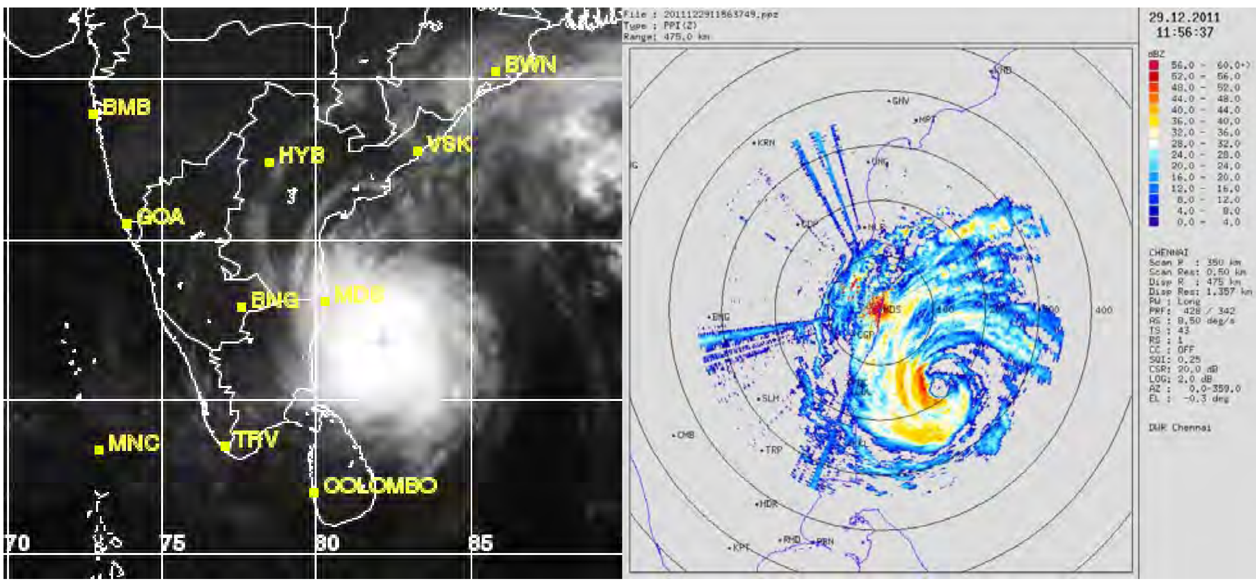
World Meteorological Organisation

India Meteorological Department

RSMC - TROPICAL CYCLONE REPORT NO.02/2012

REPORT ON CYCLONIC DISTURBANCES OVER NORTH INDIAN OCEAN DURING 2011



Satellite and DWR imageries of very severe cyclonic storm, THANE

RSMC-TROPICAL CYCLONES, NEW DELHI

JANUARY 2012

WMO

INDIA METEOROLOGICAL DEPARTMENT

RSMC- TROPICAL CYCLONES, NEW DELHI

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18.	Abstract	The activities of Regional Specialised Meteorological Centre (RSMC) – Tropical Cyclone New Delhi are briefly presented along with 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 2011. 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.
19.	Key words	Cyclogenesis, intensity, track, landfall, NWP model, forecast verification

<u>CONTENTS</u>

INTRODUCTION

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

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

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

CHAPTER- I

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

1.1 Area of Responsibility

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

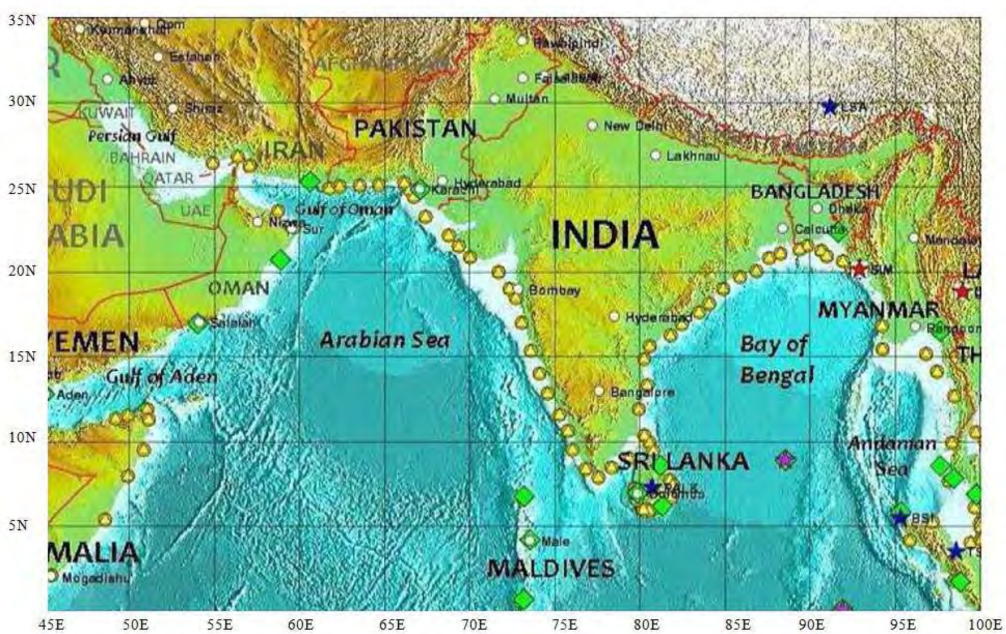


Fig. 1.1 Area of responsibility of RSMC- Tropical Cyclone, New Delhi

1.2 Naming of tropical cyclones over north Indian Ocean:

The WMO/ESCAP Panel on Tropical Cyclones at its twenty-seventh Session held in 2000 in Muscat, Sultanate of Oman agreed in principle to assign names to the tropical cyclones in the Bay of Bengal and Arabian Sea. After long deliberations among the member countries, the naming of the tropical cyclones over north Indian Ocean commenced from September 2004. RSMC New Delhi is continuing the naming of Tropical Cyclones formed over North Indian Ocean since October 2004. The first name was 'ONIL' which developed over the Arabian Sea (30 September to 03 October, 2004). According to approved principle, a list of 64 names in eight columns has been prepared. The name has been contributed by Panel members. The RSMC tropical cyclones New Delhi gives a tropical cyclone an identification name from the above name list. The Panel member's name is listed alphabetically country wise in each column. The names are used sequentially column wise. The first name starts from the first row of column one and continues sequentially to the last row in column eight. The identification system covers both the Arabian Sea and the Bay of Bengal. These lists are used sequentially, and they are not rotated every few years as are the Atlantic and Eastern Pacific lists. Out of 64 approved names, 28 names have been utilized till the end of year 2011.

1.3 Observational System

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

1.3.1 Surface Observatories

IMD has a good network of surface observatories satisfying the requirement of World Meteorological Organization. There are 559 surface observatories in IMD. The data from these stations are used on real time basis for operational forecasting. Recently a number of moored ocean buoys including Meteorological Buoy (MB), Shallow Water (SW), Deep Sea (DS) and Ocean Thermal (OT) buoys have been deployed over the Indian Sea, under the National Data Buoy Programme (NDBP) of the Ministry of Earth Sciences, Government of India. A number of Automated Weather Stations (AWS) are also in operation along the coast and provide surface observations on hourly basis which are utilized in cyclone monitoring and forecasting.

1.3.2. Upper Air Observatories

There are at present 62 Pilot Balloon Observatories, 39 Radiosonde/ Radiowind observatories and 01 Radiosonde Observatory. The upper air meteorological data collected all over the country are used on real time basis for operational forecasting.

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

1.3.3. Cyclone Detection Radars

There are 11 S-band radars for Cyclone detection located at Kolkata, Chennai, Visakhapatnam, Machilipatnam, Sriharikota, Paradip, Karaikal, Kochi, Goa, Mumbai and Bhuj. Out of these 11 stations, 6 stations (except Kolkata, Chennai, Visakhapatnam, Machilipatnam, Sriharikota) are using conventional S-band radars. Four numbers of S-band Doppler Weather Radars (Meteor 1500 S) imported from M/s Gematronik, Germany were installed, commissioned and made operational at Chennai, Kolkata, Machilipatnam and Visakhapatnam respectively with effect from 22.02.2002., 29.01.2003, 08.12.2004 and 27.07.2006 respectively. One indigenous Doppler Weather Radar developed by Indian Space Research Organization (ISRO) under IMD-ISRO collaboration has also been installed and made operational at SHAR Centre, Sriharikota (Andhra Pradesh) with effect from 9 April, 2004. Old conventional Radar at Kolkata was dismantled and was re-installed at Goa. As the radars at Goa, Mumbai, Paradip, Karaikal, Bhuj and Kochi has become old/obsolete, these radars are under the process of replacement.

IMD is modernizing its observational network in the phased manner. In the first phase, 12 numbers Doppler Weather Radar have been procured from M/s Beijing Metstar Co. Ltd. China. Out of these, 3 DWRs meant for Goa, Karaikal and Paradip could not be installed at coastal site due to some unavoidable reasons and these are planned for re-location at inland locations. 2 S-band DWRs procured from M/s BEL, Bangalore have been installed at Mumbai & Bhuj and are likely be commissioned by end of January, 2012. Four DWRs meant for Kochi, Goa, Karaikal and Paradip are under process of procurement.

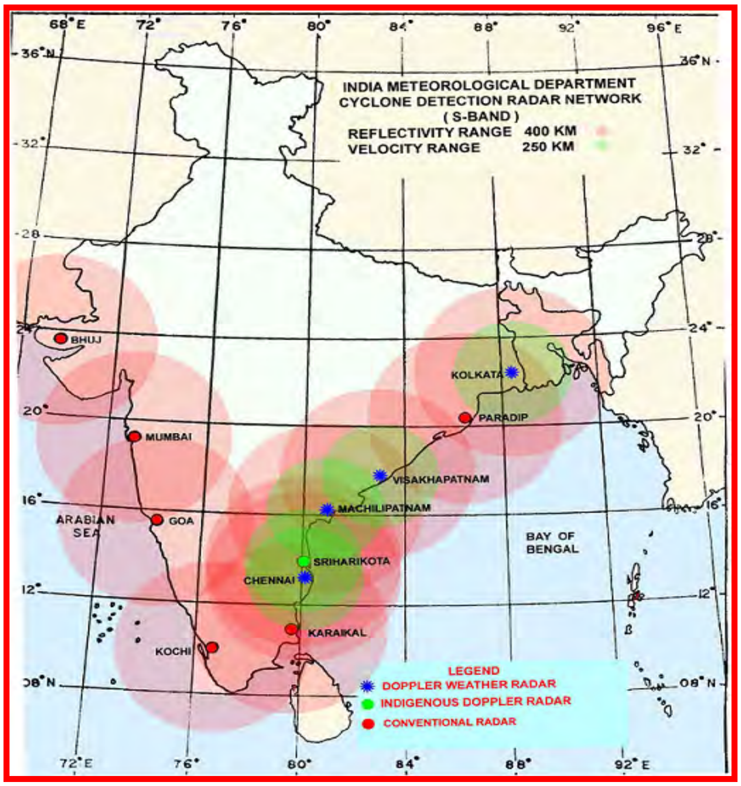


Fig. 1.2. S-Band Cyclone Detection Radar Network

Doppler Weather Radars Provide vital informations on radial velocity and spectral width in addition to reflectivity. Reflectivity estimates obtained from these radars are more accurate in comparison to those from conventional radars as the Doppler Weather Radars have capability for correcting the values for clutters, bright band etc. Surface Rainfall Intensity (second level product derived from reflectivity) and other hydrological products like Precipitation Accumulation (PAC), Vertical Integrated Liquid (VIL) is very important for issuing warnings for heavy rain, flesh flood and hail. The algorithms for generation of these products employ some adaptable parameters which depends on Drop Size Distribution (DSD) present in the precipitation (DSD is different for different season, geographical location and type of precipitation).

1.3.4 Satellite Monitoring

1.3.4.1 Current status:

At present IMD is receiving and processing meteorological data from two Indian satellites namely Kalpana-1 and INSAT-3A. Kalpana-1 was launched on 12th September, 2002 and is located at 74^0 E. INSAT-3A was launched on 10 April, 2003 and is located at 93.5^0 E. Kalpana-1 and INSAT-3A both have three channel Very High Resolution Radiometer (VHRR) for imaging the Earth in Visible (0.55-0.75 µm), Infra-Red (10.5-12.5µm) and Water vapour (5.7-7.1µm) channels having resolution of 2X2 km in visible and 8X8 km in Water Vapour (WV) and Infra red (IR) channels. In addition, the INSAT-3A has a three channel Charge Coupled Device (CCD) payload for imaging the earth in Visible (0.62-0.69um), Near IR (0.77-0.86µm) and Short Wave IR (1.55-1.77µm) bands of Spectrum. The Resolution of CCD payload in all the three channels is 1kmX 1 km. At Present about 48 numbers of satellite images are taken daily from Kalpana-1 which is the main operational satellite and 9 images are taken from INSAT-3A. Imaging from CCD is done 5 times during daytime only. All the received data from the satellite are processed and archived in National Satellite Data Centre (NSDC), New Delhi.

Indian Meteorological Data Processing System (IMDPS) is processing meteorological data from INSAT VHRR and CCD data and supports all operational activities of the Satellite Meteorology Division on round the clock basis. Cloud Imagery Data are processed and transmitted to forecasting offices of the IMD as well as to the other users in India and foreign countries.

Apart from generating half hourly cloud imagery, IMDPS produces derived products from the processed data as follows:

- Cloud Motion Vectors (CMV) are derived using three consecutive half hourly images from the operational Kalpana-I Satellite. WVWs are generated at 00, 03, 06, 09, 12, 15 & 18 UTC using IR imagery daily.
- Water Vapour Winds (WVWs) are derived using three consecutive half hourly images from the operational Kalpana-I Satellite. CMV are generated at 00, 03, 06, 09, 12, 15 & 18 UTC using water vapour imageries data.
- Sea Surface Temperatures (SST) are computed at 1^0 x 1^0 grid intervals from all Kalpana-I data on half hourly /daily /weekly/monthly basis.
- Outgoing Longwave Radiation (OLR) are computed at 0.25^0 x 0.25^0 grid intervals from all Kalpana-I data on half hourly /daily /weekly/monthly basis.
- Quantitative Precipitation Estimation (QPE) is generated at 1^0 x 1^0 Grid from Kalpana-1 imagery on half hourly/daily/weekly/monthly basis.

At present Dvorak technique is widely used but manually applied. Recently efforts have been made for automation of this technique. Automated Dvorak technique is running in experimental mode at Synoptic Application Unit, Satellite Meteorology Division.

Satellite Application Unit issues three hourly bulletins in general and hourly and half hourly bulletins in case of tropical cyclones. The unit has modified these bulletins and included the forecast part also since 2009.

The Satellite Meteorology Division updates twelve images on the IMD website every half hour from the VHRR payload. It also updates images of various geophysical products as and when available.

With the Web Archival System developed at IMD KALPANA/INSAT3A data products and imageries are being archived since January 2009. The automatic script is being used to keep and update the images/products on the website upto 2 months. These are available to all users.

On 23rd Sept 09, polar orbiting satellite OCEANSAT–II has been launched by ISRO which carries a ku-Band pencil beam scatterometer to provide ocean surface winds at 10 m ht for early detection of tropical cyclones.

Recently three-ground stations have been installed in New Delhi, Guwahati and Chennai for receiving real time MODIS and NOAA data. The following products are being received regularly:

A) Geophysical Products derived from NOAA

1. Atmospheric temperature profile
2. Atmospheric water vapour profile
3. Surface emissivity
4. Surface Temperature
5. Fractional cloud cover
6. Cloud Top Temperature
7. Cloud Top Pressure
8. Tropopause height
9. Cloud Liquid Water Content
10. Total Column Precipitable Water
11. Cloud Type (including Fog)
12. Total Ozone from GOME
13. Total Ozone from HIRS
14. Ozone Profiles
15. Land Surface Temperature
16. Sea Surface Temperature
17. Normalized Difference Vegetation Index (NDVI)
18. Fog detection

B) Geophysical Products derived from MODIS

MODIS Level 2 geophysical products (Terra and Aqua)

1. MODIS cloud mask (MOD35)
2. MODIS cloud top properties (MOD06CT)
3. MODIS atmospheric profiles, precipitable water and stability indices (MOD07)
4. MODIS aerosol product (MOD04)
5. MODIS Sea Surface Temperatures (IMAPP product)
6. Normalized Difference Vegetation Index (NDVI)
7. Enhance Vegetation Index (EVI)
8. Land Surface Temperature (LST)

IPWV measurements by GPS Satellites:

At present five GPS receiving stations are installed at New Delhi, Kolkata, Guwahati, Chennai, and Mumbai for measurements of Integrated Precipitable Water Vapour.

Digital Meteorological Data Dissemination:

IMD transmits processed imagery, meteorological and facsimile weather charts to field forecasting offices distributed over the country using the Digital Meteorological Data Dissemination (DMDD) facility, through INSAT in broadcast mode. The bulletins providing description of the cloud organization and coverage are also sent as advisory to forecasting offices every synoptic hour. When cyclones are detected in satellite imagery, these bulletins are sent every hour. Such advisories are also transmitted to the neighbouring countries.

Processed satellite imagery, analyzed weather charts and conventional synoptic data are up-linked to the satellite in C-band. Satellite broadcasts these data to DMDD receiving stations in S-band. DMDD receiving stations analyze weather imagery and other data to generate required forecast. There are 37 Nos. of DMDD stations installed in India. Three DMDD receiving stations are also operating in neighbouring SAARC countries at Sri Lanka, Nepal and Maldives. These stations are receiving direct broadcast of cloud imagery, weather facsimile charts and meteorological data on an operational basis. The frequency of transmission from ground to satellite (uplink) is 5886 MHz and that of downlink is 2586 MHz.

1.3.4.2 Future Plan:

Under INSAT-3D programme, a new Geostationary Meteorological Satellite INSAT-3D is being designed by ISRO. It will have an advanced imager with six imagery channels (VIS, SWIR, MIR, TIR-1, TIR-2, & WV) and a nineteen channel sounder (18 IR &1 Visible) for derivation of atmospheric temperature and moisture profiles. It will provide 1 km. resolution imagery in visible band, 4 km resolution in IR band and 8 km in water vapour channel. This new satellite is scheduled for launch in 2010 and will provide much improved capabilities to the meteorological community and users. In preparation for the reception and processing of this data, SAC-ISRO has installed a data reception and processing system to process the data from the INSAT 3A and Kalpana 1 satellites. After full commissioning, the system will be able to receive and process the data from all the above three satellites on real time mode and produce the following products with respect to cyclone monitoring:

1. Outgoing Long wave Radiation (OLR)
2. Quantitative Precipitation Estimation (QPE)
3. Sea Surface Temperature (SST)
4. Cloud Motion Vector (CMV)
5. Water Vapor Wind (WVW)
6. Upper Tropospheric Humidity (UTH)
7. Temperature, Humidity profile
8. Value added parameters from sounder products
    a) Geo-potential Height
    b) Layer Perceptible Water
    c) Total Perceptible Water

d) Lifted Index
e) Dry Microburst Index
f) Maximum Vertical Theta-E Differential
g) Wind Index

9. Flash Flood Analyzer
10. Tropical Cyclone-intensity /position

1.4. Analysis and Prediction

Cloud imageries from Geostationary Meteorological Satellites INSAT-3A and METSAT (KALPANA-1) are the main sources of information for the analysis of tropical cyclones over the data-sparse region of north Indian Ocean. Data from Ocean buoys also provide vital information. Ship observations are also used critically during the cyclonic disturbance period.

The analysis of synoptic observations is performed four times daily at 00, 06, 12, and 18 UTC. During cyclonic disturbance (depression and above intensity), synoptic charts are prepared and analysed every three hour to monitor the tropical cyclones over the north Indian Ocean.

The direction and speed of the movement of a tropical cyclone are determined primarily from the three hourly displacement vectors of the centre of the system and by analyzing satellite imageries. 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 WVWV 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.

1.4.1. Modernisation of cyclone analysis and prediction system

Various strategies were adopted for improvement of analysis and prediction of cyclone. The tropical cyclone analysis, prediction and decision-making process was 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 were used for this purpose. A new weather analysis and forecasting system in a digital environment was used to plot and analyse different weather parameters, satellite, Radar and Numerical Weather Prediction (NWP) model products. An integrated fully automated forecasting environment facility was thus set up for this purpose.

The manual synoptic weather forecasting was 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.1.3.

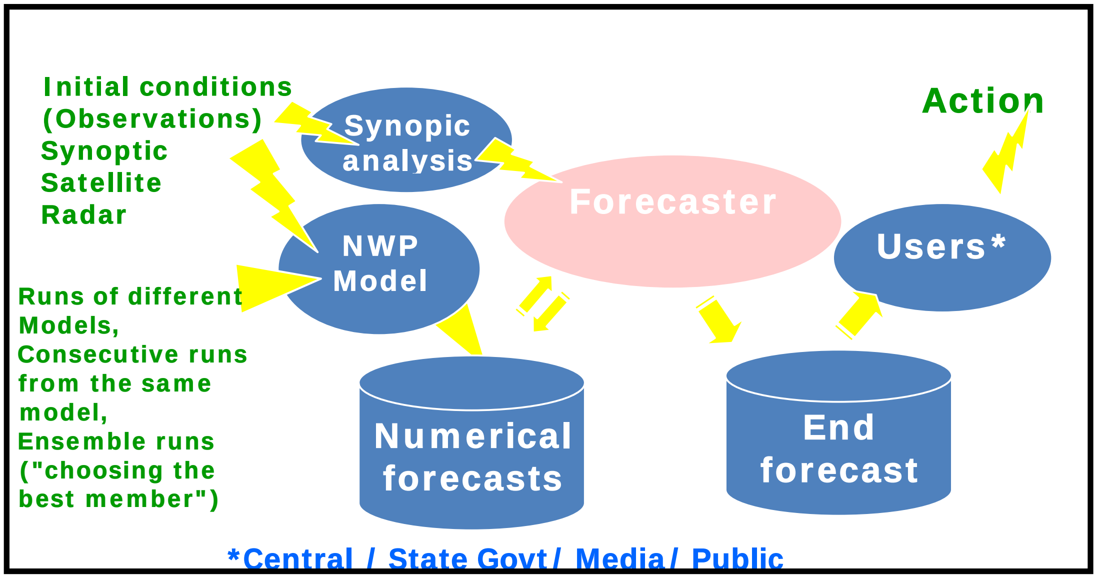


Fig.1.3. Strategy adopted for cyclone analysis and forecasting

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

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

All the available data and products form various national and international sources were 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 centres
- ❖ Dynamical and statistical Model products from various national and international centres
- ❖ Data, analysis and forecast products from various national and international centres through internet

1.5. NWP Models in operational use during the year 2011

1.5.1. Global Forecast System

The Global Forecast System (GFS), adopted from National Centre for Environmental Prediction (NCEP), at T382L64 (~ 35 km in horizontal) resolution (incorporating Global Statistical Interpolation (GSI) scheme as the global data assimilation for the forecast up to 7 days) was implemented at India Meteorological Department (IMD), New Delhi on IBM based High Power Computing Systems (HPCS) in May 2010. Currently, it runs twice in a day (00 UTC and 12 UTC). The upgraded version of the GFS (*GSI 3.0.0 and GSM 9.1.0*) model at T574L64 (~ 25 km) resolution has been also operated in the experimental mode since 1 June 2011 and real-time outputs are made available to the national web site of IMD (www.imd.gov.in).

1.5.2. Quasi-Lagrangian Model (QLM)

The QLM, a multilevel fine-mesh primitive equation model with a horizontal resolution of 40 km and 16 sigma levels in the vertical, is being used for tropical cyclone track prediction in IMD. The integration domain consists of 111x111 grid points centred over the initial position of the cyclone. The model includes parameterization of basic physical and dynamical processes associated with the development and movement of a tropical cyclone. The two special attributes of the QLM are: (i) merging of an idealized vortex into the initial analysis to represent a storm in the QLM initial state and (ii) imposition of a steering current over the vortex area with the use of a dipole. The initial fields and lateral boundary conditions are taken from the IMD GFS-382. The model is run twice a day based on 00 UTC and 12 UTC initial conditions to provide 6 hourly track forecasts valid up to 72 hours. The track forecast products are disseminated as a World Weather Watch (WWW) activity of RSMC, New Delhi.

1.5.3. Regional Forecast System

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

1.5.3.1. Non-hydrostatic mesoscale modeling system WRFDA-WRF-ARW

The mesoscale forecast system Weather Research and Forecast WRFDA (version 3.2) with 3DVAR data assimilation is being operated daily twice to generate mesoscale analysis at 27 km and 9 km horizontal resolutions using IMD GFS-T382L64 analysis/forecast as first guess. Using initial and boundary conditions from the WRFDA, the WRF (ARW) is run for the forecast up to 3 days with double nested configuration with horizontal resolution of 27 km and 9 km and 38 Eta levels in the vertical. The model mother domain covers the area between lat. 25º S to 45º N long 40º E to 120º E and child covers whole India. The performance of the model is found to be reasonably skilful for cyclone genesis and track prediction. At ten other regional centres, very high resolution mesoscale models (WRF at 3 km resolution) are also operational with their respective regional setup/configurations. The latest version of NCEP HWRF is also implemented at IMD for the Indian basins with the assimilation of local observations. The model has the provision for vortex re-location and moving nesting procedure. In this direction action has been already initiated and the model is exceeded to be available in the operational mode by the end of 2011.

1.5.4. Genesis Potential Parameter (GPP)

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

The grid point analysis and forecast of the genesis parameter up to seven days is also generated on real time (available at http://www.imd.gov.in/section/nhac/dynamic/Analysis.htm). Higher value of the GPP over a region indicates higher potential of genesis over the region. Region with GPP value equal or greater than 30 is found to be high potential zone for cyclogenesis. The analysis of the parameter and its effectiveness during cyclonic disturbances in 2010 affirm its usefulness as a predictive signal (4-5 days in advance) for cyclogenesis over the North Indian Ocean.

1.5.5. 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 72 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 ECMWF model. The method is found to be promising for the operational use.

1.5.6. 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 72-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 72-hour. The outputs at 12 hours forecast intervals of these models are first post-processed using GRIB decoder. The 12 hourly predicted cyclone tracks are then determined from the respective mean sea level pressure fields using a cyclone tracking software. Multiple linear regression technique is used to generate weights (regression coefficients) for each model for each forecast hour (12hr, 24hr, 36 hr, 48hr, 60hr, 72hr) based on the past data. These coefficients are then used as weights for the ensemble forecasts. 12-hourly forecast latitude (LAT^f) and longitude (LON^f) positions are defined by multiple linear regression technique. In the updated version, MM5 model in the ensemble member is replaced by IMD WRF model. IMD also makes use of NWP products prepared by some other operational NWP Centres like, ECMWF (European Centre for Medium Range Weather Forecasting), GFS (NCEP), JMA (Japan Meteorological Agency), UKMO etc. The MME is developed applying multiple linear regression technique using the member models WRF(ARW), QLM, GFS (NCEP), ECMWF and JMA. All these NWP products are routinely made available on the IMD web site www.imd.gov.in. The MME technique has been implemented from 2009 for real time forecasting of tropical cyclones.

1.5.7. Hurricane WRF Model

Recently under Indo-US joint collaborative program, IMD adapted Hurricane-WRF model for Tropical Cyclone track and intensity forecast for North Indian Ocean (NIO) region for its operational requirements. The basic version of the model HWRFV (3.2+) which was operational at EMC, NCEP, USA was ported on IMD IBM P-6/575 machine with nested domain of 27 km and 9 km horizontal resolution and 42 vertical levels with outer domain covering the area of 80^0x80^0 and inner domain 6^0x6^0 with centre of the system adjusted to the centre of the observed cyclonic storm. The outer domain covers most of the North Indian Ocean including the Arabian Sea and Bay of Bengal and the inner domain mainly covering the cyclonic vortex with moving along the movement of the system. The model has special features such as vortex initialization, coupled with Ocean model to take into account the changes in SST during the model integration, tracker and diagnostic software to provide the graphic and text information on track and intensity prediction for real-time operational requirement.

As part of model validation, case studies were undertaken to test the ability of the model for the Cyclonic storms formed during the year 2010 and model forecasts are produced upto 5 days during the 2011 cyclone season as an experimental forecast in real-time. In these runs only the atmospheric model (HWRF) was tested. The Ocean Model (POM-TC) and Ocean coupler requires the customization of Ocean Model for Indian Seas. In this regards, IMD is expecting to work in collaboration with INCOIS, Hyderabad which is running the Ocean Models (POM)/Hybrid co-ordinate ocean model (HYCOM) to support in porting the Ocean Model with Indian Ocean climatology and real time data of SST over Indian Seas. Few more experiments for the Tropical Cyclones formed during the last 5 years are to be taken up for further validation of the model to customize the model for Indian Ocean region ultimately to make Tropical WRF model (T-WRF).

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

As part of WMO Program to provide a guidance of tropical cyclone (TC) forecasts in near real-time for the ESCAP/WMO Member Countries based on the

TIGGE Cyclone XML (CXML) data, IMD implemented JMA supported software for real-time TC forecast over North Indian Ocean (NIO) during 2011.

The Ensemble and deterministic forecast products from ECMWF (50+1 Members), NCEP (20+1 Members), UKMO (23+1 Members) 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 is under preparation. For verification purposes, the best track data of IMD has to be embedded on the forecast track and strike probability maps. Presently the data and products are to be validated using the IMD best track data.

1.6. Products Generated By RSMC, New Delhi

RSMC, New Delhi prepares and disseminates the following bulletins.

1.6.1. Tropical Weather Outlook

Tropical Weather Outlook is issued daily at 0600 UTC based on 0300 UTC observations in normal weather for use of the member countries of WMO/ESCAP Panel. This contains description of synoptic systems over north Indian Ocean along with information on significant cloud systems as seen in satellite imageries and ridge line at 200 hPa level over Indian region. In addition, a special weather outlook is issued at 1500 UTC based on 1200 UTC observations when a tropical depression formed over north Indian Ocean. The special tropical outlook indicates discussion on various diagnostic and prognostic parameters apart from the 72 hours track and intensity forecast from the stage of deep depression. The track and intensity forecast are issued for +06, +12, +18, +24, +36, +48, +60 and +72 hours or till the system is likely to weaken into a low pressure area. It also includes the description of current location & intensity, past movement and description of satellite imageries. 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.

Tropical weather outlooks are transmitted to panel member countries through global telecommunication system (GTS) and are also made available on real time basis through internet at IMD's website: http://www.imd.ernet.in and http://www.imd.gov.in. RSMC, New Delhi can also be contacted through e-mail or cwdhq2008@gmail.com) for any real time information on cyclonic disturbances over north Indian Ocean.

1.6.2. 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 upto 72 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 when required. Tropical cyclone advisories are transmitted to panel member Countries through GTS and are also made available on real time basis through internet at IMD's website: http://www.imd.gov.in . RSMC, New Delhi can also be contacted through e-mail or cwdhq2008@gmail.com) for any real time information on cyclonic disturbances over north Indian Ocean.

1.6.3. Global Maritime Distress Safety System (GMDSS)

Under Global Maritime Distress Safety System (GMDSS) Scheme, India has been designated as one of the 16 services in the world for issuing Sea area bulletins for broadcast through GMDSS for MET AREA VIII (N), which covers a large portion of north Indian Ocean. As a routine, two GMDSS bulletins are issued at 0900 and 1800 UTC. During cyclonic situations, additional bulletins (up to 4) are issued for GMDSS broadcast. In addition, coastal weather and warning bulletins are also issued for broadcast through NAVTEX transmitting stations located at Mumbai and Chennai.

1.6.4. Tropical Cyclone Advisories for Aviation

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

1.6.5. Bulletin for India coast

These bulletins are issued from the stage of depression onwards during the stage of depression/deep depression; it is issued based on 00, 03, 06, 12, and 18 UTC observations.

When the system intensifies into a cyclonic storm over north Indian Ocean, these bulletins are issued at 00, 03, 06, 09, 12, 15, 18 and 21 UTC (every three hourly interval) based on previous observations. This bulletin contains present status of the system i.e. location, intensity; past movement and forecast intensity & movement for next 72 hours or till the system weaken into a low pressure area, likely landfall point & time and likely adverse weather including heavy rain, gale wind & storm surge. Expected damage and action suggested are also included in the bulletins. This bulletin is completely meant for national users and these are disseminated through various modes of communication including All India Radio, Telephone/Fax, Print and electronic media. It is also posted on cyclone page of IMD website.

1.6.6. Wind forecast for different quadrants

The forecast of maximum wind in four quadrants of a cyclone commenced with effect from cyclone, GIRI during October 2010. In this forecast, the radius of 34, 50 and 64 knot winds are given for various forecast periods like +06, +12, +18, +24, +36, +48, +60 and +72 hrs. A typical graphical presentation of this forecast is shown in Fig.1.4. This quadrant wind forecast was issued as bulletin from the deep depression stage onwards to various users through global telecommunication system. It was also given to NWP centres like IIT, Delhi and NCMRWF for their use in creating the synthetic vortex.

1.6.7. PWS system

A new public weather service (PWS) system has been set up in IMD with the collaboration of Meteo France International for automatic production of cyclone warning bulletins, graphical display of warnings and automatic warning dissemination to various users through different telecommunication channels. There is a Tropical Cyclone Module, especially for PWS of cyclone. An example of product generated from this system is shown in Fig.1.5.

1.7. Cyclone Warning Dissemination

Cyclone warnings are disseminated to various users through telephone, fax, e-mail and GTS, All India Radio, Television and the print & electronic media. These warnings/advisories are also put in the website www.imd.gov.in of IMD. Another means to transmit warning is IVRS (Interactive Voice Response system). The requests for weather information and forecasts from general public are automatically answered by this system. For this purpose, the person has to dial a toll free number "18001801717" from anywhere in the country. This system has been installed at 26 Meteorological Centres/ Regional Meteorological Centres. High Speed Data Terminals (HSDT) are installed at almost all MCs and RMCs. HSDTs are capable of sending short warning message as SMS and the whole warning message as email. Local weather warnings are put in IMD website for common people. GMDSS message is also put in IMD website as well as transmitted through GTS.

In addition to the above network**,** for quick dissemination of warning against impending disaster from approaching cyclones, IMD has installed specially designed receivers within the vulnerable coastal areas for transmission of warnings to the concerned officials and people using broadcast capacity of INSAT satellite. This is a direct broadcast service of cyclone warning in the regional languages meant for the areas affected or likely to be affected by the cyclone. There are 352 Cyclone Warning Dissemination System (CWDS) stations along the Indian coast; out of these 101 digital CWDS are located along Andhra coast. The IMD's Area Cyclone Warning Centres (ACWCs) at Chennai, Mumbai & Kolkata and Cyclone Warning Centre

(CWCs) at Bhubaneswar, Visakhapatnam & Ahmedabad are responsible for originating and disseminating the cyclone warnings through CWDS.

