	9.3	11.6	64.0	68.6
48	7	5.0	5.0	70.8	75.6	10.3	12.8	70.6	73.4
60	5	4.0	4.5	76.5	80.5	11.6	14.4	75.6	78.4
72	3	1.7	2.9	50.0	50.0	13.8	16.5	77.0	80.6

N: No. of observations verified, AE: Absolute error, RMSE: Root Mean Square Error, LPA: Long Period Average

4.3.2.4. Adverse weather forecast performance:

Table 4.3.2.3 Verification of Heavy Rainfall Forecast

Date	**Forecast of H Rainfall based on 0300 UTC of date** Heavy: H, Very Heavy: VH, Extremely Heavy: EH	**Realized Rainfall at 0300 UTC of date**
25th August, 2024	**West Madhya Pradesh:** H to VH rainfall at a few places on 25th& 26th with EH rainfall at isolated places on 25th August. **East Madhya Pradesh:** Light to moderate rainfall at many places with H to VH rainfall at isolated places on 25th and 26th August. **East Rajasthan:** H to VH rainfall at a few places and EH rainfall at isolated places on 25th and 26th August. **West Rajasthan:** H to VH rainfall at isolated places during 25th to 27th. **South Rajasthan:** isolated H to EH rainfall over South Rajasthan on 27th August.	**<u>25th August:</u>** **Gujarat Region:** Vapi 36, Pardi 35, Kaprada, Valsad- 34 each, Umerpada 31, Khergam, Daman, Daman- 29 each, Silvassa, Ukai, Dharampur- 27 each, Daman26, Madhbun 24, Sagbara, Khanvel- 20 each, Vyara 19, Vansda 18, Songadh 17, Waghai, Dang, Dangs, Mangrol- 15 each, Subir 15, Umergam 14, Valsad 14, Narmada 13, Khanpur, Chhota Udepur, Kadi, Garbada- 12 each, Uchchhal, Palsana- 11 each, Kamrej, Valod, Quant, Dahod, Dahod, Dahod- 10 each, Chikhli, Mandvi, Dolvan 9, Patan, Tarapur, Morva Hadaf – 9 each, Dediapada, Limkheda, Mansa, Kukarmunda, Gandevi, Surat, Deesa- 8 each, Mahesana, Netrang, Dholka, Jambughoda, Virpur, Vyara, Surat City, Vijapur, Kalol, Ghoghamba, Mahuva, Poshina, Bardoli, Garudeshwar, Kalol, Anand – 7 each. **West Madhya Pradesh:** Kathiwada 21, Biaora, Alirajpur- 14 each, Begumganj, Navibagh- 13 each, Bairagarh Airport, Maheshwar- 11 each, Badarwas, Raisen, Bhimpur, Budhni, Khategaon- 9 each, Seoni Malwa, Chicholi, Bhopal Arera Hills, Kurwai, Rehti- 8 each, Shahpur, Rahatgaon, Godadongri, Tal, Satwas, Sitamau, Hatpiplaya, Sarangpur, Bagli, Shajapur, Sonkatch, 7 each. **Madhya Maharashtra:** Velhe 18, Lonavala_agri, Peth, Harsul – 16 each, Navapur, Igatpuri- 14 each, Surgana

	Gujarat region: H to VH rainfall at a few places and isolated EH rainfall on 25th and 26th and H to VH with isolated EH rainfall over south Gujarat on 27th August. **Saurashtra & Kutch:** H to VH rainfall at a few places and EH rainfall at isolated places during 25th -28thAugust and H to EH rainfall at isolated places on 29thAugust. **Konkan & Goa:** H to VH rainfall at a few places and EH rainfall at isolated places on 25th and 26th and H to VH rainfall on 27th August. **Madhya Maharashtra:** H to VH rainfall at a few places and EH rainfall at isolated places on 25th & 26th and H to VH rainfall at isolated places on 27th August. **Odisha:** H to VH rainfall at isolated places on 25th and 26th August. **Gangetic West Bengal:** H to VH rainfall at isolated places on 25th and 26th August. **Jharkhand:** Light to moderate rainfall at many places with H to VH rainfall at isolated places on 25th and 26th August.	13, Dhadgaon/akrani- Hydro 12, Akole, Mahabaleshwar- Imd Obsy, Ozharkheda -, Paud Mulshi – 11 each, Nandurbar, Gidhade -, Dhule, Bodwad, Akkalkuwa- 8 each, Jamner, Taloda, Mulher, Vani, Chalisgaon, Trimbakshwar, Chandgad – 7 each. **Konkan & Goa:** Pernem 16, Matheran 15, Vikramgad, Valpoi, Dahanu, Quepem, Sangameshwar Devrukh – 14 each, Dabolim- Navy, Khalapur, Mapusa, Talasari, Tala, Sanguem – 13 each, Kudal, Mokheda, Lanja, Mormugao, Devgad- 12 each, Pen, Dodamarg, Jawhar, Panjim, Ratnagiri, Karjat_agri, Khed, Margao – 11 each, Mulde, Thane, Murud, Canacona – 10 each, Panvel, Tbia, Sawantwadi, Malvan, Palghar, Roha, Rajapur, Mahad – 9 each, Dapoli, Santacruz, Ulhasnagar, Vaibhavwadi, Rameshwar_agri, Ponda, Murbad, Guhagarh, Awalegaon- 8 each, Vengurla, Mangaon, Bhiwandi, Uran, Shahapur, Wakwali, Pawarwadi - Arg, Poladpur- 7 each. **East Madhya Pradesh:** Badamalhera, Tendukheda – 14 each, Panagar 12, Khurai, Tikamgarh- 11 each, Badwara 10, Bina, Buxwaha, Orchha- 9 each, Badagaon Dhasan, Karkeli, Baldevgarh, Chandia, Jabera- 7 each. **East Rajasthan:** Dausa 14, Reodar 13, Chothkabarwara 12, Sangod, Baran, Kishanganj- 9 each, Pindwara, Banera Sr, Ajmer, Pratapgarh, Ajmer, Kherwara, Khandar- 8 each, Nasirabad, Kotri, Sarmathura, Malerainadunger, Jawaja, Malpura, Garhi, Mangliawas- 7 each. **Coastal Karnataka:** Castle Rock 13, Ankola 11, Kadra, Gersoppa- 9 each. **South Interior Karnataka:** Kottigehara 11. **Chhattisgarh:** Gangalur 11, Lalpur Thana 7. **Saurashtra & Kutch:** Talala 10, Mendarda 9, Visavadar 8, Keshod, Babra- 7 each. **Odisha:** Khaira 10, Banki, Ghasipura, Chendipada- 9 each, Kaptipada, Swam-patna, Anandpur, Laikera, Jhumpura, Kirmira -8 each, Bijatala, Udala, Oupada, Jaipur – 7 each. **Coastal Andhra Pradesh & Yanam:** Palakonda 9. **Uttarakhand:** Dharchula 9, Loharkhet 7. **Jharkhand:** Chakulia 9, Bau Kanke 7. **Marathwada:** Khultabad 9. **Vidarbha:** Nagbhir 8, Chikhalda 7. **Meghalaya:** Ratacherra 8. **Telangana:** Mirdoddi 7.
26th August	**East & West Madhya Pradesh:** H to VH rainfall at a few places on 26th August.	

	East & West Rajasthan: H to VH rainfall at a few places and EH rainfall at isolated places on 26th August. H to VH rainfall at isolated places on 27th August. **Gujarat region:** H to VH rainfall at a few places and isolated EH rainfall on 26th and 27th August and H rainfall at isolated places on 28th August. **Saurashtra & Kutch:** H to VH rainfall at a few places and EH rainfall at isolated places on 26th and 27th August; H to VH rainfall at isolated places on 28th & 29th August and H rainfall at isolated places on 30th August. **Konkan & Goa:** H to VH rainfall at a few places on 26th and H rainfall on 27th & 28th August. **Madhya Maharashtra:** H to VH rainfall at a few places on 26th and H rainfall at isolated places on 27th & 28th August. **Odisha:** H rainfall at isolated places during 26th to 28th August. **Gangetic West Bengal:** H to VH rainfall at isolated places on 26th August and H rainfall at isolated places on 27th August.	**West Rajasthan:** Raniwada Sr 7. **<u>26th August:</u>** **Gujarat Region:** Khergam 35, Dangs 29, Waghai 26,Dang 24, Kaprada, Santrampur,Dharampur- 23 each, Subir 22, Shahera 21, Ukai, Vansda, Madhbun- 20 each, Nadiad 19,Valsad, Nandod, Dediapada – 18 each,Fatepura, Kukarmunda, Khanvel,Mahudha – 17 each, Sagbara, Kadana, Anand, Karjan – 16 each, Quant, Dahod,Narmada, Silvassa -15 each, Modasa 14, **East Rajasthan:** Pipalkhunt 26, Bhungra, Banswara- 19 each, Sallopat 16, Bagidora, Arthuna, Garhi, Sajjangarh- 15 each, Pratapgarh, Kesarpura, Chikali, Danpur- 13 each, Loharia, Shergarh, Arnod- 11 each, Sabla10, **Saurashtra & Kutch:** Rajkot 23, Muli, Chotila- 21 each, Wankaner 20, Halvad 18, Paddhari 17, Thangadh, Surendranagar- 14 each, Wadhvan 13, Surendranagar, Dhrangadhra, Sayla- 11 each, Lodhika 10, **West Madhya Pradesh:** Alirajpur 19, Malhargarh 15, Pansemal 13, Jaora, Kathiwada, Raoti- 12 each, Jawad, Shamshabad- 11 each, Sailana, Mandsaur-, Neemuch- 10 each, **Madhya Maharashtra:** Surgana 24, Dhadgaon/akrani-Hydro 19, Radhanagari, Peth- 16 each, Mahabaleshwar- 14, Lonavalaagri 13, Trimbakshwar 12, Igatpuri, Taloda- 11 each, Bhor 10, **Coastal Karnataka:** Castle Rock 16, Kadra 8, **Konkan & Goa:** Palgharagri, Jawhar- 15 each, Vikramgad, Wada- 13 each, Talasari, Dahanu- 12 each, Mangaon, Kankavli, Valpoi- 11 each, Mahad, Ponda, Mhasla, Matheran- 10 each, **South Interior Karnataka:** PonnampetPwd 14, Kottigehara 12**,** **Jharkhand:** Maheshpur12; **Chhattisgarh**: Sukma 10, **West Rajasthan:** Jaitran 7, **Tamil Nadu:** Taluk Office Pandalur 7, **North Interior Karnataka:** Londa 7, **Coastal Andhra Pradesh:** Chodavaram 7 **<u>27th August:</u>** **Saurashtra & Kutch:** Tankara 36, Wankaner 34, Rajkot 32, Kalavad 26, Mandvi, Khambhalia- 25 each, Lodhika 23, Chotila, Morbi, Nakhatrana- 22 each, Thangadh, Lalpur- 21 each, Kotdasangani 17, Chuda,

	Jharkhand: Light to moderate rainfall at many places with H to VH rainfall at isolated places on 26th August and H rainfall at isolated places on 27th & 28th August. **Bihar:** Light to moderate rainfall at many places with H rainfall at isolated places during 26th to 28th August.	Jodia- 16 each, Dhrol, Sayla- 14 each, Lakhtar, Barvala- 13 each, Jamnagar, Gadhda, Dasada, Vadia, Paddhari, Gondal, Botad- 12 each, Visavadar, Ranpur, Muli, Wadhvan, Jasdan, Dwarka, Naliya, Babra- 11 each, Kalyanpur, Jamnagar, Okha, Surendranagar, Keshod- 10 each. **Gujarat Region:** Morva Hadaf 34, Tarapur 31, Nadiad, Khambhat- 29 each, Borsad, Padra, Vadodara- 28 each, Godhra, Sojitra- 27 each, Wanakbori 26, Anand 24, Mahemdavad 23, Vaso 22, Balasinor, Mahudha- 21 each, Dholka 20, Bilodara_aws, Matar, Kheda, Meghraj- 19 each, Halol, Ghoghamba, Jotana- 18 each, Galteshwar, Shahera, Santrampur, Jambughoda, Limkheda, Dhandhuka- 17 each, Arnej_aws 16, Siddhpur, Fatepura, Kadi- each 15, Singvad, Dhandhuka, Mansa, Abad City, Kathalal, Chhota Udepur, Khanpur, Anklav- 14 each, Umreth, Visnagar, Modasa, Dascroi, Mc Ahmedabad, Mandal, Waghai- 13 each, Bavla, Virpur, Savli, Dholera, Becharaji- 12 each, Viramgam, Jhalod, Dang, Vadodara, Desar, Harij, Waghodia, Petlad, Bayad, Jetpur Pavi, Vadnagar, Godra_aws, Bodeli- 11 each, Vijapur, Subir, Dhanpur, Gandhinagar, Mahesana, Kalol, Sanjeli, Dahegam, Detroj, Prantij- 10 each. **Chhattisgarh:** Kusmi 25, Wandrafnagar 15, Raghunath Nagar, Manora- 9 each, Sanna 7 **East Rajasthan:** Bagidora 20, Sallopat, Shergarh- 17 each, Dhambola 14, Veja 13, Arthuna 11, Sajjangarh 10, Loharia, Khushalgarh, Chikali- 9 each, Garhi 8, Kanva, Galiakot, Sanganer Tehsil-7 each. **East Madhya Pradesh:** Kusmi 15, Sidhi, Churhat- 14 each, Nagode, Beohari, Bahri- 11 each, Rampur 10, Majhauli, Devser, Sihawal- 9 each, Orchha, Bilhari- 8 each, Naigarhi, Semariya, Gudh, Lavkushnagar- 7 each. **Madhya Maharashtra:** Gaganbawada, Mahabaleshwar- 13 each, Surgana 12, Lonavala_agri, Trimbakshwar- 11 each, Shahuwadi 10, Ajra, Chandgad, Radhanagari, Velhe- 9 each, Peth 8, Patan, Igatpuri, Harsul- 7 each **Konkan & Goa:** Jawhar 12, Awalegaon - Arg 10, Matheran, Pawarwadi- 8 each, Lanja, Mandangad, Mokheda, Vikramgad, Rajapur- 7 each. **West Madhya Pradesh:** Kathiwada 10, Bhabhra 9, Meghnagar, Udaigarh, Thandla- 7 each **Bihar:** Khaira, Silao, Sono- 7 each.
27th August	**Gujarat State:** **(a) North Gujarat region:** H to VH rainfall at isolated places is over North Gujarat on 27th August and H rainfall at isolated places on 28th & 29th August. **(b) South Gujarat Region:** H to VH rainfall at a few places and EH rainfall at isolated places on 27th H to VH rainfall at isolated places on 28th August and H rainfall at isolated places during 29th to 31st August. **(c) Saurashtra & Kutch:** H to VH rainfall at a few places and EH rainfall at isolated places during 27th to 29th and H rainfall at isolated places on 30th August. **South Rajasthan:** H to VH rainfall at isolated places is on 27th and H rainfall at isolated places on 28th August.	

	Madhya Maharashtra: H to VH rainfall at isolated places on 27th and H rainfall at isolated places on 28th August. **Konkan & Goa:** H to VH rainfall at isolated places on 27th and H rainfall at isolated places on 28th August. **West Madhya Pradesh:** H rainfall at isolated places over West Madhya Pradesh is on 27th August. **Odisha:** H rainfall at isolated places during 27th to 28th August and H to VH rainfall on 29th August. **Gangetic West Bengal:** H rainfall at isolated places on 27th August. **Jharkhand:** Light to moderate rainfall at many places with H to VH rainfall at isolated places on 27th and H rainfall at isolated places on 28th August. **Bihar:** Light to moderate rainfall at many places with H rainfall at isolated places during 27th to 28th August.	**Jharkhand:** Rania 14, Kharsema 13, Maithon, Dumri- 12 each, Bagodari 11, Panchet, Nandadih, Panchet, Nawadih, Dumri -9 each, Hunterganj, Chandil, Markachou, Gobindpur, Madhupur, Chakulia- 8 each, Torpa, Giridih Bengbad, Giridih, Jamtara, Diyakel Khunti- 7 each. **Orissa**: Jagatsinghpur 11, Cuttack, Bhuban, Kantapada- 9 each, Athgarh, Mundali, Banki- 7 each. **Chhattisgarh:** Kusmi 25, Wandrafnagar 15, Raghunath Nagar, Manora- 9 each, Sanna 7 **Gangetic West Bengal**: Bankura 13, Luchipur, Diamond Harbour- 11 each, Bankura 10, Asansol, Asansol- 9 each, Jhargram, Burnpur- 8 each, Kalaikunda, Midnapore- 7 each **<u>28th August:</u>** **Saurashtra & Kutch:** Khambhalia 43, Jamnagar 38, Jamjodhpur 32, Dwarka 31, Lalpur 30, Porbandar, Ranavav- 28 each, Bhanvad, Kalavad- 24 each, Kalyanpur 24, Kotdasangani 23, Dhrol 18, Lodhika 17, Dhoraji, Jamkandorna- 16 each, Jodia, Gondal- 15 each, Kutiana 13, Morbi, Mangrol, Tankara, Visavadar, Rajkot- 12 each, Upleta, Vanthali, Manavadar- 11 each, Bhesan, Talala, Jetpur, Paddhari- 10 each, Junagadh, Naliya- 9 each, Mendarda, Wankaner, Keshod, Babra, Abdasa- 8 each, Botad 7. **Gujarat Region:** Nadiad 8, Kapadvanj 7. **East Rajasthan:** Mounnt Abu 9. **Odisha:** Birmaharajpur, Jeypore- 10 each, Nandapur 8, Tangarpali 8, Hirakud 7. **Gujarat Region:** Umerpada 7. **Saurashtra & Kutch:** Naliya 30, Bhanvad 29, Abdasa 27, Kalyanpur 26, Dwarka, Lakhpat, Khambhalia- 23 each, Jamjodhpur 22, Nakhatrana 20, Mandvi18, Kalavad, Lalpur- 17 each, Kandla Airport 16, Dhoraji, Lodhika- 15 each, Kutiana, Jamkandorna- 13 each, Anjar, Ranavav- 12 each, Jamnagar 11, Jetpur, Mundra- 10 each, Bhuj, Porbandar, Rajkot, Manavadar, Upleta, Gondal- 9 each, Vanthali, Wankaner, Jamnagar-8 each, Gandhidham, Kandla New, Bhesan, Kotdasangani, Jodia- 7 each. **Madhya Maharashtra:** Igatpuri 8, **Gujarat:** Mandvi 39, Mundra 22, Okha 17, Abdasa16; Naliya16, Dwarka, Anjar-8 each, Gandhidham 7. **Coastal Andhra Pradesh & Yanam:** Kalingapatnam 8.
28th August	**Gujarat State:** **(a) Saurashtra & Kachchh:** H to VH rainfall at a few places and EH rainfall at isolated places on 28th August; H to EH rainfall at isolated places on 29th August and H	

	rainfall at isolated places on 30th August. **(b) Gujarat region:** Light to moderate rainfall at many places with H rainfall at isolated places is on 28th August. **South Rajasthan:** Light to moderate rainfall at many places with H rainfall at isolated places is on 28th August. **Madhya Maharashtra:** H rainfall at isolated places on 28th August. **Konkan& Goa:** H rainfall at isolated places on 28th August.	**Coastal Andhra Pradesh:** Masulipatnam, Vijayawada-18 each, Gudivada 17, Kaikalur 15, Narsapuram 14, Amaravati 13, Vijayawada, 12, Mangalagiri, Nandigama, Bheemavaram-11 each, Palakoderu, Tenali, Tiruvuru, Guntur-9 each, Eluru, Nuzvid, Atchampet-8 each, Tadepalligudem, Repalle, Kunavaram, Karamchedu-7 each. **Telangana:** Damaragidda 13, Madhira, Dornakal, Kothaguda, Thimmajipeta, Bonakal-9 each. **Odisha:** Malkangiri 11, Nandapur 8, Junagarh 5. **Coastal Andhra Pradesh:** Masulipatnam 18, Vijayawada 18, Gudivada 17, Kaikalur 15, Narsapuram 14, Amaravati 13, Vijayawada 12, Mangalagiri, Nandigama, Bheemavaram-11 each, Palakoderu, Tenali, Tiruvuru, Guntur- 9 each, Eluru, Nuzvid, Atchampet-8 each, Tadepalligudem, Repalle, Kunavaram, Karamchedu-7 each. **Telangana:** Damaragidda 13, Madhira, Dornakal, Kothaguda, Thimmajipeta, and Bonakal-9 each. **Odisha:** Malkangiri 11, Nandapur 8, Junagarh 5
29th August	**Gujarat State:** **Saurashtra & Kachchh:** H to EH rainfall at isolated places on 29th, H to VH rainfall at isolated places on 30th August and H rainfall at isolated places over coastal districts on 31st August.	**Odisha**: Padia 14. **Chhattisgarh**: Dornapal 11, Konta 10. **Andhra Pradesh & Yanam**: Amaravati, Tiruvuru 26 each, Guntur 23, Kukunoor 20, Atchampet 19, Tenali 18, Mangalagiri, Nandigama, Piduguralla, Macherla 17 each, Paleru Bridge, Velairpad 16 each, Nuzvid, Mundlamuru, Kunavaram 14 each, Jangamaheswarapuram, Bapatla, Vijayawada 13 each, Santhamaguluru, Prakasam Barrage, Vararamachandrapur 12 each, Avanigada, Addanki, Vijayawada, Chintur 11 each, Karamchedu 10, Kaikalur, Sattenapalle, Repalle 9 each, Anakapalle, Yelamanchili, Markapur, Chimakurthi 8 each, Podili, Ongole, Gudivada 7 each. **Telangana**: Malyal 40, Mahabubabad 37, Kodada 35, Manuguru, Kusumanchi 32 each, Chilkur 31, Mattampally, Huzur Nagar 30 each, Parvathagiri, Burgampadu 29 each, Madhira, Banswada 28 each, Kodakandla 27, Dornakal, Chinthakam, Tadwai Mlg, Noothankal 26 each, Gudurwrgl 25, Palawancha 24, Bhadrachalam, Khammam 23 each, Aswapuram, Thollada 22 each, Sadasivanagar, Bonakal 21 each, Mothey, Bhiknur, Chennaraopet 20 each, Jajireddigudem, Konijerla, Suryapet 19 each, Bayyaram, Kamareddy 18 each, Garla 17,
30th Aug2024	**Odisha**: H to VH rainfall at isolated places during 30th to 31st August. isolated heavy rainfall likely on 1st September. **Coastal Andhra Pradesh:** H rainfall at isolated places during 30th August to 1st September and heavy to VH rainfall at isolated places on 30th and 31st August.	

31st Aug 2024	**Odisha and Chhattisgarh:** HVH rainfall at isolated places on 31st August & 1st September over south Odisha and south Chhattisgarh. **Coastal Andhra Pradesh:** HVH rainfall at a few places and EH rainfall at isolated places likely on 31st August. **Telangana:** Light to moderate rainfall at most places EH rainfall at a few places and extremely heavy rainfall at isolated places on 31st August and isolated heavy to very heavy rainfall on 1st September.	Kothagudem, Wyra Kvk 16 each, Dhar Palle, Tadwai, Kothaguda, Kalwakurthy 16 each, Govindaraopet, Domakonda, Dummugudem, Miryalaguda, Zaffergadh, Sathupalle 15 each, Jammikunta, Vangoor, Tekulapalle, Devaruppal, Achampeta, Devarakonda, Medak, Yellandu 14 each, Thimmajipeta, Kollapur, Tandur, Huzurabad, Chandrugonda, Neredcherla, Varni, Shadnagar, Thimmapur, Khammam Urban, Jadcherla 13 each, Kodangal, Kosgi, Yellandu, Kowdipalle, Chandur, Bhoothpur, Gandeed, Khila Ghanpur, Choppadandi, Karimnagar, Mulakalapalle, Narsampet 12 each, Narsapur, Hanwada, Lingampet, Damaragidda, Koilkonda, Julurpad, Pochampalle, Elagaid, Tekmal, Gandhari, Yellareddypeta, Pinapaka 11 each, Regode, Wanaparthy, Enkuru, Aswaraopeta, Chandurthi, Palakurthi, Shankarapatnam, Bheemgal, Nagarjuna Sagar, Yellareddy, Chevella, Ibrahimpatnam, Ramayampet, Gopalpet, Choutuppal, Chinna Chinta Kunt, Nagarjunsagar, Jogipet 10 each, Jogipet, Mustabad, Papannapet, Midjil, Nanganur, Mominpet, Maganoor, Velpur, Narmetta, Atmakurwrgl, Nawabpet, Sultanabad, Nawabpetmbn, Chigurumamidy, Tamsi, Pebbair, Nangnoor, Bomraspeta, Doma, Nidamanur, Narayanpet, Boath, Gangadhara, Hathanoora, Kothakota, Bachhanpet, Jagadevpur, Nizam Sagar, Talamadugu 9 each, Talamadugu, Peddamandadi, Yadagirigutta, Kondurg, Jangaon, Veepangandla, Julapalle, Ramannapeta, Atmakur Wnp, Nallabelly, Bazarhathnoor, Vicarabad, Pargi, Tandur, Wargal, Chegunta, Atmakur M, Pedda-Adiserlapalle, Yacharam, Ghatkesar, Kondapak, Naga Reddipet, Maheswaram, Konaraopeta, Navipet, Wankdi, Utnur 8 each, Bhuvanagiri, Dindigul, Narva, Asifabad, Peddemul, Pitlam, Bala Nagar, Peddapalle, Nagar Kurnool, Ghanpur, Bejjanki, Kagaznagar, Daira, Palem, Addakal, Jurala Proj., Asifabad, Mulug, Raghunathpalle, Esci-Gachibowli, Saroornagar, Venkatapuram, Kondapur, Sirsilla, Sangareddy, Mudhole, Kukatpally Jntu, Marriguda, Utkoor, Venkatapur, Nirmal, Sarangapurnrl, Dubbak, Kammar Palle, Kathlapur 7 each. **Marathwada**: Kinwat 18, Himayatnagar 17, Mahur 11, Hadgaon, Bhokar 7 each. **West Madhya Pradesh**: Maksudangarh 7. **East Madhya Pradesh**: Harrai, Kirnapur 9 each. **Gujarat Region**: Waghai 11, Bodeli 7. **Madhya Maharashtra**: Pathardi 9. **West Rajasthan**: Nawa 7.
01st Sep 2024	**South Odisha and south Chhattisgarh**: H rainfall at isolated places likely on 1st September. **North Andhra Pradesh:** isolated HVH rainfall likely during next 24 hours. **Telangana**: isolated H to EH rainfall at isolated places over Telangana on 1st September and isolated heavy rainfall over north Telangana on 2nd September. Vidarbha. H to EH rainfall at a few places and extremely heavy rainfall at isolated places on 1st and 2nd September.	

	Marathwada: H to VH rainfall at isolated places on 1st and 2nd September. **East Madhya Pradesh:** HVH rainfall at isolated places is likely on 1st and 2nd September. **West Madhya Pradesh**: heavy rainfall at isolated places on 1st and HVH rainfall at isolated places on 2nd September. **Gujarat region:** H rainfall at isolated places on 1st and heavy to very heavy rainfall at isolated places on 2nd September.	**Vidarbha**: Pusad 10, Digras 7. **Gujarat Region**: Valia 37, Songadh, Mangrol 25 each, Vyara 22, Maktampur 20, Bharuch 19, Nadiad, Netrang, Tilakwada 17 each, Dolvan 16, Vansda, Uchchhal, Subir 15 each, Daman 14, Bayad 13, Kapadvanj 13, Karjan, Lunawada, Valod, Nandod, Valsad, Mandvi, Prantij 12 each, Kathalal, Himatanagar, Bayad, Mahesana 11 each, Waghai, Garudeshwar, Umerpada, Virpur, Vagra, Balasinor, Kamrej 10 each. **Madhya Maharashtra**: Navapur 16, Nandgaon 9, Gaganbawada, Gidhade 7 each. **West Madhya Pradesh**: Gandhwani 16, Kukshi 14, Sardarpur 13, Bagh 13, Jabot 12, Jhabua, Dahi, Rama 11 each, Alirajpur 10, Udaigarh, Meghnagar 8 each, Ranapur, Manawar, Khalwa 7 each. **Telangana**: Tekmal 11, Papannapet, Kowdipalle 8 each, Naga Reddipet, Yellareddy 7 each. **East Rajasthan**: Bhungra 11, Devel, Sajjangarh, Kherwara 10 each, Ganeshpur, Kesarpura, Sallopat 7 each. **Vidarbha**: Mangrulpir 8. **Odisha**: Padia 14. **Chhattisgarh**: Dornapal 11, Konta 10. **Andhra Pradesh & Yanam**: Amaravati, Tiruvuru 26 each, Guntur 23, Kukunoor 20, Atchampet 19, Tenali 18, Mangalagiri, Nandigama, Piduguralla, Macherla 17 each, Paleru Bridge, Velairpad 16 each, Nuzvid, Mundlamuru, Kunavaram 14 each, Jangamaheswarapuram, Bapatla, Vijayawada 13 each, Santhamaguluru, Prakasam Barrage, Vararamachandrapur 12 each, Avanigada, Addanki, Vijayawada, Chintur 11 each, Karamchedu 10, Kaikalur, Sattenapalle, Repalle 9 each, Anakapalle, Yelamanchili, Markapur, Chimakurthi 8 each, Podili, Ongole, Gudivada 7 each. **Telangana**: Malyal 40, Mahabubabad 37, Kodada 35, Manuguru, Kusumanchi 32 each, Chilkur 31, Mattampally, Huzur Nagar 30 each, Parvathagiri, Burgampadu 29 each, Madhira, Banswada 28 each, Kodakandla 27, Dornakal, Chinthakam, Tadwai Mlg, Noothankal 26 each, Gudurwrgl 25, Palawancha 24, Bhadrachalam, Khammam 23 each, Aswapuram, Thollada 22 each, Sadasivanagar, Bonakal 21 each, Mothey, Bhiknur, Chennaraopet 20 each, Jajireddigudem, Konijerla, Suryapet 19 each, Bayyaram, Kamareddy 18 each, Garla 17,

		Kothagudem, Wyra Kvk 16 each, Dhar Palle, Tadwai, Kothaguda, Kalwakurthy 16 each, Govindaraopet, Domakonda, Dummugudem, Miryalaguda, Zaffergadh, Sathupalle 15 each, Jammikunta, Vangoor, Tekulapalle, Devaruppal, Achampeta, Devarakonda, Medak, Yellandu 14 each, Thimmajipeta, Kollapur, Tandur, Huzurabad, Chandrugonda, Neredcherla, Varni, Shadnagar, Thimmapur, Khammam Urban, Jadcherla 13 each, Kodangal, Kosgi, Yellandu, Kowdipalle, Chandur, Bhoothpur, Gandeed, Khila Ghanpur, Choppadandi, Karimnagar, Mulakalapalle, Narsampet 12 each, Narsapur, Hanwada, Lingampet, Damaragidda, Koilkonda, Julurpad, Pochampalle, Elagaid, Tekmal, Gandhari, Yellareddypeta, Pinapaka 11 each, Regode, Wanaparthy, Enkuru, Aswaraopeta, Chandurthi, Palakurthi, Shankarapatnam, Bheemgal, Nagarjuna Sagar, Yellareddy, Chevella, Ibrahimpatnam, Ramayampet, Gopalpet, Choutuppal, Chinna Chinta Kunt, Nagarjunsagar, Jogipet 10 each, Jogipet, Mustabad, Papannapet, Midjil, Nanganur, Mominpet, Maganoor, Velpur, Narmetta, Atmakurwrgl, Nawabpet, Sultanabad, Nawabpetmbn, Chigurumamidy, Tamsi, Pebbair, Nangnoor, Bomraspeta, Doma, Nidamanur, Narayanpet, Boath, Gangadhara, Hathanoora, Kothakota, Bachhanpet, Jagadevpur, Nizam Sagar, Talamadugu 9 each, Talamadugu, Peddamandadi, Yadagirigutta, Kondurg, Jangaon, Veepangandla, Julapalle, Ramannapeta, Atmakur Wnp, Nallabelly, Bazarhathnoor, Vicarabad, Pargi, Tandur, Wargal, Chegunta, Atmakur M, Pedda-Adiserlapalle, Yacharam, Ghatkesar, Kondapak, Naga Reddipet, Maheswaram, Konaraopeta, Navipet, Wankdi, Utnur 8 each, Bhuvanagiri, Dindigul, Narva, Asifabad, Peddemul, Pitlam, Bala Nagar, Peddapalle, Nagar Kurnool, Ghanpur, Bejjanki, Kagaznagar, Daira, Palem, Addakal, Jurala Proj., Asifabad, Mulug, Raghunathpalle, Esci-Gachibowli, Saroornagar, Venkatapuram, Kondapur, Sirsilla, Sangareddy, Mudhole, Kukatpally Jntu, Marriguda, Utkoor, Venkatapur, Nirmal, Sarangapurnrl, Dubbak, Kammar Palle, Kathlapur 7 each. **Marathwada**: Kinwat 18, Himayatnagar 17, Mahur 11, Hadgaon, Bhokar 7 each. **West Madhya Pradesh**: Maksudangarh 7. **East Madhya Pradesh**: Harrai, Kirnapur 9 each. **Gujarat Region**: Waghai 11, Bodeli 7. **Madhya Maharashtra**: Pathardi 9. **West Rajasthan**: Nawa 7.
02nd Sep 2024	**Gujarat region:** HVH to EH rainfall at isolated places on 2st and 3rd September. **Madhya Maharashtra**: very H to EH rainfall at isolated places on 2nd September and isolated heavy rainfall on 3rd September. **Marathwada:** HVH rainfall at isolated places on 2nd September. **Vidarbha:** isolated HVH rainfall at a few	

	places on 2nd September and isolated heavy rainfall on 3rd September. **East Madhya Pradesh:** H rainfall at isolated places is likely on 2nd September. **West Madhya Pradesh:** HVH rainfall at isolated places on 2nd and 3rd September. **East Rajasthan:** H rainfall at isolated places on 2nd September. **Telangana:** H rainfall over north Telangana on 2nd September. **Saurashtra & Kachchh:** H rainfall at isolated places on 2st and very heavy rainfall on 3rd September	**Vidarbha**: Pusad 10, Digras 7. **Gujarat Region**: Valia 37, Songadh, Mangrol 25 each, Vyara 22, Maktampur 20, Bharuch 19, Nadiad, Netrang, Tilakwada 17 each, Dolvan 16, Vansda, Uchchhal, Subir 15 each, Daman 14, Bayad 13, Kapadvanj 13, Karjan, Lunawada, Valod, Nandod, Valsad, Mandvi, Prantij 12 each, Kathalal, Himatanagar, Bayad, Mahesana 11 each, Waghai, Garudeshwar, Umerpada, Virpur, Vagra, Balasinor, Kamrej 10 each. **Madhya Maharashtra**: Navapur 16, Nandgaon 9, Gaganbawada, Gidhade 7 each. **West Madhya Pradesh**: Gandhwani 16, Kukshi 14, Sardarpur 13, Bagh 13, Jabot 12, Jhabua, Dahi, Rama 11 each, Alirajpur 10, Udaigarh, Meghnagar 8 each, Ranapur, Manawar, Khalwa 7 each. **Telangana**: Tekmal 11, Papannapet, Kowdipalle 8 each, Naga Reddipet, Yellareddy 7 each. **East Rajasthan**: Bhungra 11, Devel, Sajjangarh, Kherwara 10 each, Ganeshpur, Kesarpura, Sallopat 7 each. **Vidarbha**: Mangrulpir 8.

4.3.3 Severe Cyclonic Storm "DANA" over the Bay of Bengal (22nd - 26th October, 2024)

4.3.3.1 Genesis Forecast

- First information about likely formation of an upper air cyclonic circulation over Andaman Sea around 21st October was issued in the daily report on 16th October under Tropical Cyclone Forecasting Programme carried out by IMD since 2008 during October to December as an initiative to improve forecast through enhanced observations & model guidance (about 3 days ahead of the formation of upper air cyclonic circulation over central Andaman Sea on 19th October).
- First information about likelihood of cyclogenesis (formation of Depression) with High confidence (67-100%) was issued in the extended range outlook issued on 17th October (about 5 days ahead of formation of depression on 22nd October) (Fig. 2).
- Regular updates were since then issued in six hourly forecasts given by National Weather Forecasting Centre and daily tropical weather outlook issued by Regional Specialised Meteorological Centre (RSMC) New Delhi.
- First Special Message issued by IMD at 1330 hours IST (0800 UTC) 20th October when the system lay as an upper air cyclonic circulation over central Andaman Sea indicated formation of low-pressure area around 21st, depression by 22nd and cyclonic storm by 23rd October over eastcentral BoB. It was also indicated that the system would reach northwest BoB off Odisha-West Bengal coasts by 24th morning.
- In the first Special Message itself at the stage of a cyclonic circulation, Pre-cyclone Watch for Odisha and West Bengal coasts was issued about 4.5 days ahead of landfall over Odisha coast.
- First pre-genesis (before formation of depression) track & intensity forecast along with cone of uncertainty and wind distribution around the centre of the storm was issued by IMD at 1000 hrs IST of 21st October indicating likely intensification into a severe cyclonic storm on 24th morning (0530 hours IST/0000 UTC) over northwest BoB. The pre-genesis track, intensity and landfall forecast along with observed track & intensity during life cycle of "DANA" indicating accuracy in track, intensity & landfall prediction at the stage of low-pressure area is presented in Fig. 7. There was almost zero error in prediction of landfall point, time and intensity at this stage.

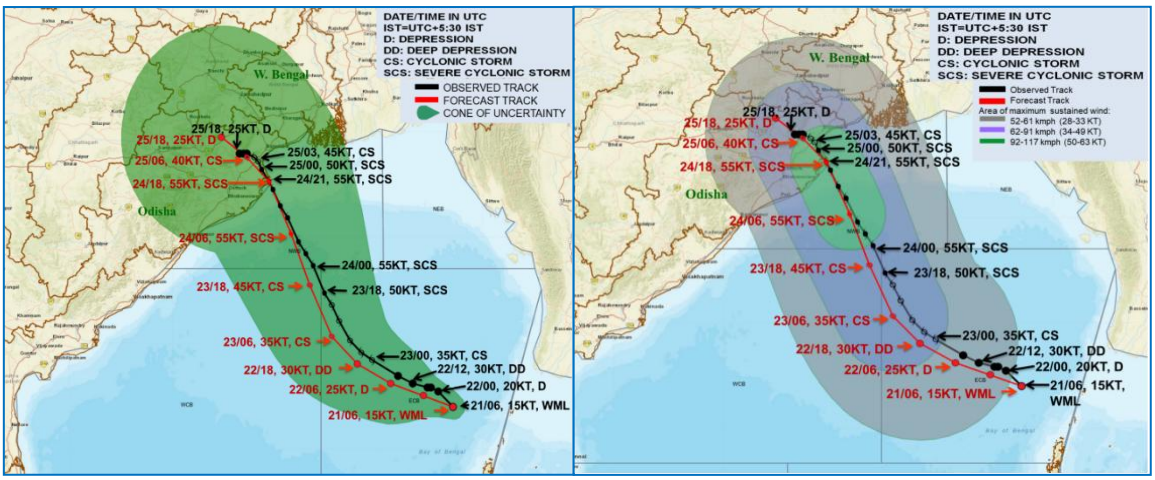


Fig. 7: Observed track & intensity along with predicted Pre-genesis track and intensity forecast issued at the stage of well-marked low pressure area on 21st October 2024 about 3.5 days ahead of landfall on 25th October demonstrating accuracy in track, landfall and intensity forecast

4.3.3.2. Track forecast error and skill

The track forecast errors for 24, 48 and 72 hrs lead period were 32, 24 and 29 km against the long period average errors of 72, 112 and 156 km respectively based on the data of 2019-23 (**Fig. 4.3.3.1a**). The track forecast skills calculated against Climatology & Persistence (CLIPER) forecast for 24, 48 and 72 hrs lead period were 84, 95 and 96 % respectively against the long period average skills of 66, 75 and 76% respectively based on the data of 2019-23 (**Fig. 4.3.3.1b**). **For all lead periods, the operational track forecast errors were markedly below the long period average errors.**

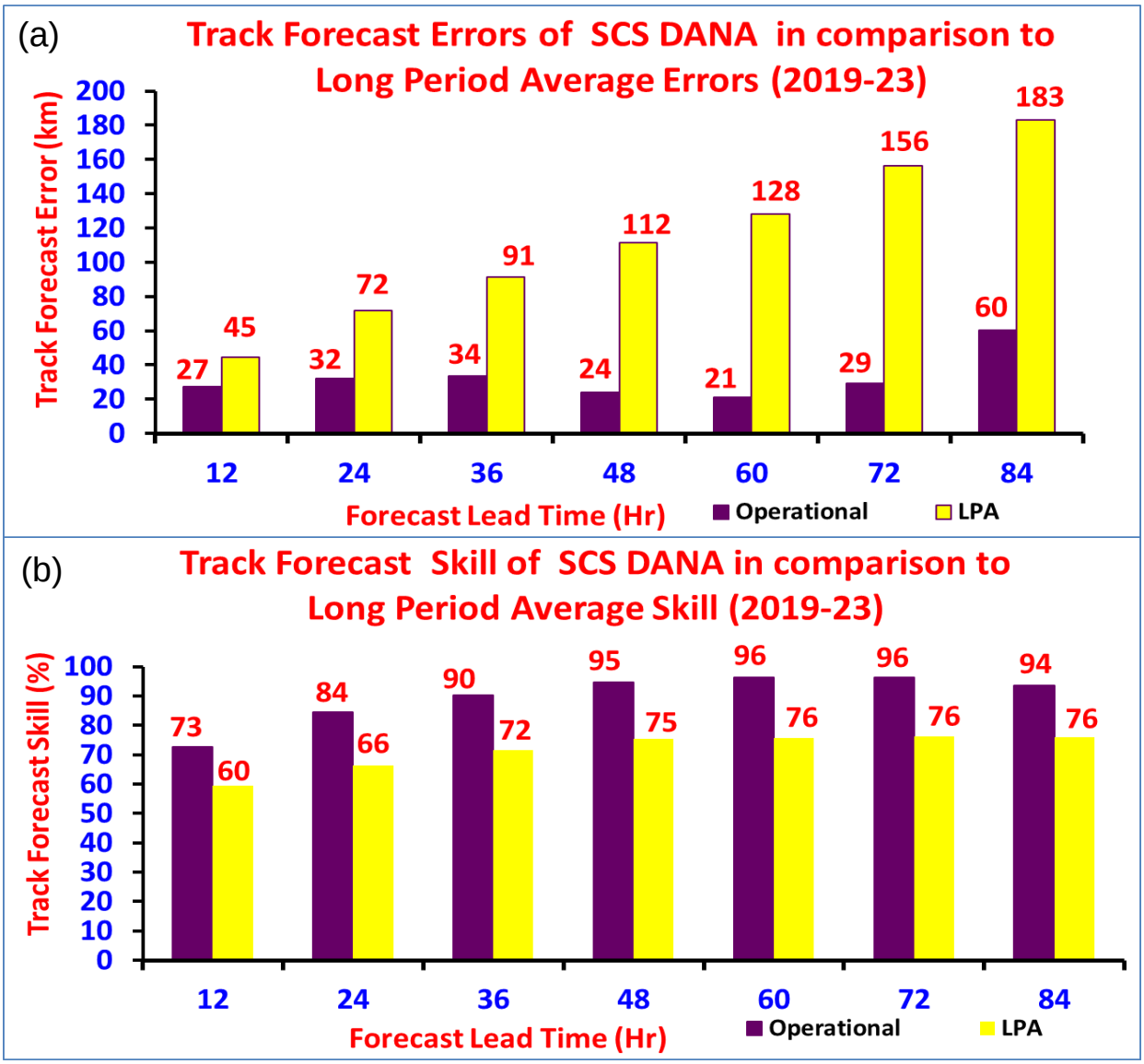


Fig. 4.3.3.1: Track forecast errors and (b) skills against Climatology & Persistence (CLIPER) compared to long period average (LPA) errors & skills respectively based on 2019-2023

Table 4.3.3.1: Operational Track forecast errors and skill of SCS "DANA" as compared to long period average (2019-23)

Lead Period (hrs)	N	Operational Track forecast error (km)	Operational Track Forecast Skill (%)	Long Period Average (2019-23)	
				Track Forecast Error (km)	Track Forecast Skill (%)
12	14	27	73	45	60
24	11	32	84	72	66
36	10	34	90	91	72
48	8	24	95	112	75
60	6	21	96	128	76
72	4	29	96	156	76
84	2	60	94	183	76

N: no. of observations verified

4.3.3.3. Intensity forecast error and skill

The absolute errors (AE) in intensity (wind) forecast for 24, 48 and 72 hrs lead period were 2.7, 5.0 and 3.8 knots against the long period average errors of 7.1, 10.3 and 13.8 knots based on the data of 2019-23 respectively (**Fig. 4.3.3.2a and table 4.3.3.2)**. The skills in intensity forecast based on AE calculated against the persistence-based forecasts for 24, 48 and 72 hours lead period were 81, 81 and 90 % against the long period average skills of 57, 71 and 77% based on data of 2019-23 respectively (**Fig. 4.3.3.2b**). **For all lead periods, the operational intensity forecast errors were less and the skills were more than the long period average.**

Table 4.3.3.2: Operational Absolute errors (AE) and Root Mean Square errors (RMSE) and corresponding skill in intensity forecast of SCS "DANA" as compared to long period average (2019-23)

Lead Period	N	AE	RMSE	Skill-AE	Skill-RMSE	Long Period Average (2019-23)			
						AE	RMSE	Skill-AE	Skill-RMSE
12	14	1.8	3.5	74	59	4.2	5.8	53	57
24	11	2.7	4.3	81	77	7.1	9.2	57	63
36	10	4.5	5.7	80	80	9.3	11.6	64	69
48	8	5.0	7.1	81	80	10.3	12.8	71	73
60	6	7.5	8.9	75	74	11.6	14.4	76	78
72	4	3.8	4.3	90	90	13.8	16.5	77	81
84	2	7.5	7.9	84	85	16.1	18.7	77	80

N: No. of observations verified, AE: Absolute error, RMSE: Root Mean Square Error, LPA: Long Period Average

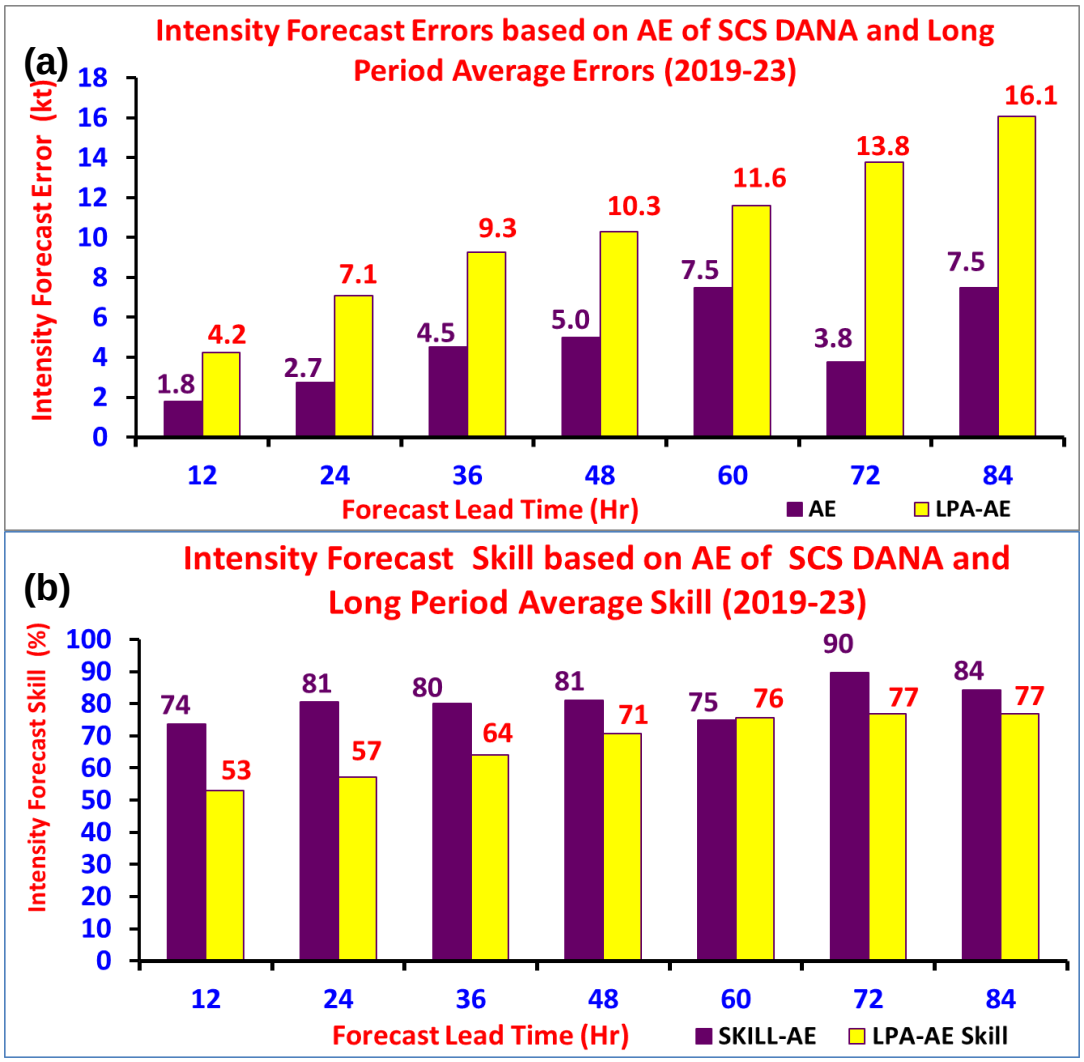


Fig. 4.3.3.2: Intensity forecast errors (AE) and (b) skills against Persistence compared to long period average (LPA) errors & skills respectively based on absolute error (AE).

The root mean square errors (RMSE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 4.3, 7.1 and 4.3 knots against the long period average errors of 9.2, 12.8 and 16.5 knots based on data of 2019-23 respectively (**Fig.4.3.3.3a**). The skills in intensity forecast based on RMSE calculated against persistence-based forecast for 24, 48 and 72 hrs lead period were 77, 80 and 90% against the long period average skills of 63, 73 and 81% based on data of 2019-23 respectively (Fig.4.3.3.3b). For all lead periods, the operational intensity forecast errors were less and the skills were more than the long period average.

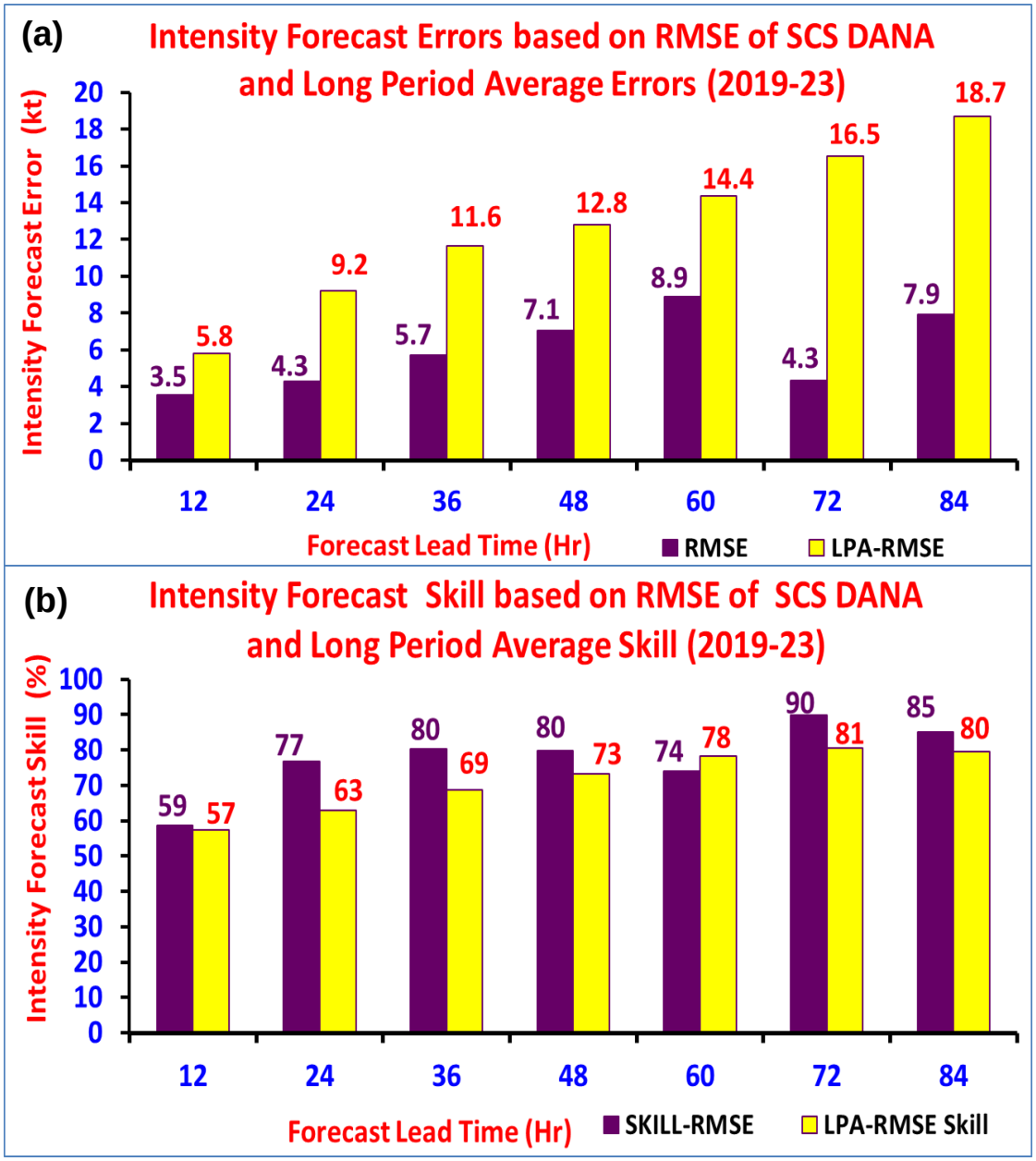


Fig. 4.3.3.3: (a): Intensity forecast errors (RMSE) and (b) skills against Persistence forecast compared to long period average (LPA) errors & skills respectively

4.3.3.4: Landfall point and time errors

The landfall point forecast errors for 24, 48 and 72 hrs lead period were 4, 2 and 2 km respectively against the long period average errors of 18, 42 and 73 km based on data of 2019 - 23 (**Fig. 4.3.3.4a**). The landfall time forecast errors for 24, 48 and 72 hrs lead period were 2.5, 0.5 and 0.5 hours respectively against the long period average error of 2.8, 4.6 and 9.5 hours respectively based on the data of 2019-23 (**Fig. 4.3.3.4b**). **The operational landfall point & time forecast errors were markedly less than the LPA errors for all**

lead periods. There was almost zero error in landfall point prediction for all lead periods upto 90 hours. The landfall intensity forecast errors were also almost zero even upto 90 hrs lead period.

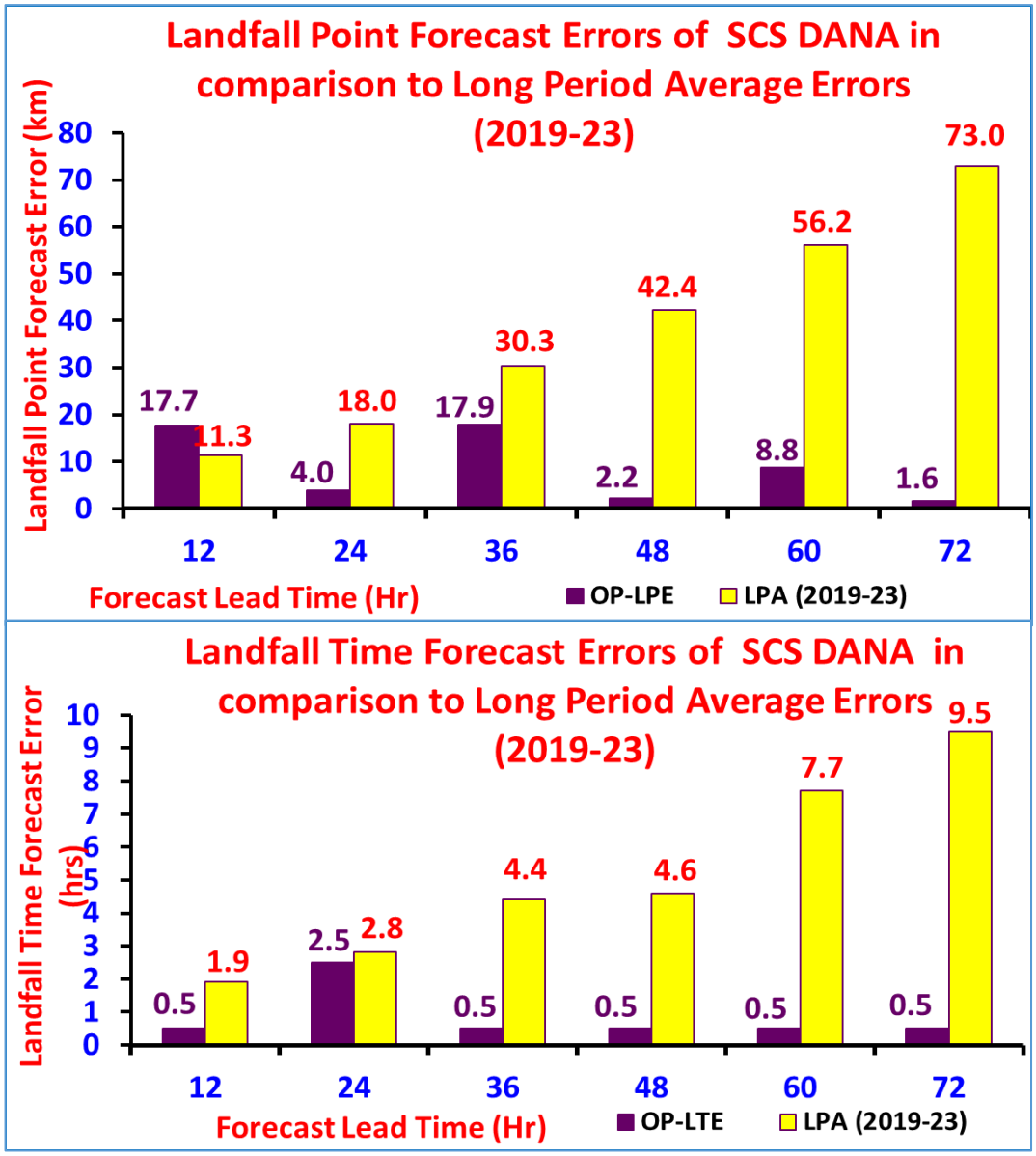


Fig.: 4.3.3.4: (a) Operational landfall point and (b) time forecast errors compared to long period average during 2019-23

Table 4.3.3.3: Landfall point and time errors of SCS "DANA" as compared to long period average (2019-23)

Lead Period	Base Time	Landfall Point (^{0}N/^{0}E)		Landfall Time (hours)		Landfall Point (^{0}N/^{0}E) and Time errors			
		Forecast	Actual	Forecast	Actual	LPE (km)		LTE (hrs)	
						Op.	LPA	Op.	LPA
12	24/12	20.63/86.92	20.79/86.94	24/2130	24/2200	17.7	0.5	11.3	1.9
24	24/00	20.81/86.97	20.79/86.94	25/0030	24/2200	4.0	2.5	18.0	2.8
36	23/12	20.95/86.91	20.79/86.94	25/0130	24/2200	17.9	0.5	30.3	4.4
48	23/00	20.79/86.96	20.79/86.94	24/2230	24/2200	2.2	0.5	42.4	4.6
60	22/12	20.79/86.86	20.79/86.94	24/2230	24/2200	8.8	0.5	56.2	7.7
72	22/00	20.78/86.95	20.79/86.94	24/2130	24/2200	1.6	0.5	73.0	9.5

Op.: Operational Error, LPA: Long period Average, LPE: Landfall point Erro, LTE: Landfall time Error