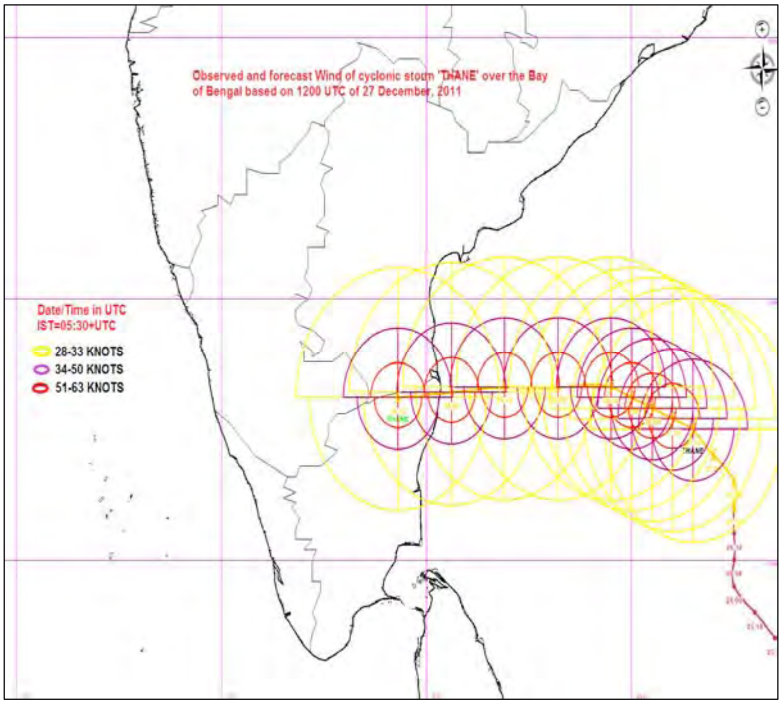


Fig.1.4. A typical graphical presentation of cyclone wind forecast during cyclone, THANE

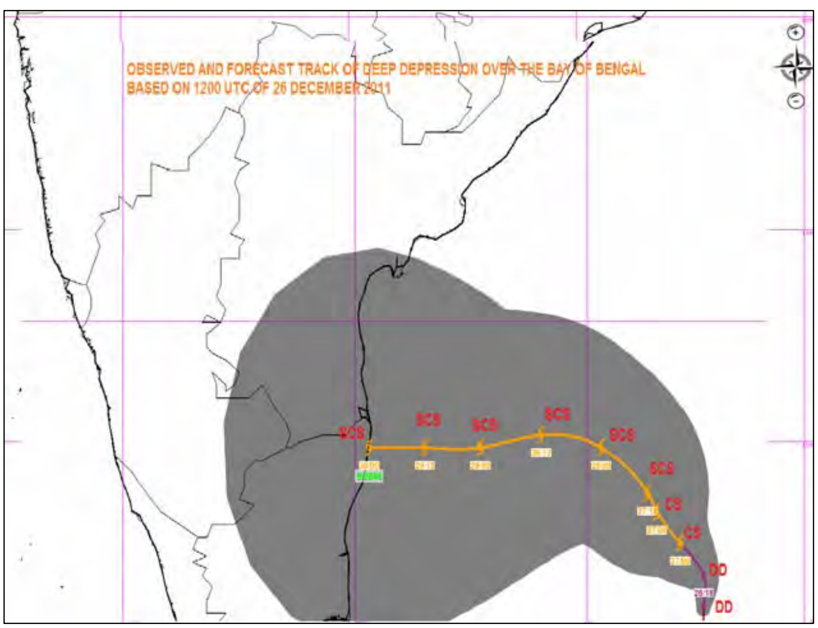


Fig.1.5. A typical example of observed and forecast track of depression which later on became the severe cyclonic storm, 'THANE'

The bulletins are generated and transmitted every hour in three languages viz English, Hindi and regional language. The cyclone warning bulletin is up-linked to the INSAT in C band. For this service, the frequency of transmission from ground to satellite (uplink) is 5859.225 MHz and downlink is at 2559.225 MHz. The warning is selective and will be received only by the affected or likely to be affected stations. The service is unique in the world and helps the public in general and the administration, in particular, during the cyclone Season. It is a very useful system and has saved millions of lives and enormous amount of property from the fury of cyclones. The digital CWDS have shown good results and working satisfactorily. This CWDS network will be replaced shortly by 500 new CWDS, which are modern and easy to maintain.

1.8. Forecast Demonstration Project (FDP) on Landfalling Tropical Cyclones over the Bay of Bengal

A Forecast Demonstration Project (FDP) on landfalling tropical cyclones over the Bay of Bengal has been taken up. It will help us in minimizing the error in prediction of tropical cyclone track and intensity forecasts. The programme has been divided into three phases

(i) Pre- pilot phase : Oct-Nov. 2008, 2009
(ii) Pilot phase : Oct-Nov. 2010, 2011
(iii) Final phase : Oct-Nov 2012

During pilot phase **(15 Oct- 30 Nov. 2011),** several national institutions participated for joint observational, communicational & NWP activities, like during 2008-2010. However there was improved observational campaign with the observation from Buoys, Oceansat-II and microwave satellites. There was intense observation period for 02 days during the field phase 2011 in association with a deep depression over Bay of Bengal. The daily reports prepared during this period will be helpful to find out the characteristics of genesis, intensification and movement of the systems as well as environmental features over the Bay of Bengal during 15 Oct. to 30 Nov., 2011.

1.9. Modernised Forecast and Warning System of IMD

India Meteorological Department has taken up an extensive modernisation programme **(2008-12)** with the following objectives and expected outcomes.

Objectives

- Induction of advanced technology for observational systems with induction of automatic weather station (AWS), Doppler Weather Radar (DWR) etc
- Digital data communication and data base integration
- Assimilation of non-conventional data into NWP systems
- Improved data dissemination and better public access
- Induction of more objective forecasting system
- Improvement in public weather services (PWS) and early warning system

The detailed observational system upgradation taken up in the programme is shown in fig.1.6.

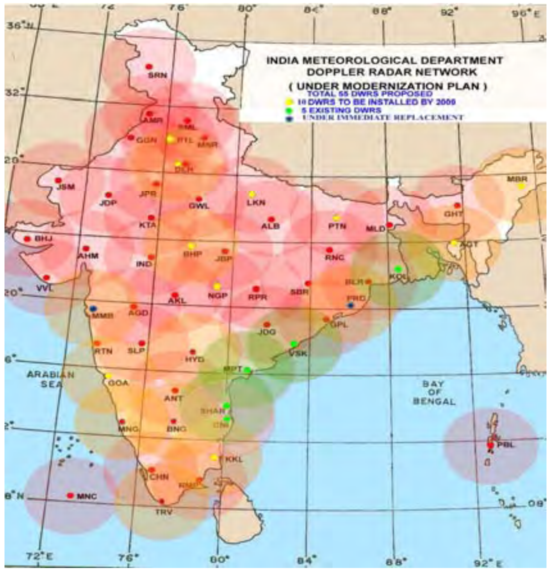


Fig. 1.6. Enhancement of Doppler Weather Radar (DWR) Network

Radar :

- Enhancement of DWR network as shown in the figure 1.6
- Assimilation of Radar data in NWP Models
- Utility of Radar in Nowcasting
- Mosaicing of Radar imagery

Automatic weather Stations / rain gauges

- Phase I : AWS 550 and automatic raingauge (ARG) 1350
- Phase II : AWS 400 and ARG 2000

Upper air systems

- GPS based Radiosonde - 10
- Optical Theodolites - 70

Forecast System

- Global Forecast System (GFS T-382): 7 days
- Regional Forecast System (WRF): 3 days
- Mesoscale Forecasting System (WRF, ARPS & HWRF-high resolution): 48 hours
- Nowcasting

Outcomes of the programme

- Improved Forecast Services at district level with more accuracy
  - Nowcasting of severe weather events
  - Extended range (10-20 days or a month) Forecast .
  - Increased accuracy of short, medium and long range forecasts
  - Multi hazard early warning
- Real Time Data Availability -
  - Rapid updation of data,

- Quicker response time for management,
- Easy accessibility,
- Opportunities for value addition
- Spatial & Temporal Coverage
- Better Service Delivery

CHAPTER –II

CYCLONIC ACTIVITIES OVER NORTH INDIAN OCEAN DURING 2011

The north Indian and adjoining land surface Ocean witnessed the formation of ten cyclonic disturbances during the year 2011. Out of ten disturbances five cyclonic disturbances formed over the Bay of Bengal, four over the Arabian Sea and one over land. Out of the five cyclonic disturbances over the Bay of Bengal, one intensified upto the stage of very severe cyclonic storm, THANE, two upto the stage of deep depression and rest two upto the stage of depression. Out of four cyclonic disturbances formed over the Arabian Sea, one intensified upto the stage of cyclonic storm, KEILA, two upto the stage of deep depression and one upto the stage of depression. Tracks of the cyclonic disturbances formed over the north Indian Ocean during the period are shown in Fig 2.1.

The salient features of the cyclonic disturbances during 2011 were as follows:

- The number of total cyclonic disturbances (depression and above) during the year was below normal, as only 10 cyclonic disturbances formed during 2011 against the normal of 13. Similarly only two cyclones formed during the year against the normal of about 5.
- Both the cyclones made landfall .While cyclone ‘Keila’ made landfall over Oman, the very severe cyclonic storm, ‘Thane’ made landfall over Tamilnadu and Puducherry coast.
- The track of the cyclone “KEILA” was rare in nature as it made a loop after the landfall over Oman near Salalah.
- There were four cyclonic disturbances formed over the north Indian Ocean and adjoining land surface during monsoon season (June-Sep.) against the normal of 7 cyclonic disturbances. There were no cyclonic disturbances over the north Indian ocean during the main monsoon month of July and August 2011. However, one land depression formed during July.

(a) Cyclonic Storm, “KEILA” over the Arabian Sea (29 October-04 November, 2011.)

A cyclonic storm ‘Keila’ developed over the southeast Arabian Sea with genesis of depression on 29th October, 2011. It moved initially west-northwestwards and then northwestwards and crossed Oman coast close to north of Salalah. It then emerged into Arabian Sea and dissipated gradually. It caused death of 14 people in Oman. The system was mainly monitored by the satellite. However, crucial ship and buoy observations also helped in estimation of location and intensity.

The special features of the storm are as follows:

- It was one of the rarest track in recent years, as the cyclone made a loop after Its landfall over Oman and emerged into the Arabian Sea.
- The track of the system could not be predicted accurately by most of the NWP models
- The cyclone slowed down during landfall period and gradually dissipated after emerging into Arabian Sea.

(b) Very Severe Cyclonic Storm, 'THANE' over the Bay of Bengal (25-31 December 2012)

A very severe cyclonic storm, 'THANE' developed from a low pressure area which lay over the southeast Bay of Bengal on 25th December, 2011. The low pressure area concentrated into a depression over the same region on 25th December, 2011 It moved initially in a north-northwesterly direction, and then west-northwestwards. Later it moved west-southwestwards and crossed Tamil Nadu and Puducherry coast close to Cuddalore between 0100 and 0200 UTC of 30th December, 2011 with a wind speed of 12-140 kmph.

The system was initially monitored by satellite. As the system came closer to coast it was monitored by DWR and coastal observations in addition to satellite observation. The crucial observations from ship and buoys also helped in estimation of location and intensity. The salient features of cyclone THANE are given below:

- The system intensified despite the relatively colder sea (SST 26-27^{0}C, low ocean thermal energy (<50 KJ/cm^2) over southwest Bay of Bengal near north Tamil Nadu coast.
- The continuous intensification could not be picked up by most of the NWP models which suggested slight weakening before landfall.
- The track was also rare, as there is no analogue in the month of December based on the recorded historical data of IMD during 1891-2010.

The statistics of the cyclonic disturbances formed during 2011 are given in Table 2.1. The characteristic features of these disturbances are given in Table 2.2. The intraseasonal variation in frequency of genesis, intensification and life period of the disturbances is shown in Table 2.3.

Table 2.1: Cyclonic disturbances formed over north Indian Ocean and adjoining land areas during 2011

1.	Depression over the Bay of Bengal 02-03 February 2011
2.	Depression over the Arabian Sea (11-12 June 2011)
3.	Deep depression over the Bay of Bengal (16-23 June, 2011)
4.	Land depression over Jharkhand (22-23 July 2011)
5.	Depression over Bay of Bengal (22-23 Sept 2011)
6.	Deep depression over the Bay of Bengal (19-20 October, 2011)
7.	Cyclonic storm 'KEILA' over the Arabian Sea (29 October- 04 November, 2011)
8.	Deep Depression over the Arabian sea (06- 10 November 2011)
9.	Deep depression over the Arabian Sea (26 November to 1st December, 2011)
10	Very Severe Cyclonic Storm "THANE" over the Bay of Bengal 25-31 December 2011

Table 2.2: Some Characteristic features of cyclonic disturbances formed over north Indian Ocean and adjoining region during 2011

Cyclonic Storm / Depression	Date, Time & Place of genesis (Lat.^{0}N/ Long.^{0}E)	Date, Time (UTC) place (Lat./Long.) of landfall	Estimated lowest central pressure, Time & Date (UTC) & lat^{o}N / long^{o}E	Estimated Maximum wind speed (kt), Date & Time	Max. T.No. Attained
Depression over the Bay of Bengal 02-03 February 2011	02 Feb. 0900 UTC near 6.5/82.5	Weakened into a well marked low pressure area over southwest Bay of Bengal at 0000 UTC of 03 Feb. 2011.	1002 hPa at 0900 UTC of 02 Feb. near 6.5/82.5	25 kt at 0900 UTC of 02 Feb. near 6.5/82.5	T-1.5
Depression over the Arabian Sea (11-12 June 2011)	11 June, 1200 UTC near 20.0/71.5	Crossed Saurashtra (Gujarat) coast near 20.8/71.2 around 2200 UTC of 11 June, 2011.	996hPa at 1200 UTC of 11 June near 20.0/71.5	25 kt at 1200 UTC of 11 June near 20.0/71.5	T- 1.5
Deep depression over the Bay of Bengal (16-23 June, 2011)	16 June, 0300 UTC near 21.5/89.0	Crossed West Bengal-Bangladesh coast near lat. 21.8^{0}N/89.0^{0}E between 1100 & 1200 UTC of 16 June, 2011	978 hPa at 0600 UTC of 17 June near 22.8/88.5	35 kt at 0600 UTC of 17 June near 22.8/88.5	T- 2.0
Land depression over Jharkhand (22-23 July 2011)	22 July 0300 UTC near 23.5/84.5	Weakened into a well marked low pressure area over north Madhya Pradesh and neighbourhood.	990 hPa at 0300 UTC of 22 July, near 23.5/84.5	20 kt at 0300 UTC of 22 July, near 23.5/84.5	T- 1.5
Depression over Bay of Bengal (22-23 Sept 2011)	22 September at 0300UTC near 21.5/87.5	Crossed north Orissa coast close to Balasore between 1700 & 1800 UTC of 22 September.	995 hPa at 1200 UTC of 22 September near 21.7/87.2	25 kt at 1200 UTC of 22 September near 21.7/87.2	T- 1.5
Deep depression over the Bay of Bengal (19-20 October, 2011)	19 October, 0000 UTC near 20.0/90.5	Crossed Bangladesh coast near lat 21.2^{0}N /92.1^{0}E around 1300 UTC of 19 October.	1000 hPa at 0300 UTC of 19 October near 20.2/91.0	30 kt at 0600 UTC of 19 October near 20.5/91.5.	T- 2.0
Cyclonic storm 'KEILA' over the Arabian Sea (29 October- 04 November, 2011)	29 October, 0600 UTC near 13.0/62.0	Crossed Oman coast close to north of Salalah near 17.1/54.3 between 1600-1700 UTC of 02 November.	996 hPa at 0600 UTC of 02 November near 16.0/54.5	35 kt at 0300 UTC of 02 November near 16.0/55.0 .	T-2.5

Deep Depression over the Arabian Sea (06- 10 November, 2011)	06 November 0600 UTC near 10.5/65.5	Weakened into a well marked low pressure area over westcentral Arabian Sea off Oman coast at 1200 UTC of 10 November, 2011	1000 hPa at 0300 UTC 08 November near 13.5/60.0	30 kt at 0300 UTC 08 November near 13.5/60.0	T-2.0
Deep depression over the Arabian Sea (26 November to 1st December, 2011)	26 November at 0300 UTC near 7.5/76.5	Weakened into a well marked low pressure area over westcentral Arabian Sea near 19.5/62.5	998 hPa at 0000 UTC of 28 November near 13.5/70.0	30 kt at 0000 UTC 28 November near 13.5/70.0	T-2.0
Very Severe Cyclonic Storm"THANE" over the Bay of Bengal (25-31 December, 2011	25 December at 1200 UTC near 8.5/88.5	Crossed north Tamil Nadu & Puducherry coast between Cuddalore and Puducherry within 0100 and 0200 UTC of 30 December, 2011 near	969 hPa at 2100 UTC of 29 December near 11.8/80.3	75 kts at 0600 UTC of 29 December near 12.0/82.0	T-4.5

Table 2.3: Statistical data relating to cyclonic disturbances over the north Indian Ocean during 2011

A) Monthly frequencies of cyclonic disturbances (CI ≥ 1.5)

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

↔ Peak intensity of the system

B) Life time of cyclonic disturbances during 2011 at different stages of intensity

S. No.	Type	Life Time in (Days)
1.	D	17.50
2.	DD	9.25
3.	CS	1.37
4.	SCS	0.25
5.	VSCS	1.25
6.	SuCS	00
Total Life Time in (Days)		29.62

C) Frequency distribution of cyclonic disturbances 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
No. of disturbances	10	5	2	1	1	1	1	0

D) Basin-wise distribution of cyclonic disturbances

Basin	Number of cyclonic disturbances
Bay of Bengal	5
Arabian Sea	4
Land depression	1

Table 2.4. Cyclonic disturbances formed over the north Indian Ocean and land areas of India during 1997-2010

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

	Land	0	0	0	0	0	0	0
	Total							**12**
2008	BOB	1	2	3	0	1	0	7
	ARB	1	1	0	0	0	0	2
	LAND	1	0	0	0	0	0	1
	Total							**10**
2009	BOB	0	2	2	1	0	0	5
	ARB	2	0	1	0	0	0	3
	LAND	0	0	0	0	0	0	0
	Total							**8**
2010	BOB	2	1	0	2	1	0	6
	ARB	0	0-	1	0	1	0	2
	LAND	0	0	0	0	0	0	0
	Total							**8**
2011	BOB	2	2	0	0	1	0	5
	ARB	1	2	1		0	0	4
	LAND	1	0	0	0	0	0	1
	Total							**10**

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

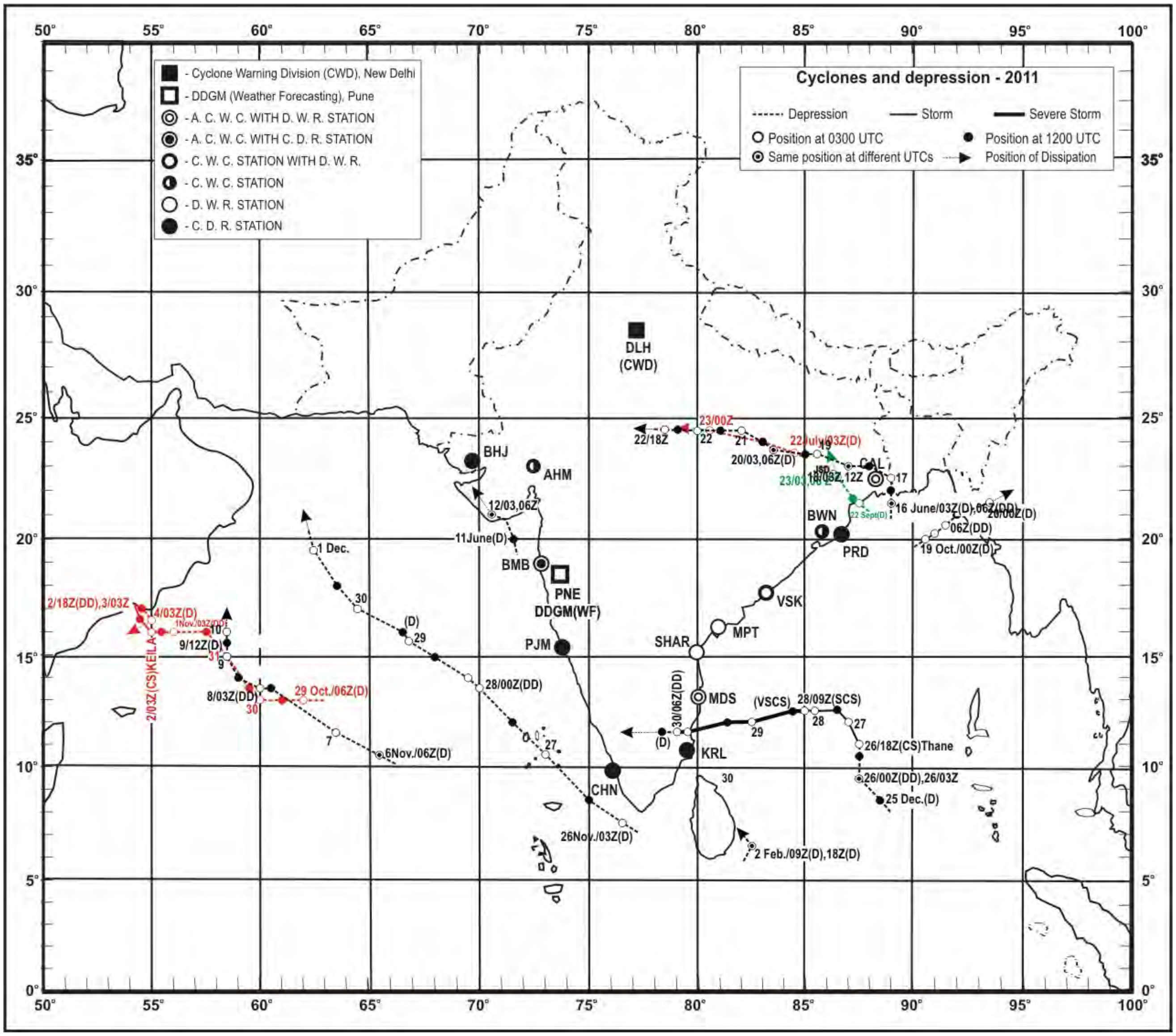


Fig. 2.1 Tracks of the cyclonic disturbances formed over the north Indian Ocean during the year, 2011

2.1 Depression over the Bay of Bengal (02-03 February, 2011)

2.1.1 Introduction:

A depression formed over the Bay of Bengal off Sri Lanka coast on 2nd Feb. 2011. Remaining practically stationary, it weakened into a well marked low pressure area at 0000 UTC of 03 Feb. 2011. The salient feature of the system included its short life (about 15 hours) and practically no movement.

2.1.2 Genesis:

In association with a deep trough in easterlies, an area of convective clouds persisted over southwest Bay of Bengal on 1st and 2nd Feb. 2011. The satellite imageries showed a developing low level circulation centre associated with increasing deep convection over the region. It was seen as a vortex with T1.0 in the evening of 1st Feb. 2011. As a result, well marked low pressure area formed over southwest Bay of Bengal off Sri Lanka coast in the evening of 1st Feb. 2011.

Moderate vertical wind shear of horizontal wind (10-20 knots) prevailed over the region on 2nd Feb. 2011 morning. Also, there was good divergence aloft as the upper tropospheric ridge lay along 12^0N at 200 hPa level. Sea surface temperature was favourable as it was about $26\text{-}28^0$C. The upper level divergence and low level relative vorticity increased gradually from 1st to 2nd February 2011. Due to all these favourable synoptic and environmental features, the well marked low pressure area concentrated into a depression and lay centred at 0900 UTC of 2nd February 2011 over southwest Bay of Bengal near lat. 6.5^0N and long. 82.5^0 E, about 100 km southeast of Pottuvil (Srilanka, 43475). Maximum sustained surface wind was about 25 knots. The estimated central pressure was 1002 hPa. According to Dvorak's classification, the intensity of the system was T1.5. The meso-scale convective clusters in association with the system merged gradually along with increase in deep convection. Associated moderate to intense convection was seen over southwest Bay of Bengal, adjoining Srilanka, Comorian, Gulf of Mannar, Palk Strait and coastal Tamilnadu. The lowest cloud top temperature was about -55^0C.

2.1.3 Intensification and movement:

As the system lay close to equator, the Coriolis force was not sufficient enough for intensification of the system. Further, the ocean thermal energy over the region was less than 40 KJ/cm^2 which was not favourable for the intensification. The Madam Julian Oscillation (MJO) index lay over equatorial Indian ocean with lower amplitude which was favourable for genesis (formation of depression) but not for further intensification. The stream line analysis of 1200 UTC of 02nd Feb. 2011 indicated existence of depression under a region with approximately 20-25 knots of vertical wind shear. Considering all these, the depression did not intensify further. The SSMIS images at 1418 UTC of 02nd Feb. 2011 showed lack of banding. The depression weakened into a well marked low pressure area at 0000 UTC of 03rd Feb. 2011 over southwest Bay of Bengal. The track of the system is shown in fig. 2.1. The best track parameters of the system are given in Table 2.1.1. The typical satellite imageries are shown in fig. 2.1.1.

Table 2.1.1 The best rack position and other parameters of depression over the Bay of Bengal during 02-03 Feb. 2011

Date	Time (UTC)	Centre lat.^{0} N/ long. ^{0} E	C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
02.02.2011	0900	6.5/82.5	1.5	1002	25	3	D
	1200	6.5/82.5	1.5	1002	25	3	D
	1800	6.5/82.5	1.5	1002	25	3	D
03.02.2011	0000	Weakened into a well marked low pressure area over southwest Bay of Bengal.					

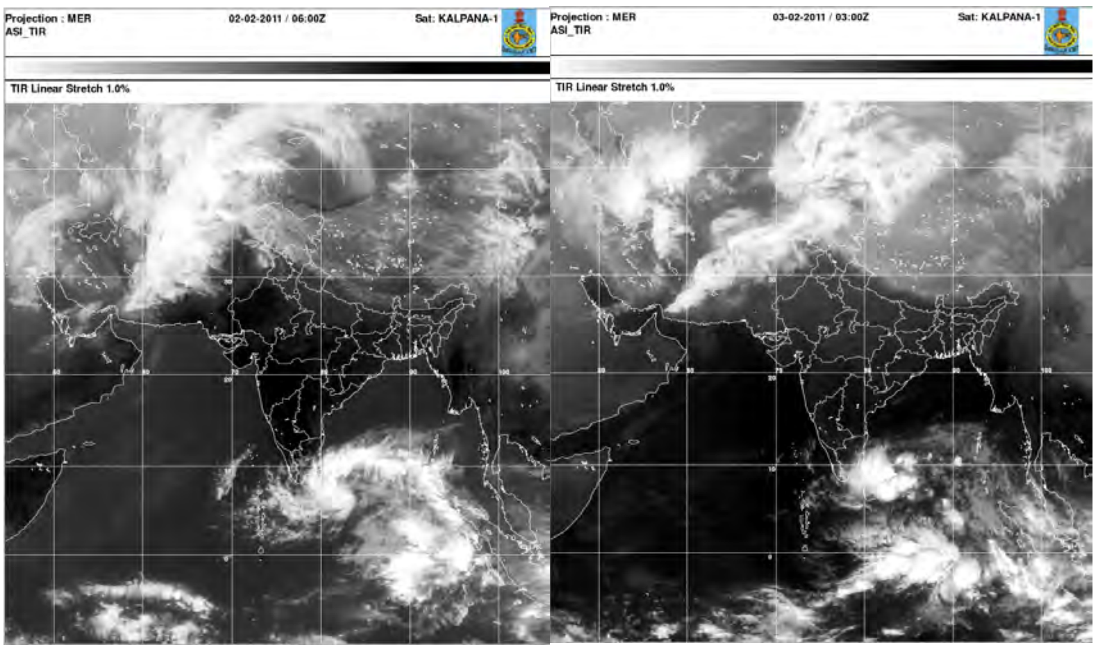


Fig. 2.1.1. Typical Satellite imageries at 0300 UTC of 02 & 03 Feb. 2011 in association with the depression over the Bay of Bengal.

2.1.4 Realised weather:

No significant weather occurred over India. Isolated heavy rainfall occurred over east coast of Sri Lanka. Squally winds (40-50 kmph) prevailed also along east coast of Sri Lanka.

2.1.5. Damage

About six fishermen died in Sri Lanka due to this system

2.2 Depression over the Arabian Sea (11-12 June 2011)

2.2.1 Introduction:

During the onset phase of monsoon, a depression formed over northeast and adjoining east central Arabian Sea on 11th June 2011. It moved north-northeast wards and crossed Saurashtra coast, about 25 km east of Diu around 2200 UTC of 11 June and weakened into a well marked low pressure area over Saurashtra and adjoining areas at 1200 UTC of 12th June It caused isolated heavy to very heavy falls and isolated extremely heavy falls over Saurashtra & Diu and Konkan & Goa. It helped in northward advance of monsoon along the west coast of India.

2.2.2 Genesis:

During onset phase of monsoon a trough of low pressure area ran from south Gujarat coast to Kerala coast on 2nd June with an embedded upper air cyclonic circulation over southeast and adjoining east central Arabian Sea. It slowly moved northwards and lay over east central Arabian Sea on 5th June. Under its influence, a low pressure area formed over east central Arabian Sea and neighbourhood on 6th June with associated cyclonic circulation extending upto mid-tropospheric levels. It persisted over the same area till 10th June maintaining same intensity.

According to INSAT imagery, a vortex formed over east central Arabian Sea with T1.0 and lay centred at 0000 UTC of 8th June near lat. 17.0^{0}N and long. 70.0^{0}E and near lat. 19.0^{0}N and long. 71.0^{0}E at 0300 UTC of 11th June. The broken intense convection in association with the system became slowly organised. Vertical wind shear over the region on 11th June was low to moderate (10-20 knots). The upper tropospheric ridge at 200 hPa level ran along 24^0 N. Hence the system lay to the south of the upper tropospheric ridge and there was favourable divergence in the upper tropospheric level. In the lower levels, the convergence increased with increased pressure gradient and cross equatorial flow over the Arabian Sea. The sea surface temperature was about 30-32^{0}C over the eastcentral Arabian Sea. The Madden Julian Oscillation (MJO) index was lying in phase 4 which is favaouable for genesis of depression.

Due to all the above mentioned favourable factors, the low pressure area over the east central Arabian Sea concentrated into a depression over northeast Arabian Sea off Maharashtra-Gujarat coast and lay centred at 1200 UTC of 11th June near lat. 20.0^{0}N and long. 71.5^{0}E, about 180 km northwest of Mumbai and 150 km southeast of Veraval. The associated maximum sustained wind sped was about 25 knots. However winds were stronger over southern part under the influence of the monsoon surge. The intensity of the system according to Dvorak's classification was T1.5. The associated broken intense to very intense convection (with cloud top temperature of -77^{0}C) lay over Arabian Sea between lat 16.5^{0}N & 21.0^{0}N and to the east of long 65.5^{0}E.

2.2.3 Intensification and movement:

The ocean heat content, however, was less than 60 KJ/cm^2 on 11th and 12th June which was not favourable for intensification. The amplitude of MJO index was also less than 1. Further, the depression was lying close to the coast. Considering all these, the depression did not intensify further. It moved north-northwestwards and crossed Saurashtra coast, about 25 km east of Diu around 2200 UTC of 11th June and lay centred at 0300 UTC of 12th June over Saurashtra and neighbourhood, about 70 km south-southwest of Amreli (Gujarat) The depression moved further northwestwards and weakened into a well marked low pressure area over Saurashtra and adjoining northeast Arabian Sea at 1200 UTC of 12^{th} June 2011. The track of the system is shown in fig. 2.1. The best track parameters of the system area given in Table 2.2.1. The typical satellite imageries of the system are shown in Fig. 2.2.1. The relative vorticity at 850 hPa level, vertical wind shear between 200 & 850 hPa and upper level wind based on initial condition of 0000 UTC of 11^{th} and 12^{th} June of ECMWF analysis are shown in Fig 2.2.2.

Table 2.2.1 Best track positions and other parameters of the depression over the Arabian Sea during 11-12 June, 2011

Date	Time (UTC)	Centre lat.^{0} N/ long. ^{0} E	C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
11-06-2011	1200	20.0/71.5	1.5	996	25	4	D
	1800	20.0/71.5	1.5	996	25	4	D
	The system crossed Saurashtra (Gujarat) coast near lat. 20.8^{0}N/71.2^{0}E around 2200 UTC of 11 June 2011						
12-06-2011	0000	21.0/70.5	-	996	25	4	D
	0300	21.0/70.5	--	998	20	3	D
	0600	21.0/70.5	--	999	20	3	D
	1200	The system weakened into a well marked low pressure area over Saurashtra and adjoining northeast Arabian Sea.					

2.2.4 Realised weather:

(i) Rainfall:

Under the influence of the system, widespread rainfall with isolated heavy to very heavy falls occurred over Saurashtra & Kutch and Diu. The significant amount of 24 hours cumulative rainfall (>7 cm) recorded at 0300 UTC of date are follows:

12-6-2011

Saurashtra, Kutch& Diu :

Sutarapada 27, veraval 17, Kodinar 9, Talala and Upleta 8 each.

Konkan & Goa:

Murud 25, Roha 22, Tala 19, Mumbai (Santacruz) 18, Sudhagod 17, Mhasla 15, Thane, Malvan, Alibagh, Uran, Mumbai (Colaba) and Mangaon 11 Each, Kalyan and Dodamarg 10 each; Pen, Khalapur, Kankavli and Sawantwadi 9 each; Khed, Matheran, Ambernath, and Mahad 8 each; Ulhasnagar, Karjat, Kudal, Bhiwandi, Panvel, Canacona, Sangameshwar, Poladpur and Dapoli 7 each.

13-6-2011

Saurashtra, Kutch& Diu:

Mangrol 14, Sutrapada 8,

Konkan & Goa;

Vaibhavwadi 12, Thane Belapur 11, Dabolim, Canacona and Poladpur 9 each; Kankavli and Sangamneshwar 8 each; Guhagar 7.

(ii) Maximum sustained wind:
Maximum sustained wind of 40-50 kmph was reported along Saurashtra and Diu coast due to this system.

2.2.5 Damage:

No Damage was reported due to this system.

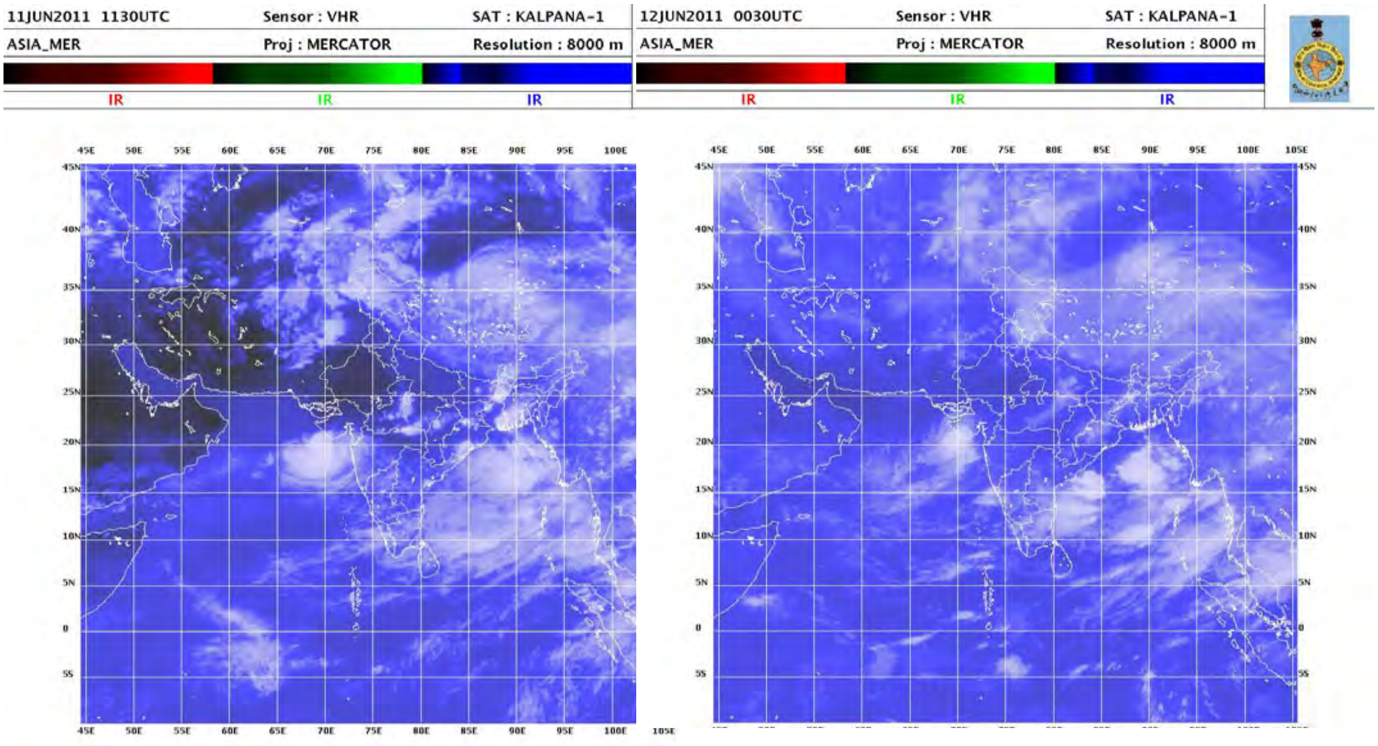


Fig. 2.2.1. Typical Satellite imageries of the Depression (11-12 June,2011)

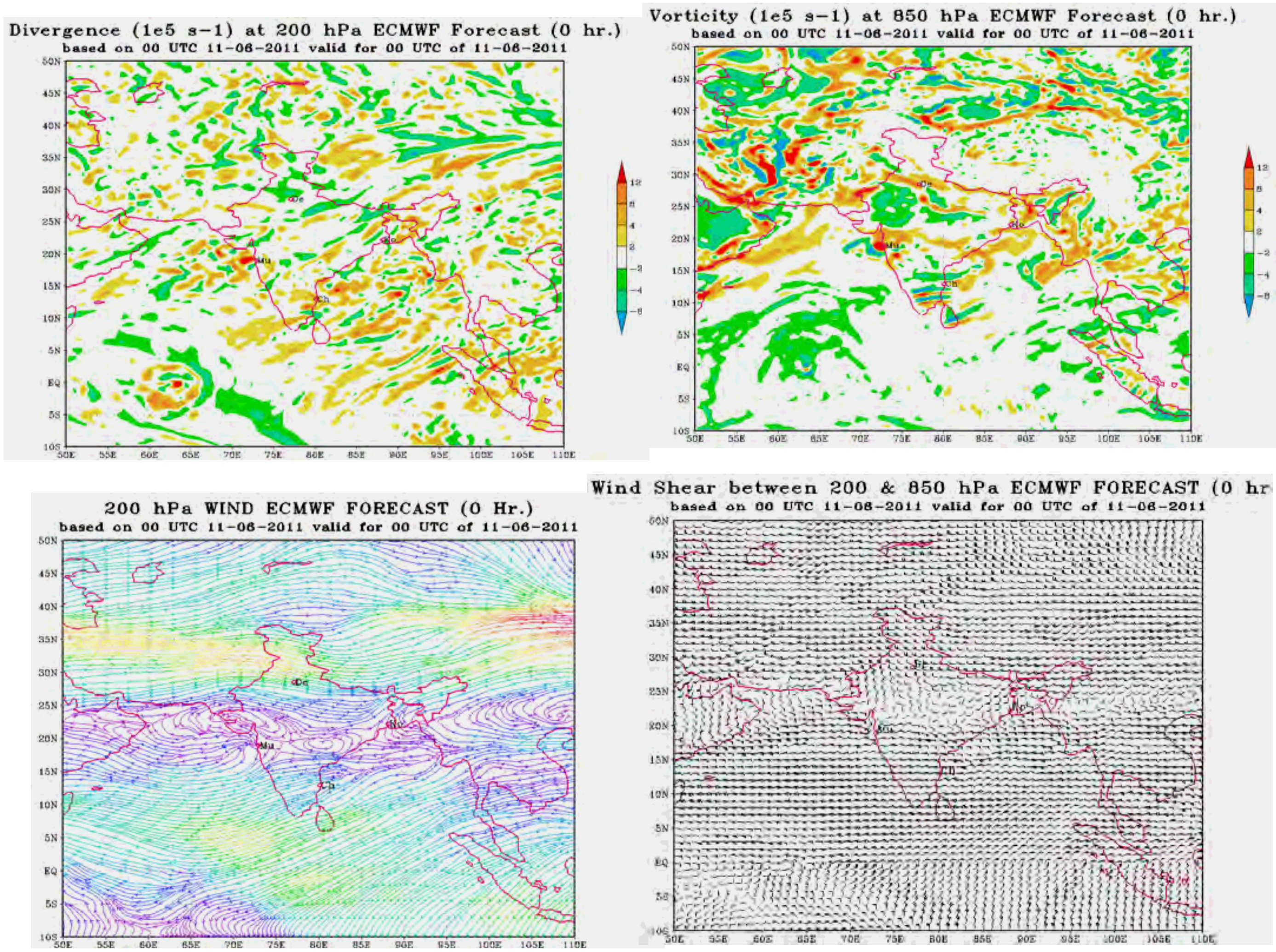


Fig. 2.2.2(a) (i) upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) wind at 200 hPa level (iv) vertical wind shear of horizontal wind between 200 & 850 hPa level based on the ECMWF model analysis of 0000 UTC of 11th June 2011.