4.3.3.5. Adverse weather forecast performance:

Table 4.3.3.4: Verification of Heavy Rainfall Forecast

Date/Base Time of observation	**24 hr Heavy rainfall warning ending at 0300 UTC of next day** Heavy: H, Very Heavy: VH, Extremely Heavy: EH	**Realised 24-hour heavy rainfall ending at 0300 UTC of date**
20.10.2023 / 0300 UTC	❖ H**eavy rainfall** at isolated places is very likely over Odisha on 23rd & **heavy to very heavy rainfall** at a few places and **extremely heavy rainfall at** isolated places on 24th & 25th October. ❖ **Heavy rainfall** at isolated places is very likely over **coastal districts of** West Bengal on 23rd and heavy to very heavy rainfall at a few places over Gangetic West Bengal on 24th & 25th October. ❖ H**eavy rainfall** at isolated places is very likely over North coastal Andhra Pradesh on 24th and 25th October.	**23 October, 2024:** **Kerala & Mahe**: Idamalayar Dam 12; Nooranad & Mavelikara 9 each; Kalamassery 8, Kottarakkara; Thenmala, Kayamkulam & Pampadumpara 7 each. **Tamil Nadu:** Kelavarapalli Dam, Thuckalay 12 each; Kovilpatti 11; Krishnagiri, Sankarapuram & Ambur 10 each; Bhavanisagar 9; Valparai, Vaniyambadi, Barur, Makkinampatti, Mambzhathuraiyaru, Hogenekal, Anaikedanku & Thirparappu 7 each. **24 October, 2024:** **Odisha:** Chandbali & Rajkanika 16 each; Nawana 14; Marsaghai, Basudevpur 11 & Oupada 11 each; Rajnagar 10; Mohakalapada 9; Aul & Paradeep 8 each; Derabis, Bhadrak, Balasore, Jajpur,
21.10.2023/ 0300UTC	❖ H**eavy rainfall** at isolated places is very likely over **Balasore, Bhadrak, Kendrapara, Jagatsingpur, Puri, Khorda, Ganjam, Gajapati**, districts of Odisha on 23rd Oct. & **heavy to very heavy rainfall** at a few places and **extremely heavy rainfall at** isolated places over **Baleswar, Mayurbhanj, Bhadrak, Kendrapara, Jagatsingpur Kendujhar, Jajpur, Cuttack and Dhenkanal and Puri** districts of Odisha on 24th & 25th October. ❖ **Heavy rainfall** at isolated places is very likely on 23rd October and heavy to very heavy rainfall at a few places **with extremely heavy rainfall** at isolated places over **South & North 24 Parganas,**	

	East & West Medinipur, Howrah, Hooghly, Kolkata and Bankura districts of Gangetic West Bengal on 24th & 25th October. ❖ H**eavy rainfall** at isolated places is very likely over **Srikakulam, Vizianagaram and Vishakhapatnam** districts of North coastal Andhra Pradesh on 24th and 25th October.	Kendrapada, Nilgiri, Kendrapara & Pattamundai 7 each **Tamil Nadu, Puducherry & Karaikal:** Anaimaduvu Dam 15; Orthanad 13; Kozhiporvilai, Mannargudi, Thuckalay, Neyyoor & Aduthurai 11 each; Suthamalli Dam, Eraniel & Kodavasal 10 each; Manjalaru & Needamangalam 9 each; Madurai, Tiruvarur, Parangipettai, Nannilam, Mayiladuthurai, Kuruvadi, Idayapatti, Tirupuvanam & Colachel 8 each; Kumbakonam, Tiruvaiyaru, Kurunthancode, Mayiladuthurai, Ariyalur, Ariyalur Taluk Office, Budalur, Vettikadu, Tiruvarur, Natham, Lower Anaicut, Natham, Thiruvidaimaruthur & Mylaudy 7 each; **Gangetic West Bengal:** Diamond Harbour, Kalaikunda & Amfu Kharagpur 9 each; Durgachack 8; Mohanpur, Jhargram & Uluberia 7 each; **Kerala & Mahe:** Mannarkkad (dist Palakkad) 7. **Coastal Karnataka:** Dharmasthala & Belthangadi 7 each; **Jharkhand:** Gurabandha 7; **25 October, 2024:** **Odisha:** Oupada 24; Dhamnagar 21, Khaira & Bhandaripokhari 21 each; Nawana, Bonth 19 each; Chandbalit 17; Bhadrak 16; Rajkanika & Bari 15 each; Jajpur, Udala, Nilgiri & Tihidi 14 each; Akhuapada 13; Aul 12; Binjharpur & Remuna 11 each; Kaptipada, Soro & G B Nagar 10 each; Ghasipura, Basudevpur, Balasore, Gobindpur & Chandanpur 9 each; Betanati, Balimundali, Kusumi, Derabis, Bahanga, Jaipur & Chandikhol 8 each; Hatadihi, Samakhunta, Anandpur,
22.10.2023/ 0300UTC	❖ H**eavy rainfall** at isolated places is very likely over **Balasore, Bhadrak, Kendrapara, Jagatsingpur, Puri and Khorda,** districts of Odisha on 23rd Oct. & **heavy to very heavy rainfall** at a few places and **extremely heavy rainfall at** isolated places over **Baleswar, Mayurbhanj, Bhadrak, Kendrapara, Jagatsingpur Kendujhar, Jajpur, Cuttack and Dhenkanal, Khorda and Puri** districts of Odisha on 24th & 25th October. ❖ **Heavy rainfall** at isolated places is very likely on 23rd October and heavy to very heavy rainfall at a few places **with extremely heavy rainfall** at isolated places over **South & North 24 Parganas, East & West Medinipur, Jhargram, Howrah, Hooghly, Kolkata and Bankura** districts of Gangetic West Bengal on 24th & 25th October. ❖ H**eavy rainfall** at isolated places on 24th and **heavy to very heavy rainfall** at isolated places on 25th October.	
23.10.2023/ 0300UTC	❖ H**eavy rainfall** at isolated places is very likely over **Balasore, Bhadrak, Kendrapara, Jagatsingpur, Puri and Khorda,** districts of Odisha commencing from evening of 23rd Oct. & **heavy to very heavy rainfall** at a few places and **extremely heavy rainfall at** isolated places over **Baleswar, Mayurbhanj, Bhadrak, Kendrapara, Jagatsingpur Kendujhar, Jajpur, Cuttack and Dhenkanal, Khorda and Puri** districts of Odisha on 24th & 25th October. ❖ **Heavy rainfall** at isolated places is very likely on 23rd October and heavy to very heavy rainfall at a few places **with extremely heavy rainfall** at isolated places over **South & North 24 Parganas, East & West Medinipur, Jhargram, Howrah, Hooghly, Kolkata and Bankura** districts of Gangetic West Bengal on 24th & 25th October. ❖ H**eavy rainfall** at isolated places on 24th and **heavy to very heavy rainfall** at isolated places on	

	25th October.	Nischintakoili, Pattamundai, Kendrapara & Kendrapada 7 each. ❖ **Gangetic West Bengal:** Barrackpur 17; Harinkhola 15; Alipore & Durgachack 12 each; Diamond Harbour, Kalyani, Amtala, Uluberia, Midnapore, Mohanpur, Midnapore & Panagarh 11 each; Burdwan, Kalaikunda, Dum Dum & Saltlake 10 each; Mankar, Gheropara, Lalgarh & Manteswar 9 each; Debagram, Kharagpur, Canning & Sri Niketan 8 each, Labpur, Bankura, Suri & Mangalkote 7 each. ❖ **Tamil Nadu, Puducherry & Karaikal:** Namakkal & Chittampatti 11 each; Colachel, Idayapatti & Usilampatti 9 each; Sholavandan, Kuppanampatti & Bhoothapandy 8each; Kallandri, Tallakulam, Uppar Dam, Dindigul, Nilakottai, Adayamadai, Madurai city, Madurai North & Periyapatti 7 each. ❖ **Jharkhand:** Maheshpur 8, Pakuria 7; ❖ **Kerala & Mahe:** Kanjirapuzha & Airport Chakka 7 each;
24.10.2023/ 0300UTC	❖ H**eavy to very heavy rainfall** at a few places and **extremely heavy rainfall at** isolated places over **Baleswar, Mayurbhanj, Bhadrak, Kendrapara, Jagatsingpur Kendujhar, Jajpur, Cuttack and Dhenkanal, Khorda and Puri** districts of Odisha on 24th & 25th October. ❖ **Heavy to very heavy rainfall** at a few places **with extremely heavy rainfall** at isolated places over **South & North 24 Parganas, East & West Medinipur, Jhargram, Howrah, Hooghly, Kolkata and Bankura** districts of Gangetic West Bengal on 24th & 25th October. ❖ H**eavy rainfall** at isolated places on 24th and **heavy to very heavy rainfall** at isolated places on 25th October.	
25.10.2023/ 0300UTC	❖ H**eavy rainfall over to very heavy rainfall** at a few places over **Keonjhar, Mayurbhanj, Balasore, Bhadrak, Dhenkanal, Cuttack, Jajpur, Kendrapara, Angul, Nayagarh, Khorda, Puri and Jagatsinghpur** districts of Odisha on 25th October. **Extremely heavy rainfall at** isolated places is very likely over **Keonjhar, Mayurbhanj, Balasore and Bhadrak** districts of Odisha on 25th October. ❖ **Heavy to very heavy rainfall** at a few places **with extremely heavy rainfall** at isolated places over **East & West Medinipur,** districts of Gangetic West Bengal on 25th October. ❖ H**eavy to very heavy rainfall** at isolated places is likely over south Jharkhand on 25th October.	

Table 4.3.3.5: Verification of Gale/Squally Wind Forecast issued by IMD

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
20.10.2023 / 0300 UTC	**Along & off Odisha-west Bengal coasts:** Squally wind speed reaching 40-50 gusting to 60 kmph is very likely to commence from 23rd Oct evening. It would gradually increase becoming gale wind speed reaching 100-110 kmph gusting to 120 kmph from 24th Oct night till 25th Oct morning.	❖ At the time of landfall, the estimated maximum sustained
21.10.2023/ 0300UTC	**Along & off Odisha-west Bengal coasts:** Squally wind speed reaching 40-50 gusting to 60 kmph is very likely to	

	commence from 23rd Oct evening. It would gradually increase becoming gale wind speed reaching 100-110 kmph gusting to 120 kmph from 24th Oct night till 25th Oct morning.	wind speed was about 100-110 kmph gusting to 120 kmph over Kendrapara and Bhadrak districts of Odisha.
22.10.2023/ 0300UTC	**Along & off Odisha-west Bengal coasts:** Squally wind speed reaching 40-50 gusting to 60 kmph is very likely to commence from 23rd Oct evening. It would gradually increase becoming gale wind speed reaching 60-70 kmph gusting to 80 kmph from 24th morning and reaching 100-110 kmph gusting to 120 kmph from 24th night till 25th Oct morning and decrease gradually thereafter.	
23.10.2023/ 0300UTC	**Along & off Odisha-west Bengal coasts:** Squally wind speed reaching 40-50 gusting to 60 kmph is very likely to commence from 23rd Oct evening. It would gradually increase becoming gale wind speed reaching 60-70 kmph gusting to 80 kmph from 24th morning and 100-110 kmph gusting to 120 kmph along & off north Odisha and east Medinipur district of West Bengal; Gale wind speed reaching 60-80 kmph gusting to 90 kmph is likely along & off south Odisha and remaining districts of coastal West Bengal from 24th night till 25th Oct morning and decrease gradually thereafter. **South Jharkhand:** Squally wind speed reaching 40-50 kmph gusting to 60 kmph would prevail during 25th morning to 26th evening.	
24.10.2023/ 0300UTC	**Along & off Odisha-west Bengal coasts:** Gale wind speed reaching 60-70 kmph gusting to 80 kmph is prevailing. It would gradually increase becoming 100-110 kmph gusting to 120 kmph along & off north Odisha and east Medinipur district of West Bengal from 24th afternoon till morning of 25th October and decrease gradually thereafter. Gale wind speed reaching 60-80 kmph gusting to 90 kmph is likely along & off south Odisha and remaining districts of coastal West Bengal from 24th evening till 25th Oct morning and decrease gradually thereafter.	
25.10.2023/ 0300UTC	**Along & off Odisha-west Bengal coasts and adjoining interior districts:** Gale wind speed reaching 60-70 kmph gusting to 80 kmph would prevail over Balasore, Mayurbhanj, Keonjhar, Bhadrak, Kendrapara districts of Odisha and East Mednipur district of West Bengal till evening of 25th October 2024 and decrease thereafter. Squally wind speed reaching 40-60 kmph gusting to 70 kmph would prevail over Jagatsinghpur, Cuttack, Dhenkanal, Angul & adjoining areas of Sundargarh & Khorda districts of Odisha and south 24 Paraganas, West Mednipur & Jhargram districts of West Bengal till evening of 25 th October and decrease thereafter. **South Jharkhand:** Squally wind speed reaching 40-50 gusting to 60 kmph is very likely to prevail from afternoon of 25th till evening of 26th October.	

Table 4.3.3.6: Verification of Storm Surge Forecast issued by IMD

Date/Base Time of observation	24 hr Storm surge warning	Realised 24-hour heavy rainfall ending at 0300 UTC of date
23.10.2023/ 0300UTC	Storm surge of 1.0 to 2.0 m height above astronomical tide is very likely to inundate low lying areas of Kendrapara, Bhadrak & Balasore districts of Odisha and East Medinipur districts of West Bengal during the time of landfall. Storm surge of 0.5 to 1.0 m height above astronomical tide is very likely to inundate low lying areas of South 24-Parganas district of West Bengal and Jagatsingpur district of Odisha during the time of landfall.	Maximum estimated storm surge of height of 1-2 m inundated low-lying areas of Kendrapara, Bhadrak and Balasore districts of Odisha during landfall.
24.10.2023/ 0300UTC	Storm surge of 1.0 to 2.0 m height above astronomical tide is very likely to inundate low lying areas of Kendrapara, Bhadrak & Balasore districts of Odisha and East Medinipur districts of West Bengal during the time of landfall. Storm surge of 0.5 to 1.0 m height above astronomical tide is very likely to inundate low lying areas of South 24-Parganas district of West Bengal and Jagatsinghpur district of Odisha during the time of landfall.	
25.10.2023/ 0300UTC	Storm surge of upto 1.0 m height above astronomical tide is very likely to inundate low lying areas of Bhadrak & Balasore districts of Odisha and East Medinipur districts of West Bengal during next 3 hours. Storm surge of upto 0.5 m height above astronomical tide is very likely to inundate low lying areas of South 24-Parganas district of West Bengal during next 3 hours.	

4.3.4 Cyclonic Storm "FENGAL" over the Bay of Bengal (23th November– 02nd December, 2024)

4.3.4.1 Genesis Forecast

- The genesis of cyclone Fengal was first predicted on 14th November 2024 in Extended range outlook with low probability and with High probability on 21st November about 11 days prior to formation of depression on 25nd November.
- First information about likely formation of a cyclonic circulation over south Andaman Sea with an advisory for continuous watch was issued in the Daily Report under Tropical Cyclone Forecasting Programme dated 19th November (about 2 days ahead of formation of cyclonic circulation on 21st November).
- Subsequently, the extended range outlook issued on 21th November (about 4 days ahead of formation of depression over the Bay of Bengal and 9 days ahead of landfall) indicated with high confidence (67-100% probability) likelihood of the formation of a depression over the central parts of south Bay of Bengal around 25th November and movement towards cross north Sri Lanka coast and south Tamil Nadu Coast.
- It was predicted to cross coast close to Puducherry since evening of 27th November (78 hrs in advance of landfall)

4.3.4.2. Track forecast error and skill

The track forecast errors for 24, 48 and 72 hrs lead period were 86, 124 and 151 km against the long period average errors of 72, 112 and 156 km respectively based on the data of 2019-23 (**Fig. 4.3.4.2a**). The track forecast skills calculated against Climatology & Persistence (CLIPER) forecast for 24, 48 and 72 hrs lead period were 0.6, 64 and 6.1 % respectively against the long period average skills of 66, 75 and 76% respectively based on the data of 2019-23. **(Fig. 4.3.4.2b).**

Table 4.3.4.1: Operational Track forecast errors and skill of CS "FENGAL" as compared to long period average (2019-23)

Lead Period (hrs)	N	Operational Track forecast error (km)	Operational Track Forecast Skill (%)	Long Period Average (2019-23)	
				Track Forecast Error (km)	Track Forecast Skill (%)
12	25	43	42.4	45	60
24	19	86	40.6	72	66
36	18	112	48.9	91	72
48	15	124	64.0	112	75
60	12	142	71.8	128	76
72	11	151	76.1	156	76

N: no. of observations verified

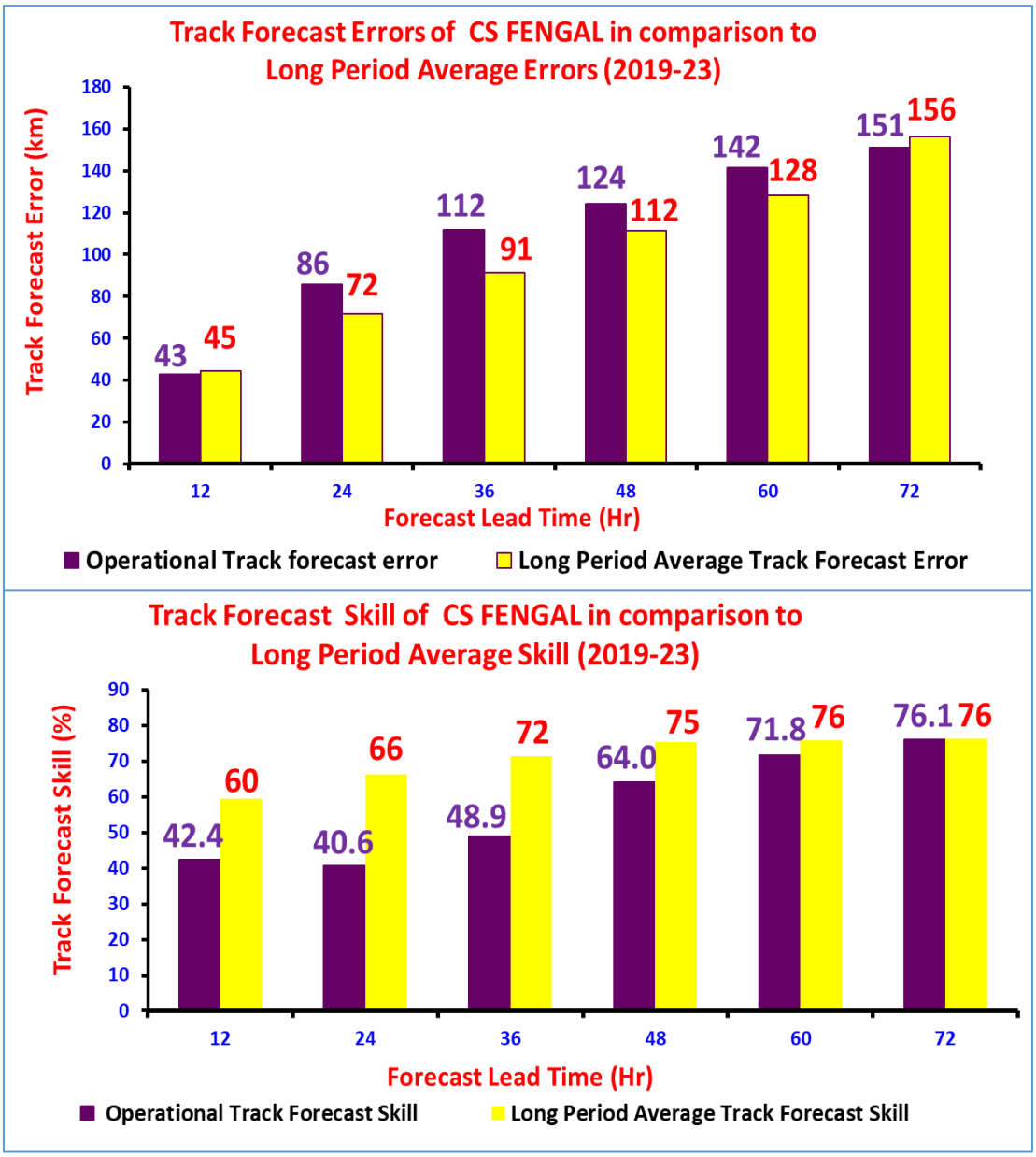


Fig. 4.3.4.2: (a) Track forecast errors and (b) skill against Climatology & Persistence (CLIPER) compared to long period average (LPA of 2019-2023) errors & skill respectively

4.3.4.3. Intensity forecast error and skill

The absolute errors (AE) in intensity (wind) forecast for 24, 48 and 72 hrs lead period were 4.2, 7.3 and 5.5 knots against the long period average errors of 7.1, 10.3 and 13.8 knots based on the data of 2019-23 respectively (**Fig. 4.3.4.3a**). **For all lead periods, the operational intensity forecast errors were less and the skills were more than the long period average**. The root mean square errors (RMSE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 5.4, 11 and 8.5 knots against the long period average errors of 9.2, 12.8 and 16.5 knots based on data of 2019-23 respectively (**Fig. 4.3.4.3b**). **For all lead periods,**

the operational intensity forecast errors were less and the skills were more than the long period average.

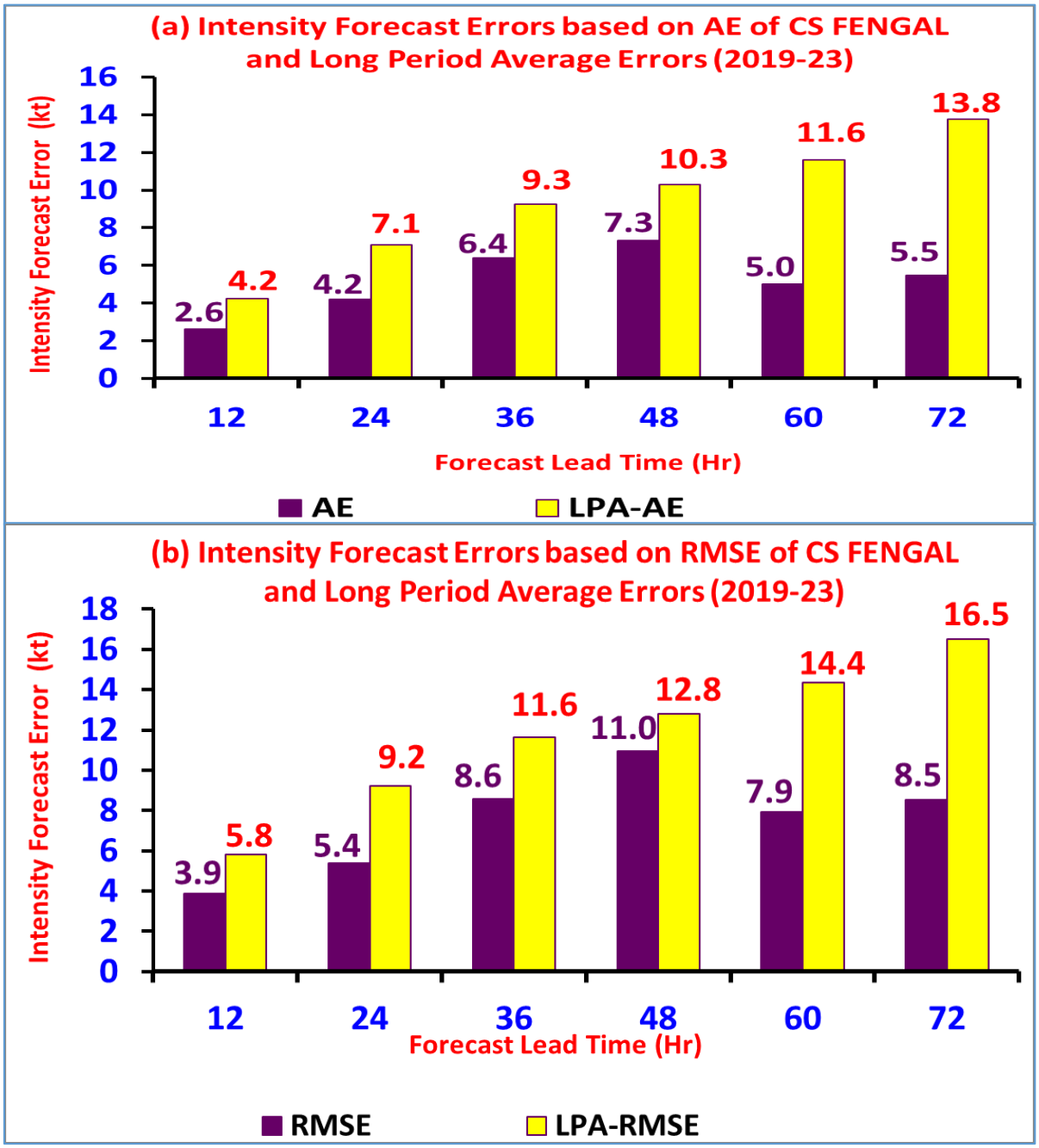


Fig. 4.3.4.3: Intensity forecast errors based on (a) AE and (b) RMSE against long period average (LPA of 2019-23) errors respectively.

The skills in intensity forecast based on AE calculated against the persistence-based forecasts for 24, 48 and 72 hours lead period were 15.8, 33.3 and 72.1 % against the long period average skills of 57.2, 70.6 and 77% based on data of 2019-23 respectively (**Fig. 4.3.4.4a)**. The skills in intensity forecast based on RMSE calculated against persistence-based forecast for 24, 48 and 72 hrs lead period were 62.9, 73.4 and 80.6% against the long period

average skills of 62.9, 73.4 and 80.6% based on data of 2019-23 respectivelyrespectively (**Fig. 4.3.4.4b**).

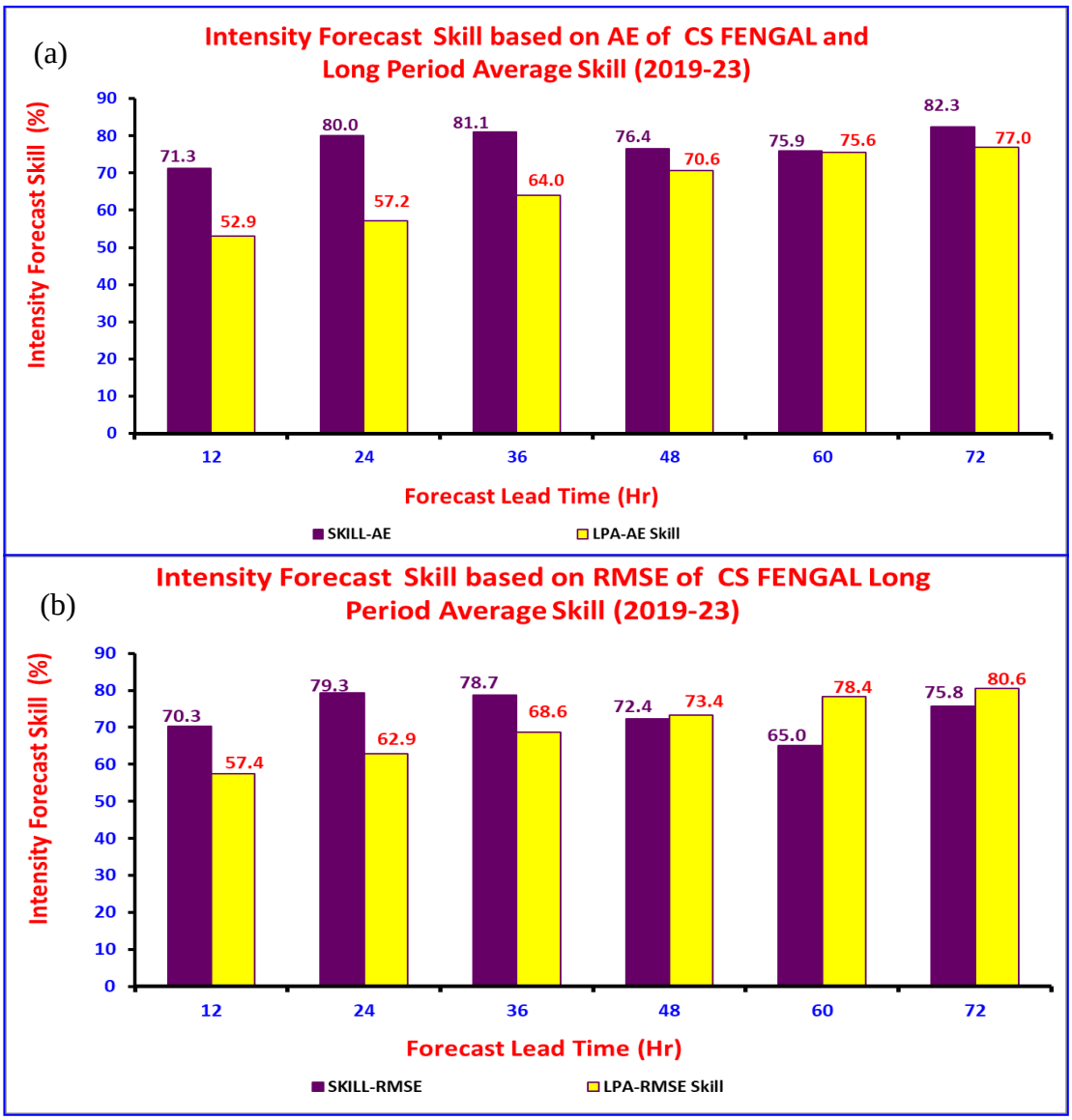


Fig. 4.3.4.4: Skill (%) in intensity forecast based on (a) Absolute errors (AE) and (b) Root Mean Square errors (RMSE) as compared to long period average (2019-23)

Table 4.3.4.2: Operational Absolute errors (AE) and Root Mean Square errors (RMSE) and corresponding skill in intensity forecast of CS "FENGAL" as compared to long period average (2019-23)

Lead Period	N	AE	RMSE	Skill-AE	Skill-RMSE	Long Period Average (2019-23)			
						AE	RMSE	Skill-AE	Skill-RMSE
12	25	2.6	3.9	27.8	31.5	4.2	5.8	52.9	57.4
24	19	4.2	5.4	15.8	26.7	7.1	9.2	57.2	62.9
36	18	6.4	8.6	23.3	21.5	9.3	11.6	64.0	68.6
48	15	7.3	11.0	33.3	23.5	10.3	12.8	70.6	73.4
60	12	5.0	7.9	67.6	59.3	11.6	14.4	75.6	78.4
72	11	5.5	8.5	72.1	64.3	13.8	16.5	77.0	80.6

N: No. of observations verified, AE: Absolute error, RMSE: Root Mean Square Error, LPA: Long Period Average

4.3.4.4: Landfall point and time errors

The landfall point forecast errors for 24, 48 and 60 hrs lead period were 5.5, 22.3 and 15.3 km respectively against the long period average errors of 18, 42 and 56.2 km based on data of 2019 - 23 (**Fig. 4.3.4.5a**). The landfall time forecast errors for 24, 48 and 60 hrs lead period were 7, 13 and 13 hours respectively against the long period average error of 2.8, 4.6 and 7.7 hours respectively based on the data of 2019-23 (**Fig. 4.3.4.5b**).

The operational landfall point & time forecast errors were markedly less than the LPA errors for all lead periods. There was 10-20km error in landfall point prediction for all lead periods upto 60 hours.

Table 4.3.4.3: Landfall point and time errors of CS "FENGAL" as compared to long period average (2019-23)

Lead Period	Base Time	Landfall Point (^{0}N/^{0}E)		Landfall Time (hours)		Landfall Point (^{0}N/^{0}E) and Time errors			
		Forecast	Actual	Forecast	Actual	LPE (km)		LTE (hrs)	
						Op.	LPA	Op	LPA
12	30/06	12.14/79.93	12.05/79.88	30/1500	30/1800	11.3	3.0	11.3	1.9
24	29/18	12.01/79.85	12.05/79.88	30/1100	30/1800	5.5	7.0	18.0	2.8
36	29/06	12.04/79.87	12.05/79.88	30/1200	30/1800	1.6	6.0	30.3	4.4
48	28/18	11.86/79.81	12.05/79.88	30/0500	30/1800	22.3	13.0	42.4	4.6
60	28/06	11.92/79.83	12.05/79.88	30/0500	30/1800	15.3	13.0	56.2	7.7

Op.: Operational Error, LPA: Long period Average, LPE: Landfall point Erro, LTE: Landfall time Error

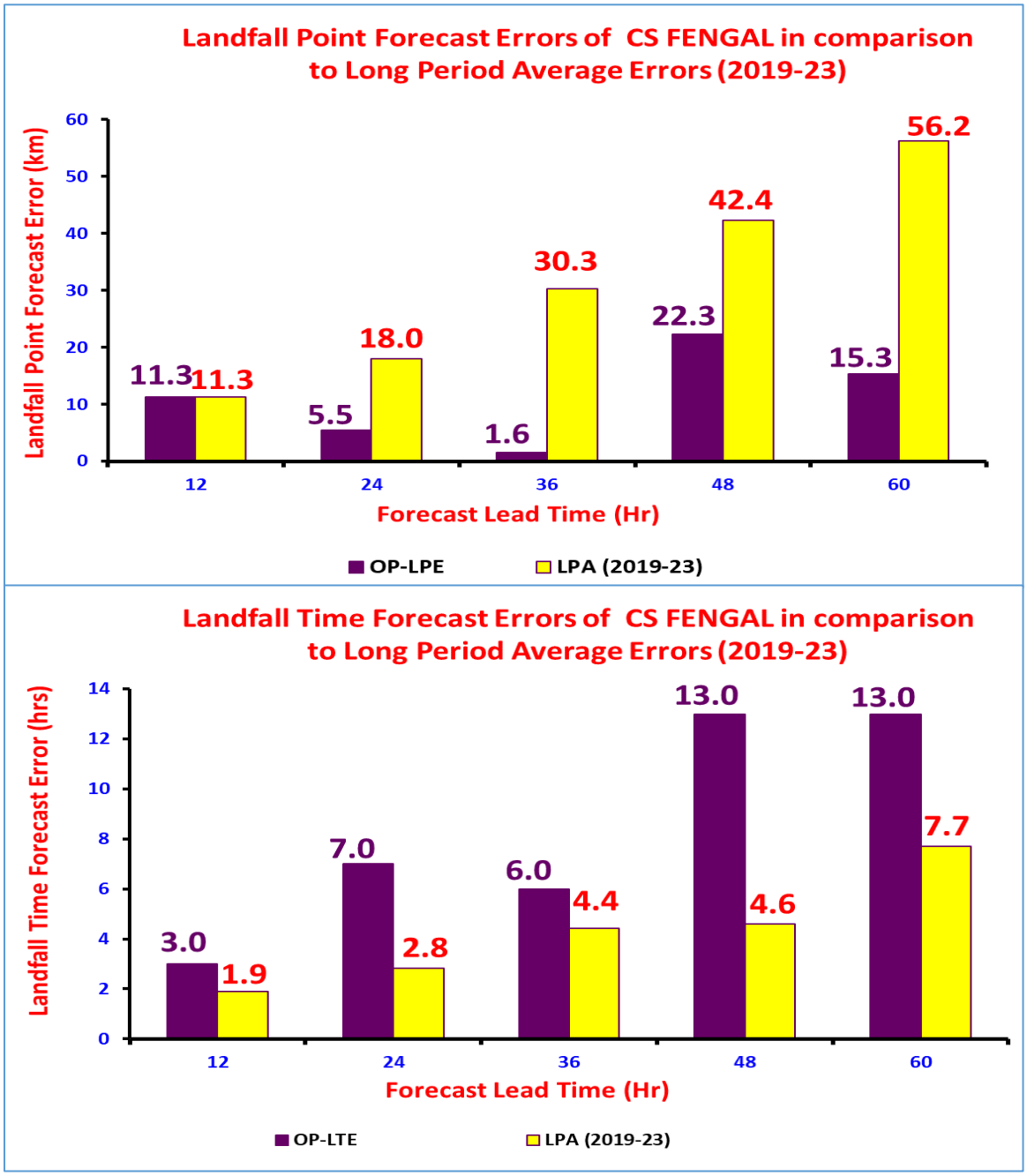


Fig. 4.3.4.5: (a) Landfall point and (b) time error against the long period average (LPA: 2019-2023) errors

4.3.4.5. Adverse weather forecast performance:

Table 4.3.4.4: Verification of Heavy Rainfall Forecast issued by IMD

Date	**Forecast of Heavy Rainfall based on 0300 UTC of date** H: Heavy, VH: Very Heavy, EH rainfall: EH rainfall	**Realized Rainfall at 0300 UTC of date**
26th Nov, 2024	➢ **Tamil Nadu & Puducherry**: H-VH rainfall at a few places with EH at isolated places on 26th & 27th ➢ H-VH rainfall at isolated places on 28th ➢ H rainfall at isolated places over on 29th ➢ **Andhra Pradesh& Rayalaseema**: H rainfall at isolated places during 26th to 27th November. ➢ H-VH rainfall at isolated places on 28th & 29th	26th Nov, 2024 **Andaman & Nicobar Islands**: Car Nicobar (Nicobar) 7 cm. 27th Nov, 2024 **Tamil Nadu, Puducherry &Karaikal**: Nagapattinam (Nagapattinam) 19 cm, Kodiayakarai (Nagapattinam), Nagapattinam (Nagapattinam), Velankanni (Nagapattinam) 18 each, Tirupoondi (Nagapattinam) 14, Manali (Chennai), Thirukuvalai (Nagapattinam) 13 each, Tiruvarur (Thiruvarur), Vedaranyam (Nagapattinam) 12 each, Mahabalipuram (Chengalpattu), Cheyyur (Chengalpattu), Thalaignayer (Nagapattinam), Sirkali (Mayiladuthurai), Kathivakkam (Chennai), Marakkanam (Villupuram), Vadakuthu (Cuddalore), Mahabalipuram (Chengalpattu), Tarangambadi (Mayiladuthurai) 11 each, Mayiladuthurai (Mayiladuthurai), Thiruthuraipoondi (Thiruvarur), Kollidam (Mayiladuthurai), Tiruvarur (Thiruvarur), Cuddalore Collector Office (Cuddalore), Cuddalore (Cuddalore), Karaikal (Karaikal), Nannilam (Thiruvarur) 10 each, Muthupet (Thiruvarur), Mannudi (Thiruvarur), Ayyampettai (Thanjavur), Needamangalam (Thiruvarur), Karaikal (Karaikal), Madukkur (Thanjavur), NIOT_Pallikaranai (Chennai) 9 each, Bahour (Puducherry), Manalmedu (Mayiladuthurai), Nctpl M ECR (Chengalpattu), Mayiladuthurai (Mayiladuthurai), Manalmedu (Mayiladuthurai), Adiramapattinam (Thanjavur), Ayinkudi (Pudukkottai), Red Hills (Tiruvallur), Pattukottai (Thanjavur), Mylam (Villupuram), Thirukalukundram (Chengalpattu), Puducherry (Puducherry), Vettikadu (Thanjavur), Ennore (Tiruvallur), Orthanad (Thanjavur), Annamalai Nagar (Cuddalore), Puducherry Town (Puducherry) 8 each, Chidambaram (Cuddalore), Puducherry (Puducherry), Puzhal (Chennai), Kodavasal (Thiruvarur), Valangaiman (Thiruvarur), NeivasalThenpathi (Thanjavur), Lower Anaicut (Thanjavur), Manjalaru (Thanjavur), Perungudi (Chennai), Taramani (Chennai), Puzhal (Tiruvallur), Nagudi (Pudukkottai),
27th Nov, 2024	➢ **Tamil Nadu & Puducherry**: H-VH rainfall at a few places with EH at isolated places on 27th ➢ H-VH rainfall at isolated places during 28th to 30th ➢ **Coastal Andhra Pradesh**: H rainfall at isolated places on 27th November. ➢ H-VH rainfall at isolated places during 28th to 30th November. ➢ **Rayalaseema:** H rainfall at isolated places during 28th to 30th November. ➢ **Kerala:** H rainfall at isolated places on 30th November.	
28th Nov, 2024	➢ **North coastal Tamil Nadu & Puducherry**: H rainfall at isolated places on 28th	

	➢ H-VH rainfall at a few places with EH at isolated places on 29th ➢ H-VH rainfall at isolated places on 30thNovember & 01st December ➢ **South Coastal Andhra Pradesh**: H-VH rainfall at isolated places during 29th to 30th November. ➢ H-VH rainfall at a few places with EH at isolated places on 29th ➢ **Rayalaseema:** H-VH rainfall at isolated places during 29th to 30th November. ➢ H-VH rainfall at a few places with EH at isolated places on 29th ➢ **South interior Karnataka:** H rainfall at isolated places on 29th November & 02nd December ➢ H-VH rainfall at isolated places on 30thNovember & 01st December ➢ **Kerala:** H rainfall at isolated places on 29th November. ➢ H-VH rainfall at isolated places on 30th November & 01st December	Madhavaram (Chennai), Thirukkanur (Puducherry), Thiruvottiyur (Chennai), Parangipettai (Cuddalore), Vanamadevi (Cuddalore), Royapuram (Chennai), Adyar Eco Park (Chennai), Adyar (Chennai), Vilupuram (Villupuram), Sholinganallur (Chennai), Peravurani (Thanjavur), Pandavaiyar Head (Thiruvarur), Avadi (Tiruvallur), Sembanarkoil (Mayiladuthurai) 7 each; 30thNov, 2024 **Tamil Nadu, Puducherry &Karaikal**: Ennore AWS (Tiruvallur) 13, Kathivakkam (Chennai) 12, Thiruvottiyur (Chennai), Tondiarpet (Chennai), Sholinganallur (Chennai), CD Hospital Tondiarpet (Chennai), Basin Bridge (Chennai) 9 each, Ponneri (Tiruvallur), Manali (Chennai), Ice House (Chennai), Chennai (N) (Chennai), Chennai Central (Chennai) 8 each, Adyar (Chennai), Alandhur (Chennai), Kolathur (Chennai), YMCA Nandnam (Chennai), Madhavaram (Chennai), Anna University ARG (Chennai), Chennai Collector Office (Chennai), DGP Office (Chennai), Sholinganallur (Chennai), Puzhal (Chennai), Hindustan_University (Chengalpattu), Manali New Town (Chennai), Vadapalani (Chennai) 7 each; 01st Dec, 2024 **Tamil Nadu**: Mylam (Villupuram) 51, Puducherry(Puducherry) 49, Puducherry(Puducherry) 48, Patthukannu(Puducherry) 45, Thirukkanur(Puducherry) 43, Puducherry Town (Puducherry) 40, Tindivanam (Villupuram) 37, Nemoor (Villupuram) 35,Bahour (Puducherry), Vallam (Villupuram) 32 each, Semmedu (Villupuram) 31, Valavanur (Villupuram), Koliyanur (Villupuram) 28 each,Vilupuram (Villupuram) 27, Gingee (Villupuram), Kedar (Villupuram) 25 each, Valathy (Villupuram), Vanur (Villupuram), Soorapattu (Villupuram), Marakkanam (Villupuram) 24 each, Cuddalore (Cuddalore), Avalurpettai (Villupuram) 23 each, Tiruvannamalai (Tiruvannamalai), Chetpet (Tiruvannamalai) 22 each, Jamunamarathur (Tiruvannamalai), Cuddalore Collector Office (Cuddalore), Anandhapuram (Villupuram), Uthiramerur (Kancheepuram) 21 each, Maduranthagam (Chengalpattu), Keelpennathur (Tiruvannamalai), Gummidipoondi(Tiruvallur), Chengalpattu Chengalpattu) 20 each, Avadi (Tiruvallur), Thirukalukundram (Chengalpattu), Vanamadevi
29thNov, 2024	➢ **North Tamil Nadu & Puducherry**: H-VH rainfall at a few places with EH at isolated places on 29th & 30th November ➢ **Interior Tamil Nadu:** H-VH rainfall at isolated places on 01st December ➢ **Tamil Nadu:** H rainfall at isolated places on 02nd & 3rd December	

	➢ **South Coastal Andhra Pradesh**: H-VH rainfall at isolated places during 29th November. ➢ H-VH rainfall at a few places with EH at isolated places on 30th. ➢ H rainfall at isolated places on 01st December ➢ **Rayalaseema:** H-VH rainfall at a few places with EH at isolated places on 29th & 30th. ➢ H rainfall at isolated places on 01st December ➢ **South interior Karnataka:** H rainfall at isolated places on 30th November ➢ H-VH rainfall at isolated places on 01st & 02nd December ➢ **Kerala:** H rainfall at isolated places on 30th November. H-VH rainfall at isolated places on 01st & 02nd December	(Cuddalore)19 each, Tiruttani (Tiruvallur), Arani (Tiruvannamalai), Mugaiyur (Villupuram), Arcot(Ranipet) 18 each, Kudithangi (Cuddalore), Cheyyar (Tiruvannamalai) 17 each, Thirukoilur (Kallakurichi), Vandavasi (Tiruvannamalai), Thamaraipakkam (Tiruvallur), Kalasapakkam (Tiruvannamalai), Kanjanur (Villupuram),Tambaram (Chengalpattu) 16 each, Thandarampettai (Tiruvannamalai), Kallakurichi (Kallakurichi), Kancheepuram (Kancheepuram), Wallajah (Ranipet), Cheyyur (Chengalpattu), MGR Nagar (Chennai), Ayanavaram Taluk Office (Chennai), Mundiyampakkam (Villupuram), Kalavai PWD (Ranipet) 15 each, Yercaud (Salem), Cheyyar (Tiruvannamalai), Arakonam (Ranipet), Sholingur(distRanipet), Vembakkam (Tiruvannamalai), Panruti (Cuddalore), Pallipattu (Tiruvallur), Kallakurichi (Kallakurichi), Mahabalipuram (dist Chengalpattu), JayaEngg College (Tiruvallur) 14 each,Koratur (Tiruvallur), PalarAnicut (Ranipet), Uthukottai (Tiruvallur), Chembarabakkam (Tiruvallur), Kaveripakkam (Ranipet), R.K.Pet (Tiruvallur), DSCL Madampoondi (Kallakurichi), Sriperumbudur (Kancheepuram),Panapakkam (Ranipet), Walajabad (Kancheepuram), Red Hills (Tiruvallur),Poondi (Tiruvallur), BASL Manampoondi (Villupuram), R.K.Pet (Tiruvallur),Minnal (Ranipet), Tiruvallur (Tiruvallur) 13 each, Meenambakkam (Chennai), Ambathur Rev (Chennai), Valasaravakkam(Chennai), Cholavaram (Tiruvallur), Thirupalapandal (Kallakurichi), Kalayanallur (distKallakurichi), Kolapakkam (Chengalpattu), Ayapakkam (Chennai), Ranipet (Ranipet), Tirukoilur (Kallakurichi), Maduravoyal (Chennai), Tiruttani (Tiruvallur), Ambattur MW (Chennai)12 each, Chennai (AP) (Chennai), Tiruttani (distTiruvallur), Alandur (dist Chennai), BASLManalurpet (Kallakurichi), Mill-1 Ariyalur (Kallakurichi), Vengur (Kallakurichi), Meenambakkam (Chennai), Valasaravakkam (Chennai), Anna Nagar (Chennai), Ammoor (Walajah Railway) (Ranipet), NctplMargECR (Chengalpattu), Vellore (Vellore), Thiru-Vi-Ka Nagar (Chennai),Ponneri (Tiruvallur), Chennai Collector Office (Chennai), Kattumayilur (Cuddalore), Sankarapuram (distKallakurichi), Perambur (dist Chennai), Chennai(N) AWS(dist Chennai), Kundrathur (distKancheepuram), Vadapalani (dist Chennai), ACSMedical College ARG
30thNov, 2024	➢ **North Tamil Nadu & Puducherry**: H-VH rainfall at a few places with EH at isolated places on 30th November ➢ **Interior Tamil Nadu:** H-VH rainfall at isolated places on 01st December ➢ **Tamil Nadu:** H rainfall at isolated places on 02nd & 3rd December ➢ **South Coastal Andhra Pradesh**: H-VH rainfall at a few places with EH at isolated places on 30th. ➢ H rainfall at isolated places on 01st December ➢ **Rayalaseema:** H-VH rainfall at a few places	

	with EH at isolated places on 30th. ➢ H rainfall at isolated places on 01st December ➢ **South interior Karnataka:** H rainfall at isolated places on 30th November ➢ H-VH rainfall at isolated places on 01st & 02nd December ➢ **Kerala:** H rainfall at isolated places on 30th November. H-VH rainfall at isolated places on 01st & 02nd December	(Kancheepuram), Ulundurpet (Kallakurichi), Sholinganallur(Chennai), Kodambakkam (Chennai), Virugavoor (Kallakurichi), Chennai(N) (Chennai) 11 each,Alangayam (Tirupathur), DGP Office (Chennai), Poonamallee (Tiruvallur), Ponnai Dam (Vellore), Tondiarpet (Chennai), Thiruvalangadu (Tiruvallur), Mugalivakkam (Chennai), Ariyalur Camp Area (Kallakurichi), DSCL Sulangurichi (Kallakurichi), Aminjikarai (Chennai), L Thiyagadurgam (Kallakurichi), DSCL Keelpadi (Kallakurichi), Basinbridge (Chennai), Ammundi (dist Vellore), Madipakkam Chennai) 10each, **Kerala**: Ulanad (Pathanamthitta) 9, Enadimangalam (Pathanamthitta district) 7 02nd Dec, 2024 **Tamilnadu, Puducherry &Karaikal**: Uthangarai (Krishnagiri) 50, Kedar (Villupuram) 42, Soorapattu (Villupuram) 38, Vilupuram (Villupuram) 35, Harur (Dharmapuri) 33, Mundiyampakkam (Villupuram), Koliyanur (Villupuram), Thirupalapandal (Kallakurichi) 32 each, Madampoondi (Kallakurichi) 31, Mugaiyur (Villupuram), Valavanur (Villupuram) 30 each, Nemoor (Villupuram), Manampoondi (Villupuram), Kanjanur (Villupuram) 29 each, Vengur (Kallakurichi) 27, Tirukoilur (Kallakurichi) 26, Jambukuttapatti (Krishnagiri), Pochampalli (Krishnagiri) 25 each, Yercaud (Salem) 24, Eraiyur (Kallakurichi), Jamunamarathur (Tiruvannamalai) 23 each, Pambar (Krishnagiri), Manalurpet (Kallakurichi) 21 each, Thandarampettai (Tiruvannamalai), Barur (Krishnagiri), Pappireddipatti (Dharmapuri) 20 each, Penucondapuram (Krishnagiri), Sankarapuram (Kallakurichi) 19 each, Kallakurichi (Kallakurichi) 18, Anandhapuram (Villupuram), Kalayanallur (Kallakurichi) 17 each, Tiruvannamalai (Tiruvannamalai), Panruti (Cuddalore), Dharmapuri (Dharmapuri) 16 each, Moorarpalayam (Kallakurichi), Vanamadevi (Cuddalore), Keelpennathur (Tiruvannamalai), Moongilthuraipattu (Kallakurichi), Ulundurpet (Kallakurichi), Kariyakovil Dam (Salem), Sulangurichi (Kallakurichi), Rishivandhiyam (Kallakurichi), SCS Mill Pillaiyarkuppam (Kallakurichi), Keelpadi (Kallakurichi) 15 each, Virugavoor (Kallakurichi), Nedungal (Krishnagiri), Kattumayilur (Cuddalore) 14 each, Ariyalur (Kallakurichi), Ariyalur
01st Dec, 2024	➢ **North Tamil Nadu & Puducherry**: H-VH rainfall at a few places with EH at isolated places on 01st December ➢ **Interior Tamil Nadu:** H-VH rainfall at isolated places on 02nd December ➢ **Interior districts of Tamil Nadu adjoining Kerala:** H rainfall at isolated places on 3rd December ➢ **South Coastal Andhra Pradesh**: H rainfall at isolated places on 01st December ➢ **Rayalaseema:** H rainfall at isolated places on 01st & 02nd December ➢ **South interior Karnataka:** H rainfall at isolated places on 01st & 03rd December ➢ H-VH rainfall at isolated places on 02nd December	

	➢ **Coastal Karnataka:** H rainfall at isolated places on 02nd & 3rd December ➢ **Kerala:** H-VH rainfall at a few places with EH at isolated places on 02nd December ➢ H-VH rainfall at isolated places on 01st December ➢ H rainfall at isolated places on 03rd December	Camp Area (Kallakurichi), Kadavanur (Kallakurichi) 13 each, Vepur (Cuddalore), Me Mathur (Cuddalore) 12 each, Thiyagadurgam (Kallakurichi), Pennagaram (Dharmapuri), Semmedu (Villupuram), Manimutharu Dam PWD (Kallakurichi), SRC Kudithangi (Cuddalore), Krishnagiri (Krishnagiri), Kachirayaopalayam (Kallakurichi), Thirukkanur (Puducherry), Paiyur (Krishnagiri) 11 each, Sethiathope (Cuddalore), Anaimaduvu Dam (Salem), Omalur (Salem), Dam (Krishnagiri), Danishpet (Salem) 10 each, Kallakurichi (Kallakurichi), Gomugi Dam (Kallakurichi), Palacode (Dharmapuri), Pelandurai (Cuddalore), Hogenekal (Dharmapuri) 9 each, Vadapudupattu (Tirupathur), Bhuvanagiri (Cuddalore), Bahour (Puducherry), Palacode (Dharmapuri), Denkanikottai (Krishnagiri), TNAU CRI Yethapur (Salem), Vaniyambadi (Tirupathur) 8 each, Dharamapuri (Dharmapuri), Arasoor (Villupuram), Kuppanatham (Cuddalore), Gudalur Bazar (The Nilgiris), Thiruvennainal (Villupuram), Tirupattur (Tirupathur), Natrampalli (Tirupathur), Ambur (Tirupathur), Lakkur (Cuddalore), Kodanad (The Nilgiris), Tirupattur (Tirupathur), Avalurpettai (Villupuram), Mangalapuram (Namakkal), Kilacheruvai (Cuddalore), Kethandapatti (Tirupathur), Chengam(Tiruvannamalai), Chidambaram (Cuddalore), Vridhachalam (Cuddalore) 7 each, **Kerala**: Kodungallur (Thrissur) 19, Kottayam18,Kurudamannil (Pathanamthitta)17, Konni (Pathanamthitta), Kanjirappally (Kottayam district) & Ranni (Pathanamthitta) 16 each, Kochi (Ernakulam), Haripad (Alappuzha) & Peerumedu (Idukki) 15 each, Perumbavur (Ernakulam) 14, Aluva (Ernakulam), Laha (Pathanamthitta) & Aluva (Ernakulam) 13 each, Cherthala (Alappuzha),Kunnathanam (Pathanamthitta) & Thycauttussery (Alapuzha) 12 each, Kalamassery (Ernakulam) 11, Kumarakom (Kottayam) & Konni(Pathanamthitta district) 8 each, Kozhikode, Vaikom (Kottayam) & Piravam (Ernakulam) 7 each. **Coastal Andhra Pradesh &Yanam**: Yanam (Yanam) 8
02nd Dec, 2024	➢ **North Interior Tamil Nadu, South interior Karnataka and adjoining Rayalaseema**: H rainfall at isolated places on 02nd December ➢ **Coastal Karnataka:** H rainfall at isolated places on 02nd & 03rd December ➢ **Kerala:** H-VH rainfall at a few places with EH at isolated places on 02nd December ➢ H rainfall at isolated places on 03rd December	

Table 4.3.4.5: Verification of Gale/Squally Wind Forecast issued by IMD

Date/ Base Time of observation	Gale/ Squally wind Forecast	Realised Wind Forecast
24.11.2024 /0300UTC	• Squally wind speed reaching 50-60 kmph gusting to 70 kmph is very likely to prevail over southwest Bay of Bengal and adjoining westcentral Bay of Bengal and along & off Tamil Nadu - Puducherry and south Andhra Pradesh coasts on 26 th and likely to increase becoming 55-65 kmph gusting to 75 kmph on 27th and 28th November over the same region.	At the time of landfall, the estimated maximum sustained wind speed was about 70-80 kmph gusting to 90 kmph over Puducherry.
25.11.2024 /0300UTC	• Squally wind speed reaching 40-50 kmph gusting to 60 kmph is very likely to prevail over southwest Bay of Bengal, adjoining southeast Bay of Bengal and along & off Sri Lanka coast on 25 November. Squally weather with wind speed reaching 35-45 kmph gusting to 55 kmph along & off Tamil Nadu - Puducherry coasts. • Squally wind speed reaching 50-60 kmph gusting to 70 kmph is very likely to prevail over southwest Bay of Bengal and adjoining westcentral Bay of Bengal and along & off Tamil Nadu - Puducherry and south Andhra Pradesh coasts on 26 th and likely to increase becoming 55- 65 kmph gusting to 75 kmph during 27th to 29 th November over the same region.	
26.11.2024 /0300UTC	• Squally wind speed reaching 40-50 kmph gusting to 60 kmph is likely to prevail along & off Tamil Nadu- Puducherry and south Andhra Pradesh coasts till 27 th morning. Thereafter, it is likely to increase becoming 50-60 kmph gusting to 70 kmph from 27th evening till 29th November.	
27.11.2024 /0300UTC	• Squally wind speed reaching 45-55 kmph gusting to 65 kmph is likely to prevail along & off Tamil Nadu- Puducherry and south Andhra Pradesh coasts till 27 th morning. Thereafter, it is likely to increase becoming 55-65 kmph gusting to 75 kmph from 27th evening till 30th November morning.	
28.05.2024 /0300UTC	• Along & off North Tamil Nadu – Puducherry and adjoining South Andhra Pradesh coasts: Squally wind speed reaching 45-55 kmph gusting to 65 kmph is prevailing along & off North Tamil Nadu - Puducherry and adjoining South Andhra Pradesh coasts. It is likely to increase becoming 50-60 kmph gusting to 70 kmph from 29 th evening till 30th November afternoon. • Along & off East Sri Lanka coasts: Squally wind speed reaching 55-65 kmph gusting to 75 kmph is very likely to prevail Along & off East Sri Lanka coasts till 29th morning. It would decrease gradually thereafter becoming 45-55 kmph gusting to 65 kmph by 30th November morning and further decrease thereafter. • Along & off South Tamil Nadu coast and Gulf of Mannar: Squally wind speed reaching 40-50 kmph gusting to 60 kmph is likely to prevail	

	till 29th evening. It would increase thereafter, becoming 45-55 kmph gusting to 65 kmph till 30th morning and gradually decrease thereafter.	
29.11.2024 /0300UTC	• Along & off North Tamil Nadu – Puducherry and adjoining South Andhra Pradesh coasts: Squally wind speed reaching 50-60 kmph gusting to 70 kmph is prevailing along & off North Tamil Nadu - Puducherry and adjoining South Andhra Pradesh coasts. It is likely to increase becoming Gale wind speed reaching 60-70 kmph gusting to 80 kmph from evening of 29th and 70- 80 kmph gusting to 90 kmph from 30th November morning to evening of 30th November. It is likely to decrease thereafter. • Along & off East Sri Lanka coasts: Squally wind speed reaching 55-65 kmph gusting to 75 kmph is very likely to prevail Along & off East Sri Lanka coasts till 29th November. It would decrease thereafter. • Along & off South Tamil Nadu coast and Gulf of Mannar: Squally wind speed reaching 45-55 kmph gusting to 65 kmph is likely to prevail till 30th evening and gradually decrease thereafter	
30.11.2024 /0300UTC	• Along & off North Tamil Nadu – Puducherry and adjoining South Andhra Pradesh coasts: Gale wind speed reaching 75-85 gusting to 95 is prevailing along & off North Tamil Nadu - Puducherry and adjoining South Andhra Pradesh coasts. It is likely to prevail till evening of 30th November and gradually decrease thereafter. • Costal districts of north Tamil Nadu & south Andhra Pradesh: Gale wind speed reaching 60- 70 kmph gusting to 80 kmph is prevailing over costal districts of Tamil Nadu (Tiruvallur, Chennai, Chengalpattu, Villupuram and Puducherry) and Andhra Pradesh (Tirupati and Nellore). It is likely to increase becoming 75-85 gusting to 95 kmph over costal districts of Tamil Nadu (Tiruvallur, Chennai, Chengalpattu, Villupuram, Puducherry Cuddalore, Mayiladuthurai and Nagappattinam) and Andhra Pradesh (Tirupati, Nellore and Prakasham) from 30th November morning to evening of 30th November. It is likely to decrease thereafter. • Along & off South Tamil Nadu coast and Gulf of Mannar: Squally wind speed reaching 45-55 kmph gusting to 65 kmph is likely to prevail till 30th evening and gradually decrease thereafter	
01.12.2024 /0300UTC	• Southwest Bay of Bengal and along & off North Tamil Nadu – Puducherry coasts: Gale wind speed reaching 60-70 kmph gusting to 80 kmph to prevail over southwest Bay of Bengal. To decrease becoming squally wind speed reaching 50-60 kmph gusting to 70 kmph from evening of 1st December and decrease gradually thereafter. • Adjoining areas of westcentral Bay of Bengal and along & off South Andhra Pradesh coast: Squally wind speed reaching 45-55 kmph gusting to 65 kmph to prevail over adjoining areas of westcentral Bay of Bengal till evening of 1 st December. To decrease thereafter. • Along & off South Tamil Nadu coast and Gulf of Mannar: Squally wind speed reaching 40-50 kmph gusting to 60 kmph to prevail till evening of 1st December and gradually decrease thereafter.	