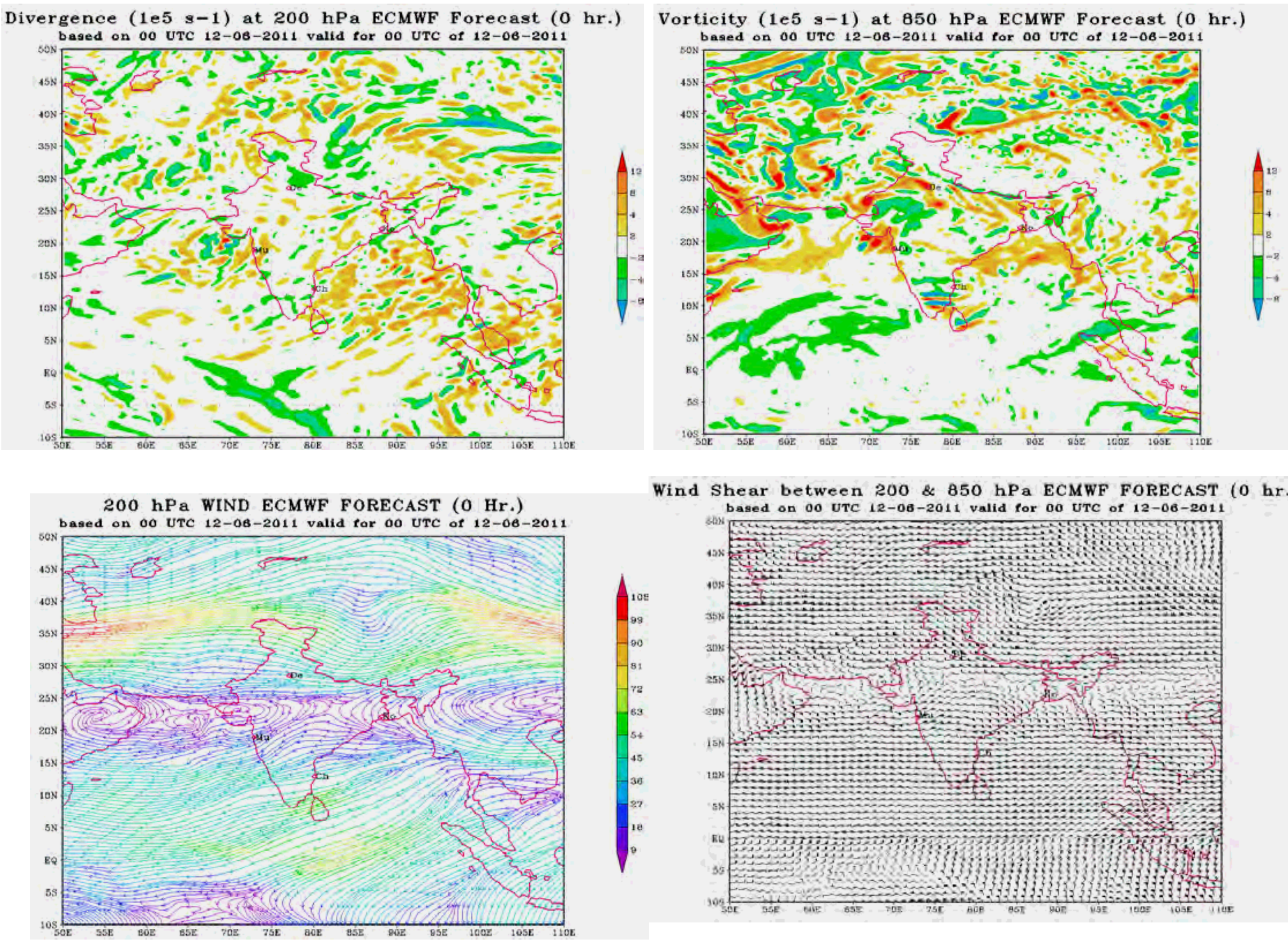


Fig. 2.2.2(b) (i) upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) wind at 200 hPa level (iv) vertical wind shear of horizontal wind between 200 & 850 hPa level based on the ECMWF model analysis of 0000 UTC of 12th June 2011.

2.3 Deep depression over the Bay of Bengal (16-23 June, 2011)

2.3.1 Introduction:

A deep depression formed over north Bay of Bengal on 16th June. Moving northwards, it crossed west Bengal-Bangladesh coast, about 100 km east of Sagar Island between 1100 and 1200 UTC of 16th June. It then continued northward movement for some time, then moved west-northwestwards across Gangetic West Bengal, Jharkhand, north Chhattisgarh and west Madhya Pradesh during 17-23 June and weakened gradually. It weakened into a well marked low pressure area on 23rd

June over west Madhya Pradesh. It ushered southwest monsoon over eastern and central India and caused excess rainfall over these regions.

2.3.2 Genesis:

During onset phase of monsoon, a cyclonic circulation extending upto mid-troposhperic level lay over northwest Bay of Bengal on 12th June 2011. Under its influence, a low pressure area formed over northwest Bay of Bengal on 14th June, which became well marked on 15th June. The favourable conditions like persistent convection over the region and its gradual organisation, low to moderate vertical wind shear(10-20 knots), upper level divergence, low level convergence, increase in relative vorticity at lower levels and higher sea surface temperature (30-32^{0}C) prevailed from 15th onwards. Also, the Madden Julian Oscillation (MJO) index was lying over phase 5 (northwest Pacific) which is favourable for cyclogenesis. Under these conditions, the well marked low pressure area concentrated into a depression and lay centred at 0000 UTC of 16th June over northwest Bay of Bengal near lat. 21.5^{0}N and long. 89.0^{0}E, about 100 km east-southeast of Sagar Island. The sustained maximum wind speed was 25 knots. However, the wind over the southern parts was higher under the influence of the monsoon surge. The organized broken intense to very intense convection lay over north Bay of Bengal to the north of 16^{0}N. The intensity of the system was estimated as T1.5 as per Dvorak's classification based on Kalpana imageries. The upper tropospheric ridge ran along 23^{0}N on 16th June.

2.3.3 Intensity and Movement:

Under the influence of above favourable conditions, the system intensified further into a deep depression at 0600 UTC of 16th June. it moved northward and crossed West Bengal- Bangladesh coast near lat 21.8^{0}N and long. 89.0^{0}E, about 100 km east of Sagar Island. It then continued to move northwards for some time over Gangetic West Bengal till 17th morning. It then moved slowly west-northwestwards across Gangetic West Bengal, Jharkhand, north Chhattisgarh, southeast Uttar Pradesh and northwest Madhya Pradesh and weakened gradually. It weakened into a depression at 0600 UTC of 20th June over north Chhattisgarh and neighbourhood and into a well marked low pressure area over west Madhya Pradesh and neighbourhood on 23rd June 2011.

An important feature of the system was abnormal pressure drop at the centre of the system (max 12 hPa) over the land, even though the maximum surface wind speed was reported as 30-35 knots over Gangetic West Bengal. The best track of the system is shown in Fig. 2.1. The best track parameters are shown in Table 2.3.1. The satellite imageries are shown in Fig. 2.3.1. The DWR Kolkata imageries are shown in Fig. 2.3.2 &2.3.3 respectively. The relative vorticity, vertical wind shear and upper level winds are shown in Fig. 2.3.4(i-viii) based on ECMWF analysis.

Table 2.3.1: Best track positions and other parameters of the deep depression over the Bay of Bengal during 16 -23 June, 2011

Date	Time (UTC)	Centre lat.^{0} N/ long. ^{0} E	C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
16-06-2011	0300	21.5/89.0	1.5	986	25	6	D
	0600	21.5/89.0	1.5	986	25	6	DD
	The system crossed west Bengal-Bangladesh coast near 21.8^{0}N/89.0^{0}E between 1100 -1200 UTC.						
	1200	22.0/89.0	--	984	30	6	DD
	1800	22.5/89.0	--	984	30	6	DD
17-06-2011	0000	22.5/89.0	--	984	30	8	DD
	0300	22.5/89.0	--	984	30	8	DD
	0600	22.8/88.5	--	978	35	12	DD
	1200	23.0/88.0	--	982	25	10	DD
	1800	23.0/88.0	--	984	25	8	DD
18-06-2011	0000	23.0/87.5	--	984	25	8	DD
	0300	23.0/87.0	--	984	25	8	DD
	0600	23.0/87.0	--	984	25	8	DD
	1200	23.0/87.0	--	984	25	8	DD
	1800	23.0/86.5	--	986	25	8	DD
19-06-2011	0000	23.0/86.0	--	986	25	8	DD
	0300	23.5/85.5	--	987	25	8	DD
	0600	23.5/85.5	--	987	25	8	DD
	1200	23.5/85.0	--	987	25	7	DD
	1800	23.5/84.5	--	987	25	7	DD
20-06-2011	0000	23.5/84.0	--	987	25	7	DD
	0300	23.7/83.5	--	987	25	7	DD
	0600	23.7/83.5	--	990	20	4	D
	1200	24.0/83.0	--	990	20	4	D
	1800	24.0/83.0	--	990	20	4	D
21-06-2011	0000	24.5/82.5	--	990	20	4	D
	0300	24.5/82.0	--	990	20	4	D
	0600	24.5/81.5	--	990	20	4	D
	1200	24.5/81.0	--	990	20	4	D
	1800	24.5/81.0	--	990	20	4	D
22-06-2011	0000	24.5/80.5	--	991	20	4	D
	0300	24.5/80.0	--	992	20	3	D
	0600	24.5/80.0	--	992	20	3	D
	1200	24.5/79.1	--	994	20	3	D
	1800	24.5/78.5	--	992	20	3	D
23-06-2011	0000	The system weakened into a well marked low pressure area over west Madhya Pradesh and neighbourhood.					

Table 2.3.2: Observed track of deep depression based on DWR, Kolkata

Date	Time (UTC)	Lat (Deg) North	Long (Deg) East
17.06.2011	0004	22.2	88.8
	0104	22.3	88.7
	0204	22.4	88.5
	0304	22.5	88.4
	0404	22.5	88.3
	0504	22.5	88.3
	0606	22.6	88.2
	0706	22.5	88.2
	0806	22.6	88.1
	0906	22.5	88.1
	1006	22.6	88.0
	1106	22.6	88.0
	1206	22.6	87.9
	1306	22.5	87.7
	1406	22.6	87.6
	1506	22.7	87.4
	1606	22.7	87.3
	1706	22.8	87.3
	1806	22.9	87.2
	1906	22.8	87.2
	2006	22.8	87.1
	2106	22.9	87.1
	2206	23.0	87.0
	2306	23.1	87.0

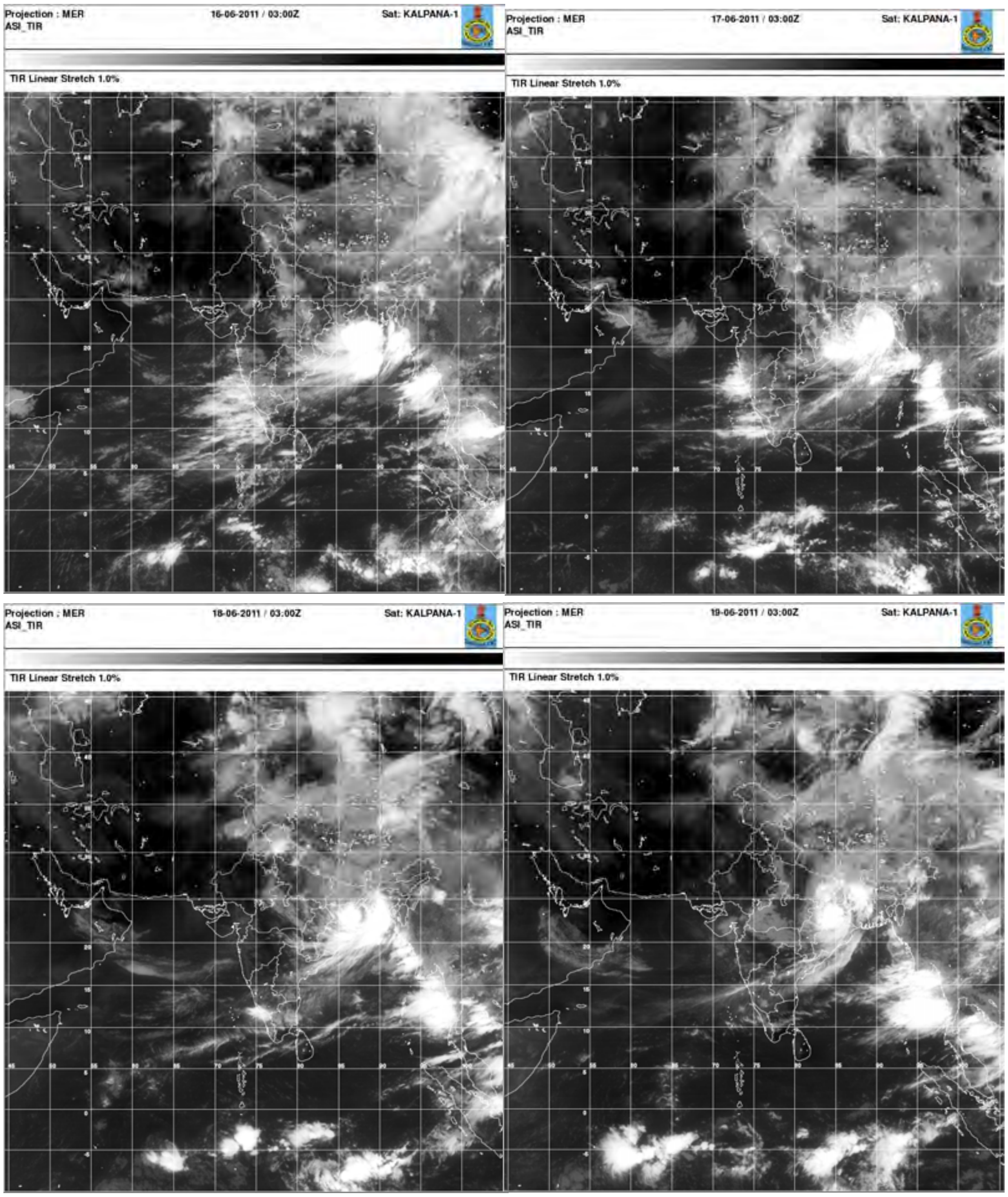


Fig. 2.3.1 (i) Typical Satellite imageries at 0300 UTC of 16-19 June 2011 in association of the system.

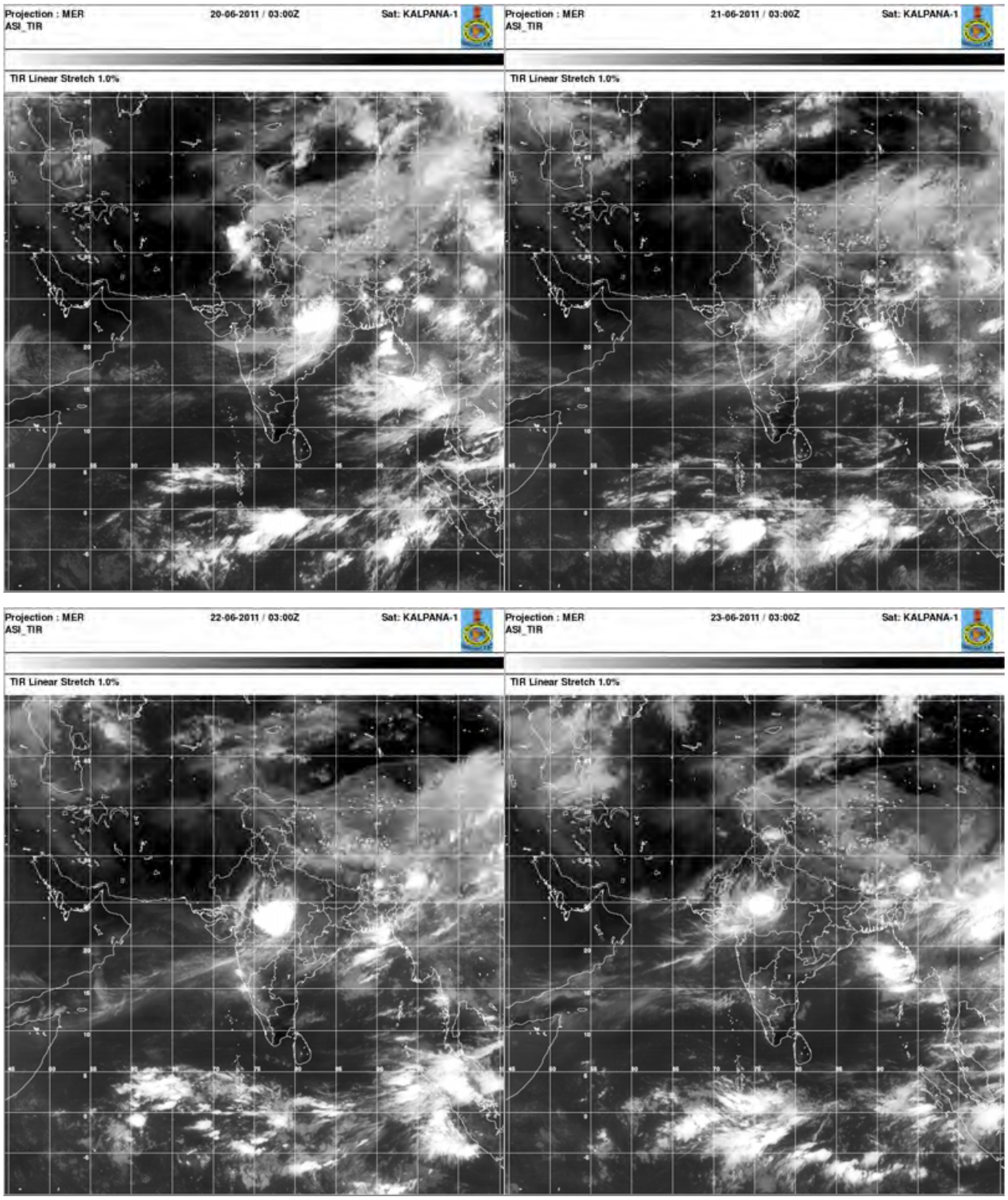
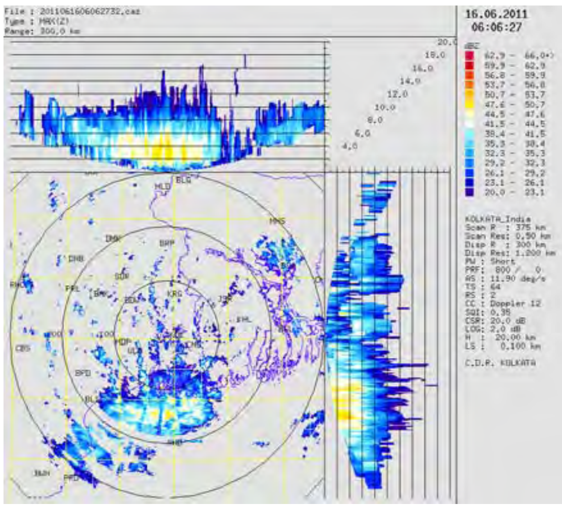
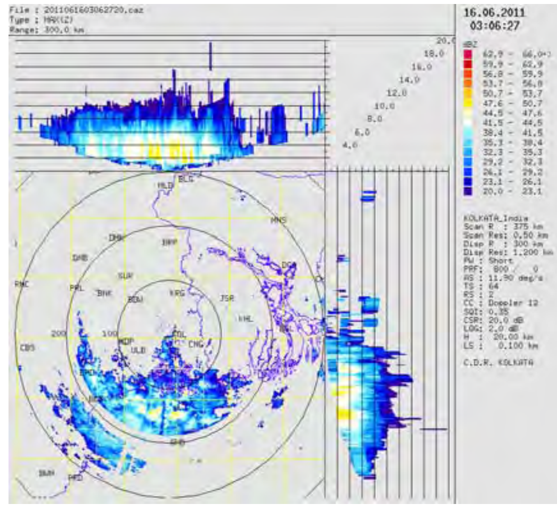


Fig.2.3.1 (ii) Typical Satellite imageries at 0300 UTC of 20-23 June 2011 in association of the system.

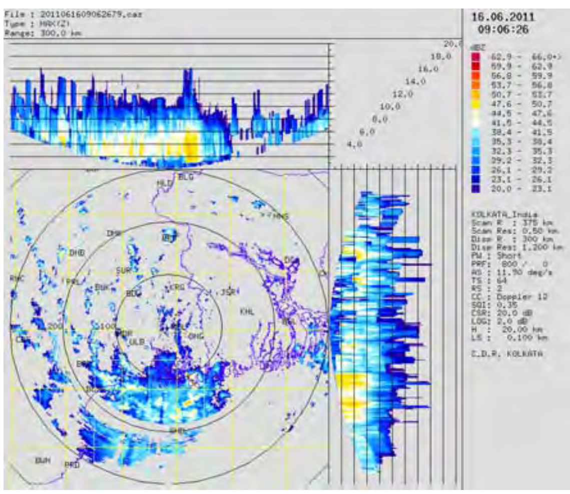
(a) 0300 UTC (16.06.2011)



(b) 0600 UTC (16.06.2011)



(c) 0900 UTC (16.06.2011)



(d) 1200 UTC (16.06.2011)

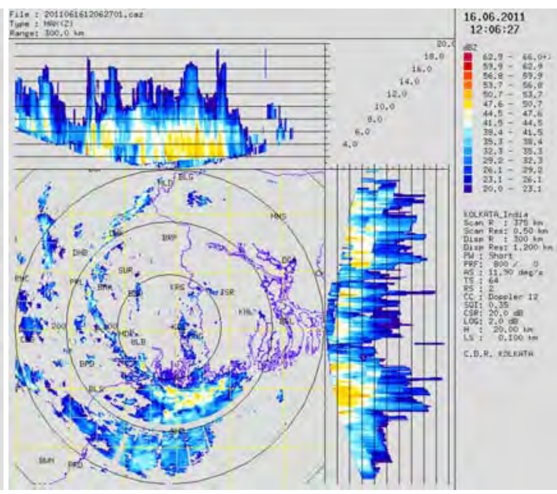
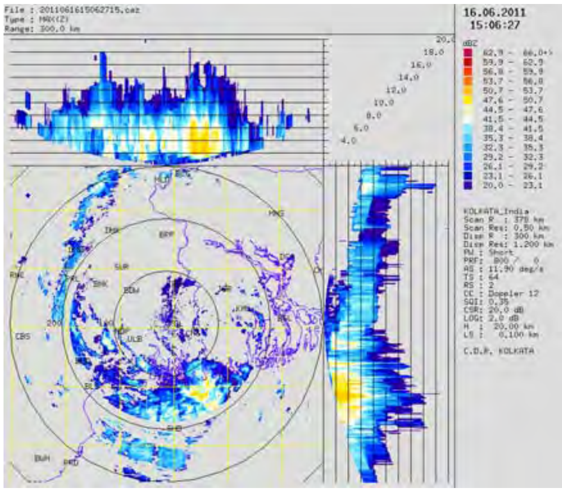
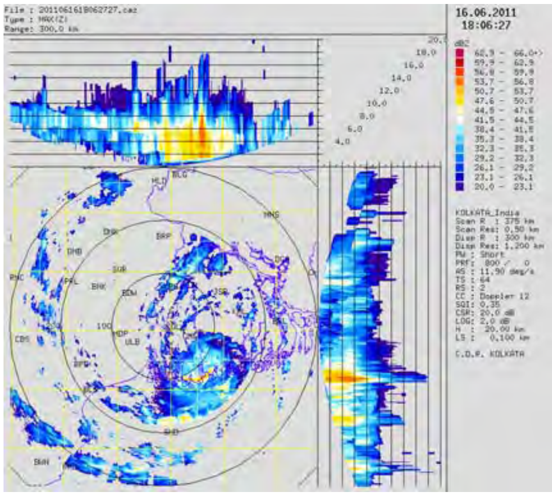


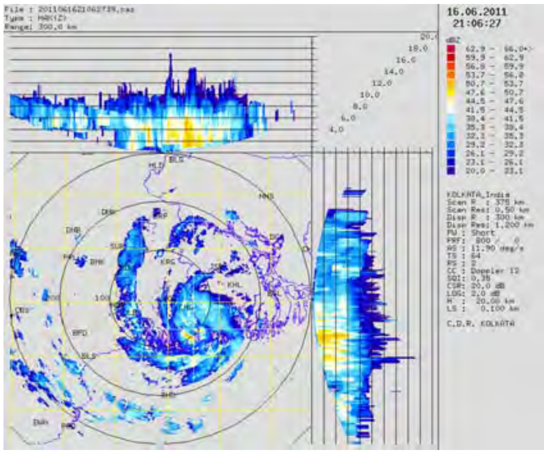
Fig. 2.3.2. Max Z imageries of Deep Depression (300 km Range) during 16 to 18th June 2011 as observed by DWR, Kolkata



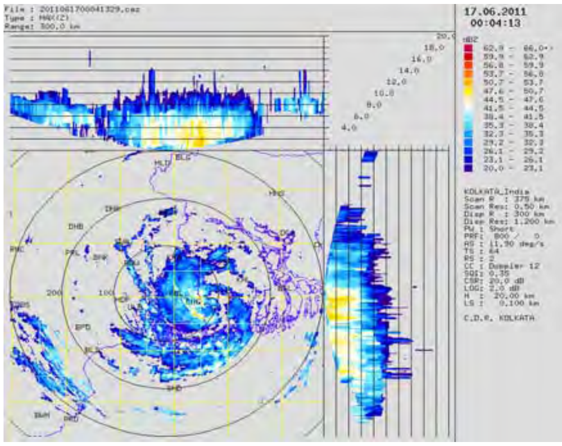
(e) 1500 UTC (16.06.2011)



(f) 1800 UTC (16.06.2011)

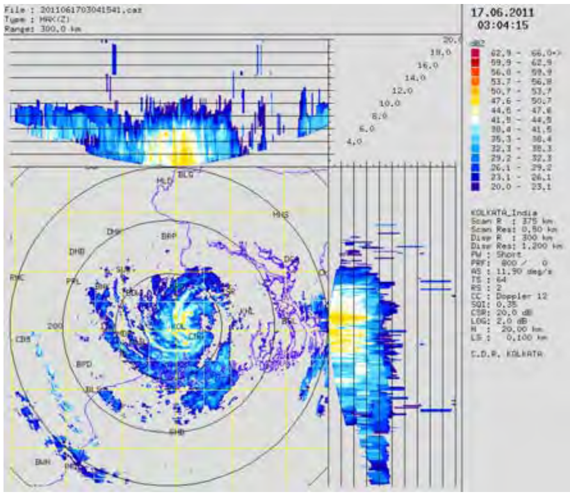


(g) 2100 UTC (16.06.2011)

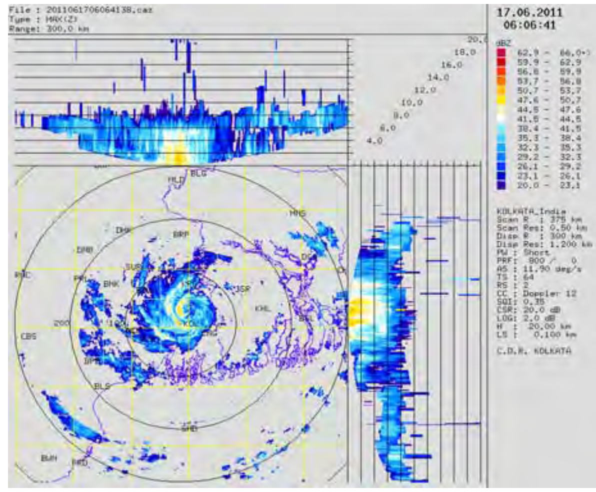


(h) 0000 UTC (17.06.2011)

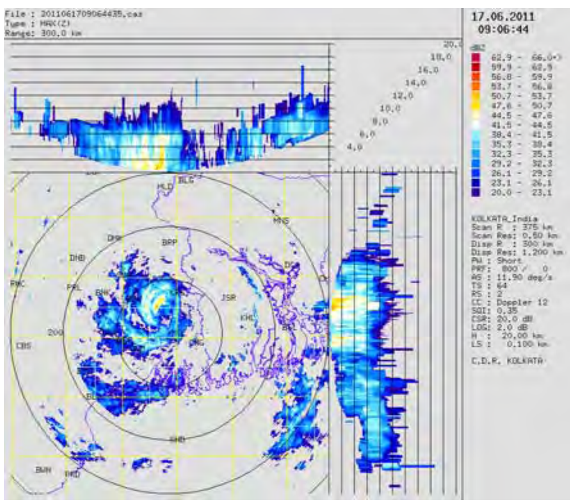
Fig. 2.3.2. (continued) Max Z imageries of Deep Depression (300 km Range) during 16 to 18th June 2011 as observed by DWR, Kolkata.



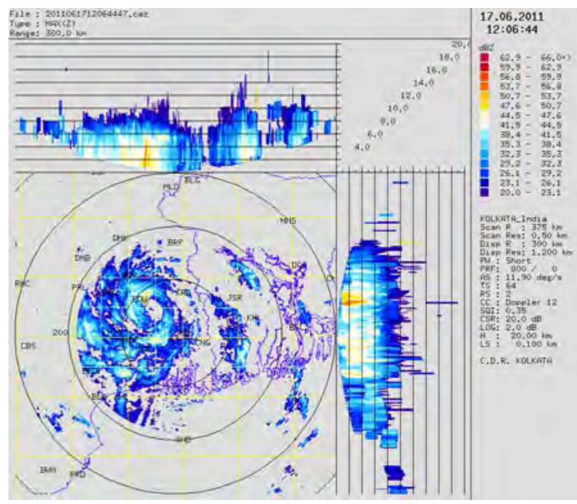
(i) 0300 UTC (17.06.2011)



(j) 0600 UTC (17.06.2011)

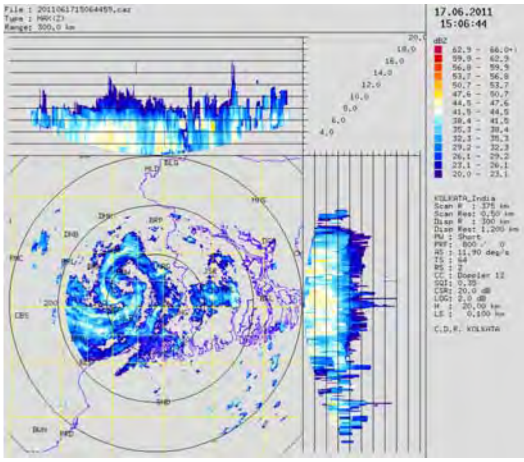


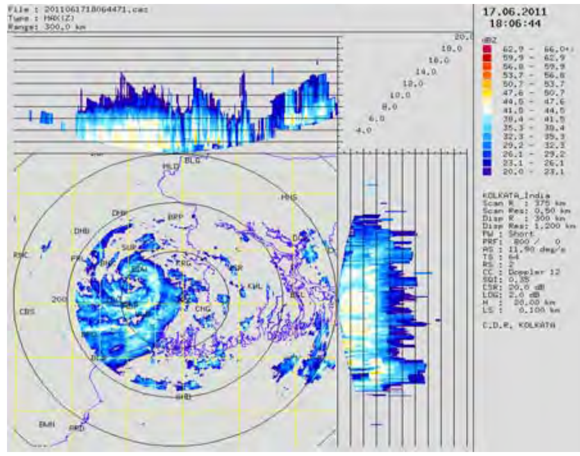
(k) 0900 UTC (17.06.2011)



(l) 1200 UTC (17.06.2011)

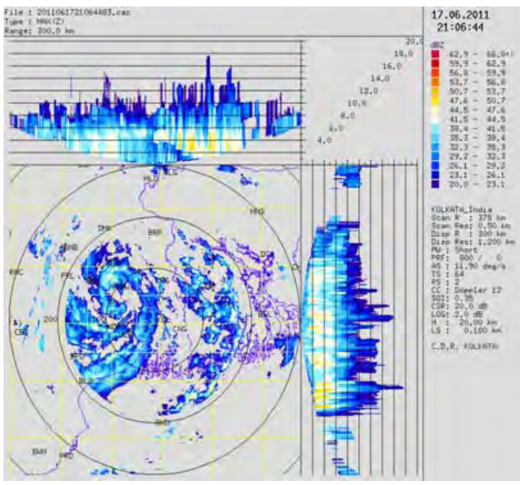
Fig. 2.3.2. (continued) Max Z imageries of Deep Depression (300 km Range) during 16 to 18th June 2011 as observed by DWR, Kolkata.