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 Storm Surge at the time of landfall
29.11.2024 /0300UTC	Storm surge of about 1 metre above the astronomical tide is likely inundate the low-lying areas of the coastal districts of north Tamil Nadu, Puducherry and adjoining south Andhra Pradesh during the time of landfall.	Maximum estimated storm surge of height 1-2 m inundated low-lying areas of coastal Tamil Nadu and Puducherry during landfall.
30.11.2024 /0300UTC	-do-	
01.12.2024 /0300UTC	Storm surge of about 0.5-meter height above astronomical tide is likely to inundate the low-lying areas of the coastal districts of north Tamil Nadu, Puducherry till evening of 1st December.	

4.4 .Annual Performance of cyclone landfall, track and intensity forecast

4.4.1 Genesis forecast (Medium & Extended range)

India Meteorological Department (IMD) maintains a continuous watch over the north Indian Ocean (NIO) including the Bay of Bengal (BoB) and the Arabian Sea (AS) and issues extended range probabilistic cyclogenesis (formation of depression) forecast over the BoB & AS for the next two weeks, every Thursday.

IMD introduced extended range forecast on 22nd April, 2018. The probability of cyclogenesis inextended range forecast (ERF) is issued in four categories viz. nil (0%), low (1-33%), moderate (34-67%) and high (68-100%) based on diagnosis of various large-scale features leading to cyclogenesis and the guidance from various global deterministic & ensemble numerical weather prediction (NWP) models & extended range forecasting models.

IMD evaluates the performance of operational ERF of cyclogenesis based on the forecasts issued for week 1 and week 2 for AS, BoB and NIO during April 2018 to 2024. For this purpose, Brier Score Operational (BSo) is calculated and analysed. To evaluate the skill, the climatological probability of cyclogenesis for each week is derived basedon the data during 1891-2020 and the same is used to determine reference BS ref. Subsequently, comparing the operational BSo with reference BS ref, the Brier Skill Score (BSS) has been calculated and analysed.

The Brier Score Skill (BSS) indicates the degree of improvement of the BS of a forecast (BSv) compared to the BS of a climatological forecast (BSc) as reference, based on an assumed equal occurrence probability of 33% for each event. The forecast is perfect when the BSS is equal to one.

Similarly, in the medium range, IMD commenced the cyclogenesis forecast for next 3 days in 2014, next 5 days in 2018 and next 7 days in 2023 as nil (0% probability), low (1-33% probability), moderate (34-67% probability) and high (68-100% probability). To evaluate the skill of genesis forecast, in a similar manner the BSS is calculated from day1 to day7 for BoB, AS and NIO regions. Every forecast is valid upto 0300 UTC of next day.

Annual BSS during the period 2018 to 2024 is presented in Fig. 4.4.1 for BOB, AS and NIO. In 2024, considering week 1 accuracy, BSS was 45 % for BOB, 11 % for AS and 39 % for the NIO region.

For the medium range forecast, the BSS has been between 60% to 80 % for the lead period of day 1 to day 5 for BoB. For the AS it has been between 45% to 60 % and for NIO it varied between 55% to 80 % for the lead period of day 1 to day 5.

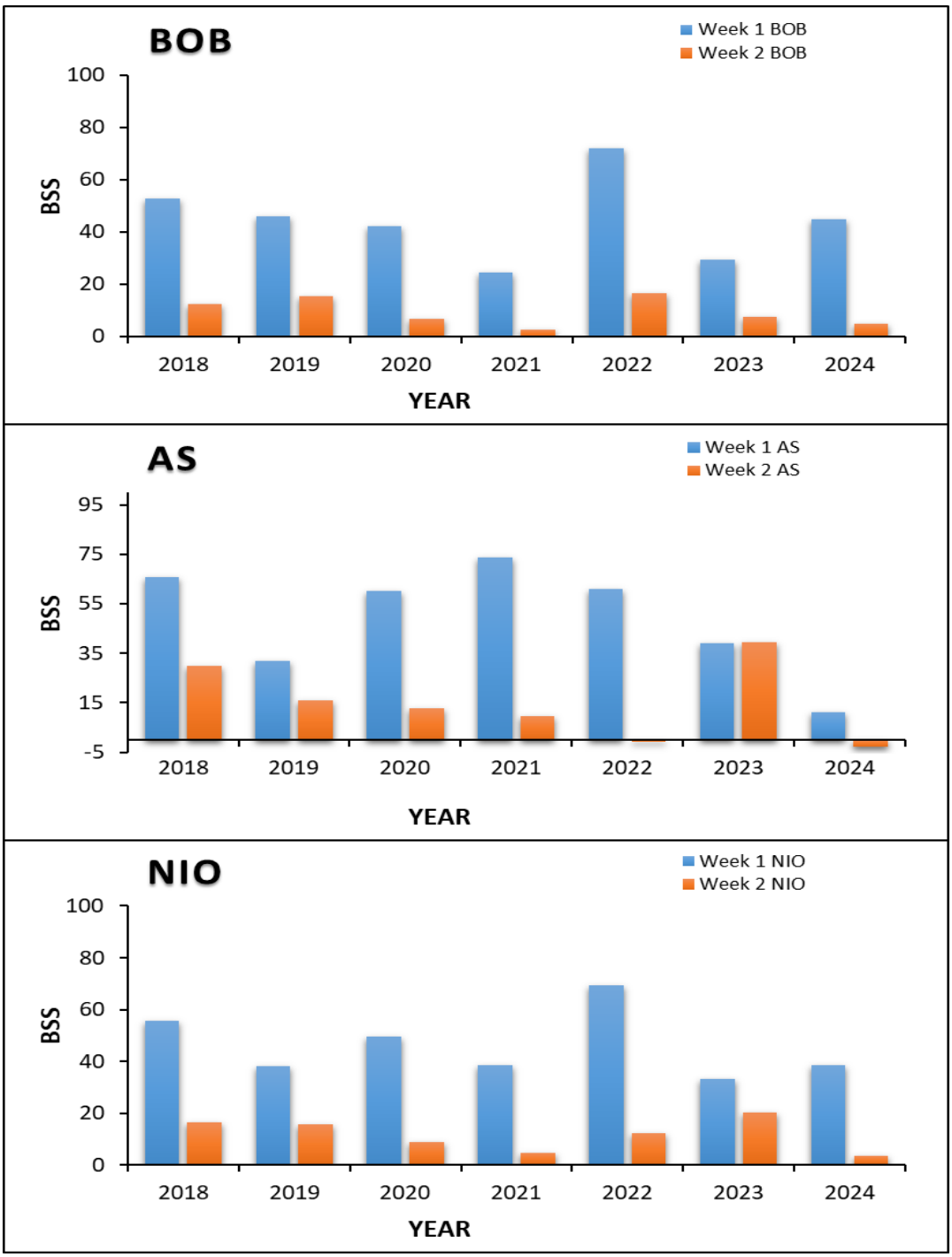


Fig.4.4.1: Annual BSS in the extended range scale for next 2 weeks

Table 4.4.1: Representation of BSS Data for verification of medium range forecast over (a) BOB, (b) AS & (c) NIO for 7 days during 2019-2024.

BSS		2019	2020	2021	2022	2023	2024
Week 1	BOB	45.8	42.2	24.4	72.1	29.4	44.9
	AS	31.8	60.0	73.9	60.8	38.9	11.3
	NIO	38.2	49.6	38.5	69.3	33.2	38.5
Week 2	BOB	15.5	6.7	2.7	16.4	7.6	5.0
	AS	16.1	12.6	9.7	-0.8	39.5	-3.0
	NIO	15.9	8.9	4.7	12.2	20.3	3.4

Table 4.4.2: Representation of BSS Data for verification of extended range forecast over (a) BOB, (b) AS & (c) NIO for week 1 & 2 during 2019-2024.

BSS		2019	2020	2021	2022	2023	2024
Day 1	BOB	49.9	11.2	28.7	20.4	93.6	86.6
Day 2	BOB	28.9	35.6	41.4	45.3	41.2	74.9
Day 3	BOB	43.4	39.6	37.7	45.1	42.5	66.7
Day 4	BOB	36.3	21.6	44.5	42.9	42.2	61.7
Day 5	BOB	41.6	10.2	47.9	36.1	45.8	58.4
Day 6	BOB						52.3
Day 7	BOB						49.2
BSS		2019	2020	2021	2022	2023	2024
Day 1	AS	21.1	15.5	14.8	67.5	-0.1	61.8
Day 2	AS	29.7	30.2	34.3	49.0	8.4	54.3
Day 3	AS	53.4	52.1	47.3	44.2	15.3	56.7
Day 4	AS	71.8	40.0	47.0	28.7	30.2	55.2
Day 5	AS	58.8	30.8	39.6	1.3	33.0	47.1
Day 6	AS						39.3
Day 7	AS						24.9
BSS		2019	2020	2021	2022	2023	2024
Day 1	NIO	36.7	12.5	22.6	29.0	29.0	79.9
Day 2	NIO	29.4	33.7	38.8	46.1	26.1	69.6
Day 3	NIO	49.0	44.8	40.8	44.9	31.9	64.5
Day 4	NIO	55.4	29.3	45.4	40.1	37.9	60.7
Day 5	NIO	50.8	18.8	44.9	29.5	41.8	56.3
Day 6	NIO						49.8
Day 7	NIO						43.5

Colour Legend for BSS (Red shades indicate BSS <50 and green shades indicate BSS>50)

100	90	80	70	60	50	40	30	20	10	0

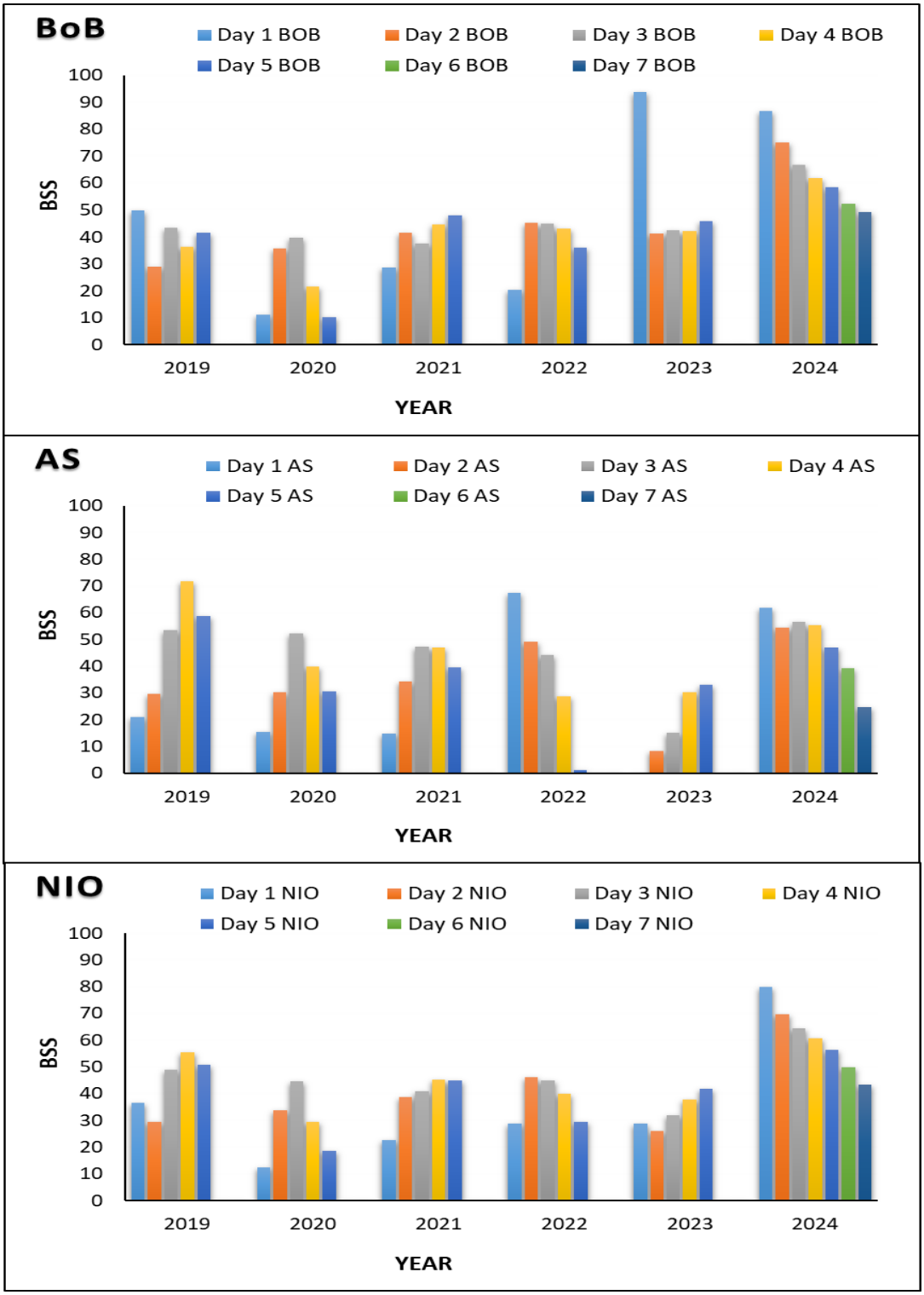


Fig.4.4.2: Annual BSS for medium range forecast for day 1 to day 7:

4.4.2 Track Forecast

Annual average track forecast error is calculated by considering the track forecast errors of all the cyclones during the year. The mean error of each cyclone is weighted by number of forecasts verified to calculate the annual average track forecast errors as mentioned below. This is calculated for 12, 24, 36, 48, 60, 72, 84, 96, 108, 120 hr forecasts.

$$\text{Annual average track forecast error} = \frac{(n1 * E1 + n2 * E2 + n3 * E3 + \ldots)}{(n1 + n2 + n3 + \ldots)}$$

Where n1, n2, n3... are number of six hourly forecasts verified for cyclone 1, 2, 3 and E1, E2, E3... are the average track forecast errors for cyclone n1, n2, n3.

Similarly, annual average CLIPER model-based track forecast errors are calculated. Subsequently, skill is calculated for a given cyclone by comparing the six hourly operational track forecast errors with track forecast errors of a reference model.

$$\text{Track forecast skill (\%)} = \frac{(\text{CLIPER track forecast} - \text{Operational track forecast})\text{error}}{\text{CLIPER track forecast error}} * 100$$

The annual average track forecast errors and skill during 2024 are presented in Fig. 4.4.3 (a-b).

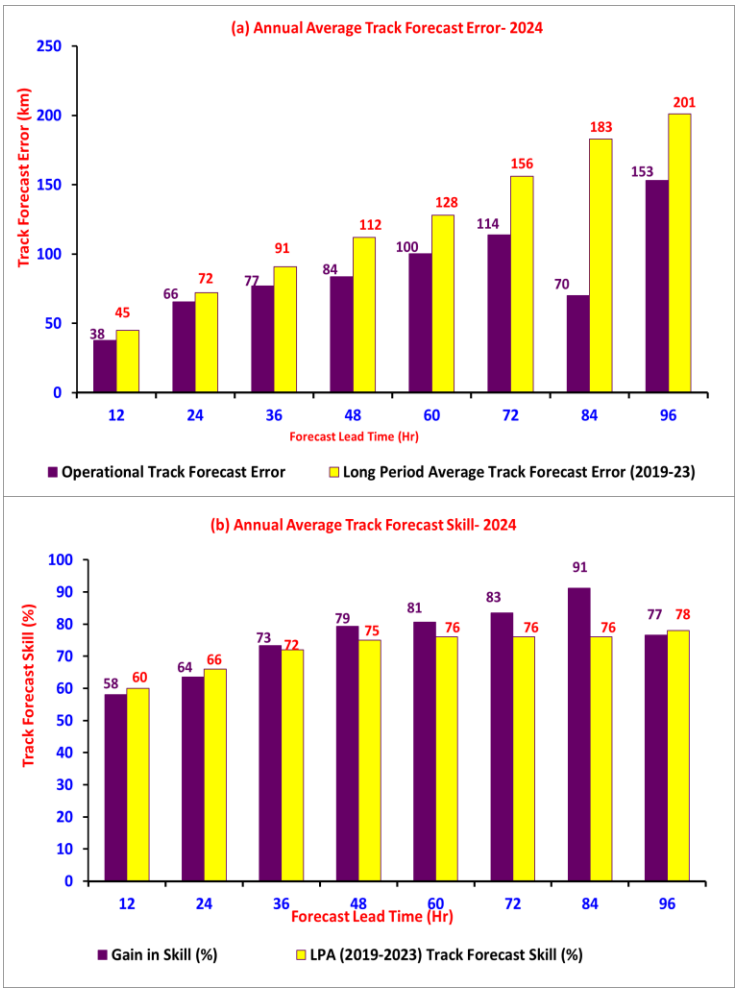


Fig.4.4.3 Annual average (a) track forecast error (km) and (b) track forecast skill against the climatology and persistence forecast during 2024 as compared to that during 2019-2023

The annual average track forecast errors in 2024 have been 66 km, 84 km and 114 km, respectively for 24, 48 and 72 hrs against the past five-years average error of 72, 112 and 156 km based on data of 2019-2023. The errors have been lesser during this year as compared to long period average (LPA) (2019-23), The track forecast skills compared to climatology and persistence forecast have been 64%, 79% and 83% respectively for the 24, 48 and 72 hrs lead period which was also less than long period average of 2019-2023 (66%, 75% & 76% respectively).

4.4.3 Landfall Forecast

The annual average landfall forecast errors for the year 2024 have been 14 km, 24 km and 2 km for 24, 48 and 72 hrs lead period against the past five years average errors of 18 km, 42 km and 73 km during 2019-2023. The landfall time forecast errors have been 3.1, 3.6 and 0.5 hrs for 24, 48 and 72 hrs lead period during 2024 against the average of past five years of 2.8, 4.6 and 9.5 hrs during 2019-2023. The annual average landfall points and time forecast errors are presented in **Fig. 4.4.4 (a-b)**.

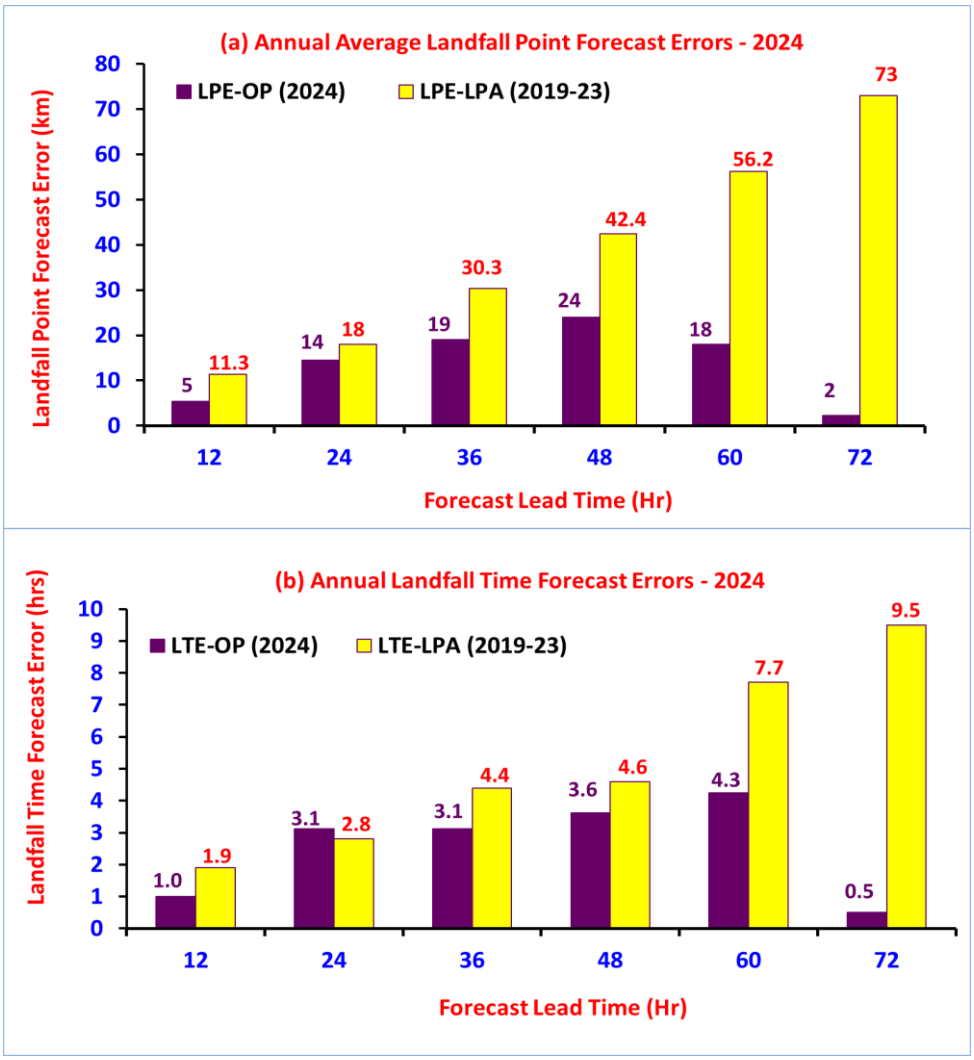


Fig.4.4.4. Annual average (a) landfall point forecast error (km) and (b) landfall time forecast errors as compared to long period average errors during 2019-2023

4.4.4 Intensity Forecast

The annual average intensity forecast error based on AE is the weighted mean of the absolute error for each cyclone. Similarly, the annual average error is calculated by persistence method. Based on these two errors, the intensity forecast skill with reference to absolute error is calculated. Errors and skills are calculated for 12, 24, 36, 48, 60, 72, 84-, 96-, 108- and 120-hour forecasts. The annual average intensity forecast error based on RMSE is calculated by taking square root of the average of squared error between the forecast and observed intensity values for 12, 24, 36, 48, 60, 72, 84, 96, 108 and 120 hours forecast period for every six hourly forecasts. Similarly, RMSE error based on persistence is calculated and hence the skill. The annual average absolute error (AE) in intensity forecast error (Fig.4.4.5 a-b) has been 4.1 knots, 5.3 knots and 5.0 knots respectively for 24, 48 and 72 hrs lead period of forecast against the past five-year average of 7.1, 10.3 and 13.8 knots. The skill in terms of AE compared to persistence forecast was 65%, 74% and 78% as compared to long period average (2019-23) of 52%, 66% and 75% for 24-, 48- and 72-hours period.

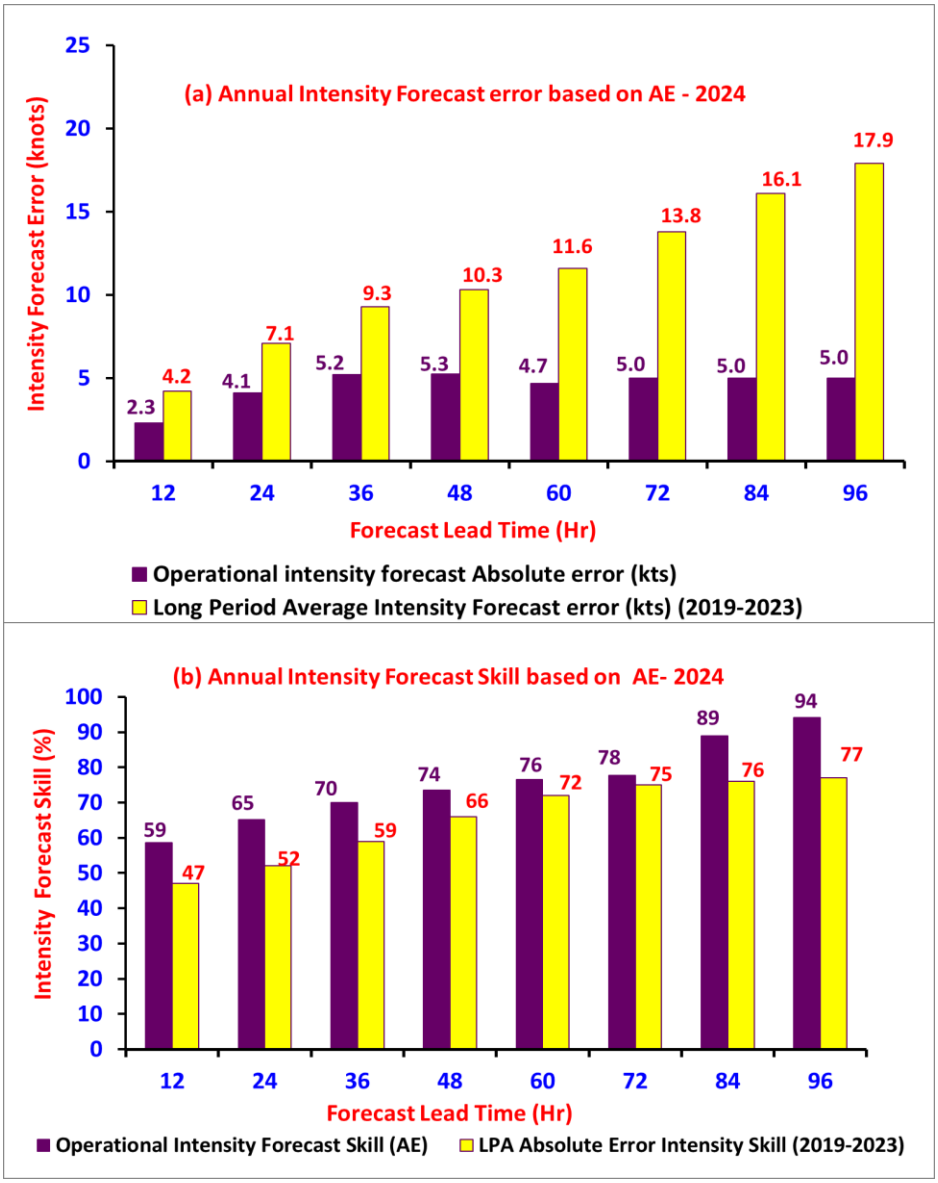


Fig.4.4.5. Annual average (a) absolute error (AE) in kts and (b) skill in % during 2024 as compared to that during 2019-2023

The annual average root mean square error (RMSE) in intensity forecast error (Fig.4.4.6 a-b) has been 5.4 knots, 7.3 knots and 7.1 knots respectively for 24, 48 and 72 hrs lead period of forecast against the past five year average of 9.2, 12.8 and 16.5 knots. The skill in terms of RMSE compared to persistence forecast was 67%, 74% and 76% as compared to long period average (2019-23) of 60%, 71% and 79% for 24, 48 and 72 hours lead period.

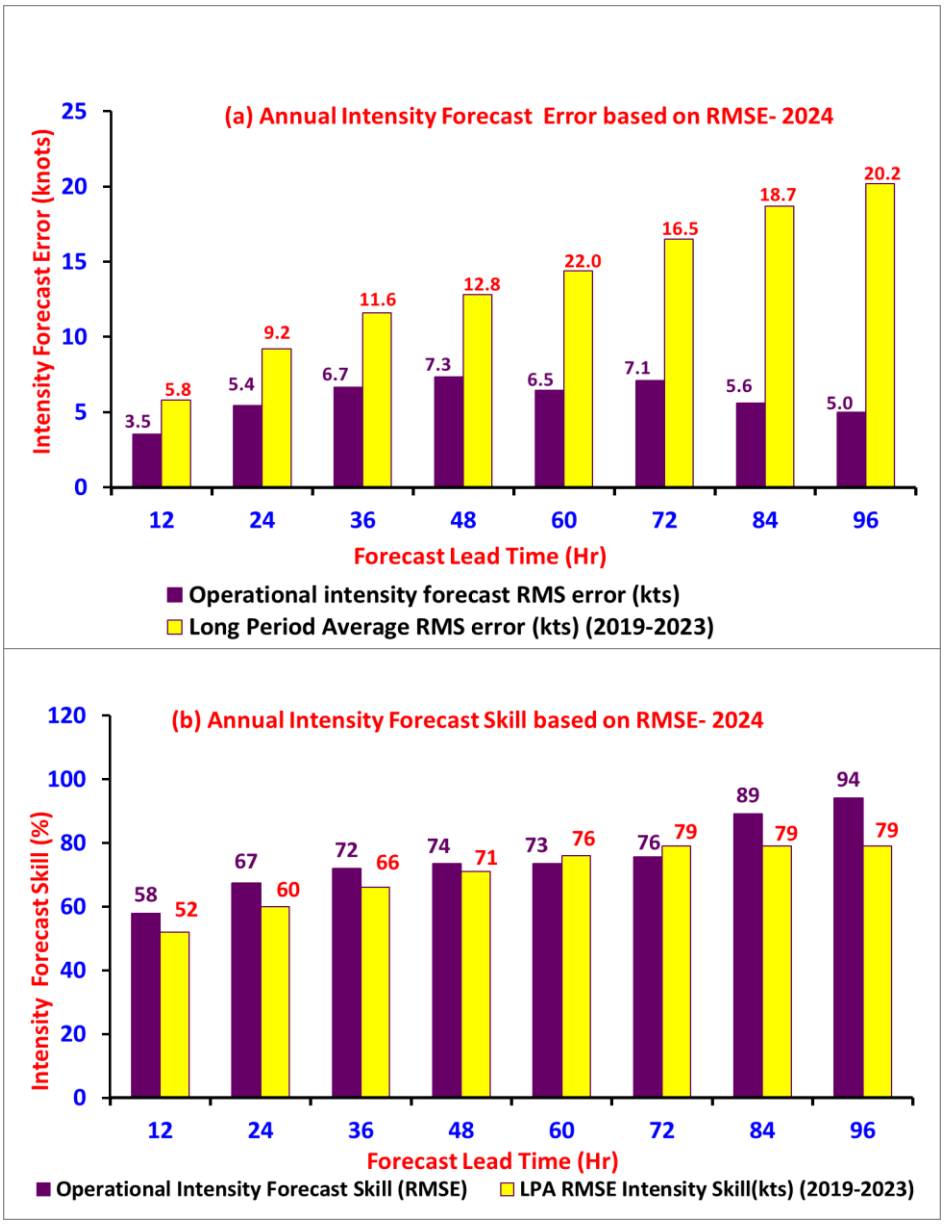


Fig.4.4.6. Annual average (a) root mean square error (RMSE) in kts and (b) skill in percentage during 2024 as compared to that during 2019-2023

4.5. Interannual variation of forecast errors of TCs over north Indian Ocean

4.5.1. Track forecast error and skill

Inter-annual variation of ftrack forecast 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 modernization 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.

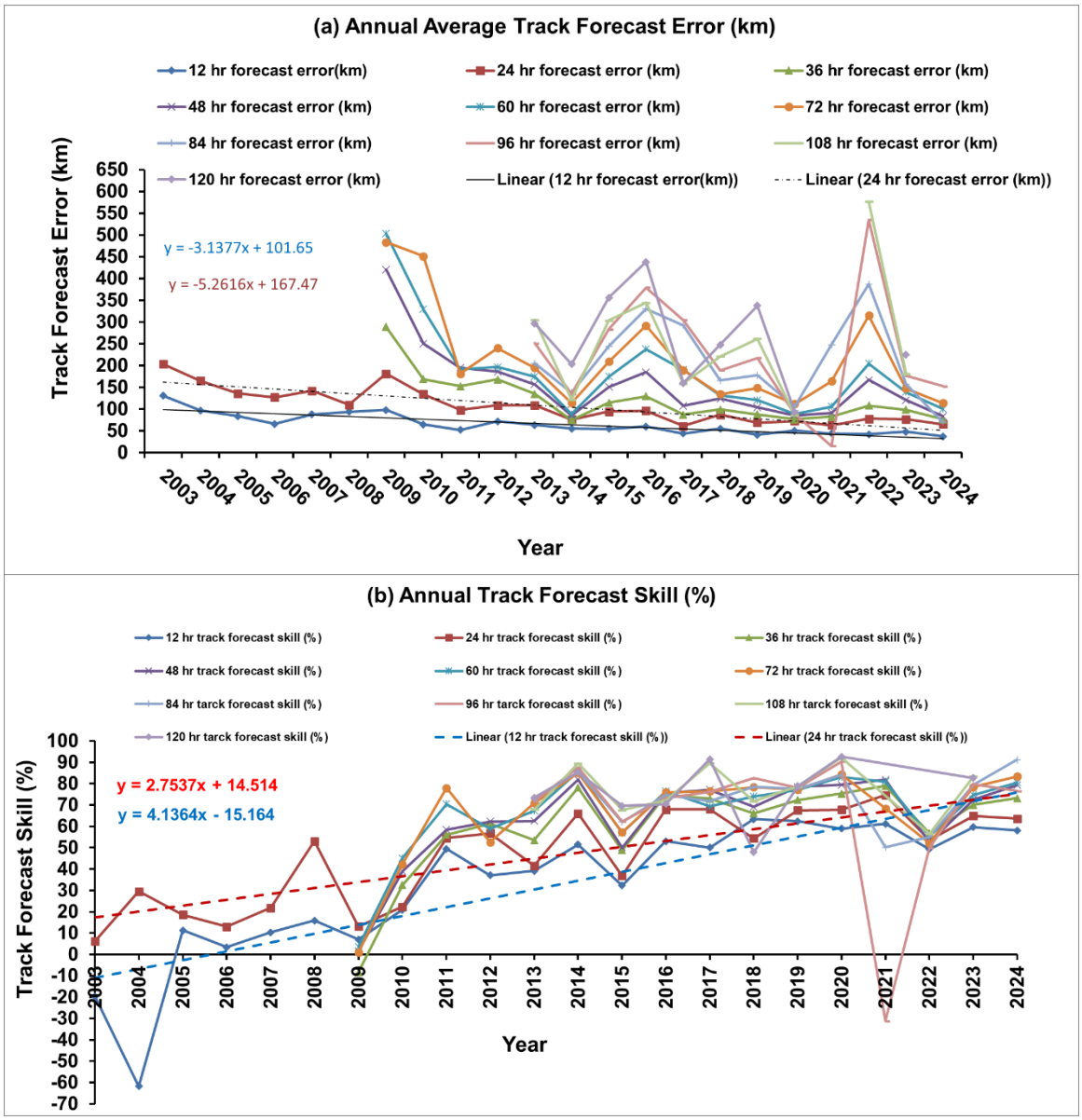


Fig. 4.5.1 Inter-annual variation of average track forecast (a) errors and (b) skill during 2023

There has been continuous improvement in track forecast accuracy with decrease in track forecast errors at the rate of 5.2 km/year (52 km in 10 years) for 24 hrs lead period and increase in skill at the rate of 2.8% per year (28% 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 3.1 km/year (31 km in 10 years) and increase in skill at the rate of 4.1% per year (41% in 10 years) since 2003.

Table. 4.5.1 (a) Inter-annual average Track forecast errors during 2003 to 2024 (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 (29)	142 (24)								
2008	94 (22)	110 (16)								
2009	98 (32)	181 (26)	289 (16)	420 (8)	503 (6)	483 (2)				
2010	65 (56)	134 (48)	169 (38)	250 (29)	329 (23)	451 (19)				
2011	52 (21)	98 (19)	153 (16)	195 (14)	191 (10)	181 (7)				
2012	72 (16)	109 (13)	168 (8)	186 (6)	197 (4)	240 (2)				
2013	63.7 (94)	109 (84)	135.1 (72)	156.9 (65)	175 (55)	194.7 (44)	205.1 (34)	251.3 (26)	304.9 (18)	296.4 (11)
2014	55 (49)	76.1 (44)	74.7 (38)	85.6 (32)	88.5 (25)	114.3 (20)	138.1 (14)	135.1 (10)	121.5 (6)	203 (3)
2015	54.7 (66)	94.4 (60)	114.7 (52)	150.9 (43)	174.9 (37)	209.1 (30)	244.3 (22)	283.3 (17)	303.5 (12)	356 (8)
2016	59.7 (58)	96.1 (50)	129.6 (42)	185.1 (34)	238 (27)	291.7 (21)	330.4 (15)	379.5 (9)	344.1 (4)	438.3 (2)
2017	43.7 (35)	61.4 (29)	87.2 (23)	107.6 (18)	190.1 (14)	189.6 (12)	292.5 (10)	304.2 (8)	158.7 (3)	159.7 (3)
2018	55.4 (127)	87.5 (111)	99.2 (97)	124.2 (80)	131.2 (63)	134.3 (51)	165.8 (34)	189 (24)	220.8 (16)	247.6 (7)
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)

2021	43.7 (68)	62.9 (56)	82.6 (50)	91.4 (41)	105.7 (32)	164.0 (15)	248 (9)	15.3 (4)		
2022	42.3 (75)	77.5 (61)	108 (51)	167.1 (35)	204.2 (24)	315.3 (13)	378.2 (8)	535.3 (4)	576.5 (2)	
2023	48.3 (125)	76.5 (109)	98.4 (97)	120.7 (85)	138.8 (73)	147.2 (63)	157.3 (52)	176.8 (41)	181.5 (33)	224.8 (25)
2024	37.6 (68)	65.6 (55)	76.9 (48)	83.5 (39)	100.3 (30)	114 (23)	70 (5)	153 (1)		

Table. 4.5.1 (b) Inter-annual average track forecast skill (%) during 2003 to 2024 (Values 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)	3.6 (6)	1 (2)				
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	39.2 (94)	41.6 (84)	53.5 (72)	62.5 (65)	67.3 (55)	70.9 (44)	72.7 (34)	71.7 (26)	67.8 (18)	73.4 (11)
2014	51.5 (49)	66 (44)	78.1 (38)	81.9 (32)	85.8 (25)	85.1 (20)	85.4 (14)	87.6 (10)	89.5 (6)	85.3 (3)
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)	70.4 (2)
2017	50 (35)	68.1 (29)	73 (23)	77.2 (18)	69.4 (14)	76.4 (12)	71.8 (10)	76.2 (8)	89.6 (3)	91.4 (3)
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)	47.9 (7)

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)
2021	61.2 (68)	74.6 (56)	78.9 (50)	81.8 (41)	80.3 (32)	68.4 (15)	50.1 (9)	-31.2 (4)		
2022	49.3 (75)	53.7 (61)	56.8 (51)	52.3 (35)	55.2 (24)	52.1 (13)	54.9 (8)	49.9 (4)	56.2 (2)	
2023	59.7 (125)	65 (109)	70 (97)	73 (85)	55.2 (73)	78.5 (63)	79.5 (52)	79.8 (41)	83.4 (33)	82.7 (25)
2024	58.1 (68)	63.6 (55)	73.3 (48)	79.3 (39)	80.6 (30)	83.4 (23)	91.2 (5)	76.6 (1)		

4.5.2. Landfall point and time forecast errors

There has been an improvement in landfall point forecast accuracy at the rate of 12.6 km/year (126 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 6.2 km/year (62 km in 10 years) since 2003.

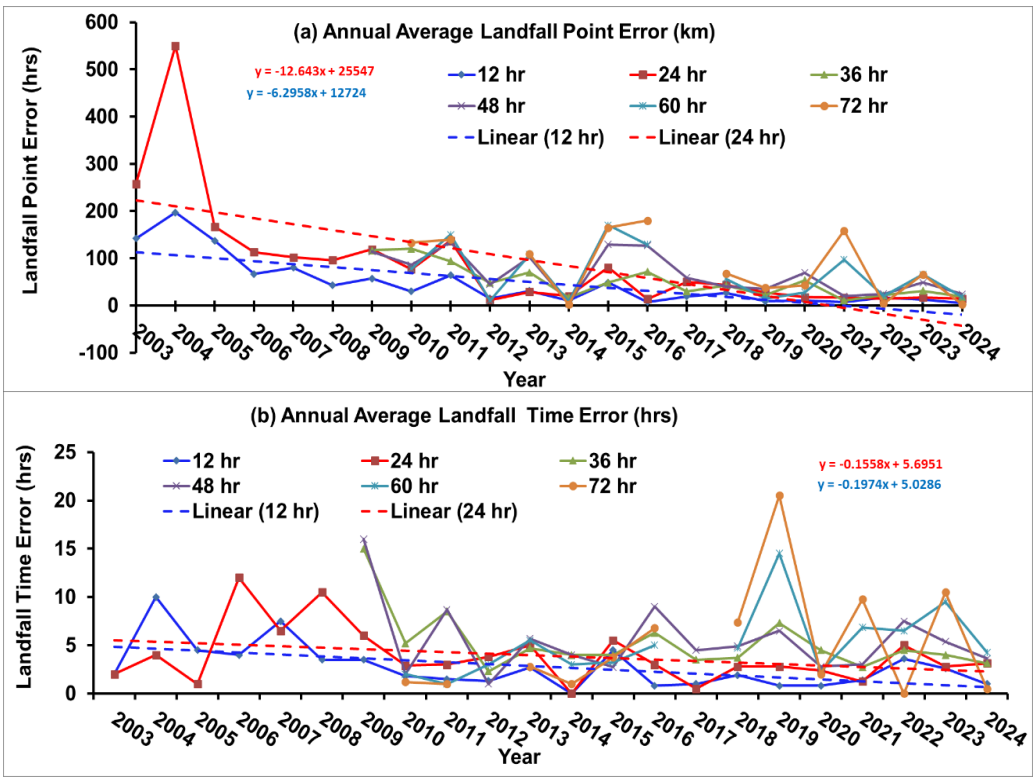


Fig. 4.5.2 Annual average (a) Landfall Point errors (b) Landfall Time errors

Considering the landfall time errors, there has been an improvement at the rate of 0.16 hrs/year (1.6 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 0.20 hrs/year (2.0 hrs in 10 years) for 12 hrs lead period since 2003**.**

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)	
2021	6.8 (4)	16.4 (4)	10.6 (4)	19.8 (4)	97 (3)	158.5 (2)				
2022	16.5 (4)	14.8 (4)	21.7 (2)	24.5 (2)	20.2 (2)	4.5 (1)	4.9 (1)			
2023	13.0 (6)	17.0 (6)	31.2 (6)	48.8 (5)	65.8 (5)	65.7 (5)	66.6 (4)	71.1 (4)	9.1 (1)	
2024	5.4(4)	14.4(4)	19(4)	24(4)	18(4)	2.2(1)	1.1(1)	1.1(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 (4)	5 (4)	4.7 (4)	5.7 (4)	5.5 (4)	2.8 (3)				
2014	0 (1)	0 (1)	4 (1)	4 (1)	3 (1)	1 (1)				
2015	4.5 (3)	5.5 (3)	4 (3)	2.75 (2)	3.25 (2)	3.7 (1)	6.5 (1)	8.5 (1)	7.5 (1)	4.5 (1)
2016	0.8 (2)	3 (2)	6.3 (2)	9 (2)	5 (2)	6.8 (2)	3.5 (1)	2.5 (1)	5 (1)	
2017	1 (2)	0.5 (2)	3.5 (2)	4.5 (2)						
2018	1.9 (8)	2.8 (7)	3.7 (7)	4.9 (5)	4.7 (5)	7.4 (3)	6.4 (3)	15.5 (1)	14.5 (1)	
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)	
2021	1.4 (4)	1.3 (4)	2.75 (4)	3 (4)	6.8 (3)	9.75 (2)				
2022	3.6 (4)	5 (4)	4.5 (2)	7.5 (2)	6.5 (2)	0 (1)	0 (1)			
2023	2.6 (6)	2.8 (6)	4 (6)	5.4 (5)	9.5 (5)	10.5 (5)	9.8 (4)	10.6 (4)	9.5 (1)	
2024	1 (4)	3.1 (4)	3.1 (4)	3.6 (4)	4.3 (4)	0.5 (1)	2.5 (1)	2.5 (1)		

4.5.3 Inter-annual variation of intensity forecast error and skill

Inter-annual variation of intensity forecast errors and skill in intensity forecast since 2005 are presented in Fig. 4.5.3 (a&b) and 4.5.4 (a&b) and Tables 4.5.3 (a&b). As regards improvement in intensity forecast based on AE, there has been decrease in errors at the rate of 0.5 knots/year (5.0 knots in 10 years) for 24 hrs lead period and increase in skill at the rate of 2.3% per year (23% in 10 years) since 2005. Similarly, for 12 hrs lead period, there has been decrease in intensity forecast errors at the rate of 0.3 knots/year (3.0 knots in 10 years) and increase in skill at the rate of 2.1% per year (21% in 10 years) since 2003. As regards improvement in intensity forecast errors based on RMSE, there has been decrease in errors at the rate of 0.57 knots/year (5.7 knots in 10 years) for 24 hrs lead period and increase in skill at the rate of 2.4% per year (24% in 10 years) since 2005. Similarly, for 12 hrs lead period, there has been decrease in intensity forecast errors at the rate of 0.37 knots/year (3.7 knots in 10 years) and increase in skill at the rate of 2.3% per year (23% in 10 years) since 2003.

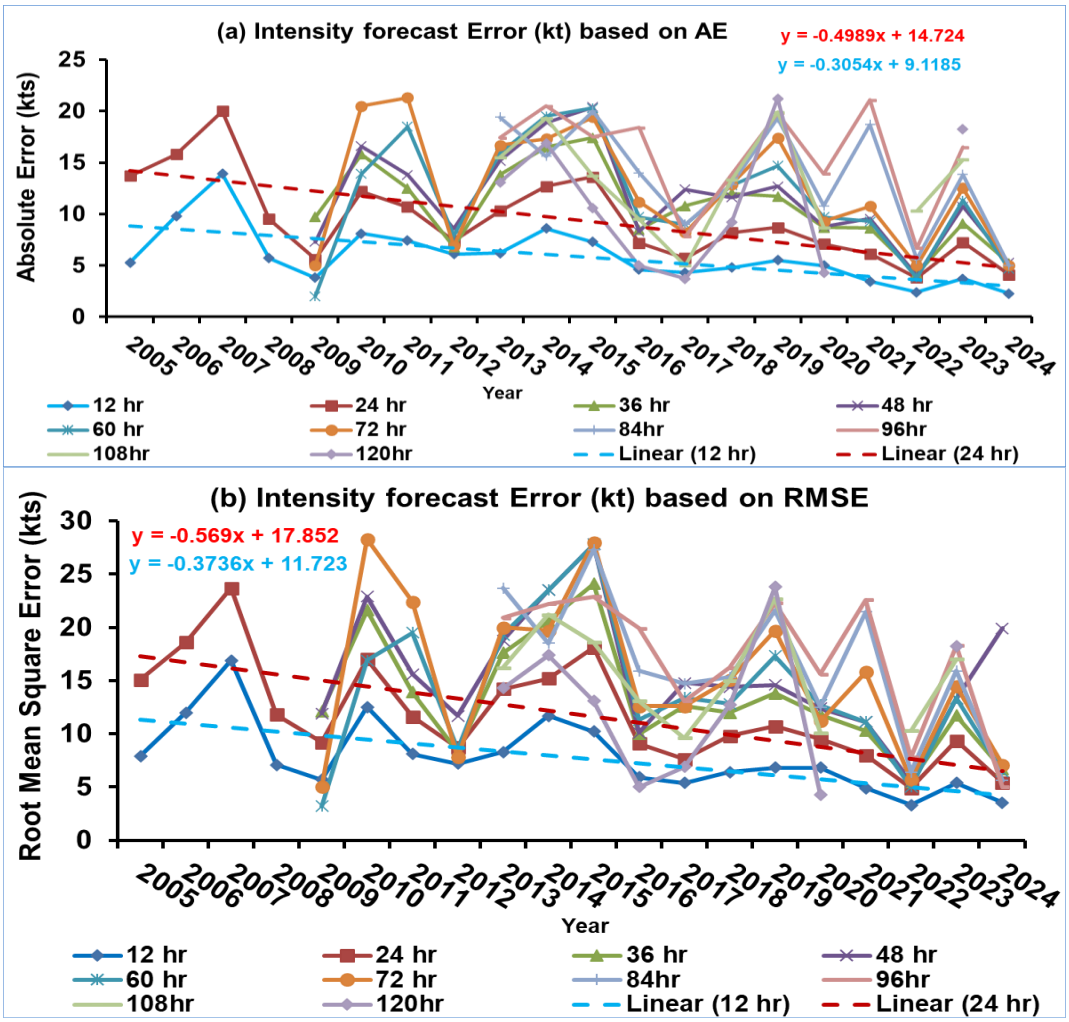


Fig. 4.5.3 Annual average intensity forecast (kt) errors based on (a) AE (b) RMSE

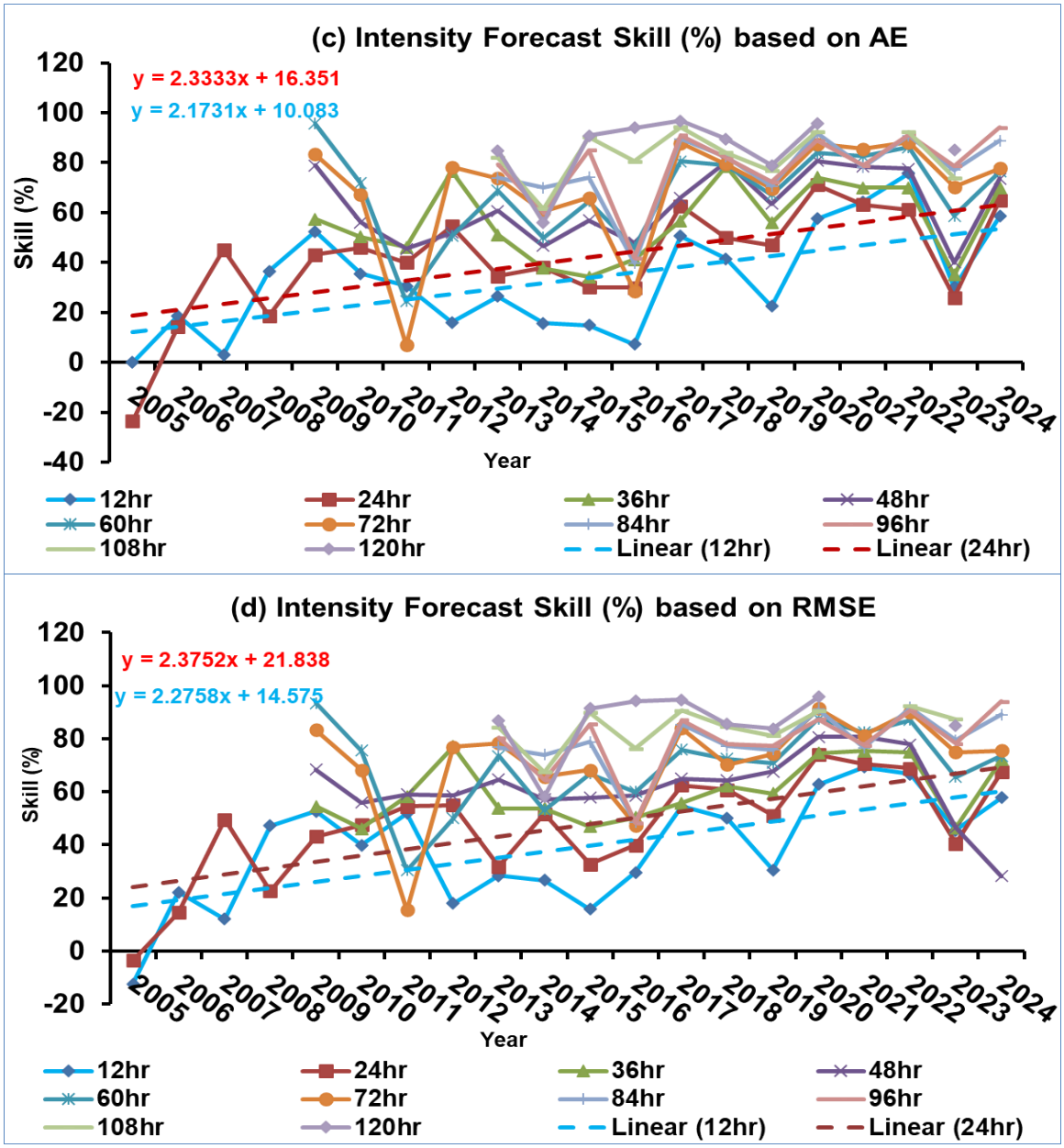


Fig. 4.5.4 Annual average intensity forecast skill (%) based on (a) AE (b) RMSE

Table 4.5.3: (a) Annual average Intensity forecast errors based on AE (Values 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)
2021	3.5 (68)	6.2 (56)	8.6 (50)	9.5 (41)	9.3 (32)	10.8 (15)	18.8 (9)	21 (4)		
2022	2.4 (75)	3.8 (61)	4.2 (51)	4 (39)	3.8 (24)	5 (12)	5.6 (8)	6.7 (4)	10.3 (2)	
2023	3.7 (125)	7.3 (109)	9.1 (97)	10.7 (85)	11.3 (73)	12.5 (63)	13.9 (52)	16.5 (41)	15.3 (33)	18.3 (25)
2024	2.3 (68)	4.1 (55)	5.2 (48)	5.3 (39)	4.7 (30)	5 (24)	5 (5)	5 (1)		

Table 4.5.3 (b): Annual average Intensity forecast errors based on RMSE (Values 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)	
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)	
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)	
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)	
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)	
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)	
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)	
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)	
2021	4.9 (68)	8 (56)	10.3 (50)	11.1 (41)	11.1 (31)	15.8 (15)	21.5 (9)	22.6 (4)		
2022	3.3 (75)	4.9 (61)	5.5 (51)	5.5 (39)	5 (24)	5.7 (12)	6.4 (8)	7.8 (4)	10.3 (2)	
2023	5.4 (125)	9.3 (109)	11.7 (97)	13.3 (85)	13.4 (73)	14.5 (63)	15.9 (52)	18.3 (41)	17 (33)	
2024	3.5 (68)	5.4 (55)	6.7 (48)	19.9 (39)	6.5 (30)	7.1 (23)	5.6 (5)	5 (1)		

Table 4.5.3 (c) Annual average Intensity forecast skill based on AE (Values 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										
2006	19 (25)	14 (19)								
2007	3 (27)	45 (20)								
2008	37 (23)	19 (18)								
2009	52 (33)	43 (26)	57 (18)	79 (11)	96 (5)	83 (1)				
2010	36 (55)	46 (49)	50 (37)	56 (29)	72 (23)	67 (19)				
2011	31 (21)	40 (19)	46 (17)	45 (14)	24 (10)	7 (7)				
2012	16 (16)	55 (13)	77 (10)	52 (7)	51 (5)	78 (3)				
2013	26 (94)	35 (84)	51 (73)	61 (63)	69 (54)	74 (42)	74 (34)	79 (26)	82 (18)	85 (11)
2014	16 (49)	38 (44)	38 (38)	47 (32)	50 (25)	60 (20)	70 (14)	60 (10)	61 (6)	56 (3)
2015	15 (66)	30 (60)	34 (52)	57 (43)	64 (37)	66 (30)	74 (22)	85 (17)	90 (12)	91 (8)
2016	7 (58)	30 (50)	41 (42)	48 (34)	46 (27)	29 (21)	40 (15)	42 (9)	81 (4)	94 (2)
2017	51 (35)	63 (29)	57 (23)	66 (18)	81 (14)	88 (12)	90 (10)	91 (8)	94 (3)	97 (3)
2018	41 (127)	50 (112)	78 (98)	80 (81)	79 (63)	79 (51)	82 (34)	82 (24)	84 (16)	89 (7)
2019	23 (168)	47 (150)	56 (136)	64 (123)	67 (109)	70 (89)	71 (66)	72 (55)	77 (46)	79 (33)
2020	58 (62)	71 (51)	74 (44)	81 (36)	84 (27)	88 (21)	92 (7)	89 (5)	92 (3)	96 (1)
2021	64 (68)	63 (56)	70 (50)	78 (41)	82 (32)	86 (15)	78 (9)	79 (4)		
2022	76 (75)	61 (61)	70 (51)	78 (39)	86 (24)	88 (12)	91 (8)	91 (4)	92 (2)	
2023	30 (125)	26 (109)	35 (97)	40 (85)	59 (73)	70 (63)	77 (52)	79 (41)	74 (33)	85 (25)
2024	59 (68)	65 (55)	70 (48)	74 (39)	76 (30)	78 (24)	89 (5)	94 (1)		

Table 4.5.3 (d) Annual average Intensity skill based on RMSE (Values 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 (31)	-4 (23)								
2006	22 (25)	15 (19)								
2007	12 (27)	50 (20)								
2008	47 (23)	23 (18)								
2009	53 (33)	43 (26)	55 (18)	68 (11)	93 (5)	83 (1)				
2010	40 (55)	48 (49)	46 (37)	56 (29)	76 (23)	68 (19)				
2011	52 (21)	55 (19)	58 (17)	59 (14)	30 (10)	15 (7)				
2012	18 (16)	55 (13)	77 (10)	59 (7)	50 (5)	77 (3)				
2013	28 (94)	32 (84)	54 (73)	65 (63)	74 (54)	78 (42)	77 (34)	80 (26)	84 (18)	87 (11)
2014	27 (49)	52 (44)	54 (38)	57 (32)	53 (25)	66 (20)	74 (14)	64 (10)	67 (6)	58 (3)
2015	16 (66)	33 (60)	47 (52)	58 (43)	67 (37)	68 (30)	79 (22)	86 (17)	90 (12)	91 (8)
2016	30 (58)	40 (50)	50 (42)	59 (34)	60 (27)	47 (21)	49 (15)	48 (9)	76 (4)	94 (2)
2017	55 (35)	62 (29)	56 (23)	65 (18)	76 (14)	84 (12)	85 (10)	87 (8)	91 (3)	95 (3)
2018	50 (127)	61 (112)	62 (98)	64 (81)	72 (63)	70 (51)	77 (34)	78 (24)	85 (16)	86 (7)
2019	31 (168)	51 (150)	59 (136)	68 (123)	71 (109)	74 (89)	76 (66)	77 (55)	81 (46)	84 (33)
2020	63 (62)	74 (51)	75 (44)	81 (36)	88 (27)	91 (21)	91 (7)	87 (5)	90 (3)	96 (1)
2021	69 (68)	71 (56)	75 (50)	81 (41)	82 (31)	81 (15)	77 (9)	78 (4)		
2022	67 (75)	69 (61)	75 (51)	78 (39)	87 (24)	90 (12)	92 (8)	91 (4)	92 (2)	
2023	46 (125)	41 (109)	47 (97)	46 (85)	66 (73)	75 (63)	79 (52)	78 (41)	87 (33)	85 (25)
2024	58 (68)	67 (55)	72 (48)	28 (39)	73 (30)	76 (23)	89 (5)	94 (1)		

4.6 Comparative analysis of forecast accuracy in recent five years (2020-24) as compared to previous five years (2015-19)

4.6.1 . Landfall Forecast Error

Comparative analysis of landfall point error (LPE) and landfall time error (LTE) during 2020-24 vis-à-vis 2015-19 is presented in Fig. 4.6.1 (a & b). The LPE for 24, 48 and 72 hrs lead period during 2020-24 were 16.2 km, 39.3 km and 69.5 km against 44.7 km, 69.4 km and 109.3 km respectively during 2015-19 which shows an improvement of 64%, 43% and 36% respectively. The LTEs for 24, 48 and 72 hrs lead period during 2020-24 were 2.9hrs, 4.2hrs & 7.5hrs against 3.0hrs, 5.4hrs & 8.6hrs respectively during 2015-19 registering an improvement of 4.8% and 22.2% for 24 and 48 hours lead period respectively.