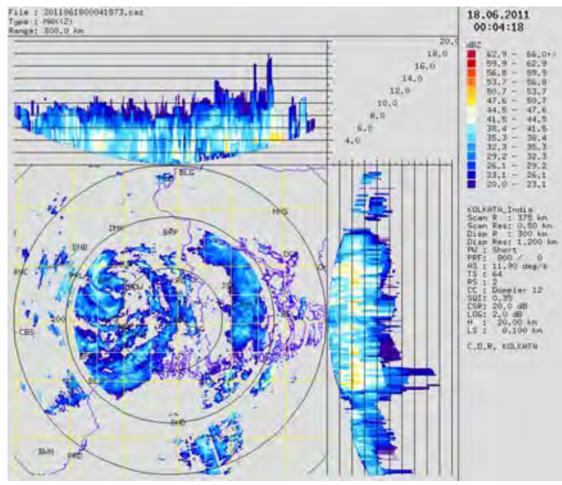




(m) 1500 UTC (17.06.2011)

(n) 1800 UTC (17.06.2011)

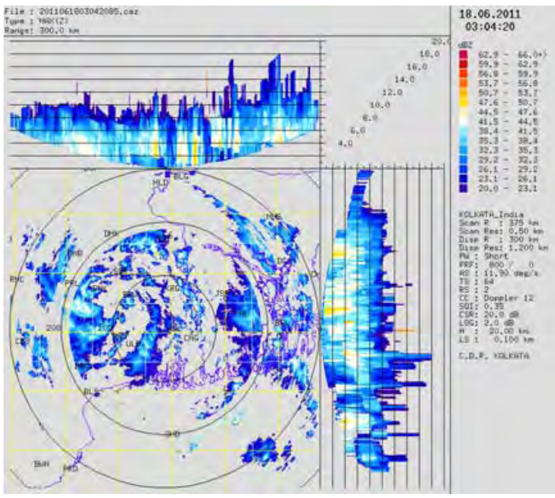




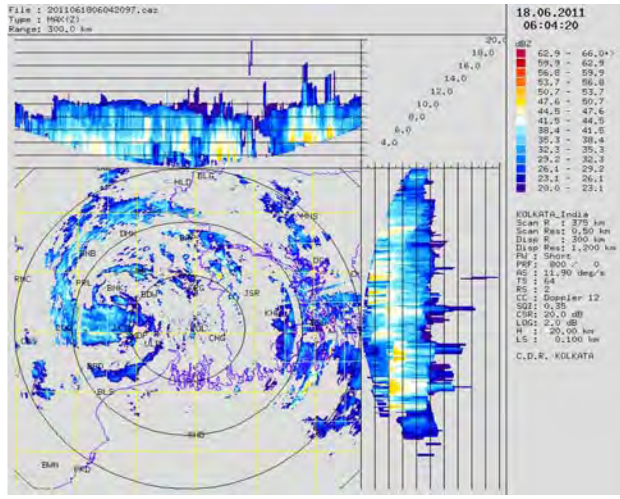
(o) 2100 UTC (17.06.2011)

(p) 0000 UTC (18.06.2011)

Fig. 2.3.2. (continued) Max Z imageries of Deep Depression (300 km Range) during 16 to 18th June 2011 as observed by DWR, Kolkata.



(q) 0300 UTC (18.06.2011)



(r) 0600 UTC (18.06.2011)

Fig. 2.3.2. (continued) Max_Z pictures of Deep Depression (300 km Range) during 16 to 18th June 2011 as observed by DWR, Kolkata

(a) 0300 UTC (17.06.2011) **(b) 0600 UTC (17.06.2011)**

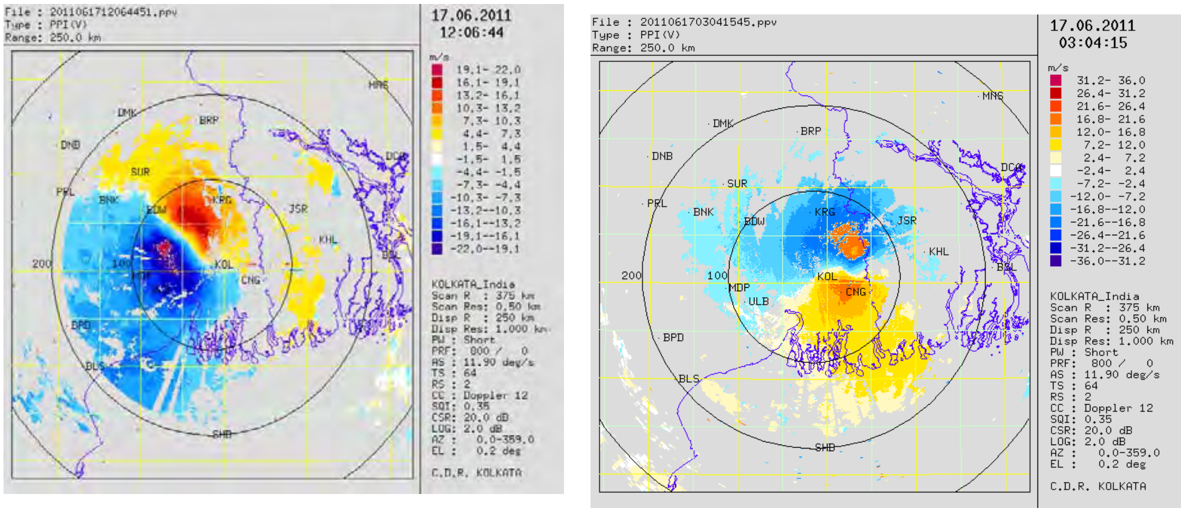
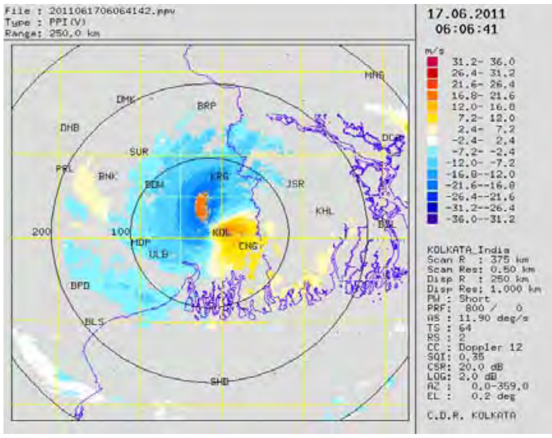
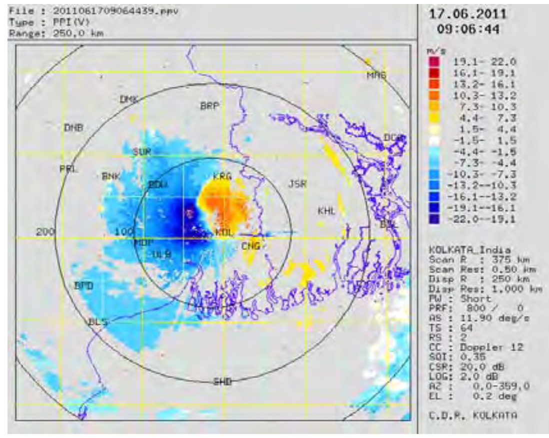


Fig.2.3.3 PPI _V imageries of deep depression (250 km Range)

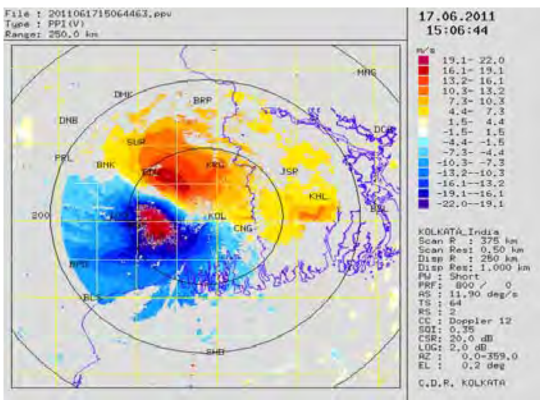
(c) 0900 UTC (17.06.2011)



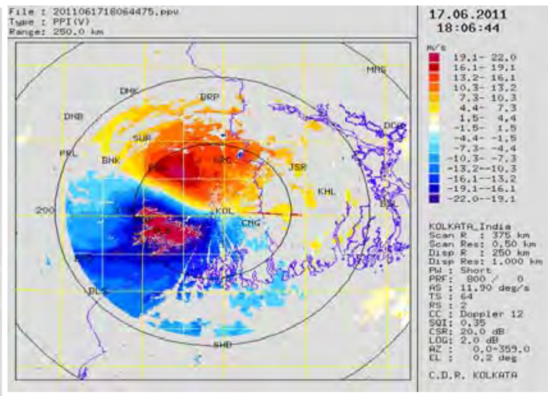
(d) 1200 UTC (17.06.2011)



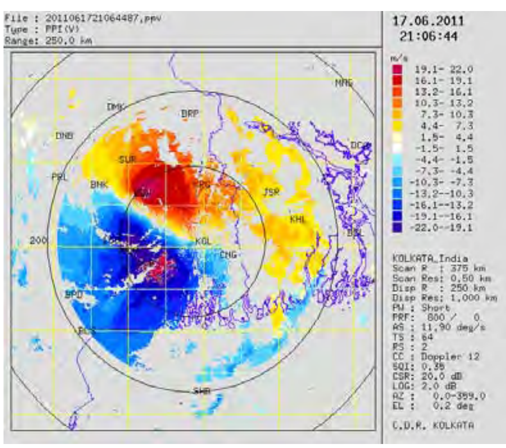
(e) 1500 UTC (17.06.2011)



(f) 1800 UTC (17.06.2011)



g) 1500 UTC (17.06.2011)



h) 1800 UTC (17.06.2011)

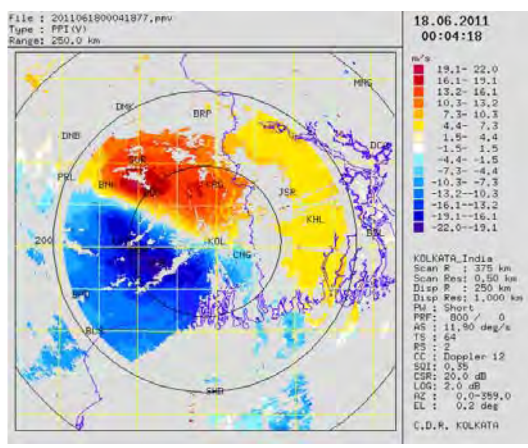


Fig.2.3.3 (continued) PPI _V imageries of deep depression (250 km Range) during 17th & 18th June 2011, as observed by DWR, Kolkata

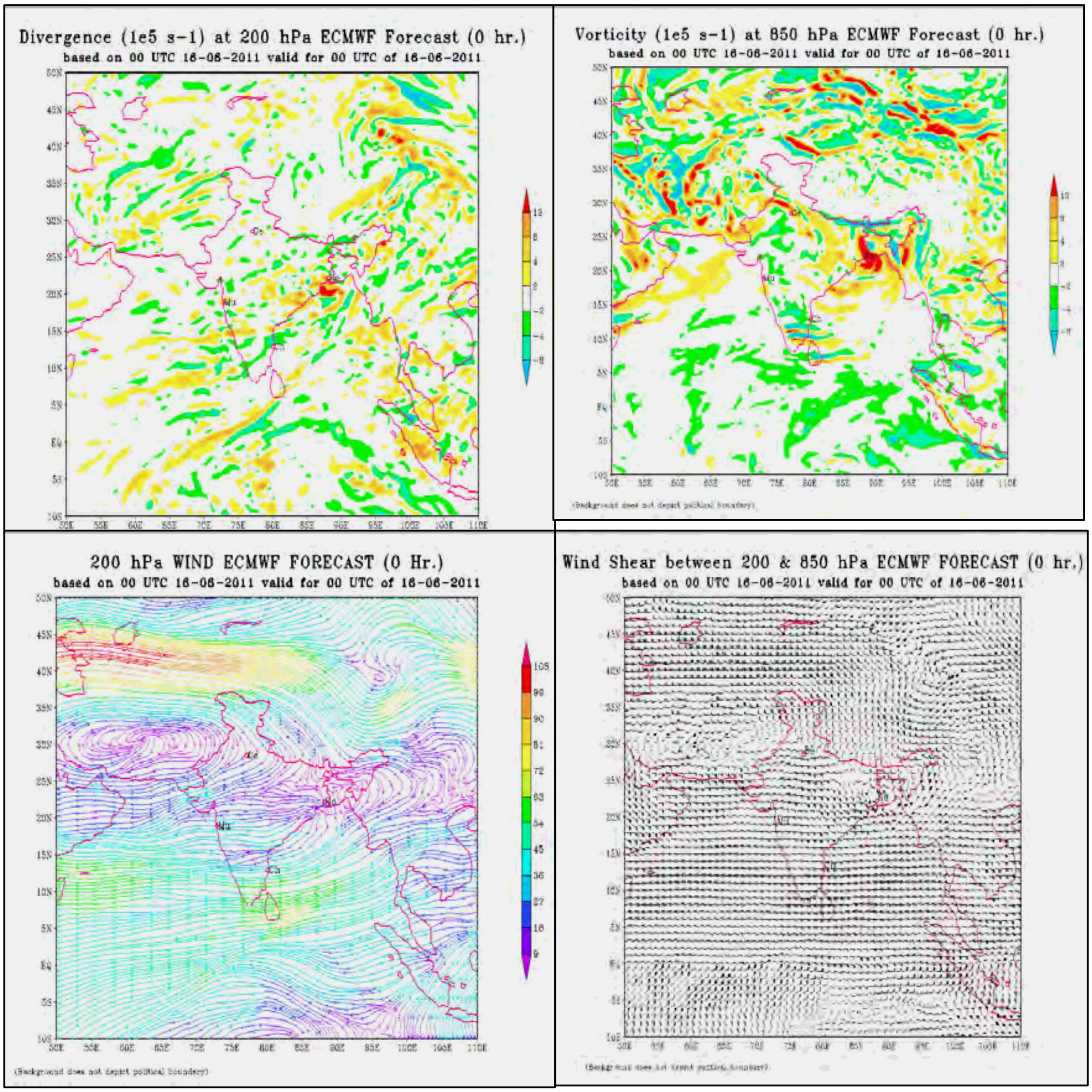


Fig. 2.3.4 Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) wind at 200 hPa level (iv) vertical wind shear of horizontal wind between 200 & 850 hPa level based on the ECMWF model analysis of 0000 UTC of 16th June 2011.

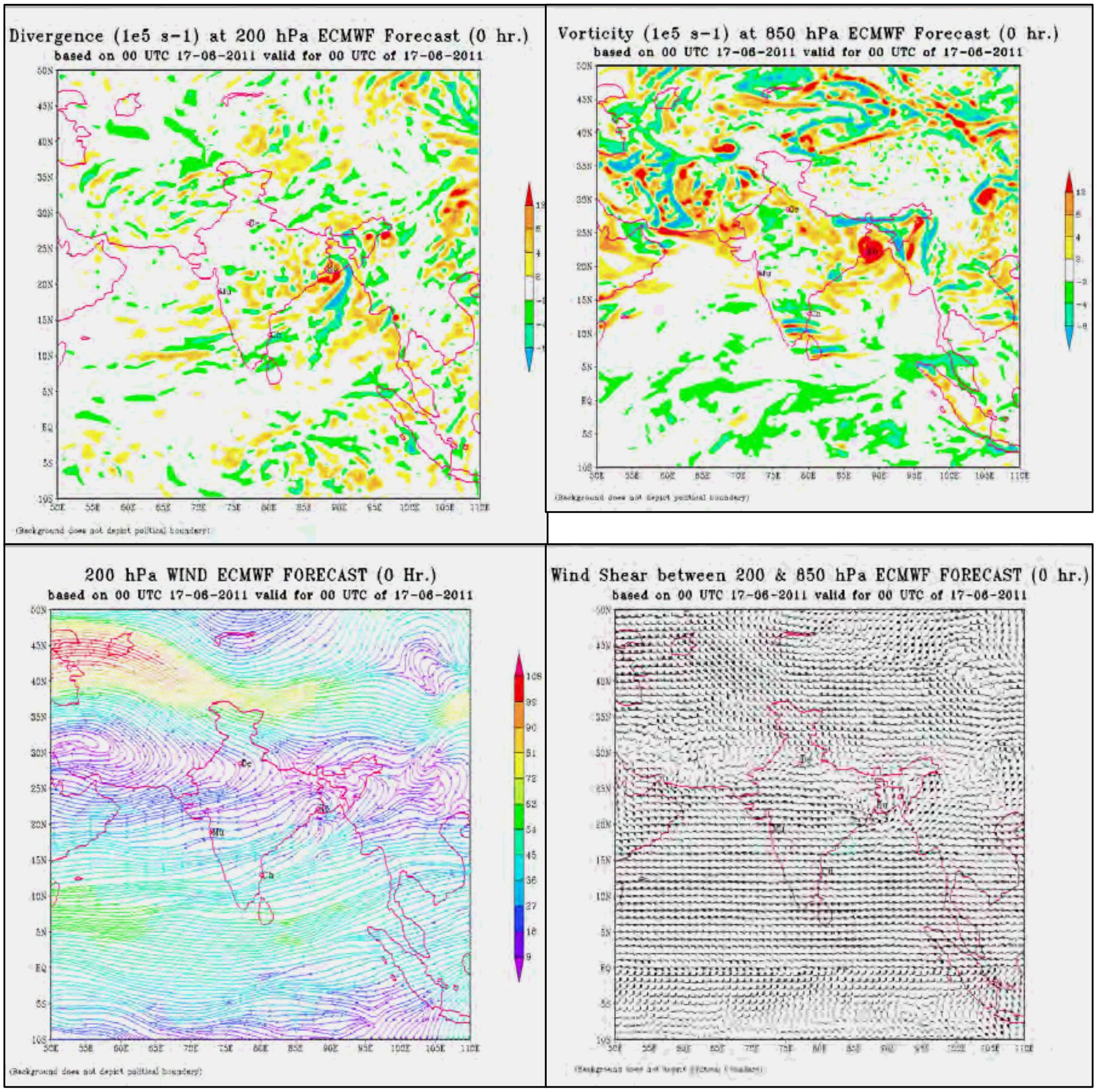


Fig. 2.3.4 (continued) upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) wind at 200 hPa level (iv) vertical wind shear of horizontal wind between 200 & 850 hPa level based on the ECMWF model analysis of 0000 UTC of 17th June 2011.

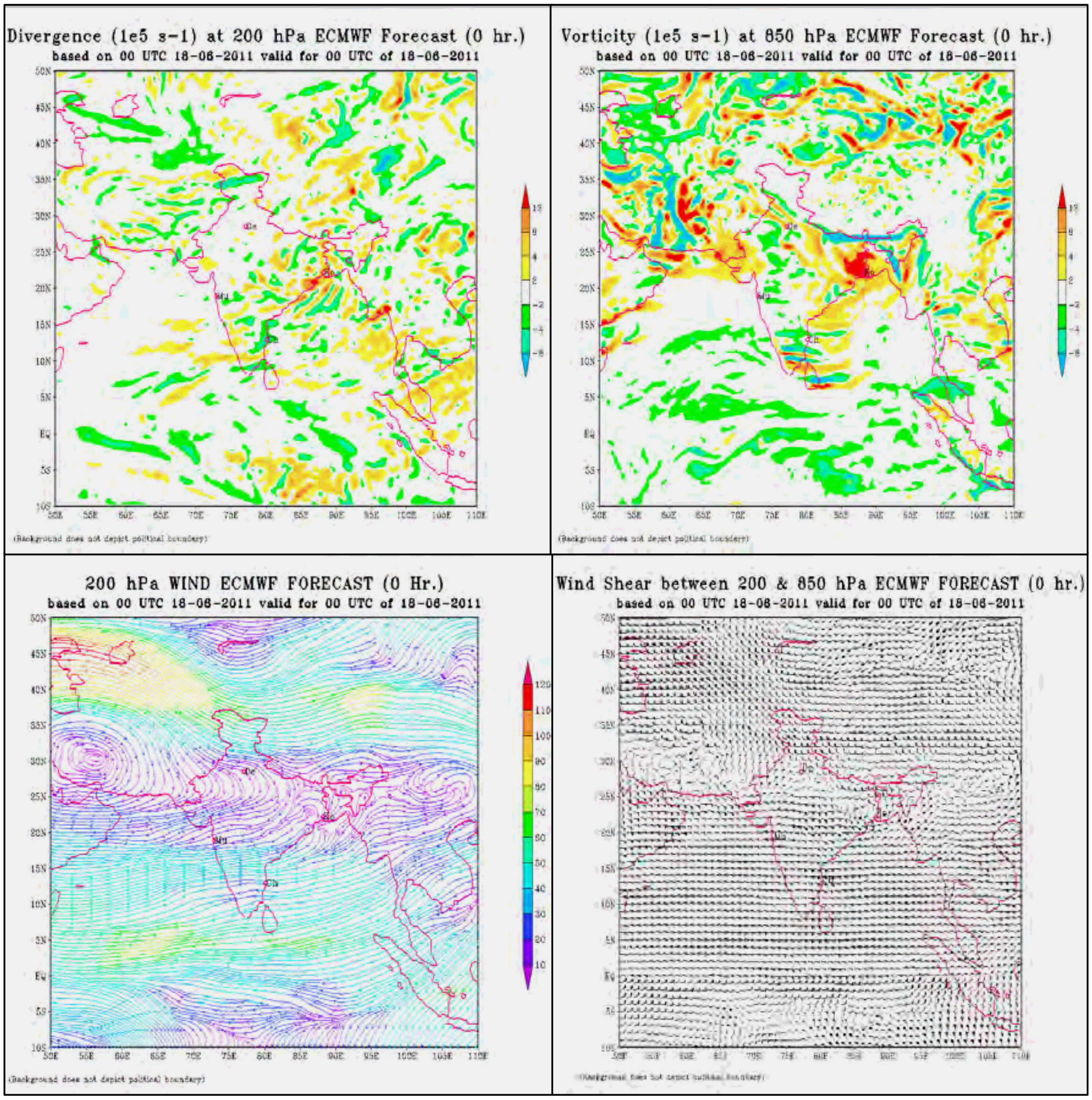


Fig. 2.3.4 (continued) upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) wind at 200 hPa level (iv) vertical wind shear of horizontal wind between 200 & 850 hPa level based on the ECMWF model analysis of 0000 UTC of 18th June 2011.

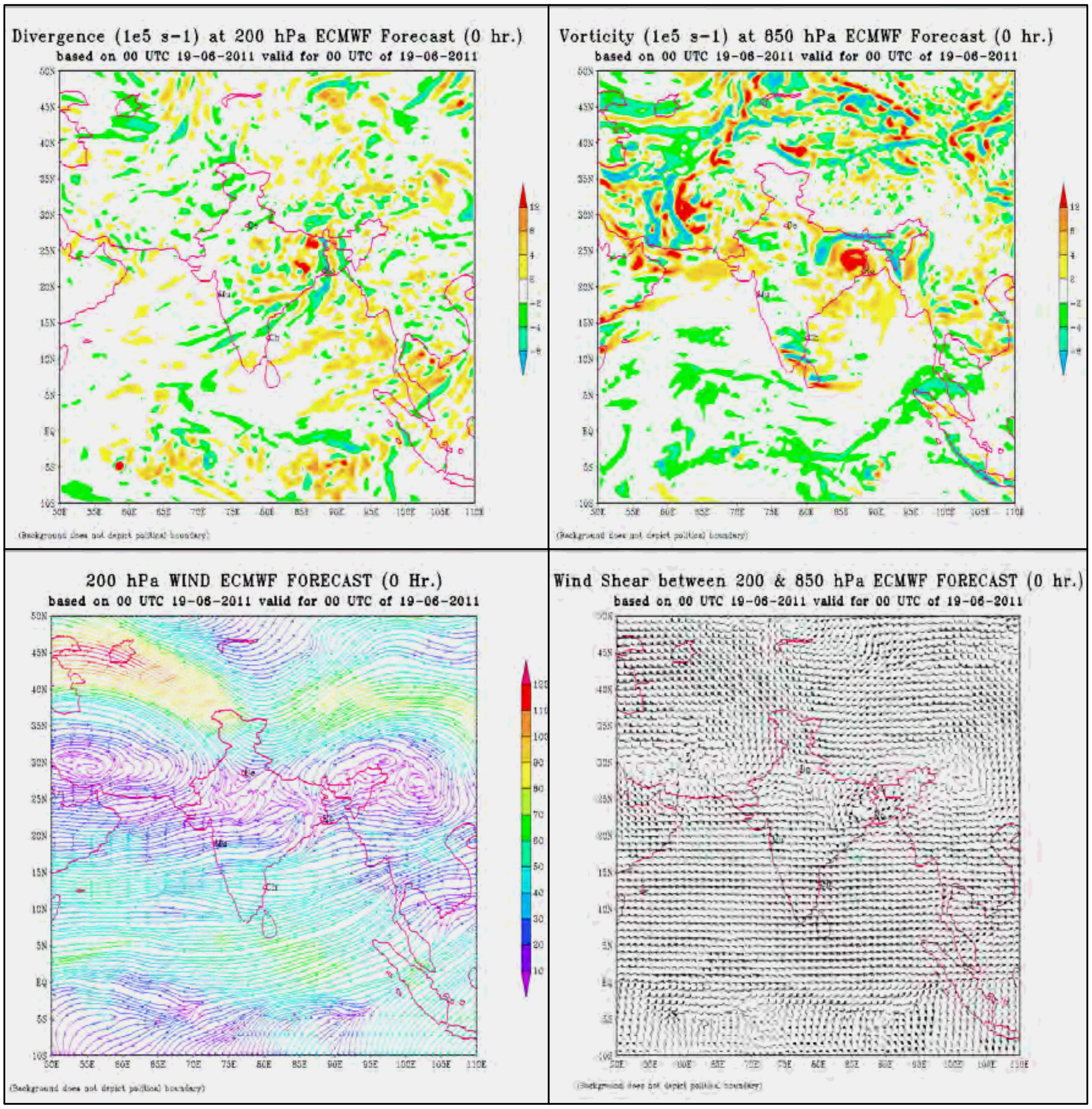


Fig. 2.3.4 (continued) upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) wind at 200 hPa level (iv) vertical wind shear of horizontal wind between 200 & 850 hPa level based on the ECMWF model analysis of 0000 UTC of 19th June 2011.

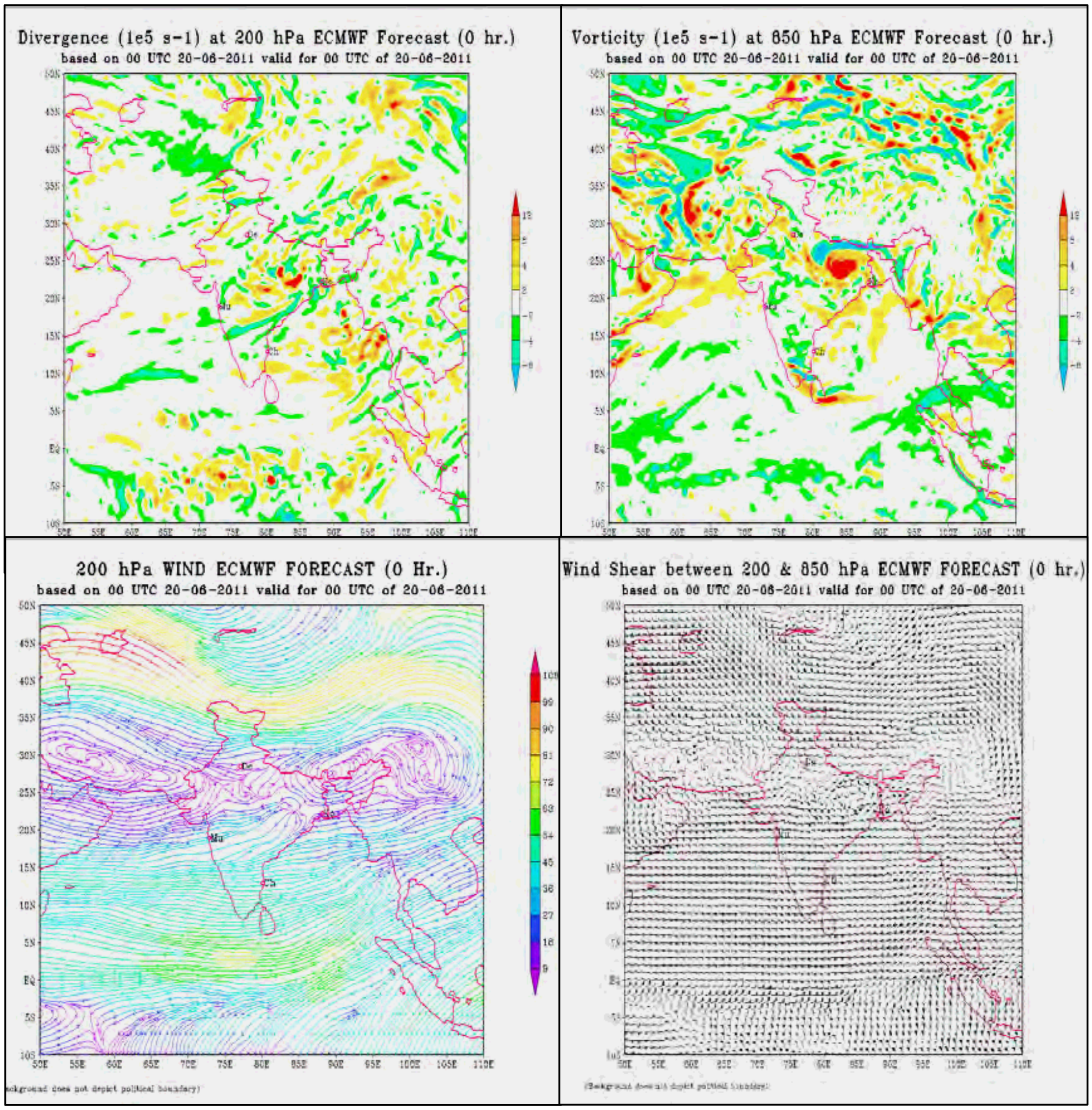


Fig. 2.3.4(continued) upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) wind at 200 hPa level (iv) vertical wind shear of horizontal wind between 200 & 850 hPa level based on the ECMWF model analysis of 0000 UTC of 20th June 2011.

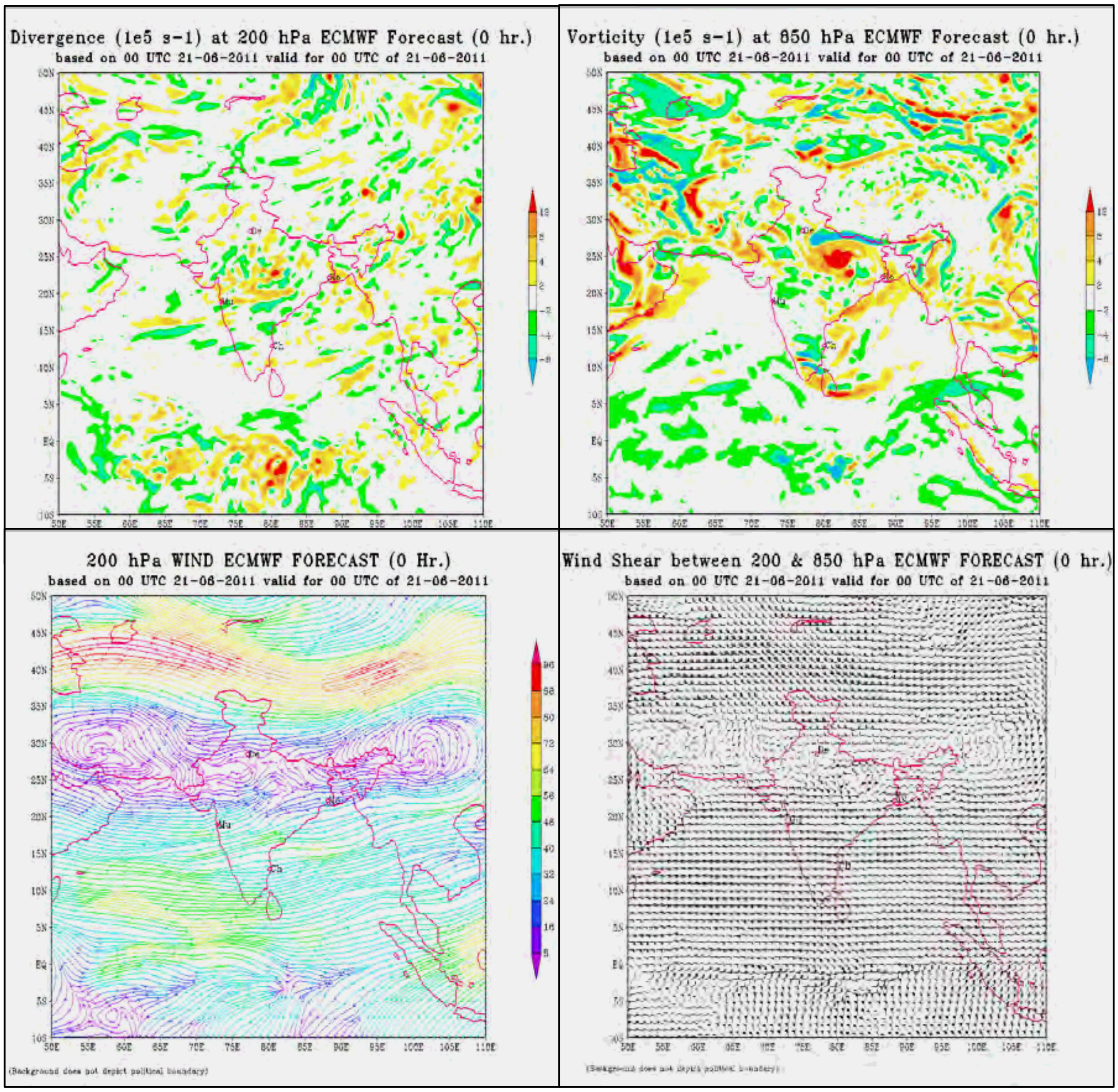


Fig. 2.3.4 (continued) upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) wind at 200 hPa level (iv) vertical wind shear of horizontal wind between 200 & 850 hPa level based on the ECMWF model analysis of 0000 UTC of 21st June 2011.

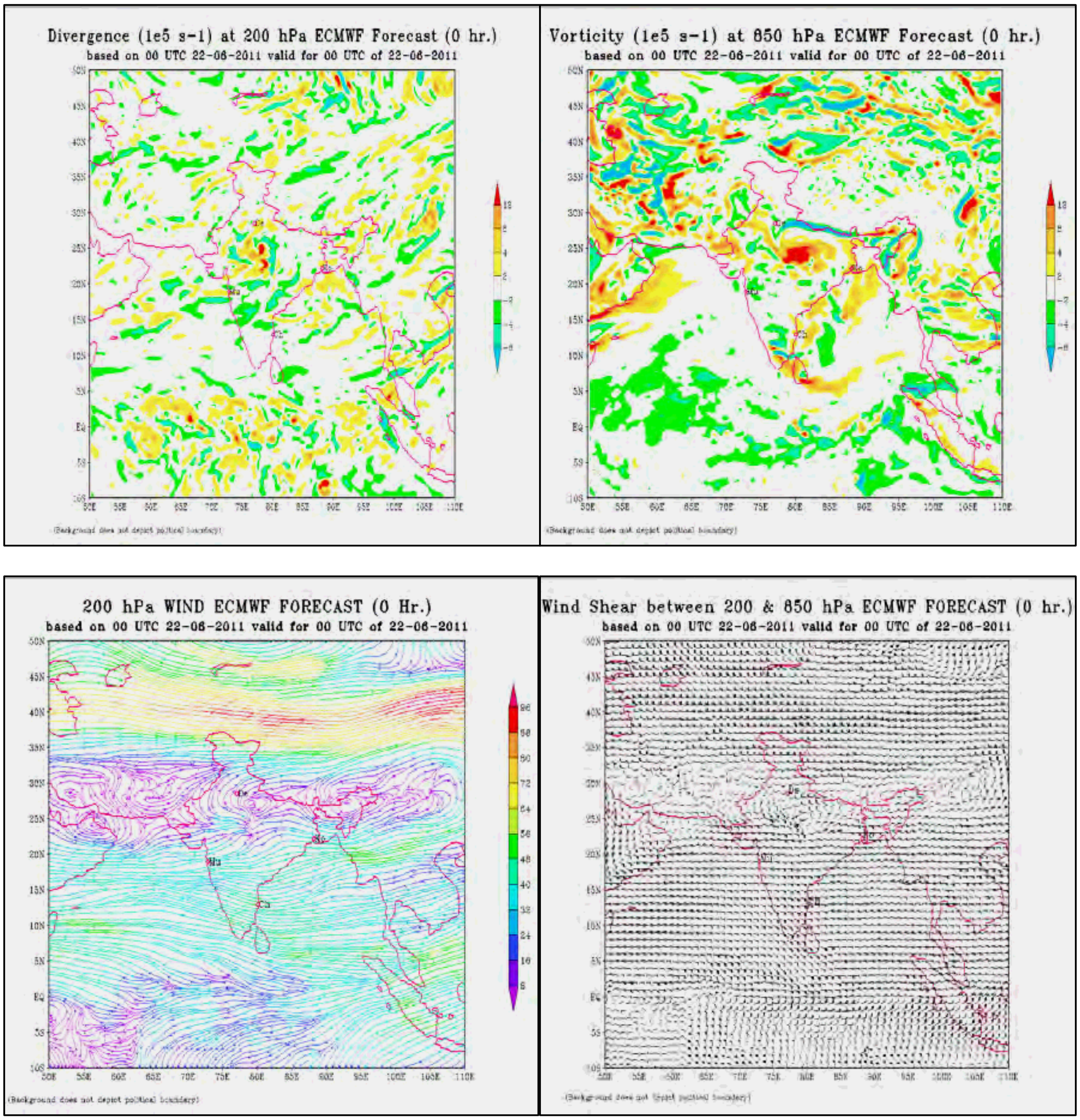


Fig. 2.3.4 (continued) upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) wind at 200 hPa level (iv) vertical wind shear of horizontal wind between 200 & 850 hPa level based on the ECMWF model analysis of 0000 UTC of 22nd June 2011.