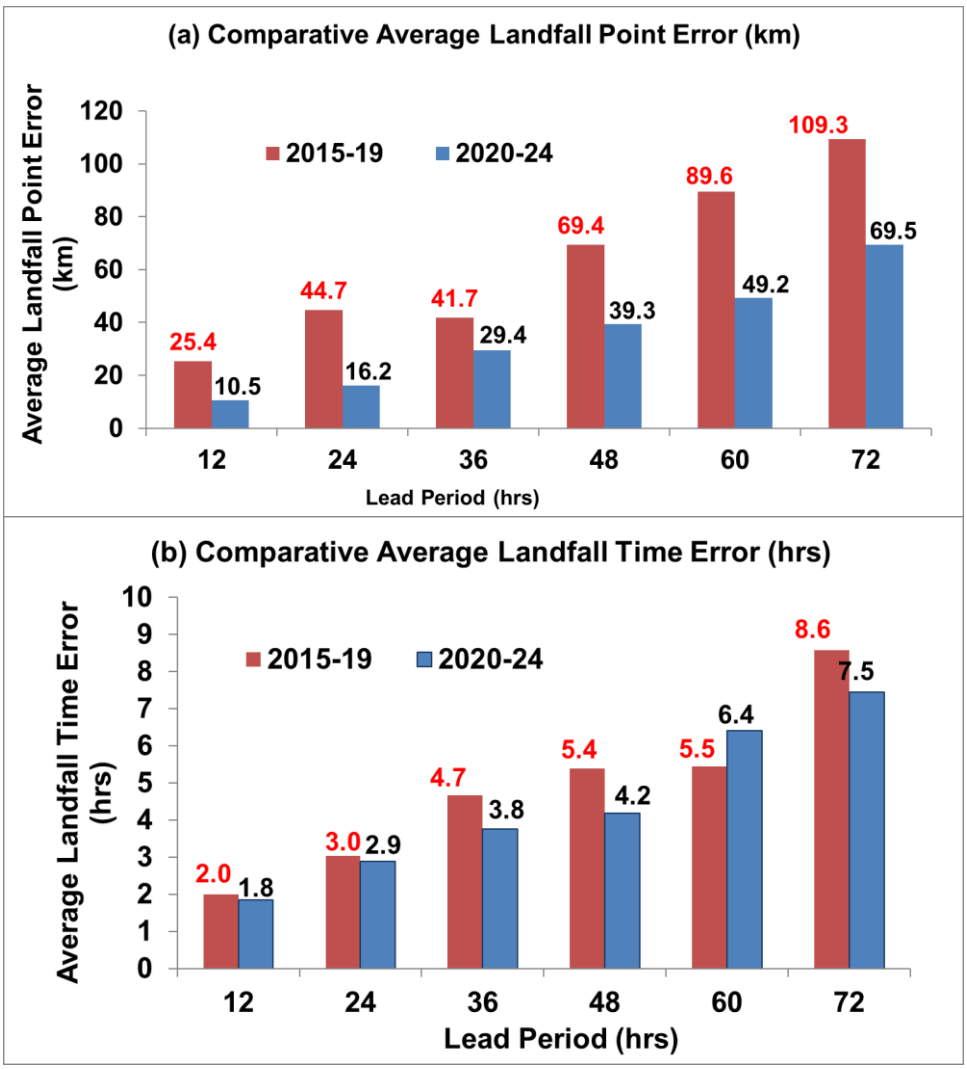


Fig. 4.6.1: Comparative average landfall (a) point and (b) time forecast errors during 2020-24 vis-à-Vis 2015-19

4.6.2 Track forecast error and skill

The comparative analysis of average track forecast error and skill during 2020-24 and 2015-19 is presented in Fig.4.6.2. The average track forecast errors during 2020-24 were 72 km, 111 km & 154 km against 81 km, 126 km & 171 km during 2015-19 for 24, 48 and 72 hrs lead period respectively. There has been an improvement of 11%, 12% & 10% in track forecast errors for 24, 48 and 72 hours lead period during 2020-24 with respect to 2014-2018. The 24, 48 and 72 hr average track forecast skill during 2020-24 were 65%, 74% and 77% against 61%, 73% and 74% respectively during 2015-19 with an improvement of 5%, 2% and 3% for 24, 48 and 72 hours lead period.

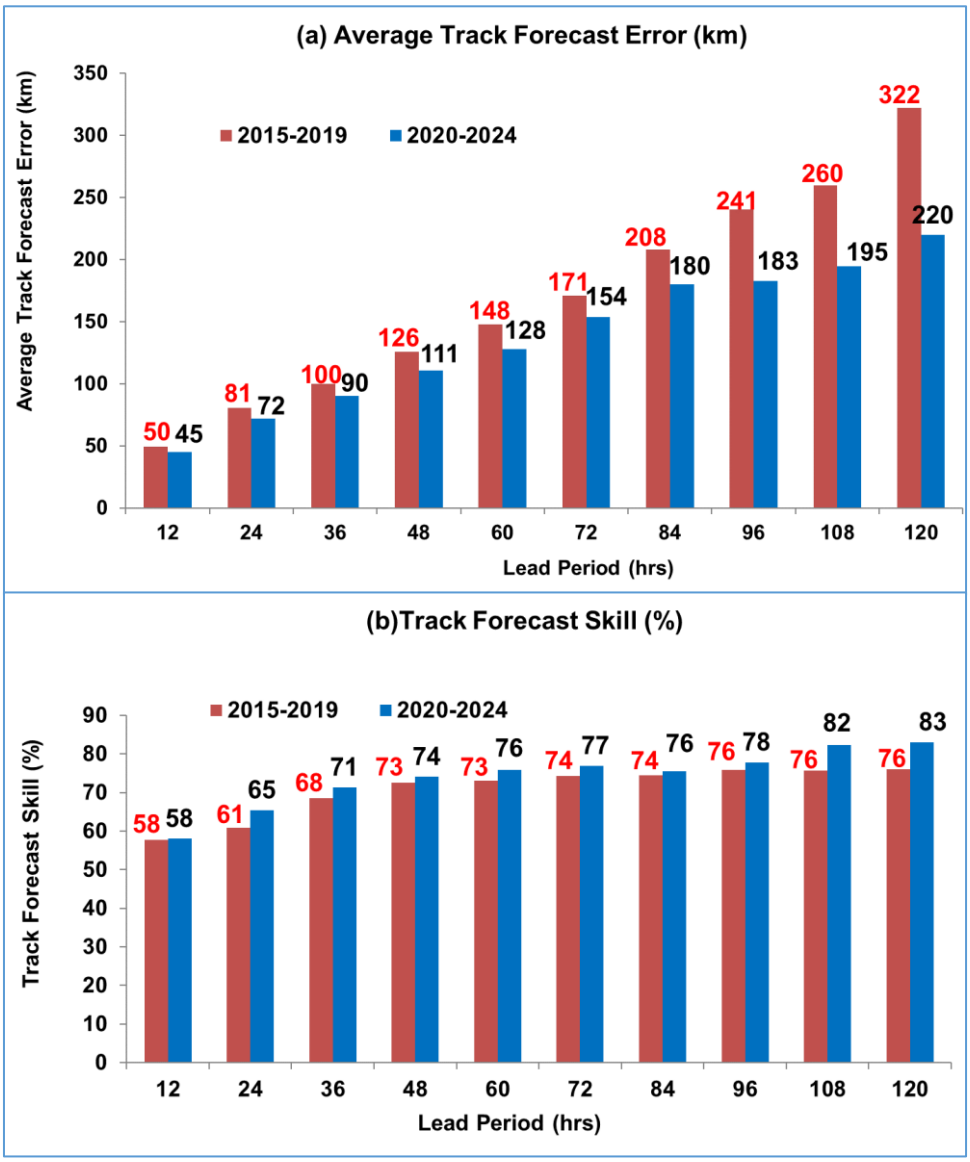


Fig. 4.6.2: Comparative Average track forecast (a) error and (b) skill during 2020-24 Vis-à-Vis 2015-19

4.6.3 Intensity forecast error and skill

The comparative analysis of average intensity forecast error and skill based on AE and RMSE during 2020-24 and 2015-19 are presented in Fig.4.6.3 and 4.6.4 respectively. The average intensity forecast error based on AE for 24hrs, 48hrs and 72hrs are 5.9 knots, 8.3 knots and 9.8 knots during 2020-24 against 8.9 knots, 13.0 knots and 15.4 knots during 2015-19. Based on RMSE the intensity forecast errors were 7.9 knots, 13.3 knots and 12.6 knots during 2020-24 against 11.5 knots, 16.7 knots, and 19.2 knots during 2015-19. It can be seen that there has been marginal improvement in intensity forecast during recent five years (2020-24) as compared to previous five years (2015-19).

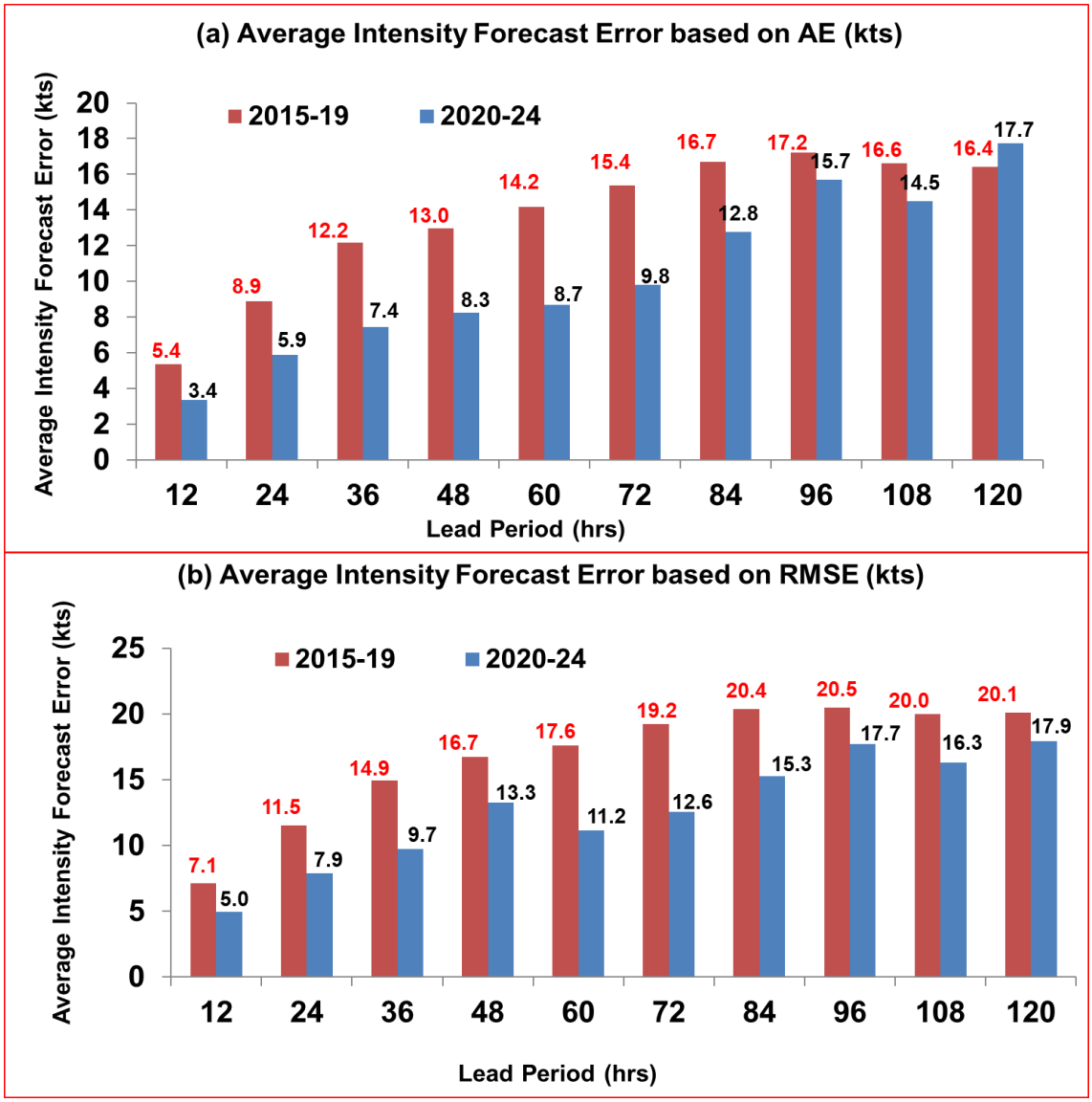


Fig. 4.6.3: Comparative Average Intensity forecast errors (kts) based on (a) absolute error and (b) root mean square errors during 2020-24 vis-à-vis 2015-19

The average intensity forecast skill based on AE for 24hrs, 48hrs and 72hrs are 45%, 69% and 79% during 2020-24 against 45%, 69% and 72% during 2015-19. Based on RMSE the intensity forecast skill were 60%, 71% and 79.0% during 2020-24 against 49%, 63% and 72% during 2015-19. It can be seen that there has been marginal improvement in intensity forecast during recent five years (2020-24) as compared to previous five years (2015-19).

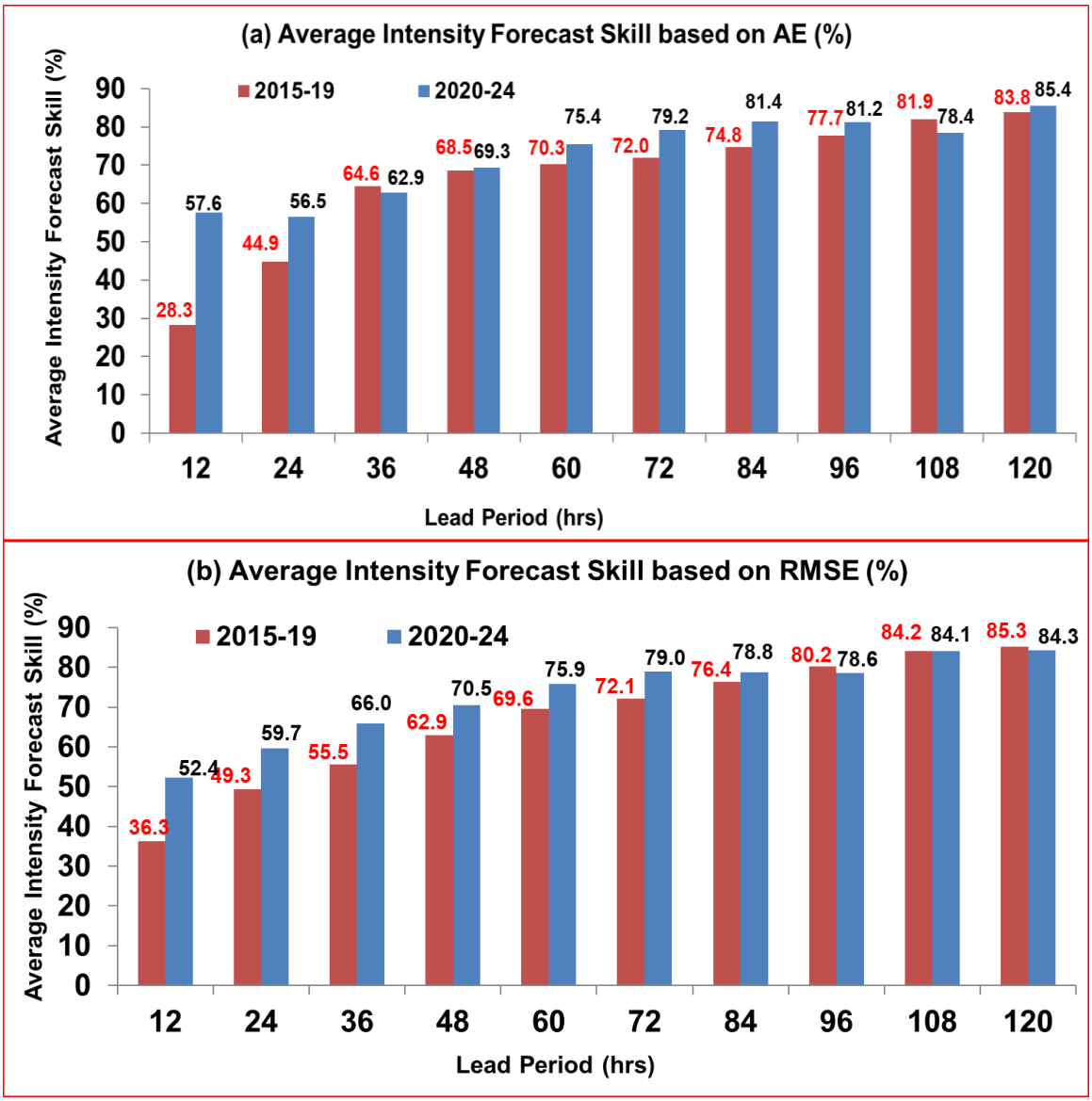
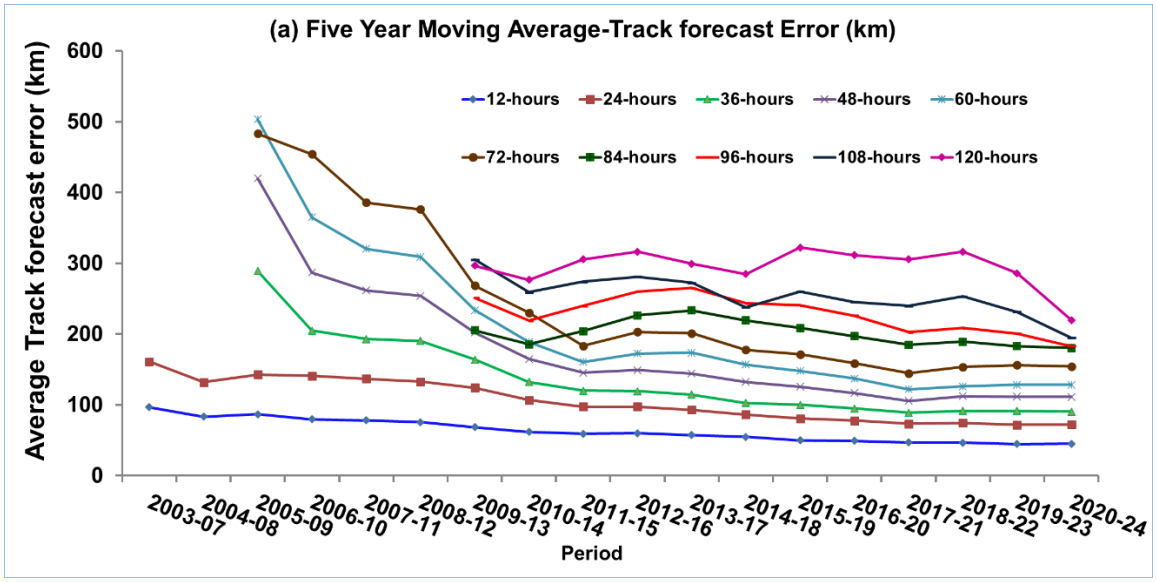


Fig. 4.6.4: Comparative Average Intensity forecast skill (%) based on (a) absolute error and (b) root mean square errors during 2020-24 vis-à-vis 2015-19

4.7 Five Year Moving Average errors and skill over north Indian Ocean

It can be seen from Fig.4.7.1-4.7.4 that there has been continuous improvement in forecast accuracy with decrease in landfall and track forecast errors and increase in skill over the years. Due to modernization programme of IMD and other initiatives of MoES, the improvement has been more significant since 2009. However, the rate of improvement in intensity forecast over the years has been marginal as can be seen from Fig.4.7.3. The 36-72

hours forecasts commenced from 2009 and it was further extended to 120 hrs from 2013 onwards.



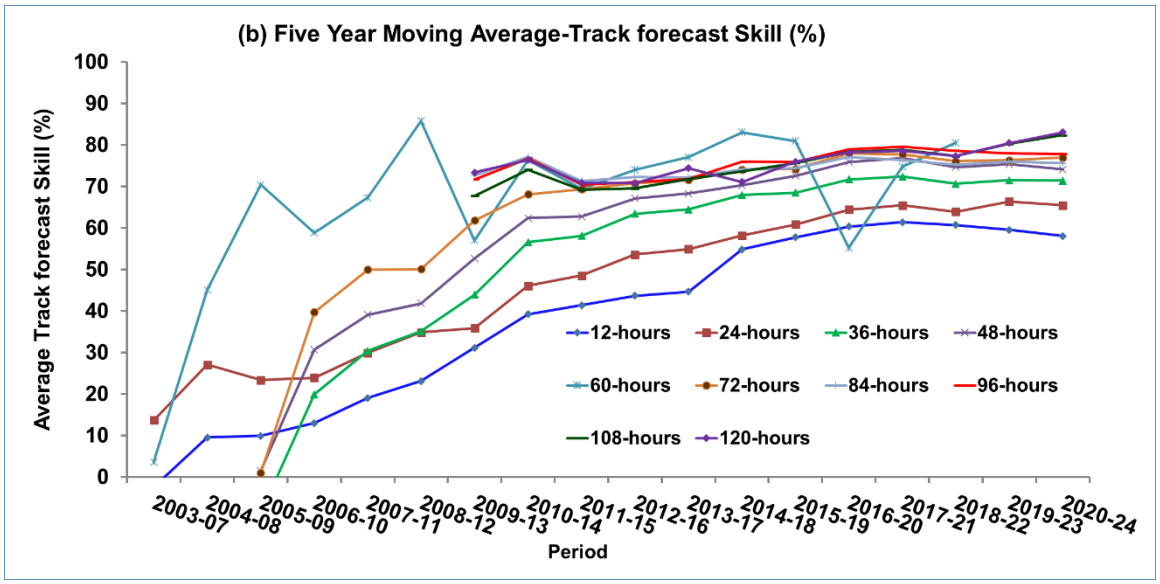


Fig. 4.7.1: (a) Five Year Moving Average Track Forecast Error (km) of RSMC, New Delhi over North Indian OceanFig. 4.7.1: (b) Five Year Moving Average Track Forecast Skill (%) of RSMC, New Delhi over North Indian Ocean

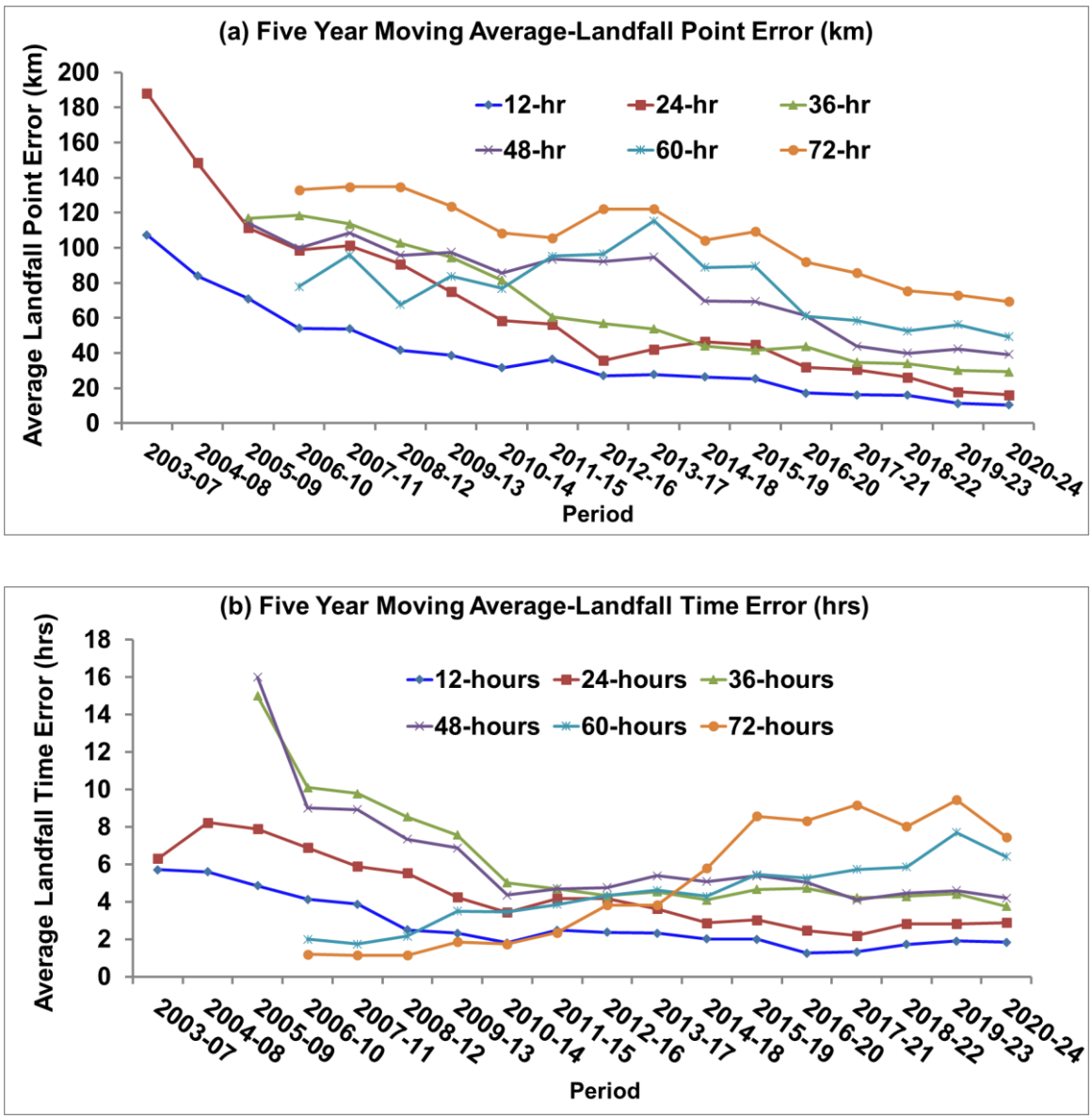
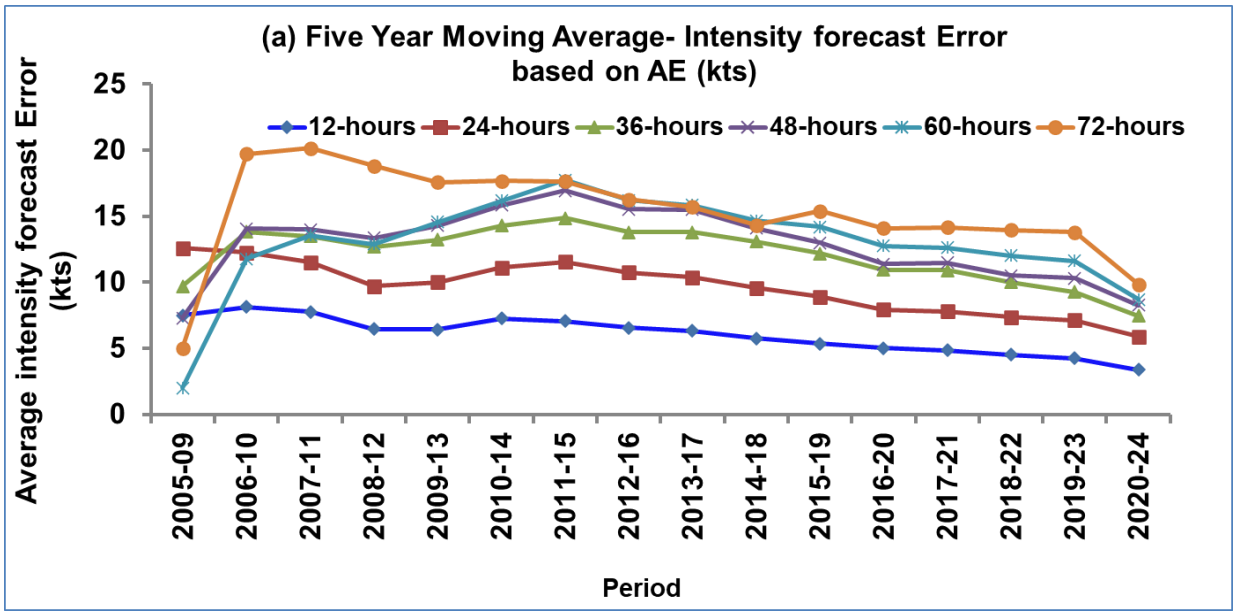


Fig. 4.7.2: Five Year Moving Average Errors in (a) Landfall Point (km) and (b) Landfall Time (hrs) of RSMC, New Delhi over north Indian Ocean.