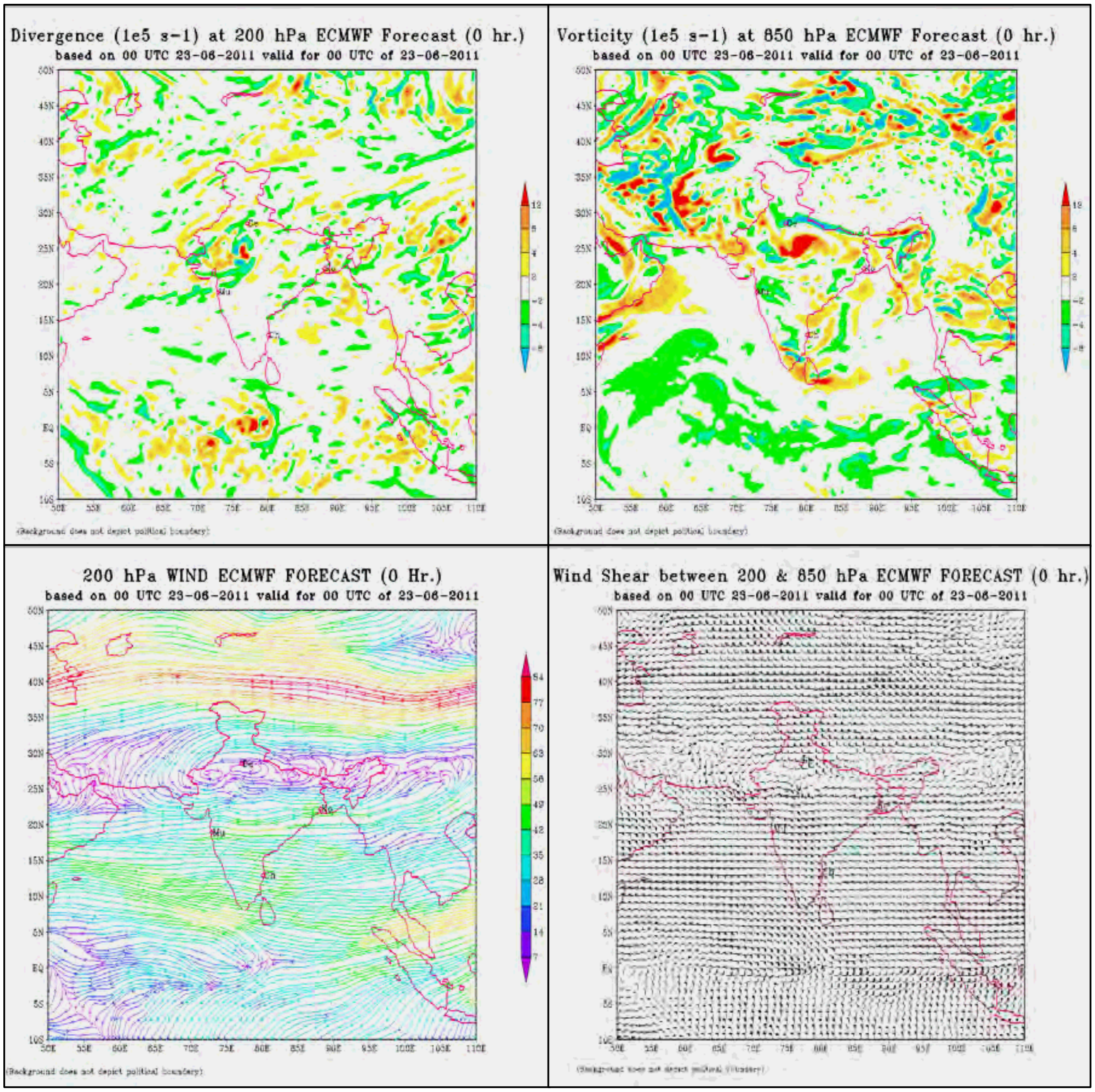


Fig. 2.3.4 (continued) upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) wind at 200 hPa level (iv) vertical wind shear of horizontal wind between 200 & 850 hPa level based on the ECMWF model analysis of 0000 UTC of 23rd June 2011.

Doppler Weather Radar (DWR), Kolkata was observing the system since 0300 UTC of 15TH June 2011 at every 10 minutes interval. The initial echoes of the system were observed in the form of scattered clouds at about 100–300 km in south, south-southwest (SSW) and southwest (SW) of Kolkata. Convective clouds were increasing in the subsequent observations and at 2300 UTC of 15th June moderate type of clouds were observed with reflectivity about 46 dBz and vertical extension from 6 to 8 km towards SSW and S of Kolkata. The front part of the system hit the coast at about 1106 UTC of 16th June at 108 km SSE of Kolkata. The storm centre was found at 1206 UTC of 16th June at 22.0^0N /88.6^0E and its azimuthal position was 125.8^0/ 80 km from the Radar. Moderate convective clouds of reflectivity about 48 dBZ with vertical extension up to 12-14 km were observed in DWR images. The system got better organized with two spiral bands by 1206 UTC of 16th June. Ill defined eye was observed in DWR images at 0204 UTC of 17th June and clouds of 42 dBZ reflectivity were observed over Kolkata. The intensity of the system increased and clouds of 55 dBZ were observed over Kolkata, (NW) and west-southwest (WSW) of Kolkata at 0558 UTC of 17th June. At 1206 UTC of 17th June almost circular eye was observed at a distance 56 Km NW of Kolkata. The system moved further westward and its position was observed at 0604 UTC of 18th June near to the south of Bankura and its approximate centre was located at Lat. 23.0^{0}N/Long. 87.3^{0}E. The reflectivity imageries from 160300 UTC to 180600 UTC are shown in Fig 3.3. The track of the systems observed by DWR Kolkata is shown Table 3.2.

2.3.4. Estimated Central Pressure and maximum wind

The maximum radial wind as observed from PPI (V) was 25 mps at a height of 0.5 km above ground level at 1806 UTC of 17th June at a distance 60-65 km west-southwest of DWR Kolkata. The maximum horizontal wind estimated from VVP_2 product is 40 knots at height 1.2, 2.4, 2.7 & 3.0 km within 50 km radius of Kolkata at 1836 UTC of 17th June 2011. The maximum sustained surface wind (MSW) was reported as 35 knots by an AWS to the northeast of Kolkata around 0600 UTC of 17th June. The estimated MSW was thus 30-35 knots with lowest ECP of 978 hPa (Table 3.1)

2.3.5. Realised Weather:

(i) Rainfall:

Under the influence of the system, widespread rainfall with isolated heavy to very heavy falls occurred over Orissa, Gangetic West Bengal Jharkhand, Chattisgarh, Madhya Pradesh, Bihar and Uttar Pradesh. The significant amount of 24 hours cumulative rainfall (>7 cm) recorded at 0300 UTC of date are as follows:

16-6-2011:

Orissa:

Chandbali and Hindol 12 each; Chendipada, Champua, Rajkanika, Keonjhargarh and Kakatpur 9 each; Jaleswar and Jaipur 8 each; Naktideul, Paradip, Rajghat, Thakurmunda and Bhubaneswar 7 each.

17-6-2011

Gangetic West Bengal:

Canning 10; Digha; Durgachak and Uluberia 7 each.

Orissa:

Sukinda 25; Tensa 18; Jenapur 12; Bhograi 11; Pallahara, Pattamundai, Akhuapada and Jaleswar 9 each; Joshipur , Kendrapara and Rajkanika 8 each; Dhenkanal, Jaipur, Madanpur Rampur Chandbali 7 each.

18-6-2011:

Gangetic West Bengal:

Mohanpur 27; Bankura 23; Kalakunda 21; Purihansa 17; Barackpur and D.P. Chat 16 each; Kolkata Alipur, Kolkata Dumdum Midnapore (PT) and Midnapore (CWC)15 each; Contai Kharidwar and Tusuma 14 each; Asansol, Bagati, Burdwan, Kansabati dam and Panagarh 13 each; Durgapur 12; Harinkhola, Simulia, and Digha 10 each; Uluberia and Gheropara 9 each; Durgachak 8; Diamond Harbour and Sriniketan 7 each.

Orissa:

Baripada, jamsolaghat and Bhograi 14 each; Rairangpur and Bangiriposi 13 each; Tining, Jaleswar and Chandanpur 11 each; sukinda 10; Rajghat 9; Rairakhol, Joshipur, Rajkishorenagar and Athmalik 7 each.

Jharkhand:

Ghatsila 13; Kuru and Panchet 10 each; Maithon 9; Ranchi 8; Lohar-daga, Gumla, Dhanbad, and Jamshedpur 7 each.

19-6-2011:

Gangetic West Bengal:

Bankura 16; Berhampore and Bankura 13 each; Phulberia, Tusuma Kharidwar and Kansabati dam 11 each; Asansol 10 Purihansa and Tantloi 9 each; Durgapur and Suri 8 each; Panagarh IAF, simulia and DP Ghat 7 each.

Jharkhand:

Ramgarh and Putki 17 each; Ranchi AP and jsamshedpur aero 16 each; Tenughat and Jamshedpur 15 each; Jamtara 14; Papunki 13; Balumath and Hindgir 11 each; Nandagih, Moharo, hariharganj and Messenjore 9 each; Barkisuriya and Daltonganj 7 each.

Bihar:

Sherghati 15; Gaya 9; Arwal 7.

20-6-2011:

Orissa :

Tensa 8; Rajkishorenagar 7.

Jharkhand:

Lohar-daga and Raidih 17 each; Kuru 16; Nandadih 13; Gumla, Daltonganj and Balumath 10 each; Ranch AP 8; Hindgir 7.

Chhattisgarh:

Ambikapur 13; Ramanujganj 11; Baikunthpur 9.

Bihar:

Arwal 10; Bihar and Palmerganj 9 each; Bhabhua 8; Indrapuri, Patna, Chenari, Kursela and Dehri 7 each.

East Uttar Pradesh:

Robertsganj 12; Chunar 11; Churk and Muhammadbad 10 each; Dudhi and Jaunpur 9 each; Rajghat, Deogaon Lalganj, Ghazipur, Gonda and Zamania 7 each.

21-6-2011

GangeticWest Bengal: Basirhat 11.

East Uttar Pradesh:

Ankinghat 11; Gyanpur, Karwi, sultanpur, Muhammadabad 9 each; Patti, and Bikpur 8 each; Mahul Phulpur, Haidargarh and Chhatnag 7 each.

Chhattisgarh:

Janakpur 17; Manendragarh 10; Baikunthpur 8.

East Madhya Pradesh:

Rewa and Sidhi 16 each; Satna 15; Singrauli 13; Khurai 11; Kotma and Dindori 10 each; Umaria 9; Anuppur 8; Jabalpur Ajaigarh and Khajuraho aero 7 each.

22-6-2011

East Madhya Pradesh:

Damoh 28; Buxwaha 21; Hatta 20; Garhakota 18; Sagar 16; Ghamspre 14; Rehli and Gotegaon 13 each; Kaneli 12; Khurai 11; Rajnagar 10; Narsinghpur and Jabalpur 9 each; Khajuraho and Amarwara 8 each; Panna, Tikamgarh, Keolari and Lakhnadon 7 each.

West Madhya Pradesh:
Mungaoli 16; Chanderi 13; Kuwai 11; Lateri and Benumganj 9 each; Pichhore 8; Ganjbasoda, Vidisa, Datia, Pachmarhi and Sironj 7 each.
23-6-2011:
East Madhya Pradesh:
Sagar 1; Khurai 14; Garhakota 12.
West Madhya Pradesh:
Guna 34; Ashoknagar 29; Ganjbasoda 20; Mungaoli 19; Sironj 18; Begumganj 17; Chanderi 16; Isagarh and Lateri 15 each; Biiaora 13; Narsingarh 11; Bhanpur, Rajgarh, Pichhore,
Kolaras, Udaipura, Salwani 9 each; Vidisha, Khilchipur and Garoth 8 each; Sheopur, Sailana, Manasa, Shivpuri, sarangpur and Ratlam 7 each.
East Rajasthan:
Baran 29; Baran 25; Kanwas 22; Kishanganj and Sangod 21 each; Atru and Anta 19 each; Chhabara 18; Chipaboard 17; Mangrol 15; Khanpur and Shahbad 14 each; Jhalawar, Asnawar and Jhalawar 13 each; Iklera,and Manoharthana 11 each; Bakani and Pratapgarh 10 each; Patan keshorai, Degod, Ramganjmandi, Mandana, Begu and Kota Airport 9 each; Jhalarapatan, Ladpura, Kota, Deoli, Kekri, Jhazpur, Newai and Bhainjsroadgarh 8 each; Kotri Nimbahera, vanasthali, Mandalgarh, Pirawa, Telera, Pachpahar, Malpura and Chechat 7 each.

(ii) Maximum Sustained Wind (MSW):
The MSW of 30-35 kmph prevailed over Gangetic West Bengal on 17th June, 2011.

2.3.6 Damage:
Jharkhand:
Due to the system, the following damage has been reported in Jharkhand
Loss of Lives: 10 persons
Loss of property: It caused heavy damage to houses and crops. Trees were uprooted and power supply was disrupted. The national highway number 75 from Ranchi to Chaibasa was badly affected and Jolo bridge collapsed.

2.4. Land depression over Jharkhand (22-23 July 2011)

2.4.1 Introduction:

A land depression formed over Jharkhand on 22nd July 2011. It moved west-northwestwards upto north Madhya Pradesh and weakened there into a well marked low pressure area on 23rd July 2011. It was a short lived system with life period of about 20 hours. It caused good rainfall over central parts of the country.

2.4.2 Genesis

As the Madden Julian Oscillation (MJO) entered into phase 3 on 17th July, phase 4 on 19th July and phase 5 on 21st July and the typhoon Ma-on over northwest Pacific Ocean gradually moved southeastward after touching Japan coast and weakened gradually, the large scale environment over the Bay of Bengal and adjoining areas became favouable for active monsoon conditions. The eastern end of monsoon trough ran to east central Bay of Bengal across north Bay of Bengal on 17th July. There was gradual increase in embedded convection and its organisation over north Bay of Bengal and adjoining Gangetic West Bengal and Bangladesh. Under these conditions, an upper air cyclonic circulation extending upto mid-tropospheric level lay over Bangladesh and adjoining Gangetic West Bengal at 0000 UTC of 20th July 2011. Under its influence, a low pressure area formed over Gangetic West Bengal and neighbourhood on 21st July morning. It concentrated into a depression and lay centred at 0300 UTC of 22nd July 2011 over Jharkhand about 50 km southeast of Daltanganj.

2.4.3 Intensification and movement:

It moved west-northwestwards along the monsoon trough and lay centred at 0000 UTC of 23rd July 2011 east Madhya Pradesh, about 150 Km east of Sagar. It further moved west-northeastwards and weakened into a well marked low pressure area over north Madhya Pradesh and neighbourhood at 0300 UTC of 23rd July 2011. The best track of the system in fig 2.1. The best track parameters of the system are shown in Table 2.4.1. The typical satellite imageries are shown in fig. 2.4.1respectively. The ECMWF model analysis of upper level divergence, low level relative vorticity, wind at 200 hPa level and vertical wind shear between 200 and 850 hPa level based on 0000 UTC of 22nd and 23rd July are shown in fig. 2.4.2.

2.4.4 Realisded weather:

Under the influence of the system, widespread rainfall with isolated heavy to very heavy falls occurred over Madhya Pradesh, Madhya Maharashtra, Konkan & Goa and Rajasthan. The significant amount of rainfall (>7 cm) are follows:

23 July, 2011

East Madhya Pradesh:

Kurwai 12, Dewas 11, Ganjbasoda, Guna and Begumganj 10 Each; Salwani/Silvani and Ashoknagar 9 each; Mungaoli 8; Narsingarh, Kolaras, Udaipura, Lateri, Sirinj and Puchhore 7 each.

West Madhya Pradesh:

Narsinghpur 16; Tendukheda 15; Gotegaon 13; Deori, Rehli Jabalpur (New) 11 each; Kaneli Sagar and Khurai 10 each; Bichhia and Umaria 9 each; Nowgoan 8 Sidhi; Buxwaga, Patan and Garhakota 7 each.

Madhya Maharashtra:
Gaganbavada 9; Mahabaleshwar 7.
Konkan & Goa: Lanja 7.

24 July, 2011
East Rajasthan:
Tadaraisingh 10; Anta 9; Bakani, Manohar Thana and Gangapur 8 each; Nagrarfort, Bagidora, Kotri and Arnod 7 each.
West Madhya Pradesh:
Tarana 11; Bhanpura and Shujalpur 7 each.
Konkan & Goa:
Sawantwadi, Vaibhavwadi and Lanja 11 each; Kudai 9; Sangamneshwar and Rajapur 8 each; Kankavli, Khed, Bhira 7 each.
Madhya Maharashtra:
Radhanagari 15; Chandgad and Bhudargad 12 each; Mahabaleshwar 7.

Damage:
No damage was reported due to this system.

Table- 2.4.1 Best track positions and other parameters of the depression over Jharkhand during 22-23 July, 2011

Date	Time (UTC)	Centre lat.^{0} N/ long. ^{0} E	C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
22.07.2011	0300	23.5/84.5	--	990	20	3	D
	0600	24.0/84.0	--	990	20	3	D
	0900	24.0/84.0	--	990	20	3	D
	1200	24.083.0	--	990	20	3	D
	1800	24.081.5	--	992	20	3	D
23.07.2011	0000	24.5/80.5	--	992	20	3	D
	0300	Weakened into a well marked low pressure area over north Madhya Pradesh and neighbourhood.					

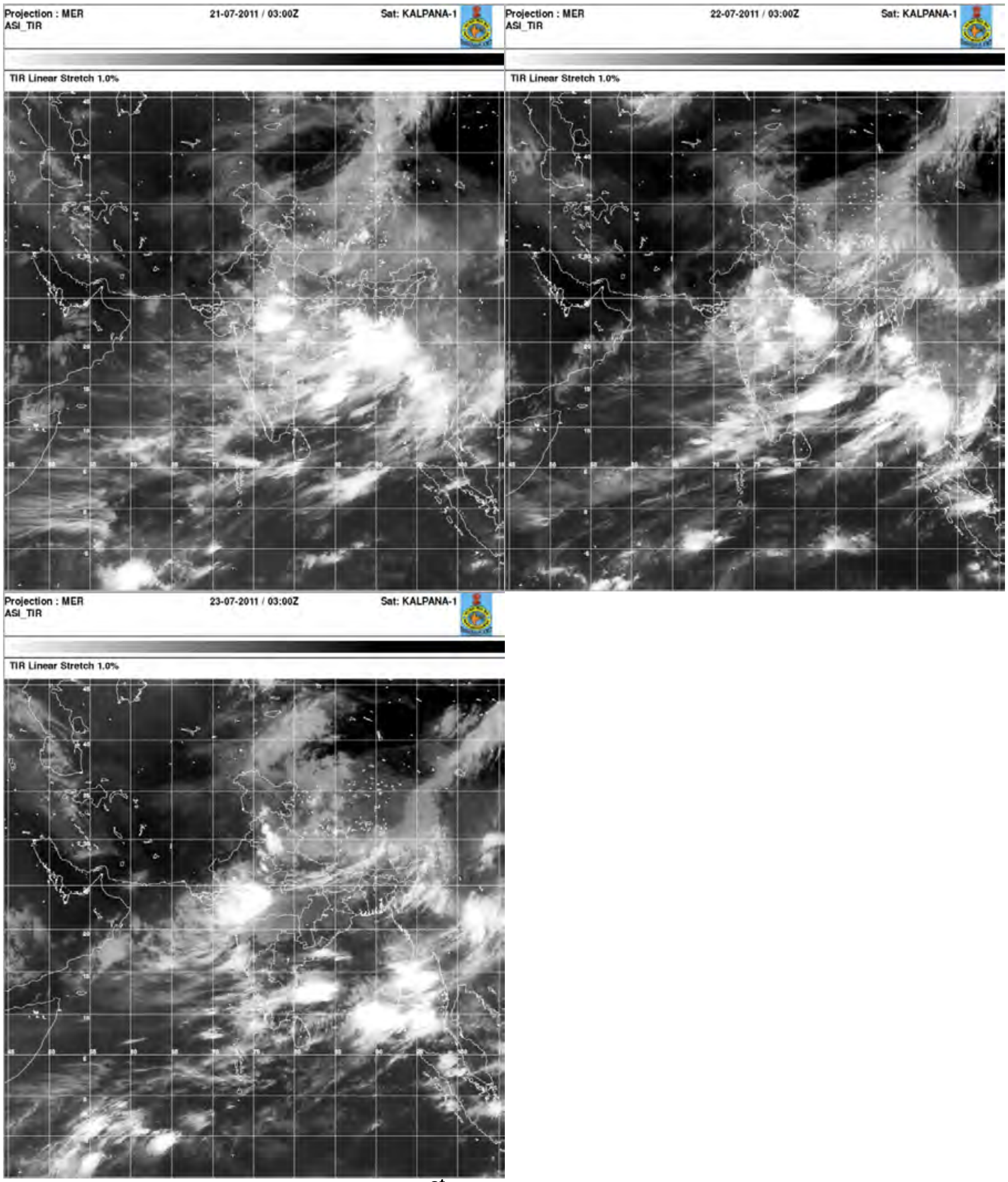


Fig. 2.4.1 Satellite imageries (a) 21st July showing deep convection over north Bay of Bengal and adjoining West Bengal and Orissa before the genesis of the depression (b) at 0300 UTC of 22nd July and 23rd July 2011 showing intense convection in the southwest sector of the depression and (i) at 0300 UTC of 23rd July 2011 showing weakening and disorganization of convection due to weakening of depression.

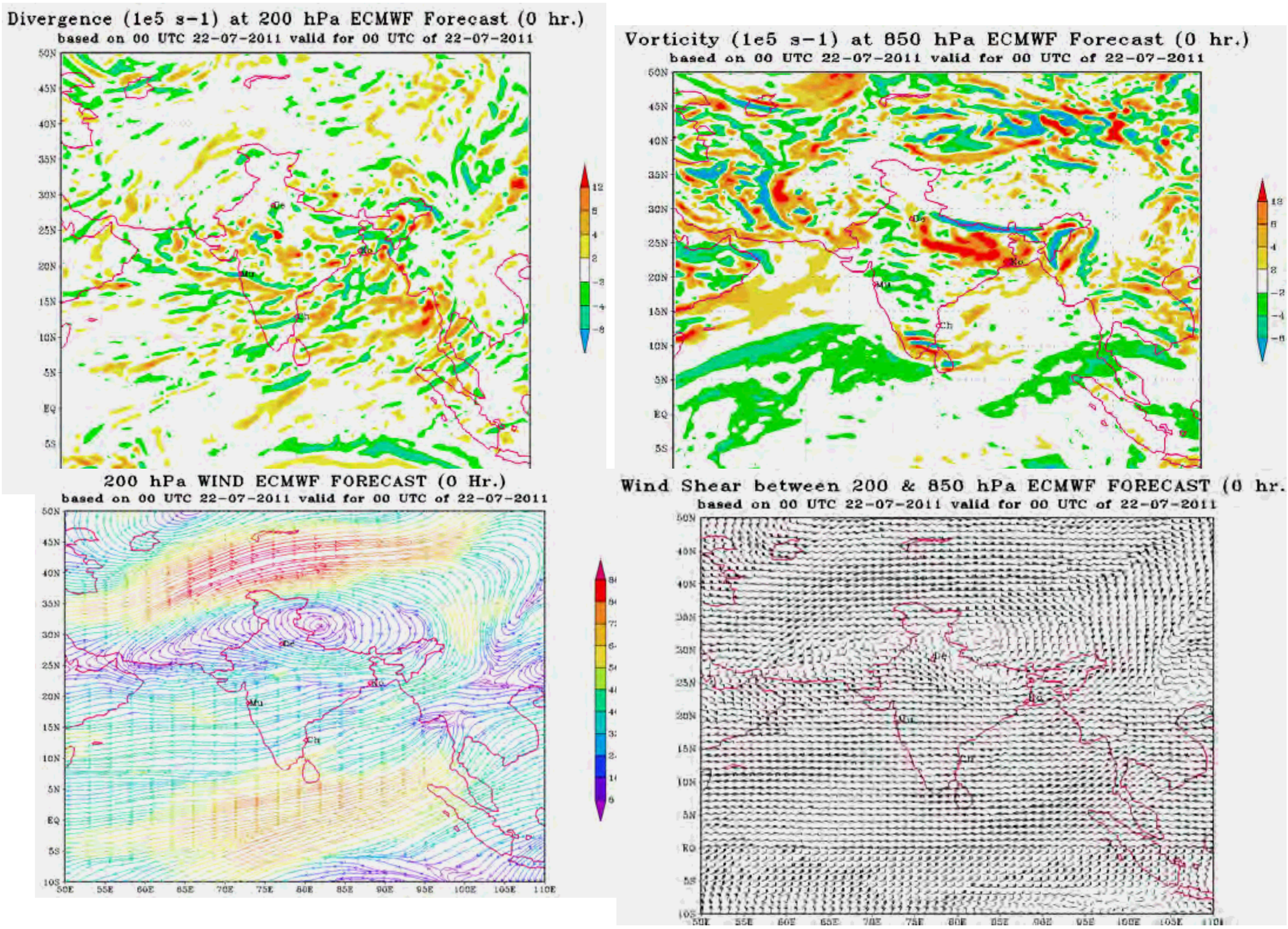


Fig. 2.4.2(a) (i) upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) wind at 200 hPa level (iv) vertical wind shear of horizontal wind between 200 & 850 hPa level based on the ECMWF model analysis of 0000 UTC of 22rd July 2011.

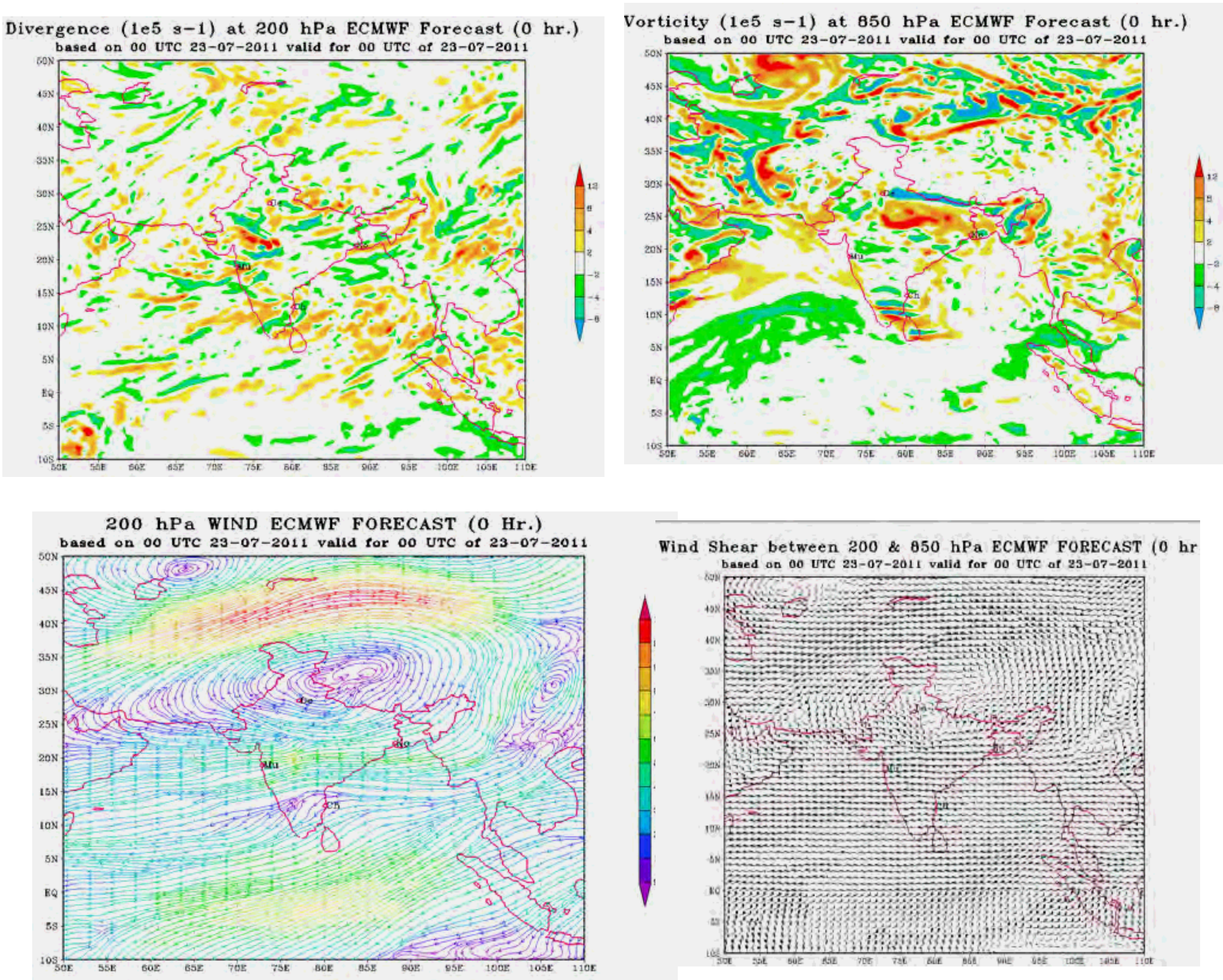


Fig. 2.4.2(b) (ii) upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) wind at 200 hPa level (iv) vertical wind shear of horizontal wind between 200 & 850 hPa level based on the ECMWF model analysis of 0000 UTC of 23rd July 2011.

2.5 Depression over Bay of Bengal (22-23 Sept 2011)

2.5.1 Introduction

A **depression** formed over northwest Bay of Bengal on 22 September, 2011 morning. Moving in a westerly direction, it crossed north Orissa coast, close to Balasore and then moved northwestwards across north Orissa and Jharkhand and weakened gradually into a well marked low pressure area on 23rd September 2011 afternoon over Jharkhand and neighbourhood. Under the influence of this system heavy to very heavy rainfall occurred over north Orissa, Jharkhand, north Chhattisgarh, east Uttar Pradesh and Bihar. The genesis, intensification and movement and other characteristic are described below.

2.5.2 Genesis

In association with an active monsoon trough, a low pressure area formed over the north Bay of Bengal on 21st September, 2011. The sea surface temperature over the Bay of Bengal was about 28-32^{0}C. The vertical wind shear of horizontal wind between 850 and 200 hPa was low to moderate (10-20 knots). The associated intense convection persisted over the region, mainly to the southwest sector of the low pressure area. There was increase in lower level relative vorticity and upper level divergence also over the region. The upper tropospheric ridge in association with the Tibetan high ran along 22^{0}N. Under these favourable synoptic and environmental conditions, the low pressure area concentrated into a depression at 0830 hrs IST of 22nd September, 2011 over the northwest Bay of Bengal near Lat. 21.5^{0}N and long. 87.5^{0}E, about 50 km east-southeast of Balasore. The estimated central pressure was about 998 hPa and the lowest MSLP of 998.2 hPa was reported by Balasore followed by 998.3 hPa at Digha at 0830 hrs IST of 22nd September, 2011.

2.5.3 Intensification and movement

Though the sea surface temperature was favourable being 28-32^{0}C, the Ocean heat content was not favourable for intensification as it was about 40KJ/cm^{2} over the north Bay of Bengal. Further the system was interacting with land surface as it lay close to coast. It moved slowly in the westerly direction and crossed north Orissa coast, close to Balasore between 2230 and 2330 hrs IST of 22nd September, 2011. After the landfall, the depression moved northwest wards across north Orissa and Jharkhand and weakened gradually. It weakened into a well marked low pressure are over Jharkhand and neighbourhood at 1430 hrs IST of 23rd September 2011. However the well marked low pressure area moved to east Uttar Pradesh on 24th and to Bihar on 25th September under the influence of westerly trough. It became less marked on 26th September, 2011.

The best track of depression is given in Fig. 2.1. The best track parameters are shown in Table 2.5.1. The typical satellite imageries of the system are shown in Fig.2.5.1.The ECMWF model analysis of lower level vorticity; upper level divergence, lower level wind and wind shear during 21-23 September 2011 are shown in Fig. 2.5.2

Table: 2.5.1 Best track position and other parameters of depression over the northwest Bay of Bengal during 22-23 September, 2011

Date	Time	Centre (lat^{0}N/long^0 E)	C. I. No.	Estimated centre pressure (hPa)	Estimated pressure drop at the centre (hPa)	Estimated Maximum sustained wind (kts)	Grade
22-9-2011	0300	21.5/87.5	1.5	998	4	25	D
	0600	21.6/87.3	1.5	998	4	25	D
	1200	21.7/87.2	1.5	995	4	25	D
	The system crossed north Orissa coast close to Balasore between 1700 & 1800 UTC						
	1800	21.8/87.0		998	4	25	D
23-9-2011	0000	22.5/86.5		1000	4	25	D
	0300	22.5/86.5		1002	4	25	D
	0600	22.5/86.5		1004	4	25	D
	0900	The system weakened into a low pressure area over Jharkhand close to Jamshedpur.					

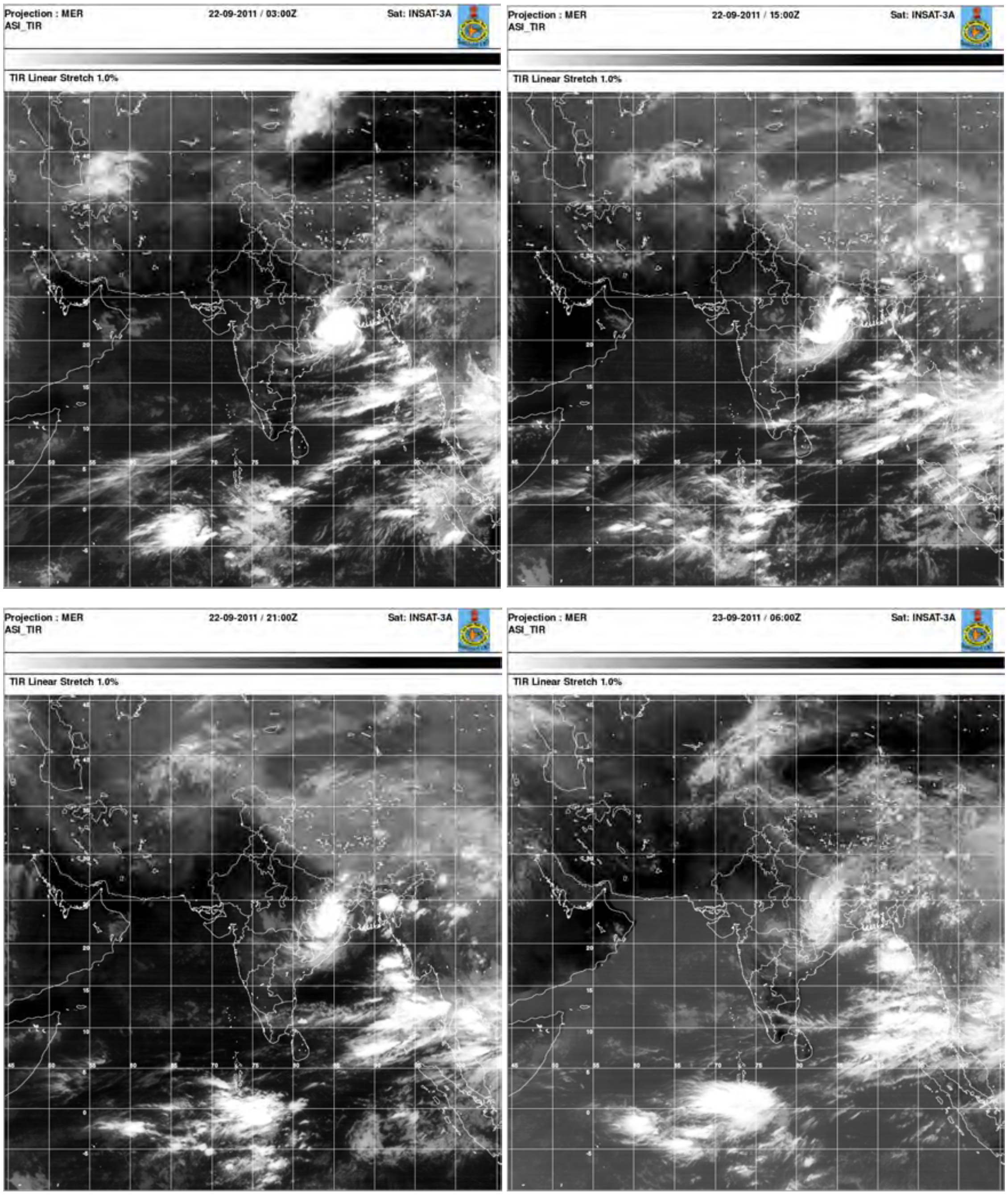


Fig. 2.5.1 Typical Satellite imageries at 0300, 1500 and 2100 UTC of 22-09-2011 and 0600 UTC of 23-09-2011 in association with the depression over the Bay of Bengal.

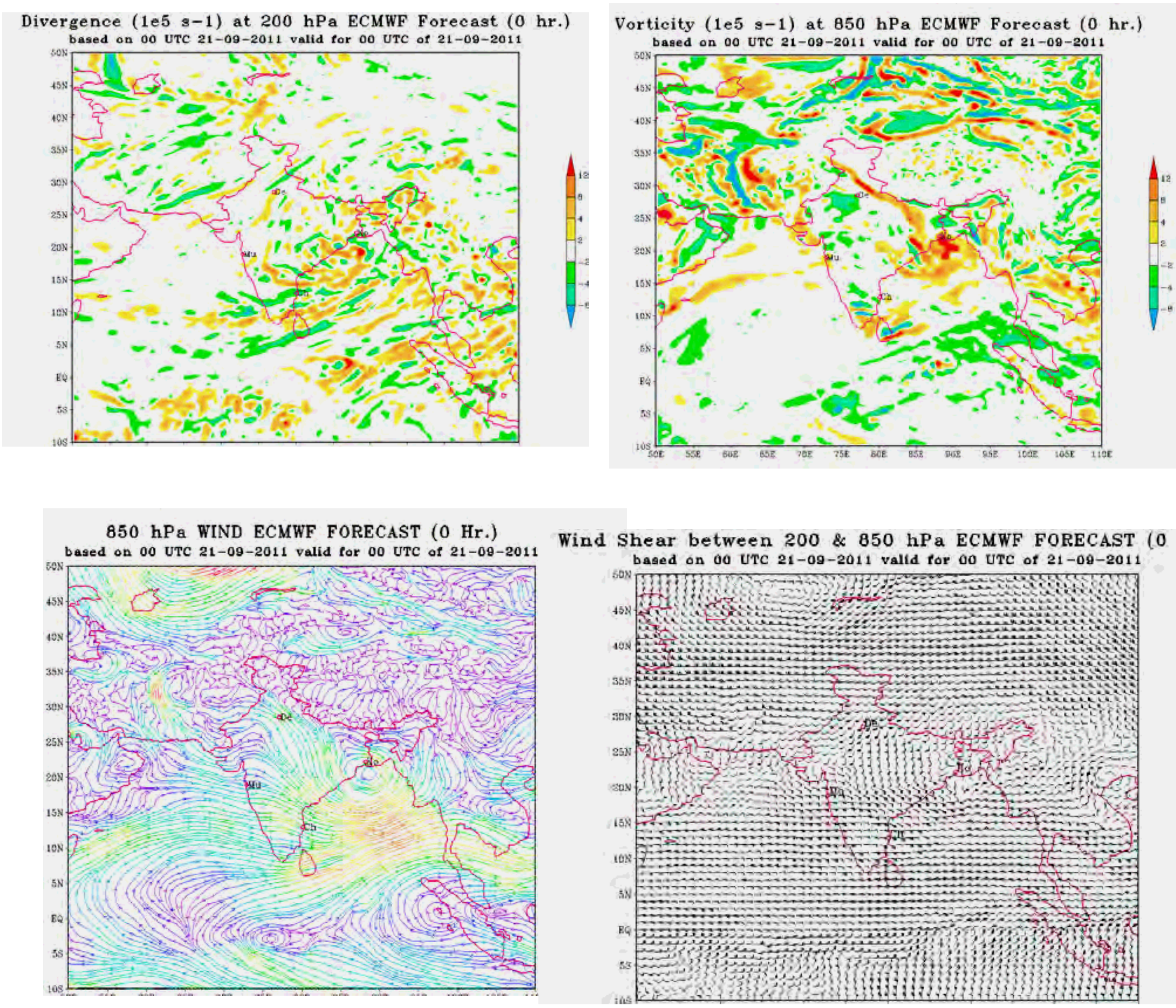


Fig. 2.5.2 (a) (i) upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) wind at 850 hPa level (iv) vertical wind shear of horizontal wind between 200 and 850 hPa level based on the ECMWF model analysis of 0000 UTC of 21st September, 2011.

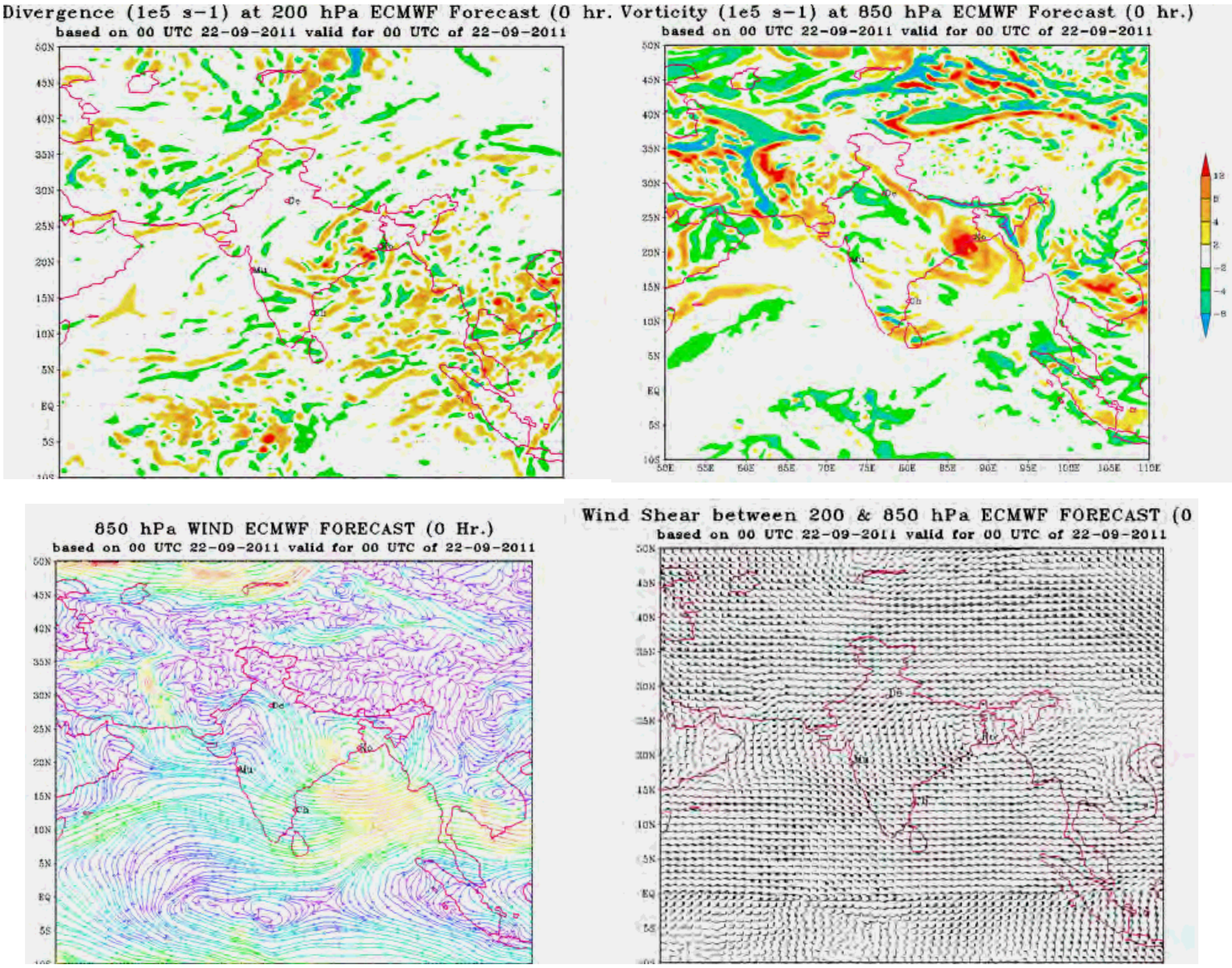


Fig. 2.5.2(b) (i) Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) wind at 850 hPa level and (iv) vertical wind shear of horizontal wind between 200 and 850 hPa level based on the ECMWF model analysis of 0000 UTC of 22nd September, 2011.

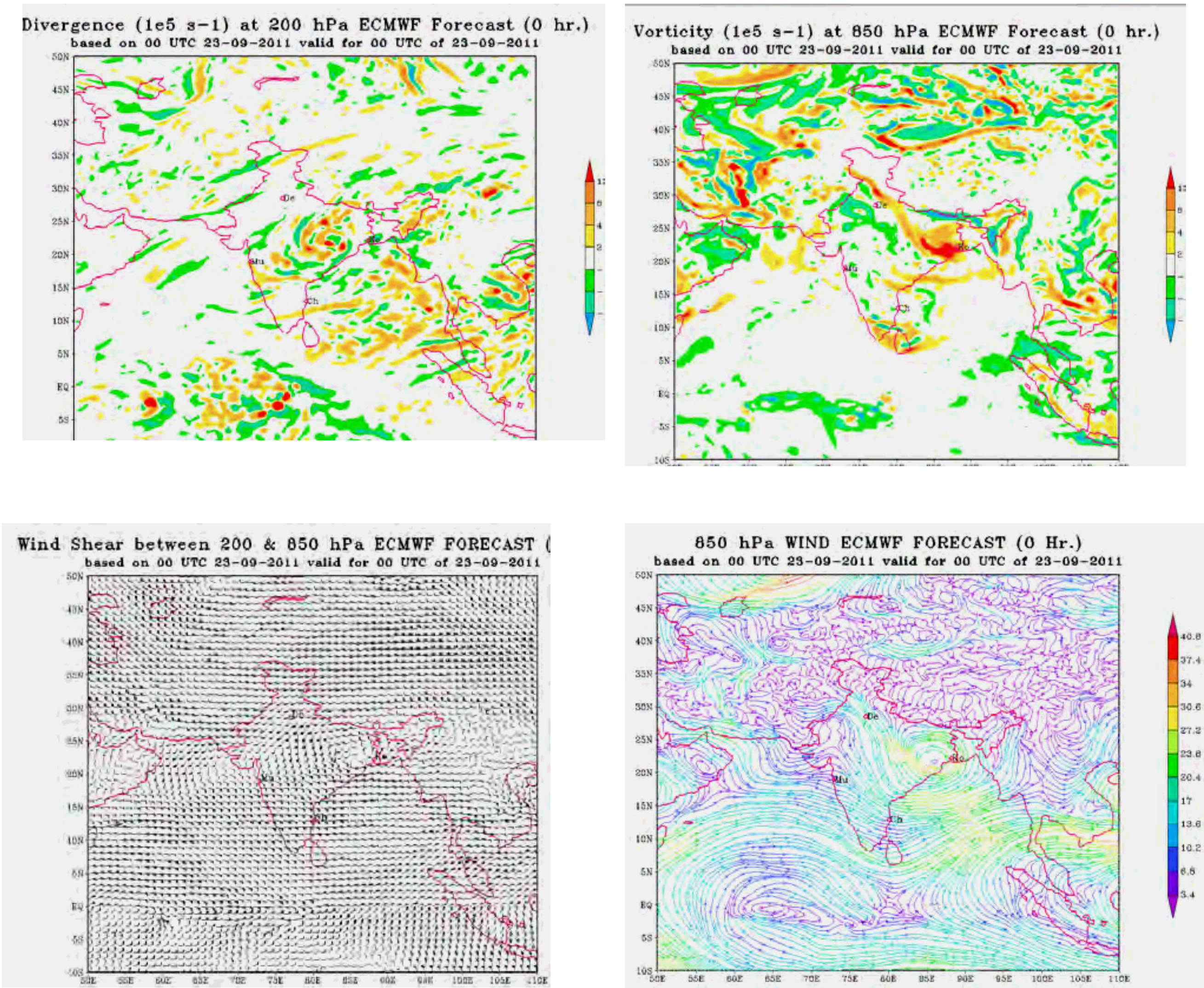


Fig. 2.5.2 (c) (i) Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) wind at 850 hPa level and (iv) vertical wind shear of horizontal wind between 200 and 850 hPa level based on the ECMWF model analysis of 0000 UTC of 23rd September, 2011.

2.5.4 Realised weather

Under the influence of this system heavy to very heavy rainfall occurred over north Orissa, Jharkhand, north Chhattisgarh, east Uttar Pradesh and Bihar. The significant amount of 24 hours cumulative rainfall (>7 cm) recorded at 0830 hrs IST of date are as follows:

22 September 2011

Gangetic West Bengal:

Kharagpur (AWS)-11, Kharagpur (I.I.T)-10, Kalaikunda (IAF)-9, and Tilpara Barrage-7.

Orissa:

Nawana-16, Udala-16, Soro-15, Thakurmunda-14, Balimundali, Tensa-13 each, Champua, Swampatna-12 each, Joshipur, Bangiriposi-11 each, Karanjia-10, Keonjhargarh, Jaipur, Rairakhol, Akhuapada, Pallahara, Harabhanga, Chandbali-9, Baripada, Binjharpur, Chandanpur, Sukinda and Bonth 9 each, Anandpur, Jamsolaghat, Tihidi and Nilgiri-8 each, Rengali, Boudhgarh, Tikarpara-7 each.

Jharkhand:

Chaibasa-7

BIHAR: Lakhisarai, Benibad and Barhiya-11 each, Phulparas and Dhengraghat-7each.

23 September 2011

Orissa:

Keonjhargarh and Tensa-19 each, Panposh-14, Rajgangpur, Lahunipara and, Mandira Dam-13 each, Nawana-12, Ghatagaon-11, Swam-Patna-10, Bargaon and Pallahara-9 each, Bonth-8, Keiri, Jenapur, Rajkishorenagar, Joshipur, Laikera, Kuchinda, Kankadahad, Tiring and Chiplima-7 each,

Jharkhand:

Lohar-Daga and, Kuru-13 each, Ranchi Aero-9, Japla-7,

Bihar:

Indrapuri-15, Dehri and Aurangabad-8 each, Palmerganj-7,

24 September 2011

Orissa:

Pallahara-7,

Jharkhand:

Garhwa-9,

East Uttar Pradesh:

Basti-17, Dudhi-16, Robertsganj-15, Basti-14, Churk-13, Haraiya and Elgin Bridge-11 each, Patti, Bansi, Salon, Bikapur and Sultanpur-9 each, Handia-8, Akbarpur-7,

2.5.5 Damage

The heavy rain caused flood over Orissa leading to loss of life and property. The death and damage over Orissa are given below.

Number of human deaths: 42
Number livestocks death: 981
Houses damaged: 157770
Crop area affected: 252266 hectare

2.6 Deep Depression over Bay of Bengal (19-20 October, 2011)

2.6.1 Introduction

A deep depression formed over northeast Bay of Bengal on 19 October, 2011 morning. Moving northeaster wards, it crossed Bangladesh coast near lat. 21.2^0N and long. 92.1^0E (south of Cox's Bazar) around 1300 UTC of 19^{th} October. The characteristics of the system are described below.

2.6.2 Genesis

Synoptic analysis suggested that a low level cyclonic circulation lay over the southeast and adjoining eastcentral Bay of Bengal from 12^{th} October onwards. There was an active east-west shear zone passing through this circulation. Under the influence of these synoptic conditions, the cross equatorial flow over the Bay of Bengal leading to southerly surge increased gradually. As a result, the lower level relative vorticity and convergence also increased. It was manifested in the satellite imageries with gradual organisation of convective clouds over the southeast and eastcentral Bay of Bengal.

Considering the large scale environmental conditions, the sea surface temperature over the Bay of Bengal continued to be about $28\text{-}32^0$C. The upper tropospheric ridge at 200 hPa level lay to far north of the area of circulation (around 19^0N on 15^{th} October) and provided the required divergence over the region. The vertical wind shear was low to moderate over the central and north Bay of Bengal. There was no significant system over the south China Sea. The cyclone, Banyan over the south China Sea lay as a depression near 17.5^0 N and 116^0E on 14^{th} and became less marked on 15^{th} October. However, the Ocean heat content was about 80 KJ/cm^2 over the south and central Bay of Bengal and less than 50 KJ/cm^2 over the north Bay of Bengal. The Madden Julian Oscillation (MJO) index lay in phase 8 on 14^{th} and moved gradually to phase 1 during $14\text{-}19^{th}$. As such, it was not favourable for cyclogenesis. Due to this unfavourable MJO condition, the convection could not be amplified rapidly. Rather, the convection exhibited a marked diurnal variation. However, the cyclonic circulation over southeast & adjoining east central Bay of Bengal moved to east central Bay of Bengal & neighbourhood and extended upto mid tropospheric level on 16^{th} October 2011. The east-west trough also extended upto mid tropospheric level through the above system. Under the influence the cyclonic circulation, a low pressure area formed over the same region with associated cyclonic circulation extending upto mid-tropospheric level on 17^{th} October. It became well marked over east central & adjoining north and west central Bay of Bengal on 18^{th}. The well marked low pressure area concentrated into a depression over north Bay of Bengal and lay centred at 0000 UTC of 19^{th} October 2011 over north Bay of Bengal near latitude 20.0^0N and longitude 90.5^0E.

2.6.3 Intensification and movement

All the above mentioned favourable and unfavourable conditions continued during 19^{th} and 20^{th}. At 0300 UTC of 19^{th} October, the 24 hrs pressure change was negative over Bangladesh coast (around -3.0 hPa) and negative over north Andhra Pradesh and Orissa-West Bengal coast (around -2.0 hPa). Maximum pressure fall was reported as -4.2 hPa over Cox's Bazar. Pressure departure from normal was negative (-5.0 to -6.0 hPa) over Cox's Bazar and Chittagong. The depression moved to the north of upper tropospheric ridge, which roughly ran along 19^0N on 19^{th} October 2011 in association with an anticyclonic circulation to the southeast of the system centre. As a result of these, the system moved east-northeastwards and intensified into a deep depression and lay centred at 0300 UTC over northeast Bay of Bengal near lat 20.2^{0}N and long. 91.0^{0}E. It then moved northeastwards and crossed Bangladesh coast near lat. 21.2^{0}N and long. 92.1^{0}E (south of Cox's Bazar) around 1300 UTC of 19th October. After the landfall it also continued to move northeastwards for sometime and then eastwards and weakened gradually. It weakened into a low pressure area at 0300 UTC of 20th October 2011 over Myanmar and adjoining Bangladesh, Mizoram and northeast Bay of Bengal.

At 0900 UTC of 19th, Cox's Bazar reported lowest pressure of 999.5 hPa and northeasterly wind of 15 knots. Sittwe (Myanmar) reported southwesterly wind of 20 knots. The track of deep depression is shown in Fig. 2.1. The best track parameters are shown in Table 2.6.1. The typical satellite imageries of the system are shown in fig. 2.6.1. The ECMWF model analyses of lower level vorticity, upper level divergence, upper level wind and vertical wind shear are shown in fig. 2.6.2.

Table 2.6.1: Best track position and other parameters of deep depression over the northeast B ay of Bengal during 19-20 October, 2011

Date	**Time (UTC)**	**Centre (lat^{0}N/long ^{0}E)**	**C. I. No.**	**Estimated centre pressure (hPa)**	**Estimated pressure drop at the centre (hPa)**	**Estimated Maximum sustained wind (kts)**	**Grade**
19-10-2011	0000	20.0/90.5	1.5	1002	3	25	D
	0300	20.2/91.0	1.5	1000	3	25	D
	0600	20.5/91.5	2.0	1000	5	30	DD
	1200	21.0/92.0	2.0	1000	5	30	DD
	The system crossed Bangladesh coast near lat. 21.2^{0}N and long. 92.1^{0}E (south of Cox's Bazar) around 1300 UTC.						
	1800	21.5/92.5	2.0	1002	5	30	DD
20-10-2011	0000	21.5/93.5	1.5	1004	3	25	D
	0300	The system weakened into a low pressure area over Myanmar and adjoining Bangladesh, Mizoram and northeast Bay of Bengal.					

2.6.4. Realised Weather:

Not available from Bangladesh and Myanmar. However according to media reports, along the border between Myanmar and Bangladesh, torrential rain produced devastating flash floods. Squally winds also prevailed over the region.

2.6.5. Damage:

In the Magway region, roughly 2000 homes were washed away and more than 6000 remained flooded for days. Initial estimates placed the damage of 1.64 million US dollars. At least 215 people were confirmed to have been killed with many more missing.

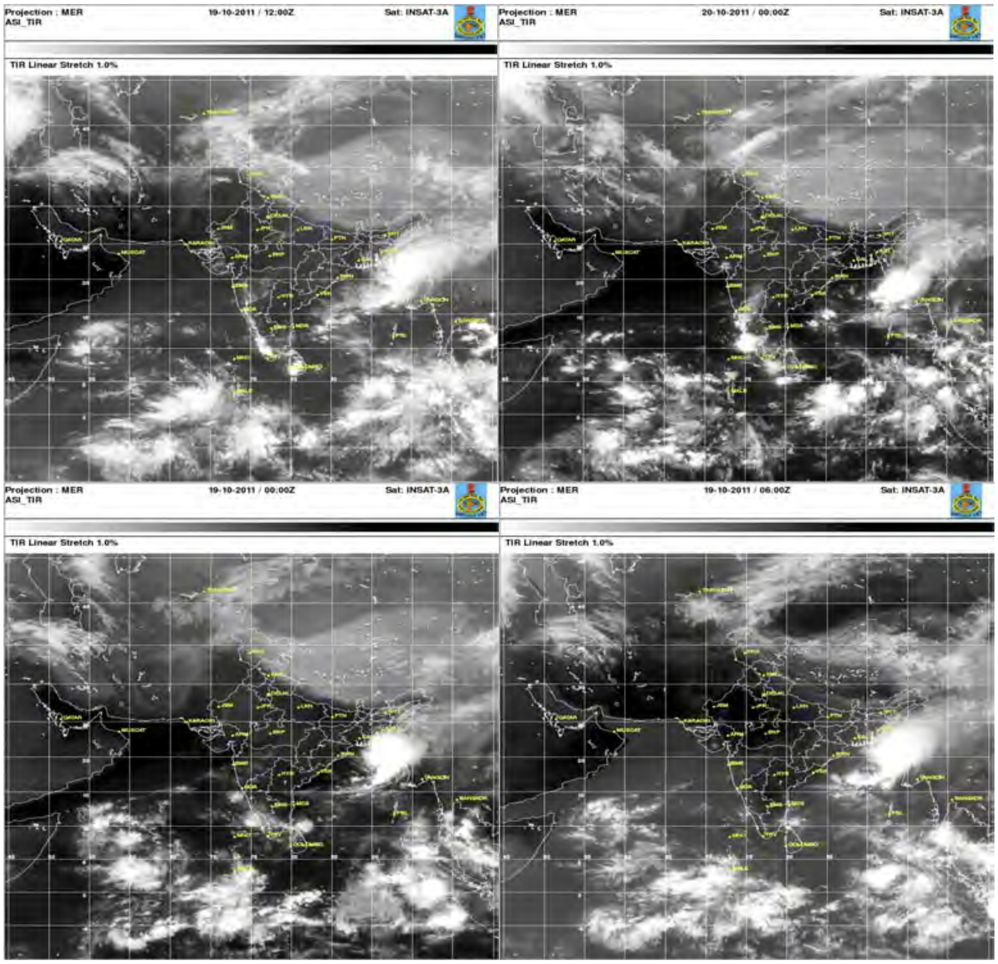


Fig. 2.6.1 Typical Satellite imageries at 0000, 0600 and 1200 UTC of 19-10-2011 and 0000 UTC of 20-10-2011 in association with the depression over the Bay of Bengal.

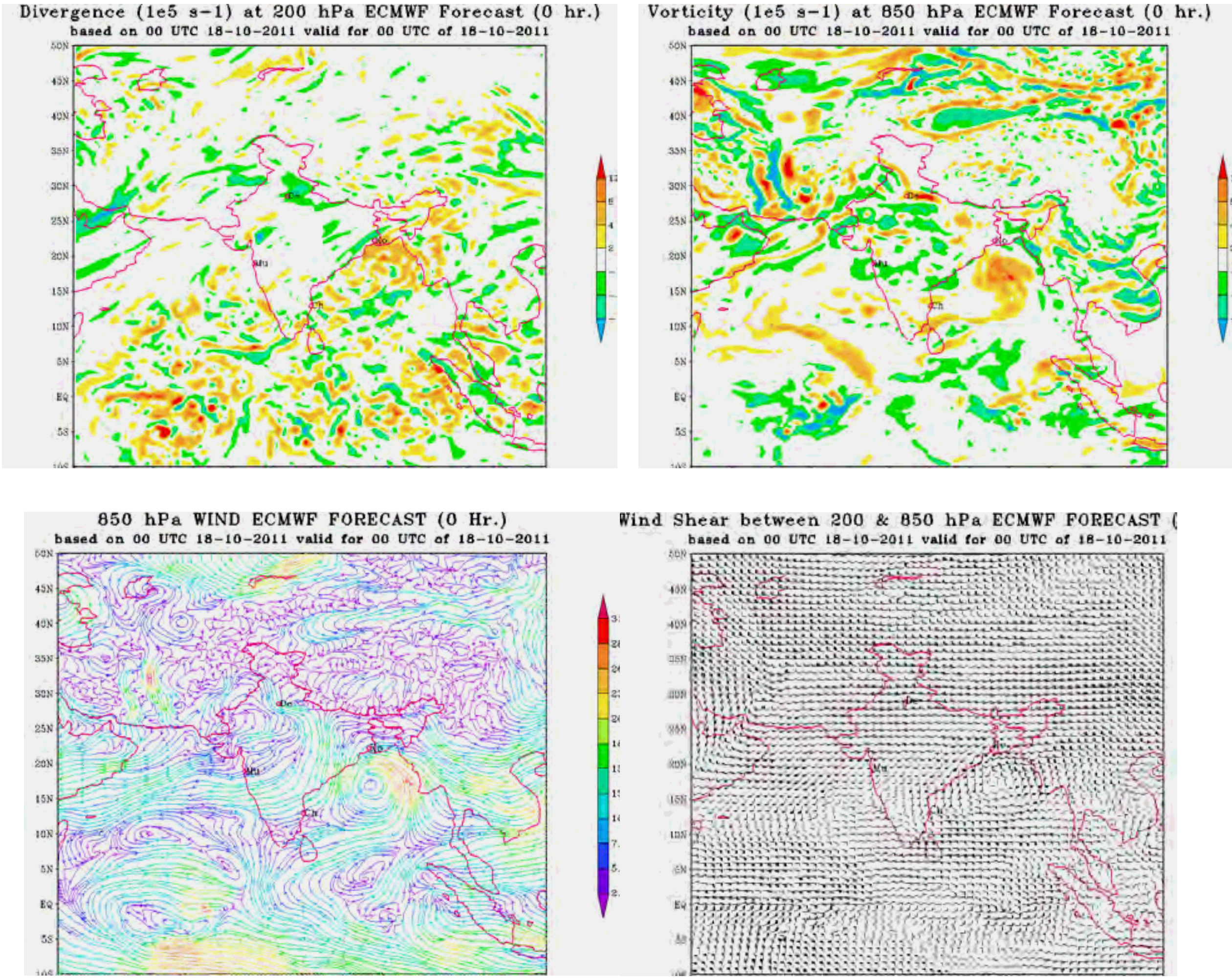


Fig. 2.6.2 (a) (i) Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) wind at 850 hPa level (iv) vertical wind shear of horizontal wind between 200 and 850 hPa level based on the ECMWF model analysis of 0000 UTC of 18th October, 2011.

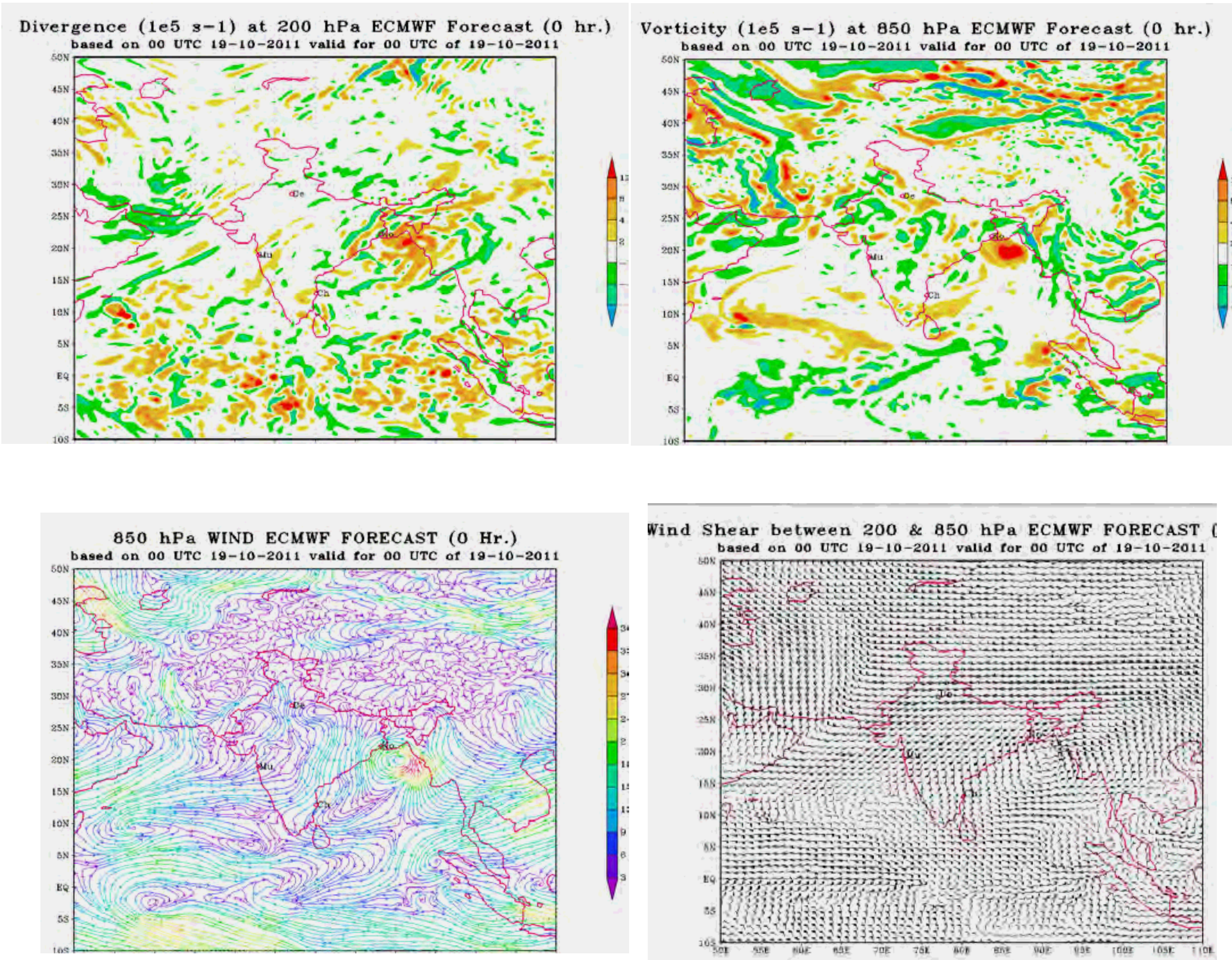


Fig. 2.6.2(b) (i) Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) wind at 850 hPa level (iv) vertical wind shear of horizontal wind between 200 and 850 hPa level based on the ECMWF model analysis of 0000 UTC of 19th October, 2011**.**

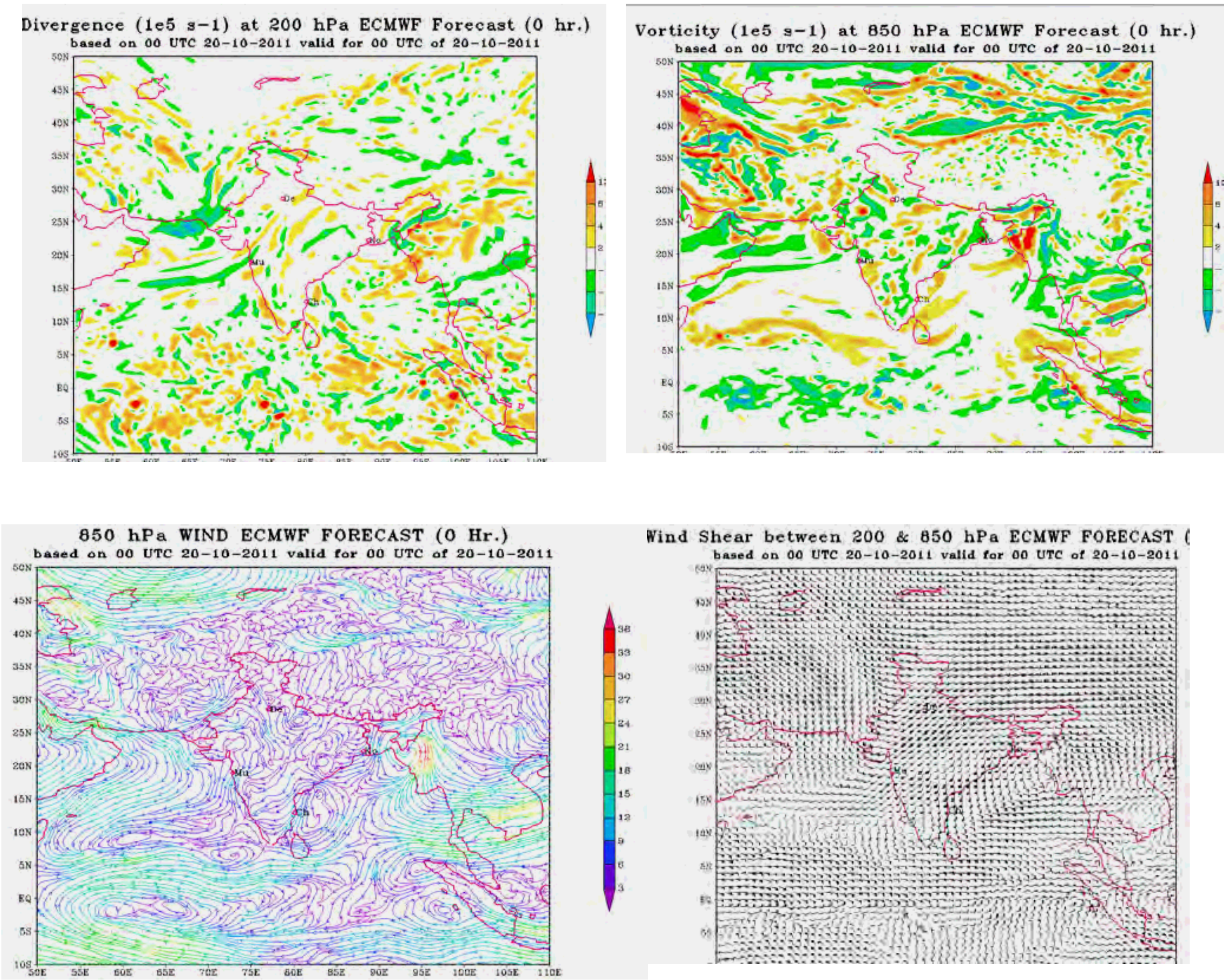


Fig. 2.6.2 (c) (i) Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) wind at 850 hPa level (iv) vertical wind shear of horizontal wind between 200 & 850 hPa level based on the ECMWF model analysis of 0000 UTC of 20th October, 2011.