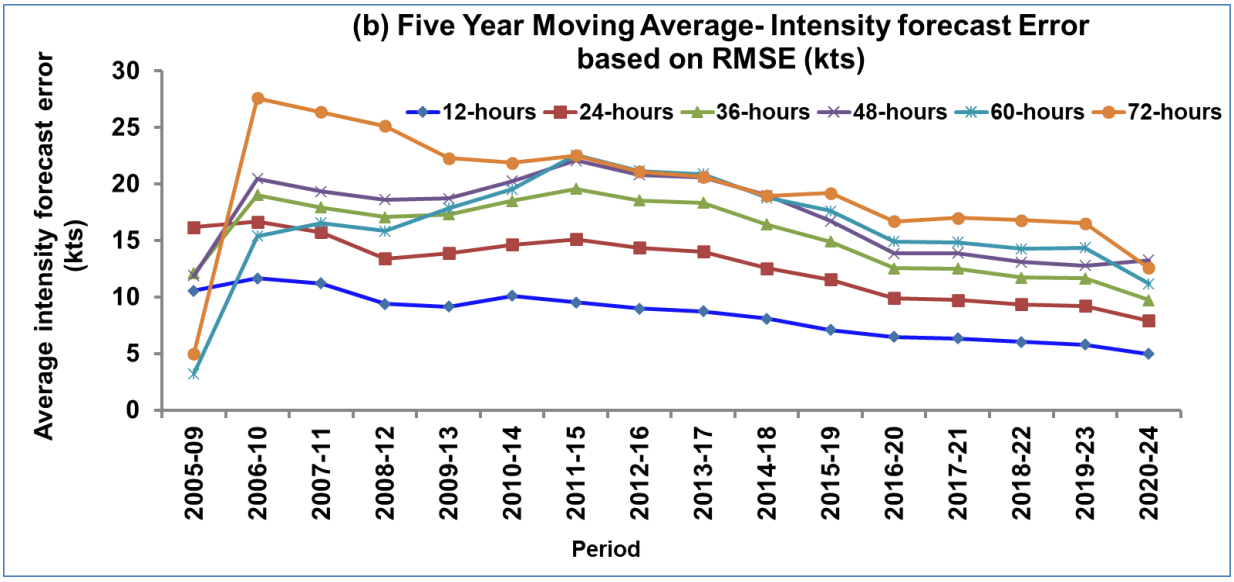
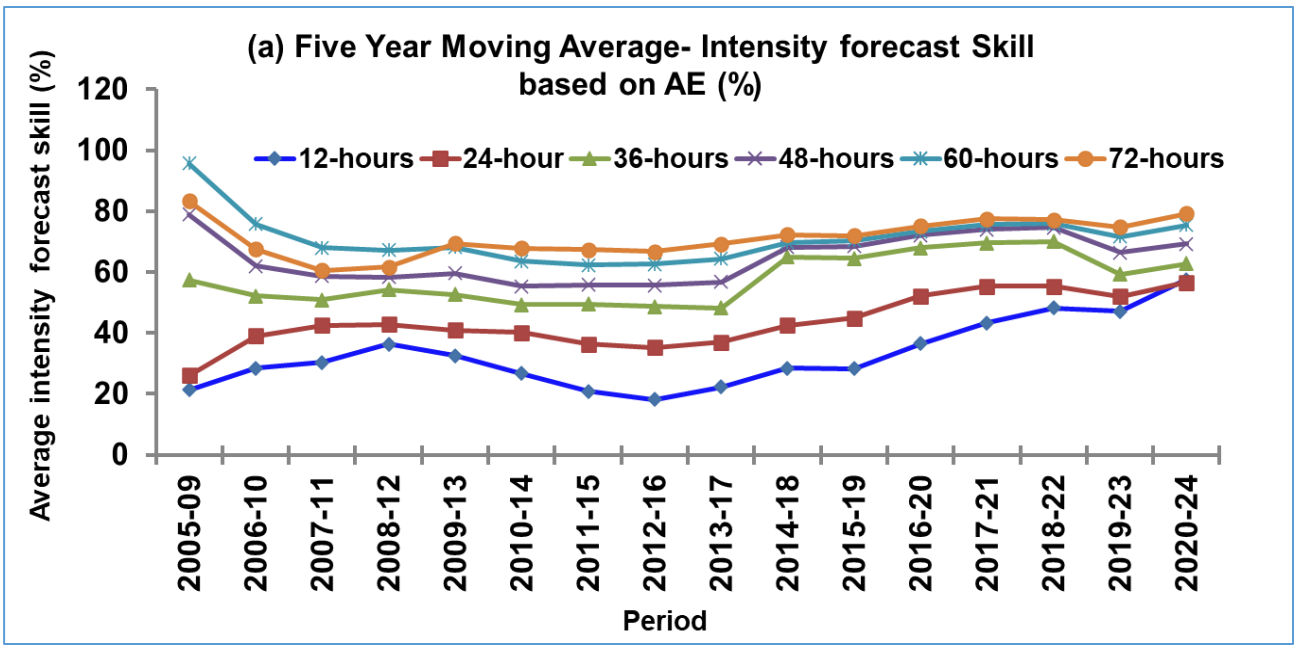


Fig. 4.7.3: Five Years Moving Average Intensity Forecast (a) Absolute Error (kts) and (b) Root Mean Square Error (kts) of RSMC, New Delhi over the NIO



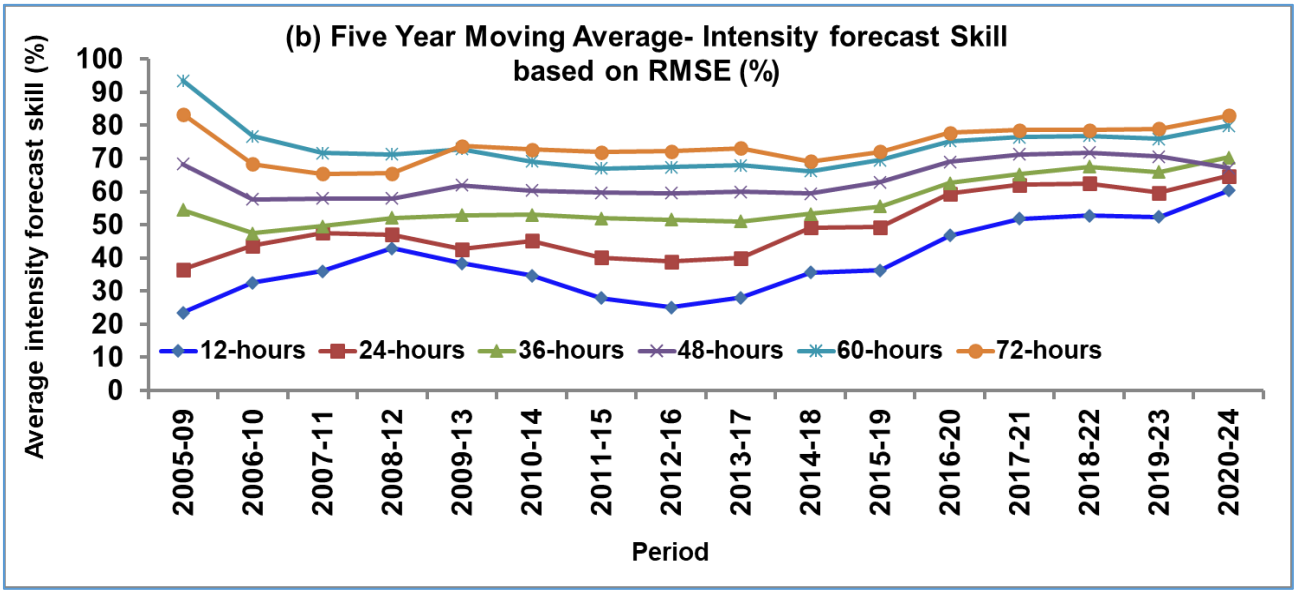


Fig. 4.7.4: Five Year Moving Average Intensity Forecast skill based on (a) AE and (b) RMSE of RSMC, New Delhi over North Indian Ocean

Table 4.7.1: Homogeneous comparison of official landfall forecast errors over north Indian Ocean in 2024 with averages during 2019-23 and 2014-23.

Parameter	Forecast Period (hr)					
	12	24	36	48	60	72
2024						
2024 Mean OFCL Landfall Point Error (km)	5.4	14.4	19.0	24.0	18.0	2.2
2024 Mean OFCL Landfall Time Error (hr)	1.0	3.1	3.1	3.6	4.3	0.5
2024 No. of cases	4	4	4	4	4	1
2019-23						
Mean OFCL Landfall Point Error (km)	11.3	18.0	30.3	42.4	56.2	73.0
Mean OFCL Landfall Time Error (hr)	1.9	2.8	4.4	4.6	7.7	9.5
No. of cases	22	22	20	17	13	10
2014-23						
Mean OFCL Landfall Point Error (km)	17.7	29.6	36.2	53.7	70.4	85.9
Mean OFCL Landfall Time Error (hr)	2.0	2.8	4.3	4.8	6.2	7.9
No. of cases	38	37	35	29	23	17
Relative Error						
2024 OFCL Landfall Point Error relative to 2019-23 mean (%)	52.1	19.9	37.4	43.4	68.0	97.0
2024 OFCL Landfall Time Error relative to 2019-23 mean (%)	47.5	-10.5	29.3	21.1	44.8	94.7
2024 OFCL Landfall Point Error relative to 2014-23 mean (%)	69.4	51.3	47.5	55.3	74.5	97.4
2024 OFCL Landfall Time Error relative to 2014-23 mean (%)	48.8	-9.8	27.0	24.4	31.7	93.7

The landfall forecast was issued upto 24 hrs from 2003 to 2008, upto 72 hrs from 2009 to 2012 and 120 hrs from 2013 onwards, OFCL: Official (+ve represents improvement & -ve represents deterioration).

Table 4.7.2 Homogeneous comparison of OFCL & CLIPER Track Forecast Errors over NIO in 2024 with Averages for 2019-23 and 2014-23

Parameter	Forecast Period (hr)									
	12	**24**	**36**	**48**	**60**	**72**	**84**	**96**	**108**	**120**
2024										
2024 Mean OFCL Forecast Error (km)	38	66	77	84	100	114	70	153		
2024 Mean CLIPER Error (km)	90	180	287	403	516	688	797	654		
2024 Mean OFCL Skill wrt CLIPER (%)	58	64	73	79	81	83	91	77		
2024 No. of cases	68	55	48	39	30	23	5	1		
2019-2023										
2019-23 Mean OFCL Forecast Error (km)	45	72	91	112	128	156	183	201	231	286
2019-23 Mean CLIPER Error (km)	110	213	320	452	529	659	762	911	1172	1463
2019-23 Mean OFCL Skill wrt CLIPER (%)	60	66	72	75	76	76	76	78	80	80
2019-23 No. of cases	498	427	378	320	265	201	142	109	84	59
2014-2023										
2014-23 Mean OFCL Forecast Error (km)	49	78	96	120	139	165	197	217	233	285
2014-23 Mean CLIPER Error (km)	113	217	334	467	579	709	827	1082	1130	1329
2014-23 Mean OFCL Skill wrt CLIPER (%)	57	64	71	74	76	77	76	80	79	79
2014-23 No. of cases	833	721	630	527	431	335	237	177	125	82
Relative Error										
2024 relative to 2019-23 mean (%)	16	8	16	25	22	27	62	24		
2024 CLIPER error relative to 2019-23 mean (%)	18	16	10	11	2	-4	-5	28		
2024 Skill relative to 2019-23 mean (%)	-3	-3	1	5	7	9	20	-1		
2024 relative to 2014-23 mean (%)	23	15	20	30	28	31	65	30		
2024 CLIPER error relative to 2014-23 mean (%)	21	17	14	14	11	3	4	40		
2024 Skill relative to 2014-23 mean (%)	2	0	3	7	7	8	20	-4		

The track forecast was issued upto 24 hrs from 2003 to 2008, upto 72 hrs from 2009 to 2012 and 120 hrs from 2013 onwards, OFCL: Official (+ve represents improvement & -ve represents deterioration).

Table 4.7.3 Homogeneous comparison of OFCL & Persistence Intensity Forecast Errors based on Absolute Error over NIO in 2024 with Averages for 2019-23 and 2014-23

Parameter	Forecast Period (hr)									
	12	**24**	**36**	**48**	**60**	**72**	**84**	**96**	**108**	**120**
2024										
2024 Mean OFCL Forecast Error (kts)	2.3	4.1	5.2	5.3	4.7	5.0	5.0	5.0		
2024 Mean Persistence Error (kts)	5.5	16.7	17	19.9	19.8	22.4	45.0	85.0		
2024 Mean OFCL Skill wrt Persistence (%)	59	75	70	74	76	78	89	94		
2024 No. of cases	68	55	48	39	76	24	5	94		
2019-2023										
2019-23 Mean OFCL Forecast Error (kts)	4.2	7.1	9.3	10.3	11.6	13.8	16.1	17.9	17.5	19.7
2019-23 Mean Persistence Error (kts)	8.0	14.8	22.7	30.7	40.9	54.7	68.2	77.5	77.3	109.8
2019-23 Mean OFCL Skill wrt Persistence (%)	47.1	52.0	59.2	66.5	71.6	74.8	76.4	77.0	77.4	82.1
2019-23 No. of cases	498	427	378	324	265	200	142	109	84	59
2014-2023										
2014-23 Mean OFCL Forecast Error (kts)	4.9	8.1	10.8	11.8	12.8	14.0	15.5	17.0	16.1	16.8
2014-23 Mean Persistence Error (kts)	8.0	15.5	28.6	36.0	43.9	53.5	66.6	77.6	79.2	105.4
2014-23 Mean OFCL Skill wrt Persistence (%)	39.6	47.8	62.3	67.3	70.8	73.8	76.7	78.1	79.7	84.0
2014-23 No. of cases	833	722	631	532	431	334	237	177	125	82
Relative Error										
2024 OFCL error relative to 2019-23 mean (%)	46.3	42.3	43.8	49.0	59.8	63.7	68.9	72.0		
2024 Persistence error relative to 2019-23 mean (%)	31.3	-12.9	23.9	35.2	51.6	59.0	34.0	-9.7		
2024 Relative Skill wrt 2019-23	24.4	45.2	18.0	10.7	6.7	3.8	16.3	22.3		
2024 OFCL error relative to 2014-23 mean (%)	53.0	49.4	51.8	55.4	63.5	64.3	67.8	70.6		
2024 Persistence error relative to 2014-23 (%)	31.5	-7.4	39.6	44.7	54.9	58.1	32.5	-9.5		
2024 Relative Skill wrt 2014-23	48.0	57.7	12.3	9.4	7.9	5.2	15.9	20.5		

The intensity forecast was issued upto 24 hrs during 2003 to 2008, 72 hrs during 2009-12 and 120 hrs from 2013 onwards, OFCL: Official (+ve represents improvement & -ve represents deterioration).

Table 4.7.4 Homogeneous comparison of OFCL & Persistence Intensity Forecast Errors based on Root Mean Square Error over NIO in 2024 with Averages for 2019-23 and 2014-23

Parameter	Forecast Period (hr)									
	12	**24**	**36**	**48**	**60**	**72**	**84**	**96**	**108**	**120**
2024										
2024 Mean OFCL Forecast Error (km)	3.5	5.4	6.7	19.9	6.5	7.1	5.6	5.0		
2024 Mean Persistence Error (km)	8.4	16.7	24	27.7	24.3	29.1	51.7	85.0		
2024 Mean OFCL Skill wrt Persistence (%)	58	67	72	28	73	76	89	94		
2024 No. of cases	68	55	48	39	73	23	5	94		
2019-2023										
2019-23 Mean OFCL Forecast Error (km)	5.8	9.2	11.6	12.8	14.4	16.5	18.7	20.2	20.0	21.4
2019-23 Mean Persistence Error (km)	12.2	22.9	34.2	43.4	59.6	78.7	88.0	94.5	126.1	136.0
2019-23 Mean OFCL Skill wrt Persistence (%)	52.4	59.7	66.0	70.5	75.9	79.0	78.8	78.6	84.1	84.3
2019-23 No. of cases	498	427	378	324	264	200	142	109	84	59
2014-2023										
2014-23 Mean OFCL Forecast Error (km)	6.8	10.7	13.8	15.8	16.2	17.5	18.9	19.8	19.0	19.3
2014-23 Mean Persistence Error (km)	12.3	23.6	34.6	45.7	61.6	72.3	85.6	97.6	126.2	129.7
2014-23 Mean OFCL Skill wrt Persistence (%)	44.8	54.7	60.2	65.3	73.7	75.7	77.9	79.7	84.9	85.1
2014-23 No. of cases	833	722	631	510	430	334	237	177	125	82
Relative Error										
2024 OFCL error relative to 2019-23 mean (%)	38.9	49.2	51.7	-25.6	60.2	59.5	70.4	74.8		
2024 Persistence error relative to 2019-23 mean (%)	30.9	29.3	31.2	39.4	60.5	59.7	39.6	12.9		
2024 Relative Skill wrt 20116-20	10.5	13.1	9.2	-60.1	-3.2	-4.3	13.2	19.7		
2024 OFCL error relative to 2014-23 mean (%)	47.9	89.0	87.1	177.9	89.3	88.1	92.0	93.3		
2024 Persistence error relative to 2014-23 mean (%)	31.8	29.3	31.2	39.4	60.5	59.7	39.6	12.9		
2024 Relative Skill wrt 2014-23	29.2	23.3	19.6	-56.9	-0.3	-0.2	14.4	18.1		

The intensity forecast was issued upto 24 hrs during 2003- 2008, 72 hrs during 2009-12 and 120 hrs from 2013 onwards OFCL: Official (+ve represents improvement & -ve represents deterioration)

CHAPTER-V

MAJOR INITIATIVES IN VARIOUS COMPONENTS OF EARLY WARNING SYSTEM FOR TROPICAL CYCLONES DURING 2024

1. Major initiatives during 2024

a. Forecasting and Warning Services:

(i) Introduction of probabilistic storm surge forecast experimentally during cyclone Remal

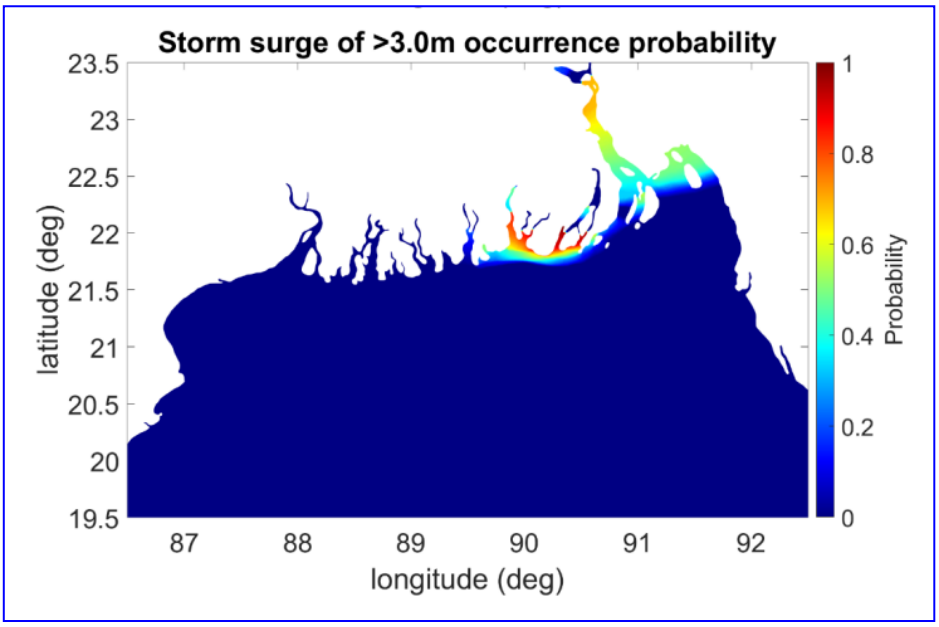


Fig. 5.1: Probabilistic Storm Surge during SCS REMAL

(ii) Extension of customized location specific forecast to Ports, Nuclear Power Corporation, Indian Air Force, Indian Coast Guard locations

TABLE 4: CYCLONIC DISTURBANCE FORECAST FOR PORTS BASED ON 2330 hrs IST of 25th May,2024														
SI	DESCRIPTION OF PORT NAME(LAT°N /LON°E)	LOCATION		CURRENT LOCATION FROM CENTRE OF CYCLONIC DISTURABANCE		FORECAST PARAMETERS WHEN THE CYCLONIC DISTURBANCE WOULD BE NEAREST TO THE PORT								
		LAT (°N)	LON (°E)	DISTANCE (KM)	DIRECTION	DATE/ TIME(IST) OF OCCURRENCE	DISTANCE OF CD FROM PORT	DIRECTION OF CD FROM PORT	MSW OVER PORT(KTS)	UNCERTAINTY IN DISTANCE (KM)	UNCERTAINTY IN MSW (KTS)	STORM SURGE	SIGNIFICANT WAVE HEIGHT (M)	STATE OF SEA
ACWC Kolkata														
12.	Port Blair (11.67,92.5)	19.3	89.4	912	NNW	25.05.24/2330	912	SSE	<27	5	5		<4	Rough
13.	Sagar Island (21.72,88.1)	19.3	89.4	302	SSE	26.05.24/2030	124	W	49	20	10		6-10	High
14.	Haldia (22.02,88.06)	19.3	89.4	333	SSE	26.05.24/2330	128	W	49	25	10		6-10	High
15.	Kolkata Port (22.32,88.18)	19.3	89.4	359	SSE	26.05.24/2330	121	WNW	49	25	10		6-10	High
CWC Bhubaneswar														
16.	Checked out Gopalpur (19.27,84.92)	19.3	89.4	471	E	25.05.24/2330	471	W	<27	5	5		<4	Rough
17.	Puri (19.81,85.83)	19.3	89.4	379	E	26.05.24/0830	373	W	<27	10	5		<4	Rough
18.	Paradip (20.27,86.67)	19.3	89.4	306	ESE	26.05.24/1130	278	W	33	15	5		4-6	Very Rough
19.	Dhamra (20.78,86.97)	19.3	89.4	303	ESE	26.05.24/1130	243	W	33	15	5		4-6	Very Rough

Fig. 5.2: Customised Location specific bulletin for Ports

(iii) Dissemination of Severe Weather Guidance to 9 member countries under Severe Weather Forecasting Programme by email.

Fig. 5.3: Severe Weather Guidance to 9 countries in South Asia

(iv) Introduction of new webpage for PTC Secretariat

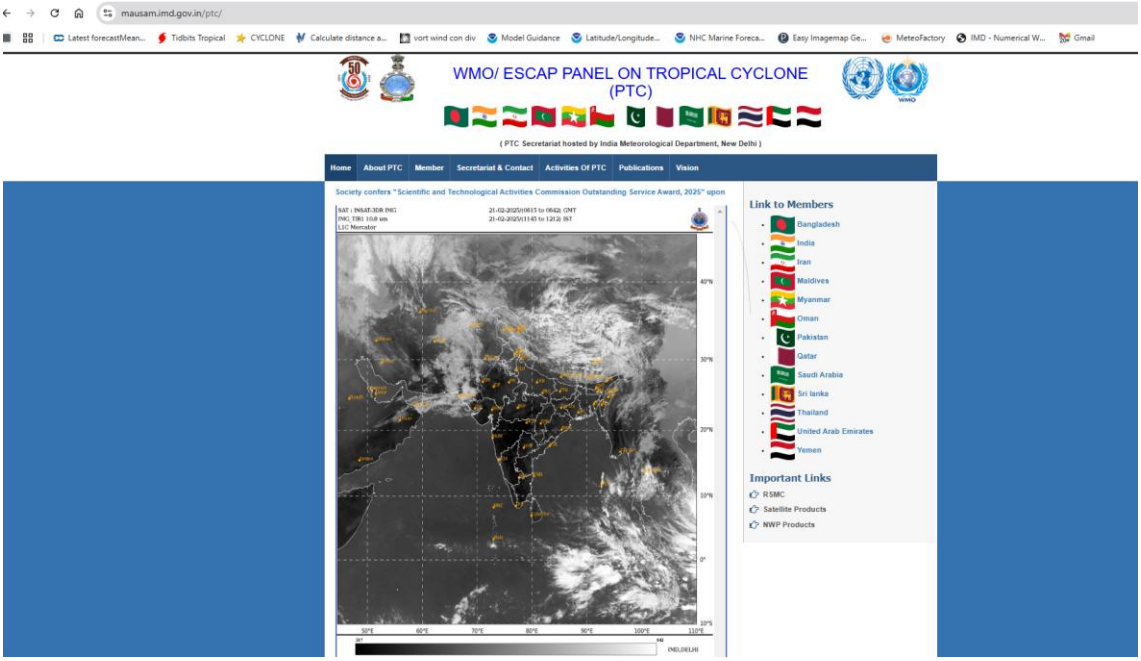


Fig. 5.4: New webpage for Cyclone & Marine weather services

b. Warning Dissemination:

IMD and RSMC New Delhi utilized all means of communication for transmission including email, FAX, websites, social networking platforms (Facebook, X, WhatsApp to national & international users), SMS etc., Application Programming Interface (API), crowd sourcing, Common Alert Protocol (CAP), Global Multi-hazard Alert System (GMAS).

Fig. 5.5: Warning Dissemination Systems used by IMD

All these measures enabled the disaster managers and general public in reducing the loss of life to double digit during the year not only in India, but also in 13 PTC member countries. It also helped in building confidence among disaster managers, media & general public and earned appreciation for IMD and RSMC New Delhi.

2. Trainings and Outreach activities:

IMD conducted following significant meetings and trainings:

I. Pre-cyclone exercise meetings on 10th April & 08th October, 2024

Fig. 5.6: RSMC New Delhi organized 20th Annual Training for Cyclone Forecasters during 19-30 August, 2024 in hybrid mode.

II. 20th RSMC New Delhi Attachment Training for Forecasters of 13 member countries of WMO/ESCAP Panel during 19-30 August.

Fig. 5.7: 1st Training on Multi-hazard Interoperability Implementation was held at New Delhi during 09-13 December under WMO's Severe Weather Forecasting Programme

III. 1st Severe Weather Forecasting Programme (SWFP) Regional Training Workshop on Multi-Hazard Early Warning System (MHEWS) Interoperability Implementation during 9th to 13th December, 2024.

IV. 51st Session of WMO/ESCAP Panel on Tropical Cyclones (online) during 16th-20th December, 2024.

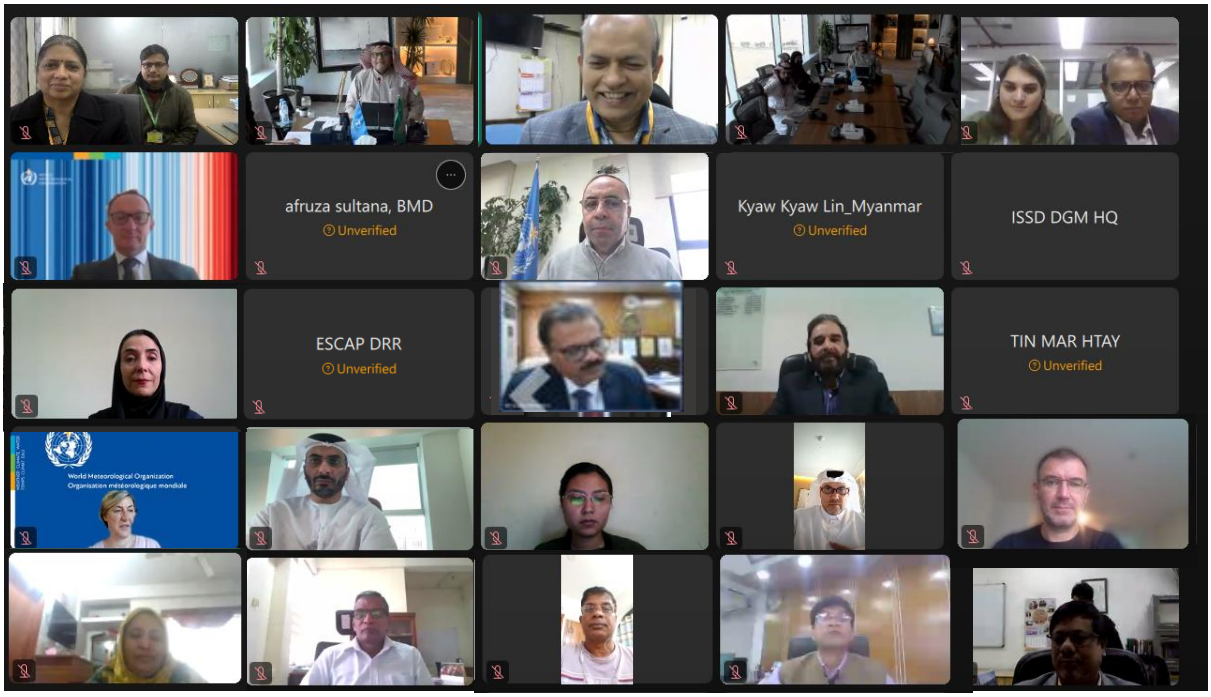


Fig. 5.8: 51st Session of WMO/ESCAP Panel on Tropical Cyclones (online) during 16th-20th December, 2024.

3. Major achievements:

I. WMO appreciated RSMC New Delhi for organizing 20th Annual Attachment Training for cyclone forecasters in August.

II. WMO/ESCAP Panel on Tropical Cyclones appreciated the role of PTC Secretariat for preparation of Vision 2030 of PTC, PTC News Letter, updation of Tropical Cyclone Operation Plan (TCP-21) and for organizing 51st session

Acknowledgement

India Meteorological Department (IMD) and RSMC New Delhi duly acknowledge the contribution from various national and international organizations/institutes for their contribution in early warning services against various cyclonic disturbances over the North Indian Ocean during 2024.

- World Meteorological Organisation (WMO) and all the 13 WMO/ESCAP Panel member countries including Bangladesh, Iran, Maldives, Myanmar, Pakistan, Qatar, Sri Lanka, Saudi Arabia, Sultanate of Oman, Thailand, United Arab Emirates, Yemen.
- All sister organisations of Ministry of Earth Sciences including National Centre for Medium Range Weather Forecasting Centre (NCMRWF), Indian Institute of Tropical Meteorology (IITM), Indian National Centre for Ocean Information Services (INCOIS), National Institute of Ocean Technology (NIOT).
- Research institutes including IIT Bhubaneswar, IIT Delhi and Indian Space Research Organisation (ISRO).
- Various international modeling centres including European Centre for Medium Range Weather Forecasting (ECMWF), UK Meteorological Office, National centre for Environmental Prediction (NCEP), USA, Japan Meteorological Agency and Meteo-France
- 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

We also acknowledge the contribution and support from various Divisions/Centres of IMD including Area Cyclone Warning Centres (ACWCs) Chennai, Mumbai, Kolkata, Cyclone Warning Centres (CWCs) Bhubaneswar, Visakhapatnam, Thiruvananthapuram & Ahmedabad, various Regional Meteorological Centres, Meteorological Centres, Meteorological Offices, Doppler Weather Stations along the east and west coast of India, National Weather Forecasting Centre, Numerical Weather Prediction Division, Satellite and Radar Division, Surface & Upper Air Instruments Divisions, Information System and Services Division, Agrometeorological Advisory Services Division and Central Aviation Meteorology Division of IMD.

(a) Storm surge and associated damage due to Cyclone Remal in coastal Bangladesh (ddindia.co.in, 27th May, 2024), (b) Cyclone Remal made landfall in Bangladesh on May 26, 2024 (edition.cnn.com, 26th May, 2024), (c) Damage in Bangladesh's coastal districts by SCS Remal (asinews.it, 28th May, 2024), (d) Damage in West Bengal by Cyclone Remal (economictimes.indiatimes.com, 27th May, 2024), (e) A tree falls on a school bus in Sonitpur Assam (indiatvnews.com, 28th May, 2024) and (f) Rescue team clearing fallen trees in West Bengal (Air News Alerts, 28 May 2024)

DAMAGE DUE TO SEVERE CYCLONIC STORM 'REMAL'