2.7 Cyclonic storm 'KEILA' over the Arabian Sea (29 October- 04 November, 2011)

2.7.1 Introduction:

A cyclonic storm 'KEILA' developed over the Arabian Sea. It moved initially west-northwestwards and then northwestwards and crossed Oman coast close to the north of Salalah. It then remerged into the Arabian Sea and dissipated gradually. It caused death of 14 people in Oman. It caused death of 14 people in Oman. The salient features of the system are given below. The system was mainly monitored by the satellite imageries and products. However, the crucial ship and buoy observation also helped in estimating the location and intensity of the system. When the system came close to the Oman coast, coastal observations were also useful.

2.7.2 Genesis:

In association with active ITCZ, convective cloud cluster developed over southeast and adjoining eastcentral Arabian Sea during last week of October 2011. It gradually concentrated into a low pressure area on 27th October, 2011. It became well marked, while moving west-northwestwards on 28th October and concentrated into a depression over westcentral and adjoining southwest Arabian Sea and lay centred at 0600 UTC of 29th October 2011 near lat. 13.0^{0}N and long. 62.0^{0}E with gradual increase in depth and organisation of convection. The intensity of the system was T1.5 as per Dvorak's technique applied to Kalpana imageries. The associated broken intense to very intense convection lay over the area between lat. 9.0^{0}N to 18.0^{0}N and long 56.0^{0}E to 72.0^{0}E. The lowest cloud top temperature (CTT) was -79^{0} C. The sustained Maximum wind speed was 25 knots around the system centre with rough to very rough sea condition. The estimated central pressure was 1004 hPa.

The cyclogenesis on 29th occurred due to increase in relative vorticity and convection at lower levels and upper air divergence. It was also due to low to moderate vertical wind shear (5-10 knots) with decreasing tendency (5-10 knots in past 24 hours). The upper level divergence was provided by the anticyclonic circulation which lay to the northeast of the system centre with ridge running along 15^{0}N.

The best track parameters of the system are given in Table 2.7.1. The track of the system is shown in Fig. 2.1. The typical satellite imageries showing the genesis and intensification/weakening of the system are shown in Fig. 2.7.1. The ECMWF analysis showing the lower level relative vorticity, lower level wind & upper level divergence and vertical wind shear are shown in Fig. 2.7.2. The genesis potential of the system could be picked up by the Genesis potential parameters of IMD.

2.7.3 Intensification and movement:

The favourable environmental condition prevailed over the Arabian Sea during 29-31 October 2011. However, the tropospheric ridge gradually moved northwards and ran along 18^{0}N on 1st November 2011. It resulted in west-northwestward movement of depression. The depression gradually intensified into a deep depression and lay centred at 0300 UTC of 1st November, 2011 over westcentral Arabian Sea near Lat. 16.0^{0}N and long. 56.0^{0}E, about 230 km east-southeast of Salalah (Oman).

As per Dvorak's technique, the intensity of the system was T2.0. The lowest CTT was -84^{0}C indicating increase in depth of convection. The maximum sustained wind speed was 30 knots and ECP was 1000 hPa.

The sea surface temperature over the central Arabian Sea and Gulf of Aden was about 28-29^{0}C as reported by the ships and buoys and the satellite estimation. However, the Ocean thermal energy was less (<40 KJ/cm^2) over Gulf of Aden and adjoining Arabian Sea. Considering all these the intensification of the system was slow. Further, the MJO was not favourable for intensification of the system as it lay in phase 8. Considering all these, the deep depression continued to move west-northwestwards, intensified into a cyclonic storm 'KEILA' and lay centred at 0300 UTC of 2nd November 2011 over westcentral Arabian Sea near lat 16.0^{0}N and long. 55.0^{0}E, about 150 km southeast of Salalah (Oman). The maximum sustained surface wind speed was 35 knots with ECP of 998 hPa. The intensity according to Dvorak's technique was T2.5. The lowest CTT was -85^{0}C.

As the cyclonic storm 'Keila' lay over colder sea surface and close to the land surface, it did not intensify further. Also there was cold air entrainment to the region. As a result, the cyclonic storm continued to move west-northwestwards and crossed Oman coast close to the north of Salalah between 1600-1700 UTC and lay centre at 1800 UTC of 2nd November 2011 over coastal Oman close to Salalah as a deep depression. Around the time of landfall, Salalah reported maximum wind of 23 knots at 1500 UTC and 6 knots at 1800 UTC of 2nd November 2011. It indicates that the system weakened just after the landfall.

On 3rd November the system lay to the north of the upper tropospheric ridge and in the periphery of the anticyclonic circulation to the east. As a result, the system re-emerged into the Arabian Sea on 3rd November. The anticyclonic circulation over Oman-Yemen area emerged into the Arabian Sea on 3rd November evening also. As a result, the system lay close to the anticyclonic circulation and meander over the region. At last the system moved eastwards and then southwards over the west central Arabian Sea and weakened gradually. It weakened into a low pressure area on 4th November 2011over westcentral Arabian Sea off Oman coast.

Crucial observation with respect to location and intensity are given in Table 2.7.2.

Table 2.7.1: Best track positions for cyclonic storm 'KEILA' (29 Oct-04Nov 2011)

Date	Time (UTC)	Centre lat.^{0}N/long^{0}E	C.I. No.	Estimated centre pressure (hPa)	Estimated maximum sustained surface wind (kts)	Estimated pressure drop at the centre (hPa)	Grade
29-10-2011	0600	13.0/62.0	1.5	1004	25	3.0	D
	1200	13.0/61.0	1.5	1004	25	3	D
	1800	13.0/61.0	1.5	1004	25	3	D
	0000	13.0/60.5	1.5	1004	25	3	D
30-10-2011	0300	13.0/60.0	1.5	1004	25	3	D
	0600	13.0/60.0	1.5	1002	25	3	D
	1200	13.5/59.5	1.5	1002	25	3	D
	1800	14.0/59.0	1.5	1002	25	3	D
31-10-2011	0000	14.5/59.0	1.5	1002	25	3	D
	0300	15.0/58.5	1.5	1000	25	3	D
	0600	16.0/57.0	1.5	1000	25	3	D
	1200	16.0/57.5	1.5	1000	25	3	D
	1800	16.0/57.0	1.5	1000	25	3	D
01-11-2011	0000	16.0/56.5	1.5	1000	25	3	D
	0300	16.0/56.0	2.0	1000	30	4	DD
	0600	16.0/56.0	2.0	1000	30	4	DD
	1200	16.0/55.5	2.0	1000	30	4	DD
	1800	16.0/55.5	2.0	1000	30	5	DD
02-11-2011	0000	16.0/55.3	2.0	1000	30	5	DD
	0300	16.0/55.0	2.5	998	35	7	CS
	0600	16.0/54.5	2.5	996	35	7	CS
	0900	16.0/54.5	2.5	996	35	7	CS
	1200	16.5/54.5	2.5	996	35	7	CS
	1500	16.8/54.3	2.5	996	35	6	CS
	The cyclonic storm 'KEILA' crossed Oman coast close to the north of Salalah (near lat.17.1^{0}N and long. 54.3^{0}E) between 1600-1700 UTC						
	1800	17.1/54.2	2.0	1000	30	5	DD

2.7.4 Realised Weather:

Heavy to very heavy rainfall occurred over coastal Oman.

2.7.5 Damage:

It caused death of 14 people and 200 people were injured in Oman.

Table 2.7.2 Crucial observation with respect to location and intensity of cyclonic storm 'KEILA;

Date/Time (UTC)	Station (Index/ Lat & Long.)	MSLP (hPa)	Wind (Direction/ speed)	Pressure fall (hPa)
30-10-2011/0300	Thumrait (41314)	--	--	-5.1
30-10-2011/1200	Salalah (41316)	1003.8	340/16	-2.8
	Yaaloni (41295)	1004.5	040/22	--
	Masirah (41288)	1007.1	090/18	--
	Buoy (16.3^{0}N/56.2^{0}E)	1003.2	--	-1.7
31-10-2011/0300	Al-ghaidah (41398)	1005.2	270/13	-1.8
	Salalah (41316)	1006.7	040/13	-1.7
	Buoy (16.3^{0}N/56.0^{0}E)	1003.6	--	--
	Ship (14.3^{0}N/59.4^{0}E)	1000.9	210/08	--
31-10-2011/1200	Salalah (41316)	1003.0	--	-0.9
	Ship(13.7^{0}N/55.4^{0}E)	1003.0	--	--
	Ship (14.5^{0}N/56.9^{0}E)	1002.5	310/12	--
01-11-2011/1200	Salalah (41316)	1004.0	--	-1.7
01-11-2011/1200	Salalah (41316)	1001.2	--	-1.8
02-11-2011/0300	Salalah (41316)	1004.0	--	--
	Buoy (16.3^{0}N/55.1^{0}E)	999.2	--	-1.1
02-11-2011/0600	Salalah (41316)	1005.9	350/13	--
	Buoy (16.5^{0}N/55.0^{0}E)	998.3		-1.0
02-11-2011/1200	Salalah (41316)	1000.5	320/16	-0.7
	Ship (15.6^{0}N/54.5^{0}E)	1003.5	--	-4.0
02-11-2011/1500	Salalah (41316)	1001.5	320/23	--
	Ship (16.5^{0}N/54.9^{0}E)	1002.5	--	--
02-11-2011/1800	Salalah (41316)	1003.4	330/16	-1.0
	Ship (16.2^{0}N/55.3^{0}E)	1009.1	190/23	+4.3
03-11-2011/0000	Salalah (41316)	1002.2	310/17	-1.2
03-11-2011/0300	Salalah (41316)	--	330/21	--
03-11-2011/1200	Salalah (41316)	1003.6	340/24	--

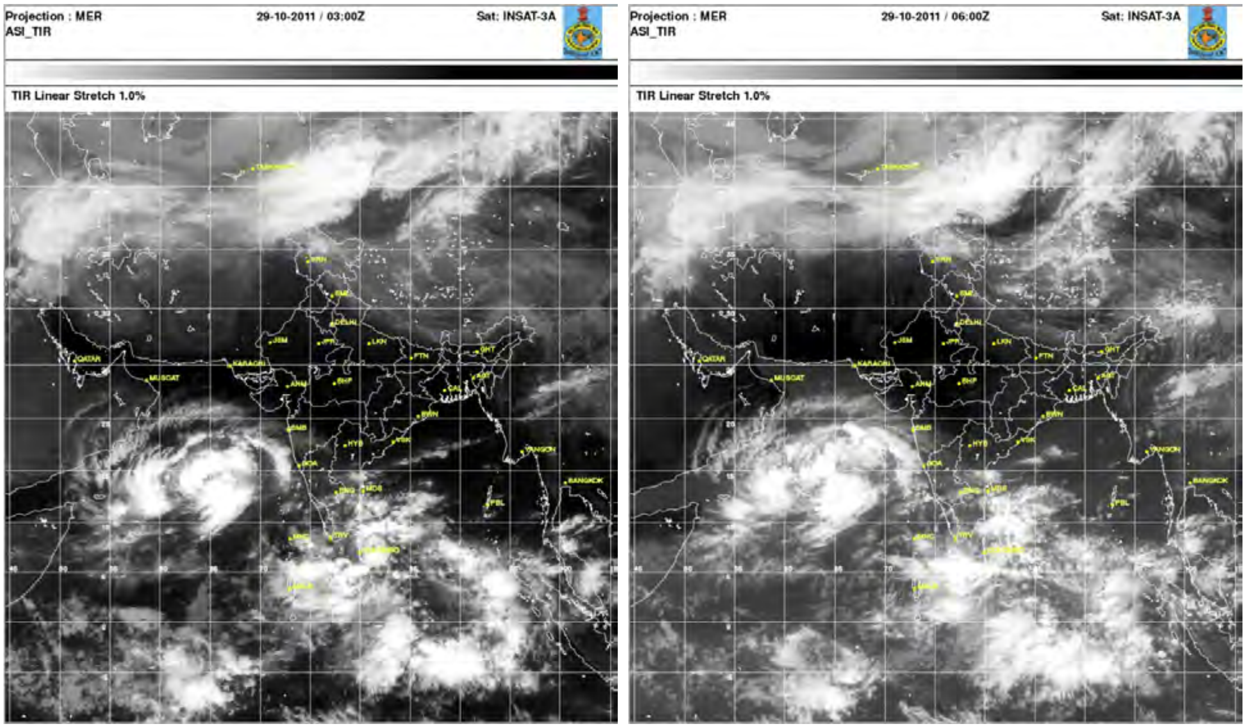


Fig. 2.7.1 The typical satellite imageries showing the genesis and intensification/weakening of the system.

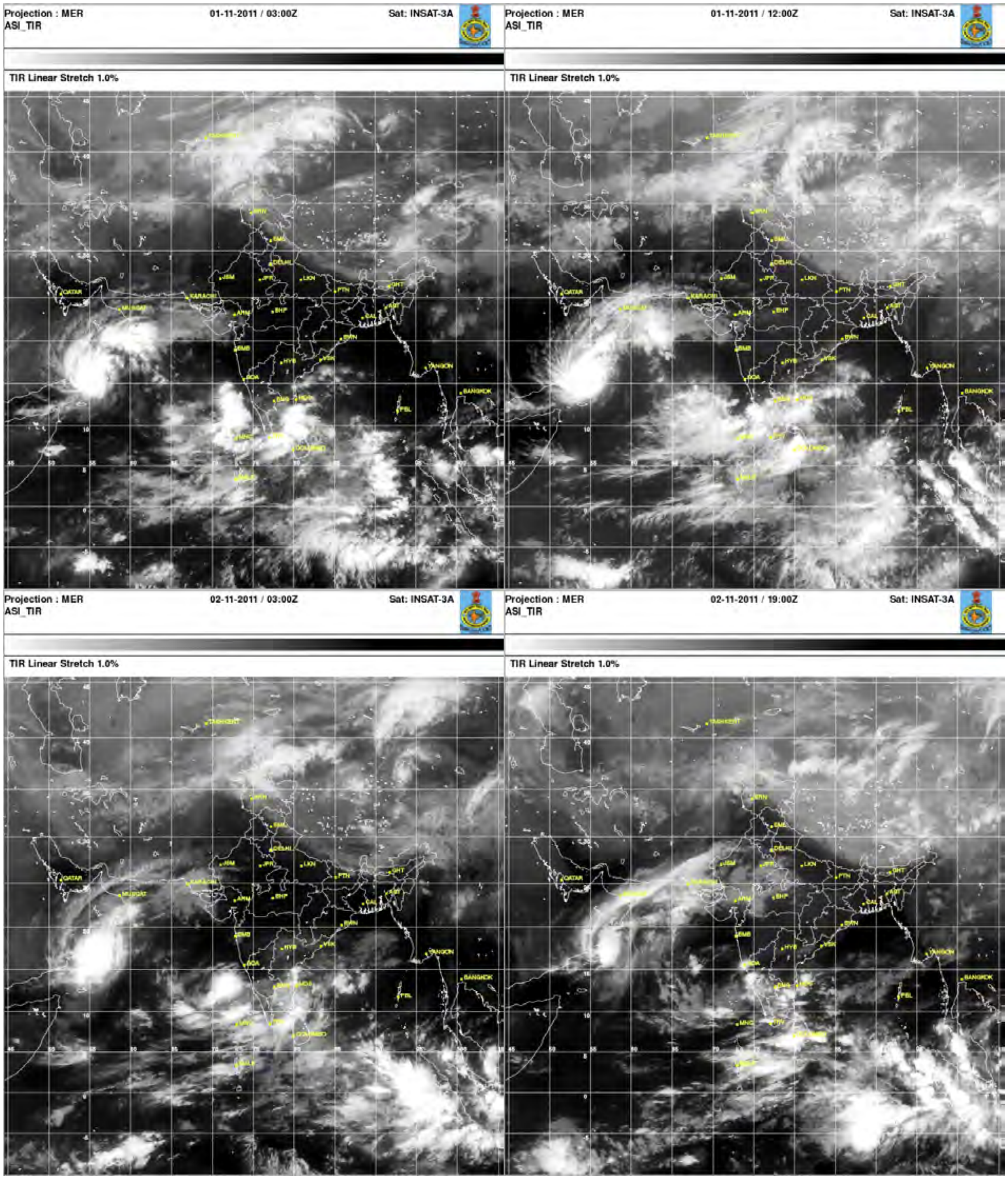


Fig.2.7.1 (contd) The typical satellite imageries showing the genesis and intensification/weakening of the system

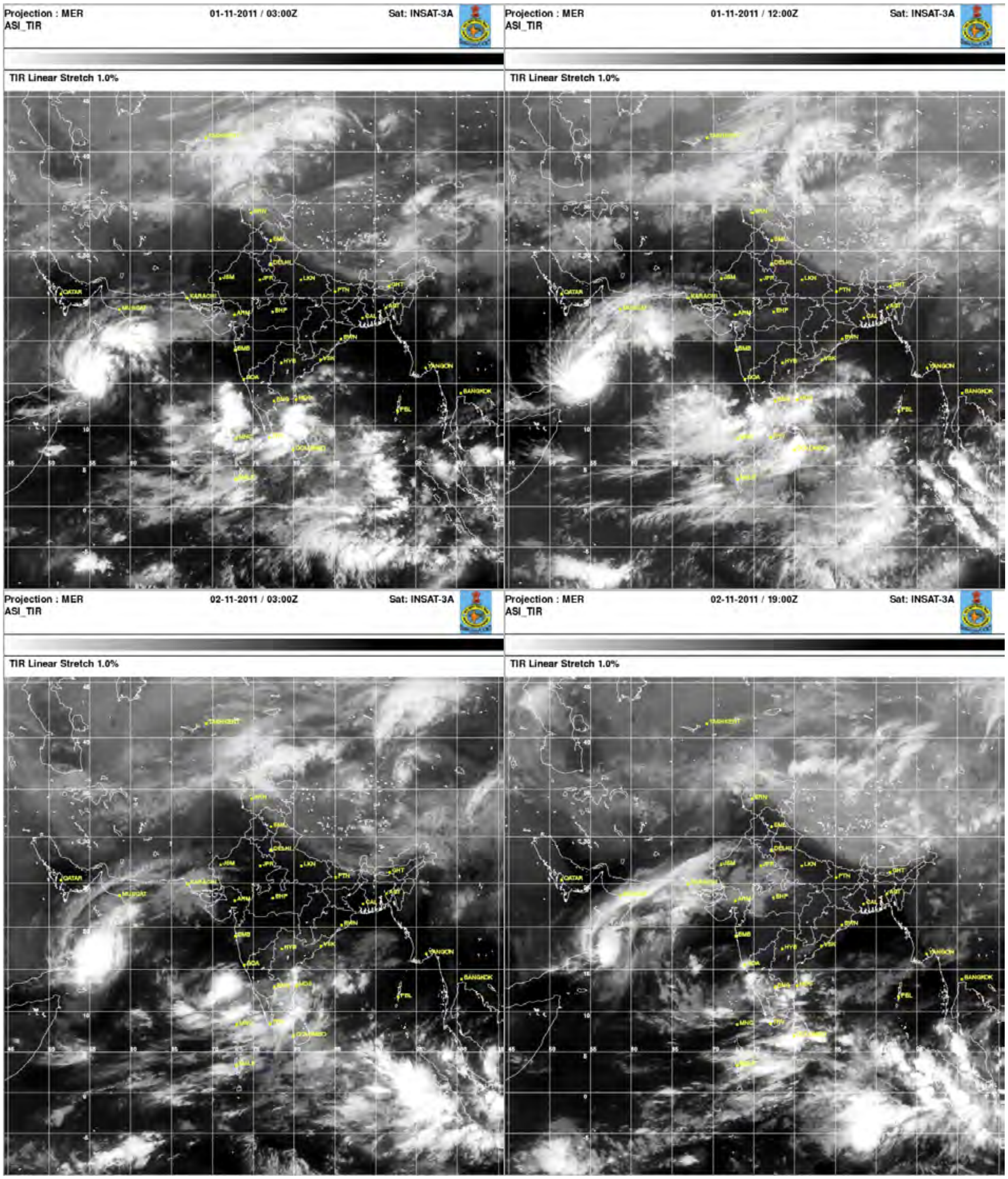


Fig. 2.7.1 (contd). The typical satellite imageries showing the genesis and intensification/weakening of the system

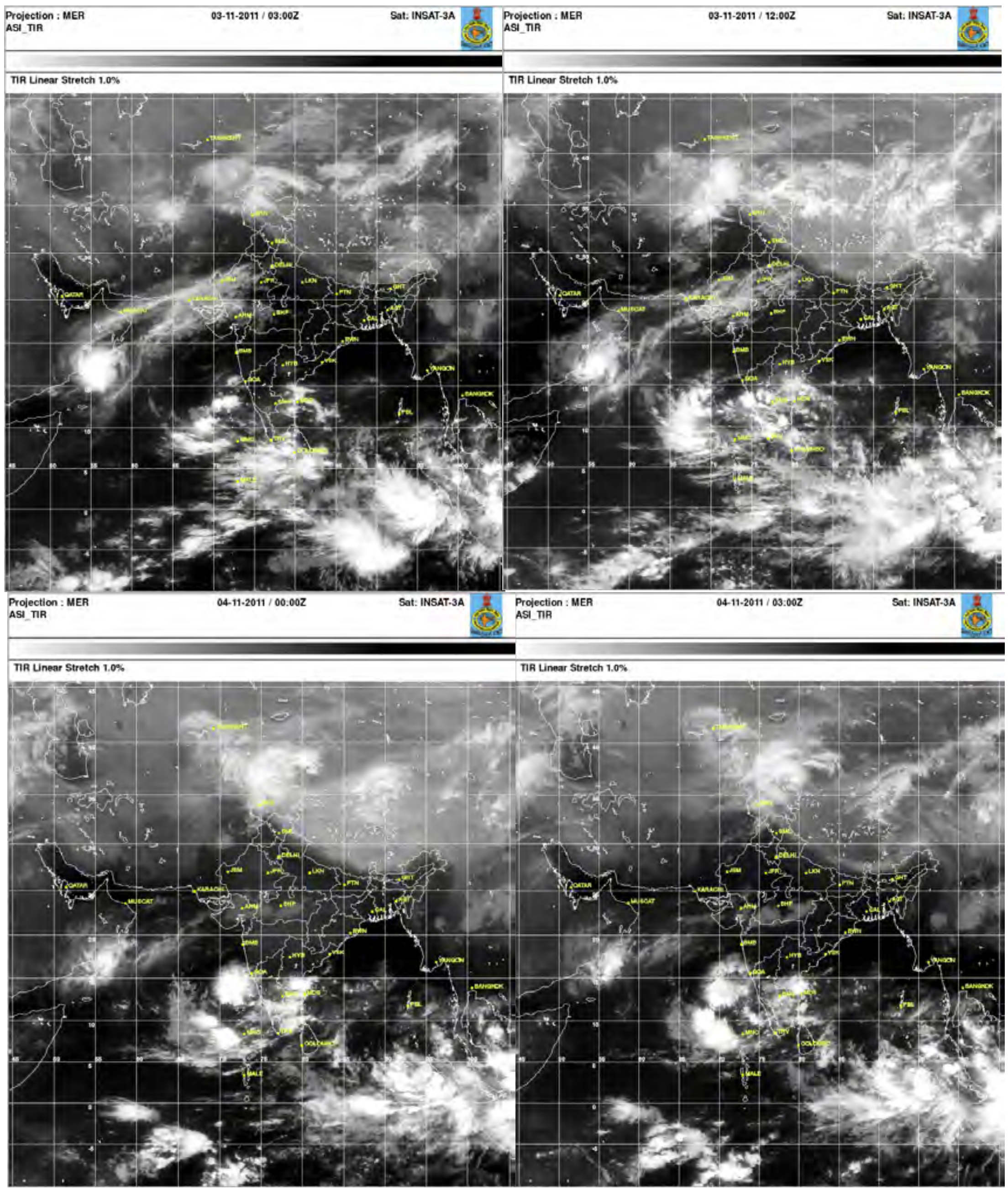


Fig.2.7.1 (contd) The typical satellite imageries showing the genesis and intensification/weakening of the system

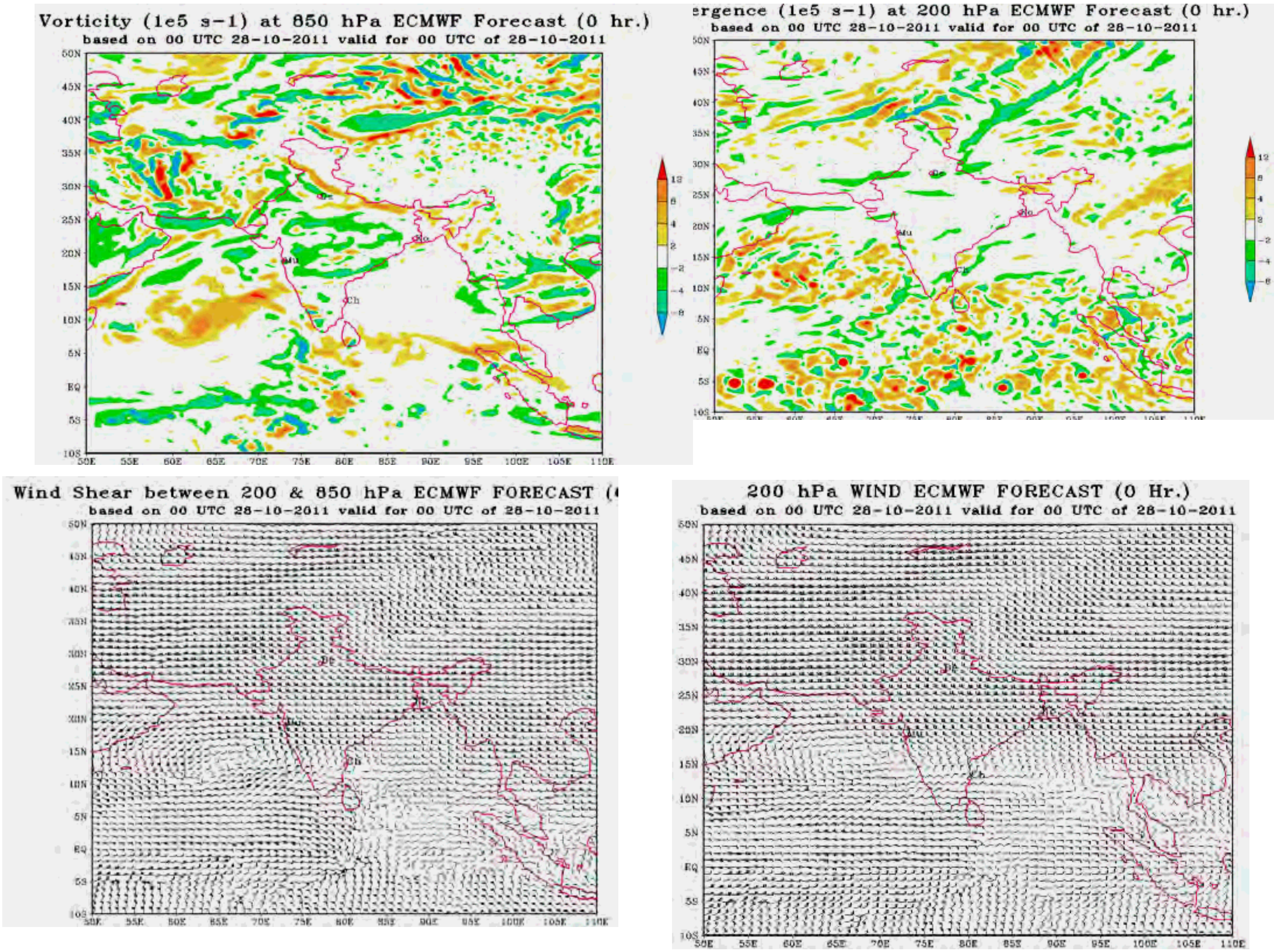


Fig.2.7.2 (a) (i) Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) vertical wind shear of horizontal wind between 200 and 850 hPa level (iv) wind at 200 hPa level based on the ECMWF model analysis of 0000 UTC of 28th October, 2011.

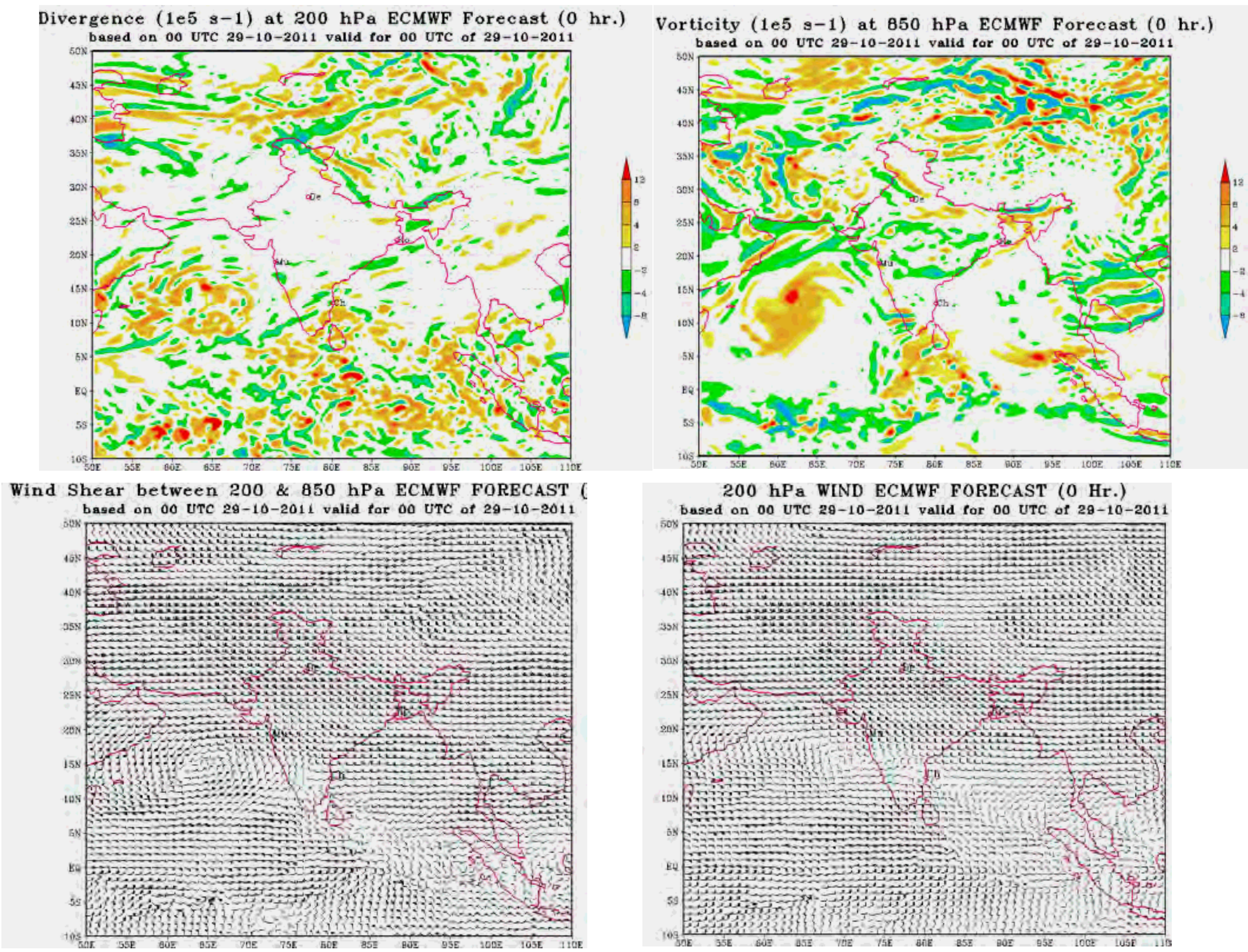


Fig. 2.7.2 (b) (i) Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) vertical wind shear of horizontal wind between 200 and 850 hPa level (iv) wind at 200 hPa level based on the ECMWF model analysis of 0000 UTC of 29th October, 2011.

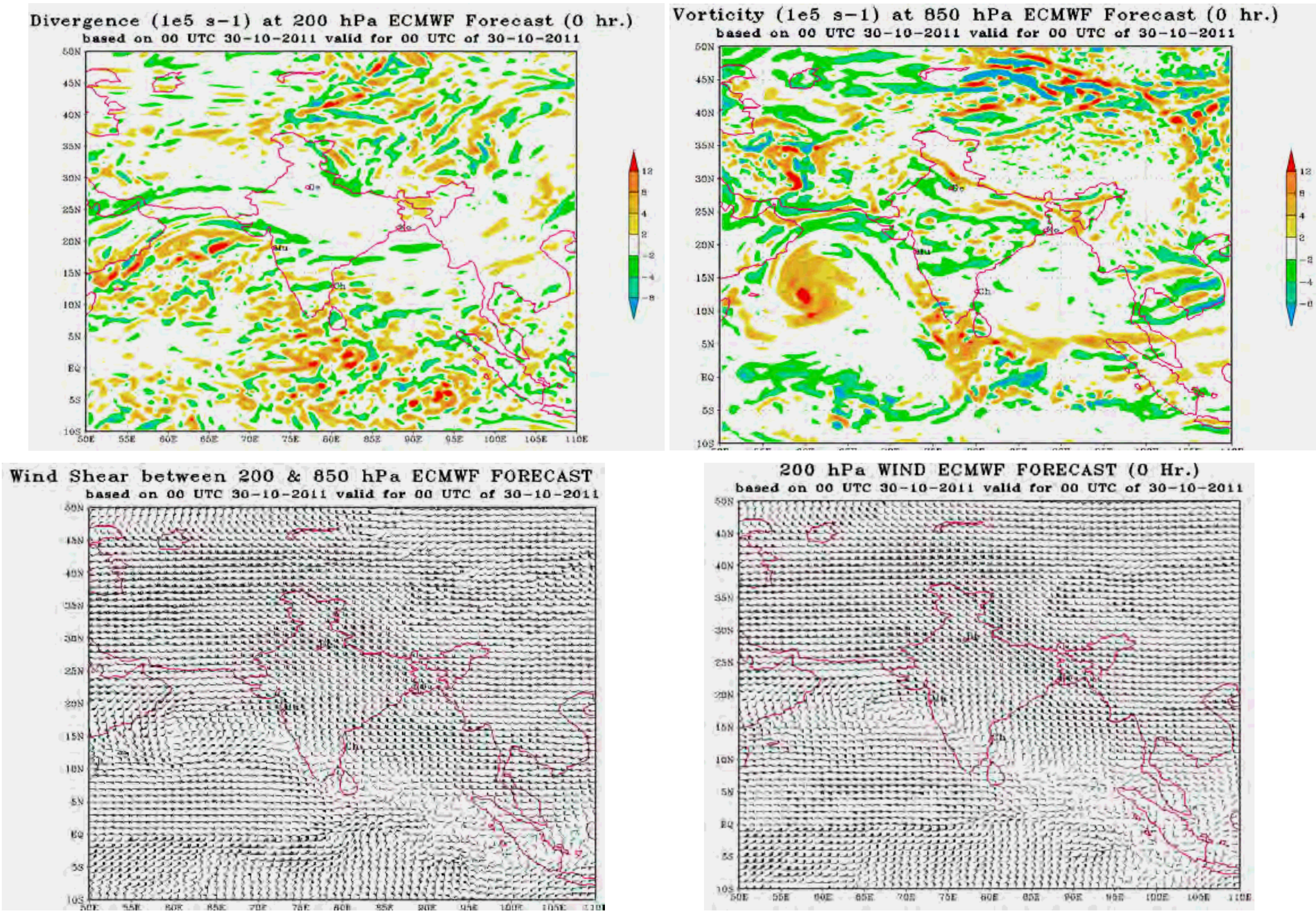


Fig.2. 7.2 (c) (i) Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) vertical wind shear of horizontal wind between 200 and 850 hPa level (iv) wind at 200 hPa level based on the ECMWF model analysis of 0000 UTC of 30th October, 2011.

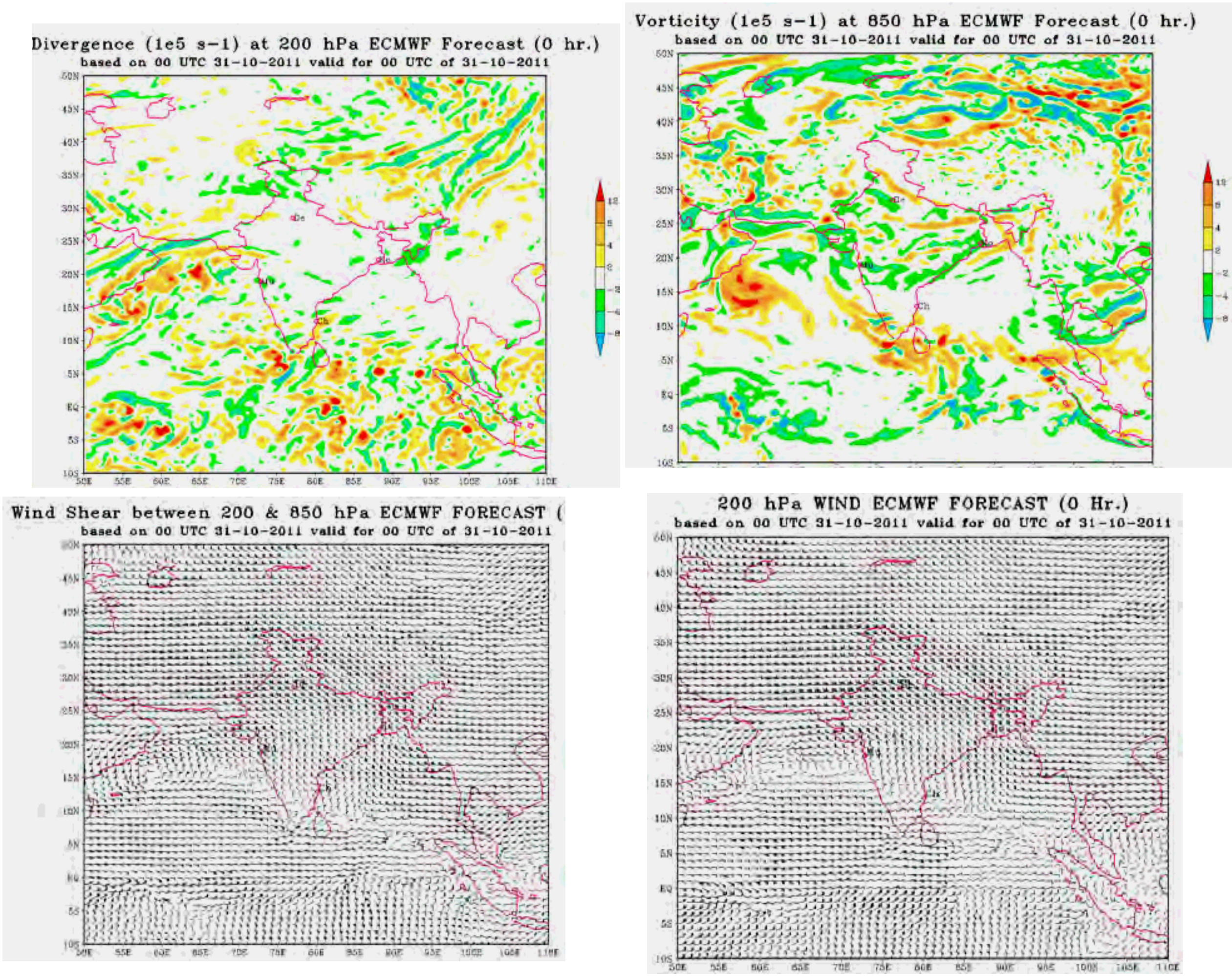


Fig. 2.7.2 (d) (i) Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) vertical wind shear of horizontal wind between 200 and 850 hPa level (iv) wind at 200 hPa level based on the ECMWF model analysis of 0000 UTC of 31st October, 2011.

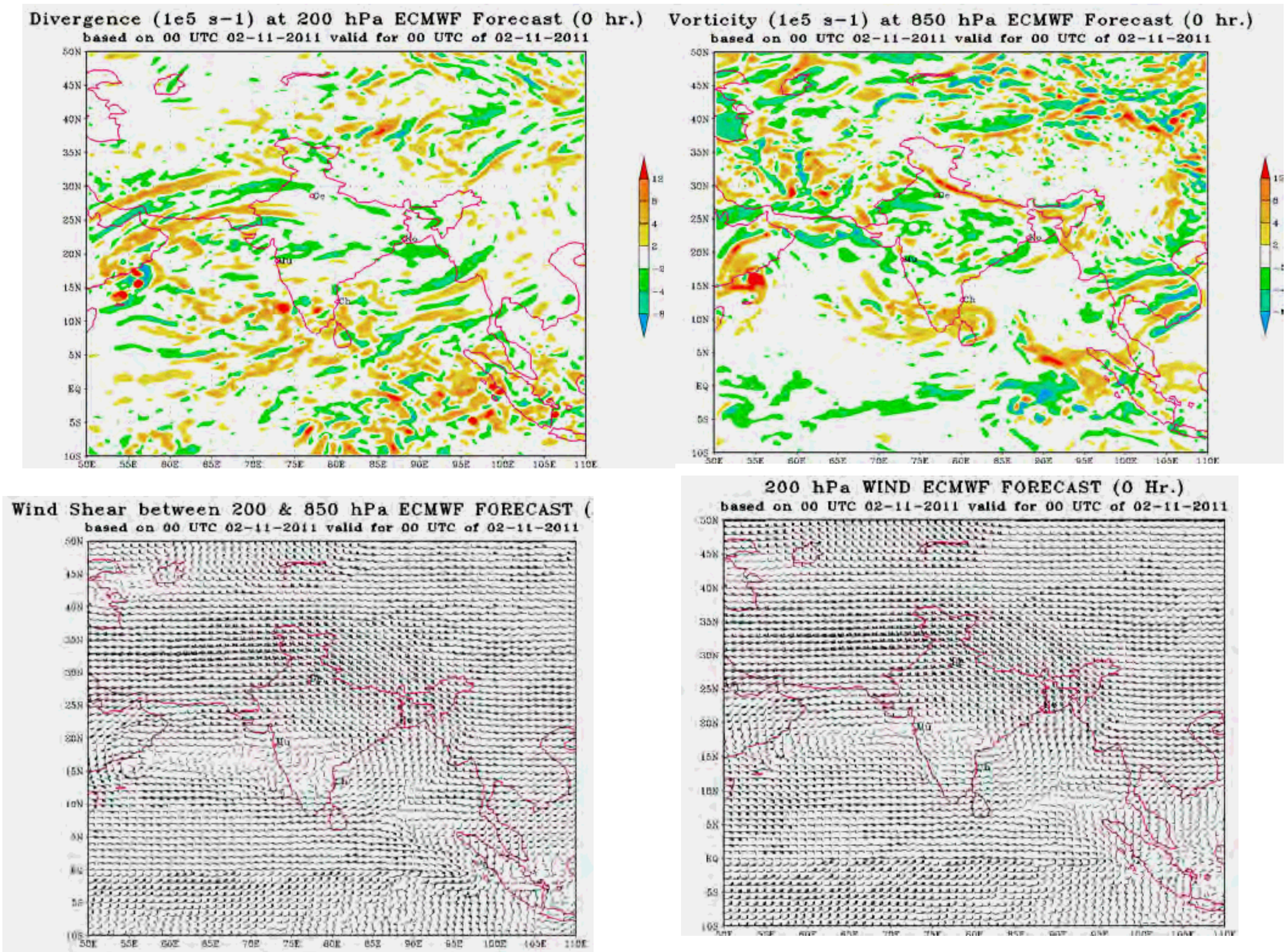


Fig. 2.7.2 (e) (i) Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) vertical wind shear of horizontal wind between 200 and 850 hPa level (iv) wind at 200 hPa level based on the ECMWF model analysis of 0000 UTC of 01st November, 2011.

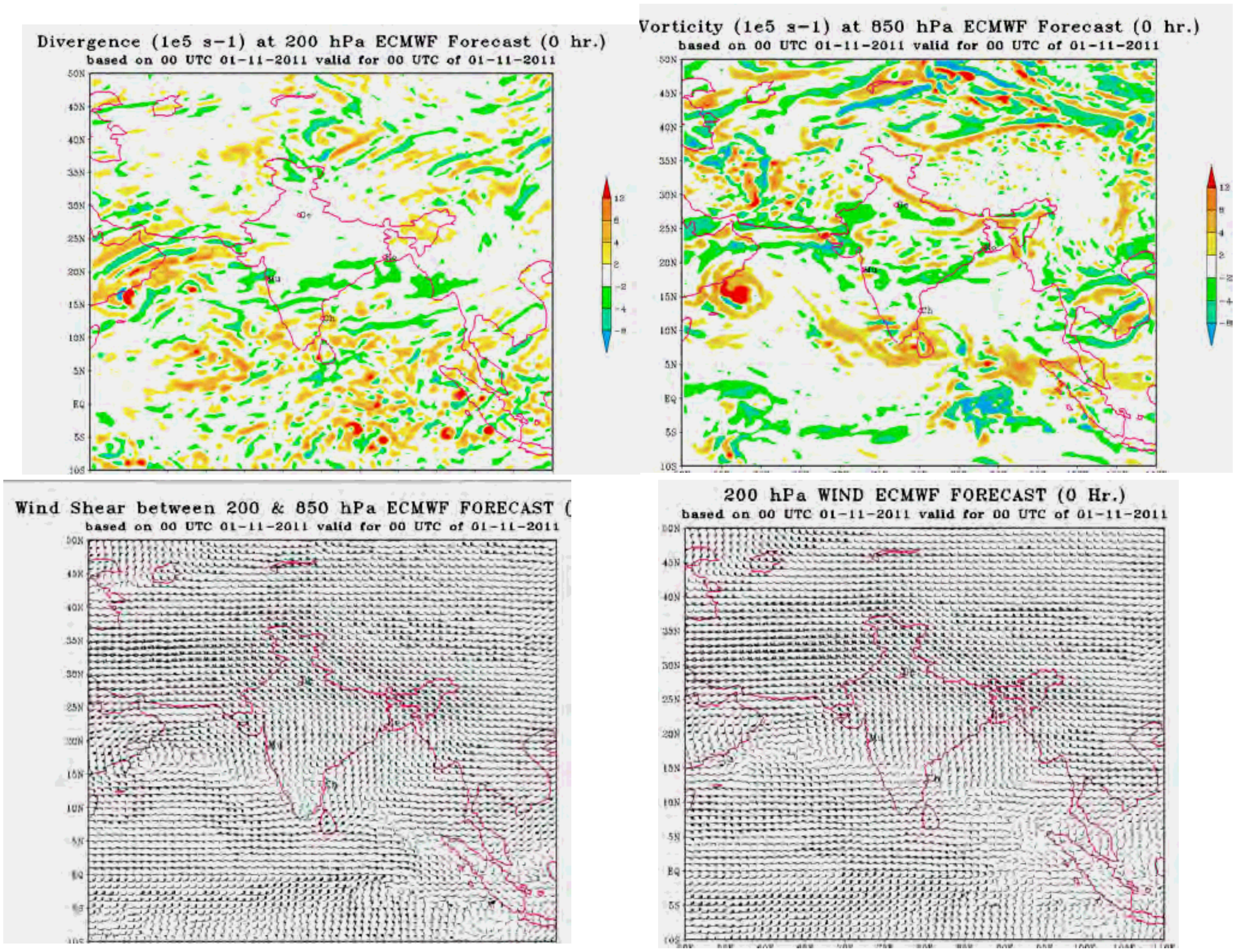


Fig. 2.7.2 (f) (i) Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) vertical wind shear of horizontal wind between 200 and 850 hPa level (iv) wind at 200 hPa level based on the ECMWF model analysis of 0000 UTC of 02nd November, 2011.

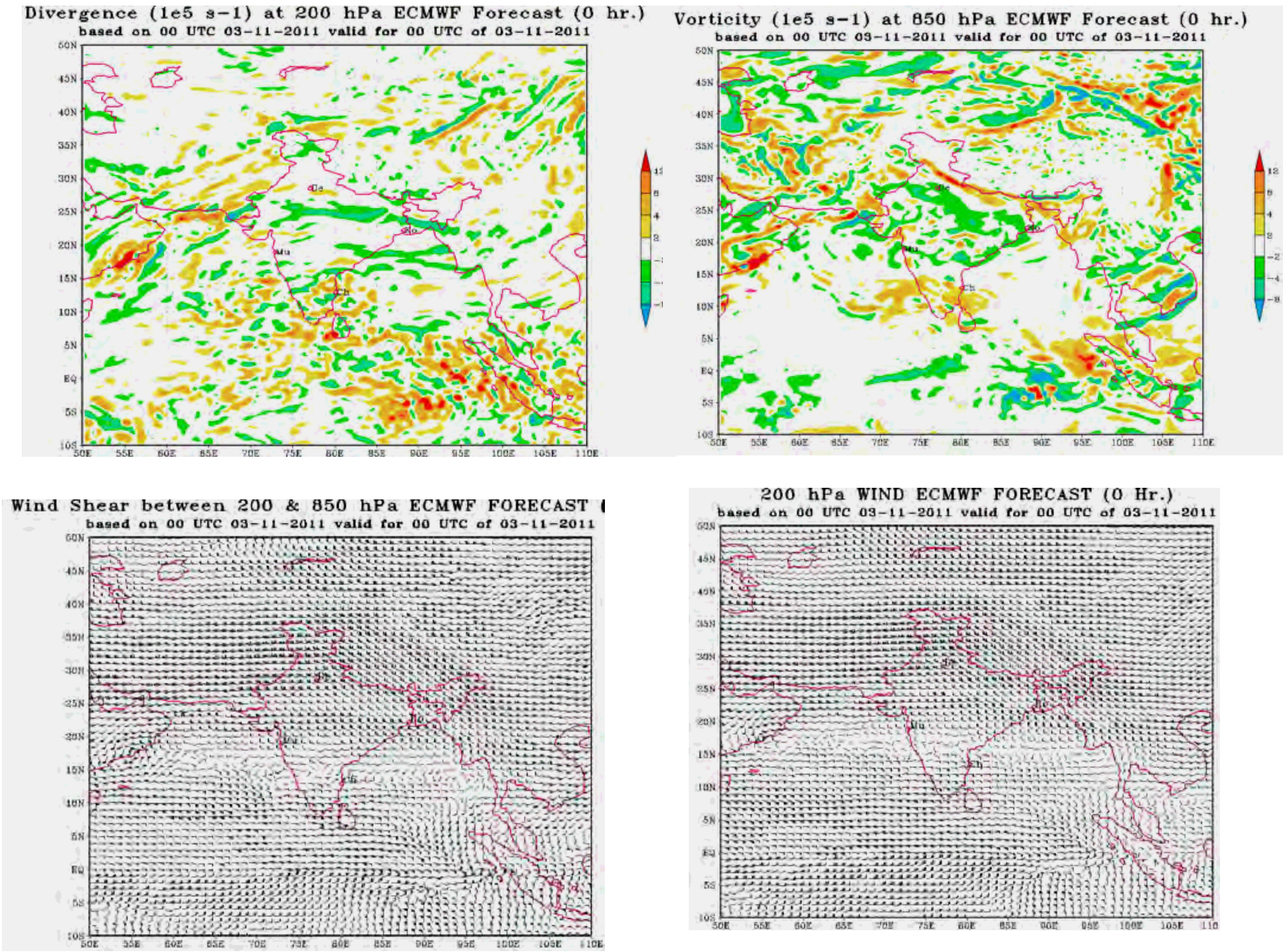


Fig. 2.7.2 (g) (i) Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) vertical wind shear of horizontal wind between 200 and 850 hPa level (iv) wind at 200 hPa level based on the ECMWF model analysis of 0000 UTC of 03rd November, 2011.

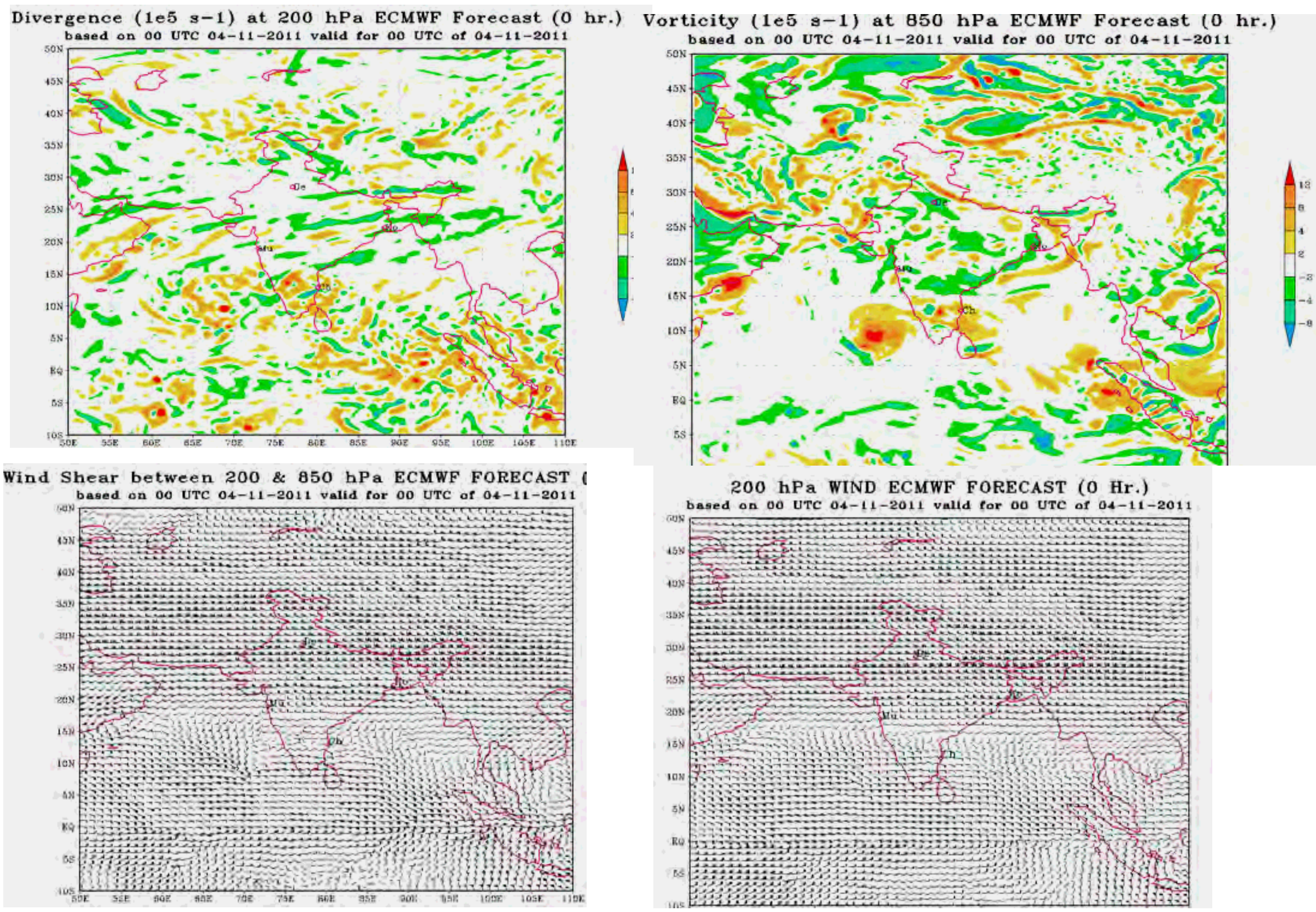


Fig. 2.7.2 (h) (i) Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) vertical wind shear of horizontal wind between 200 and 850 hPa level (iv) wind at 200 hPa level based on the ECMWF model analysis of 0000 UTC of 04th November, 2011.

2.8 Deep Depression over Arabian Sea (06- 10 November 2011)

2.8.1. Introduction:

A depression formed over southeast Arabian Sea on 6th November 2011, moved initially west-northwestwards and intensified into a depression and further into a deep depression. However, as it moved then northwestwards/northwards towards, westcentral Arabian Sea, it entered into colder sea and gradually dissipated over westcentral Arabian Sea off Oman coast on 10th November, 2011. The salient features of the system are described below.

2.8.2. Genesis:

Under the influence of active Inter Tropical Convergence zone (ITCZ) running roughly along 10^0N over the Arabian Sea a low pressure area formed over southeast Arabian Sea on 4th November 2011. It became well marked on 5th with formation of a vortex (T=1.0) as seen in Kalpana satellite imagery. The Madden Julian Oscillation (MJO) index lay over phase 4 with amplitude more than 1. While phase 4 is favourable, phase 5 and 6 are not favourable for cyclogenesis and intensification over the Arabian Sea. Sea surface temperature was 28^0-29^0 C. The ocean heat content was less (60-80 KJ/cm^2). The relative vorticity at 850 hPa level and upper level divergence increased on 6th November, 2011. The vertical wind shear of horizontal wind over the region was favourable as it was low to moderate (between 10-20 knots). There was negative (05 knots) 24 hour tendency of vertical wind shear around system centre. The system lay to the south of upper tropospheric ridge, which roughly ran along 17^0 N in association with an anticyclonic circulation to the northeast of system centre. Considering all these, the well marked low pressure area concentrated into a depression over southeast Arabian Sea and lay centred at 0600 UTC of 06th November 2011 near latitude 10.5^0N and longitude 65.5^0E. Satellite imagery indicated gradual increase in convection and organisation of the system. Associated broken intense to very intense convection are seen over Arabian Sea between lat. 8.5^0N to 15.0^0N long. 59.0^0E to 65.5^0E. The lowest cloud top temperature (CTT) due to convection was around -78^0C in association with the system. Sustained maximum surface wind speed was estimated to be about 25 knots around system centre. The estimated central pressure is about 1004 hPa. The ship (position near 9.5^0N and 68^0E) reported MSLP of 1010.5 hPa with tendency of +1.5 hPa and wind of 210/19 knots. Another ship (position near 13.6^0N and 62.9^0E) reported MSLP of 1011.1 hPa with tendency of -1.0 hPa and wind of 010/30 knots.

2.8.3. Intensification and movement:

All the above mentioned synoptic and environmental condition continued during 6-8th November 2011. It resulted in the west-northwestward movement of the system and gradually intensification. It intensified into a deep depression and lay centred at 0300 UTC of 8th November, 2011 over westcentral Arabian Sea near lat. 13.5^0N and long.60.0^0E.

The MJO index moved to phase 6 on 9th November which is not favourable for intensification of the system. Also the system lay over the colder Sea with SST of 26-28^0 C and Ocean heat content of < 40 KJ/cm^2. The vertical wind shear of the horizontal wind also increased to 15-25 knots, as the system came under the influence of middle and upper tropospheric westerly trough to its west along 40^{0}E. It also lay closed to the south of upper tropospheric ridge. As a result the deep depression moved north-northwestwards/northwards on 9th and 10th and weakened gradually. It weakened into a depression at 1200 UTC of 9th and into a well marked low pressure area at 1200 UTC. Though the system came under the influence of upper tropospheric westerly trough, it could not recurve northeastwards and rather moved slowly northward, as it was sandwitched between two anticyclonic circulations, one over the eastcentral Arabian Sea and another over Yemen and adjoining Oman in lower and middle levels.

The best track of the system is shown in Fig. 2.1. The typical satellite imageries are shown in Fig 2.8.1. The best track and other parameters are show in Table 2.8.1. The crucial observations are given in Table 2.8.2. The ECMWF analysis based on 0000 UTC initial conditions during 5-10 November 2011 are shown in Fig. 2.8.2.

Table 2.8.1. The best track position and other parameters of the deep depression over the Arabian Sea during 06-10 November, 2011.

Date	Time (UTC)	Centre lat.^{0}N/long^{0}E	C.I. No.	Estimated centre pressure (hPa)	Estimated maximum sustained surface wind (kts)	Estimated pressure drop at the centre (hPa)	Grade
06-11-2011	0600	10.5/65.5	1.5	1004	25	3	D
	1200	10.5/65.5	1.5	1004	25	3	D
	1800	11.0/64.5	1.5	1004	25	3	D
07-11-2011	0000	11.5/64.0	1.5	1002	25	3	D
	0300	11.5/63.5	1.5	1002	25	3	D
	0600	12.5/62.0	1.5	1002	25	3	D
	1200	13.5/60.5	1.5	1002	25	3	D
	1800	13.5/60.5	1.5	1002	25	3	D
08-11-2011	0000	13.5/60.0	1.5	1002	25	3	D
	0300	13.5/60.0	2.0	1000	30	4	DD
	0600	13.7/59.5	2.0	1000	30	4	DD
	1200	14.0/59.0	2.0	1000	30	4	DD
	1800	14.5/58.5	2.0	1000	30	4	DD
09-11-2011	0000	15.0/58.5	2.0	1000	30	4	DD
	0300	15.0/58.5	2.0	1000	30	4	DD
	0600	15.0/58.5	2.0	1000	30	4	DD
	1200	15.5/58.5	1.5	1002	25	3	D
	1800	15.5/58.5	1.5	1002	25	3	D
10-11-2011	0000	16.0/58.5	1.5	1002	25	3	D
	0300	16.0/58.5	1.5	1002	25	3	D
	1200	The system weakened into a well marked low pressure area over westcentral Arabian Sea off Oman coast.					

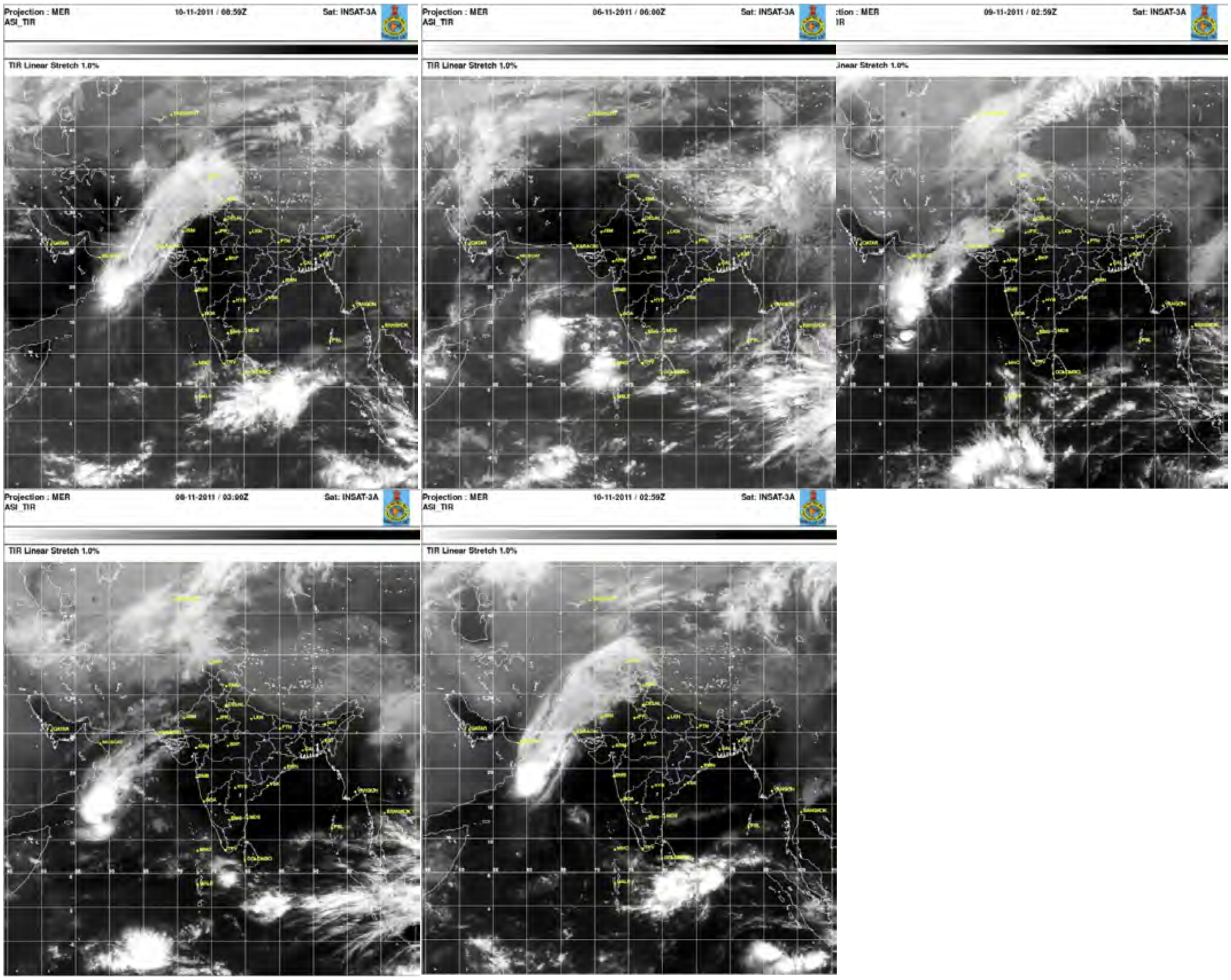


Fig 2.8.1 The typical satellite imageries during 06-10 November 2011 showing the intensification, movement and disorganization of the system.

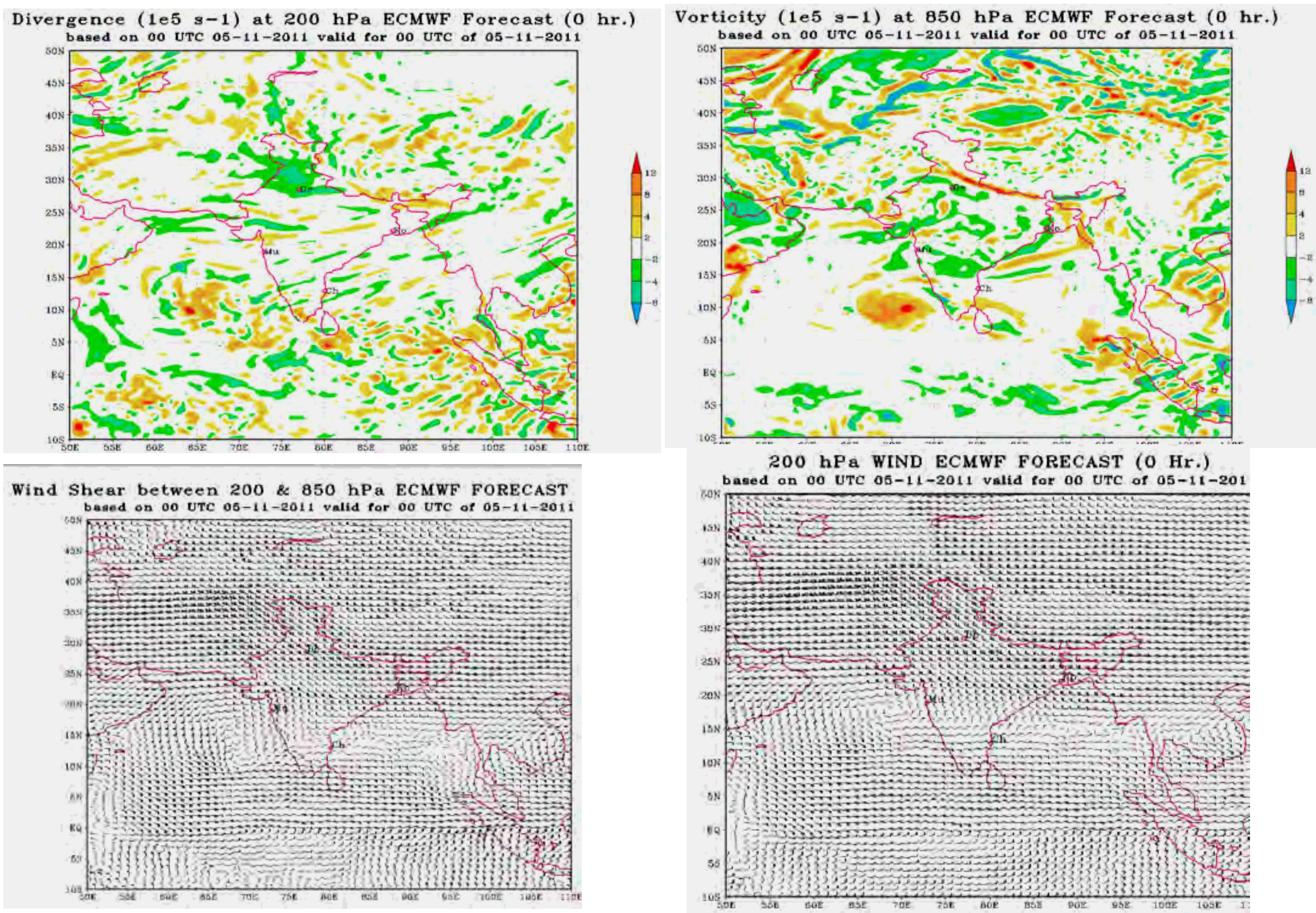


Fig. 2.8.2 (a) (i) Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) vertical wind shear of horizontal wind between 200 and 850 hPa level (iv) wind at 200 hPa level based on the ECMWF model analysis of 0000 UTC of 5th November, 2011.

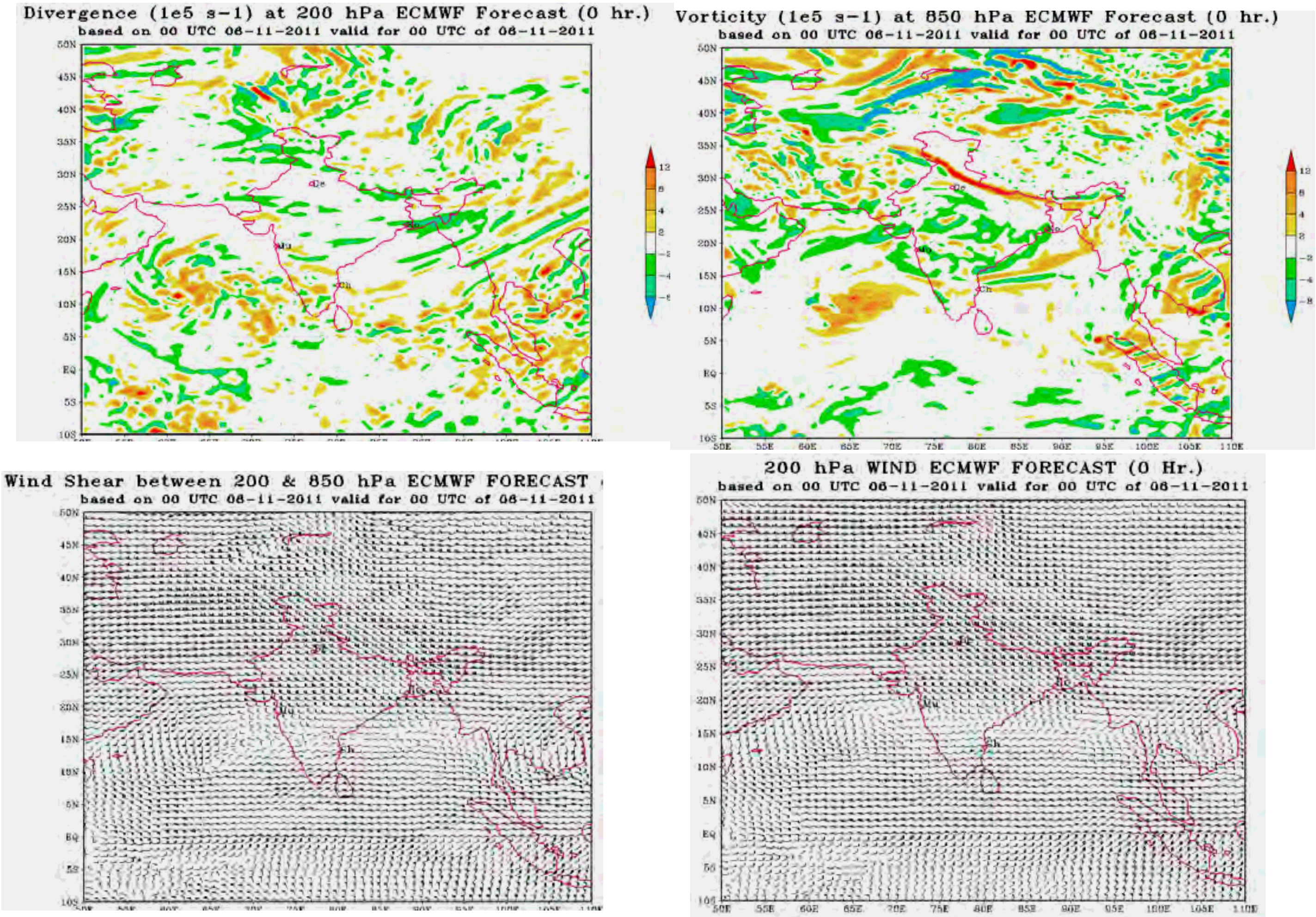


Fig. 2.8.2 (b) (i) Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) vertical wind shear of horizontal wind between 200 and 850 hPa level (iv) wind at 200 hPa level based on the ECMWF model analysis of 0000 UTC of 6th November, 2011.

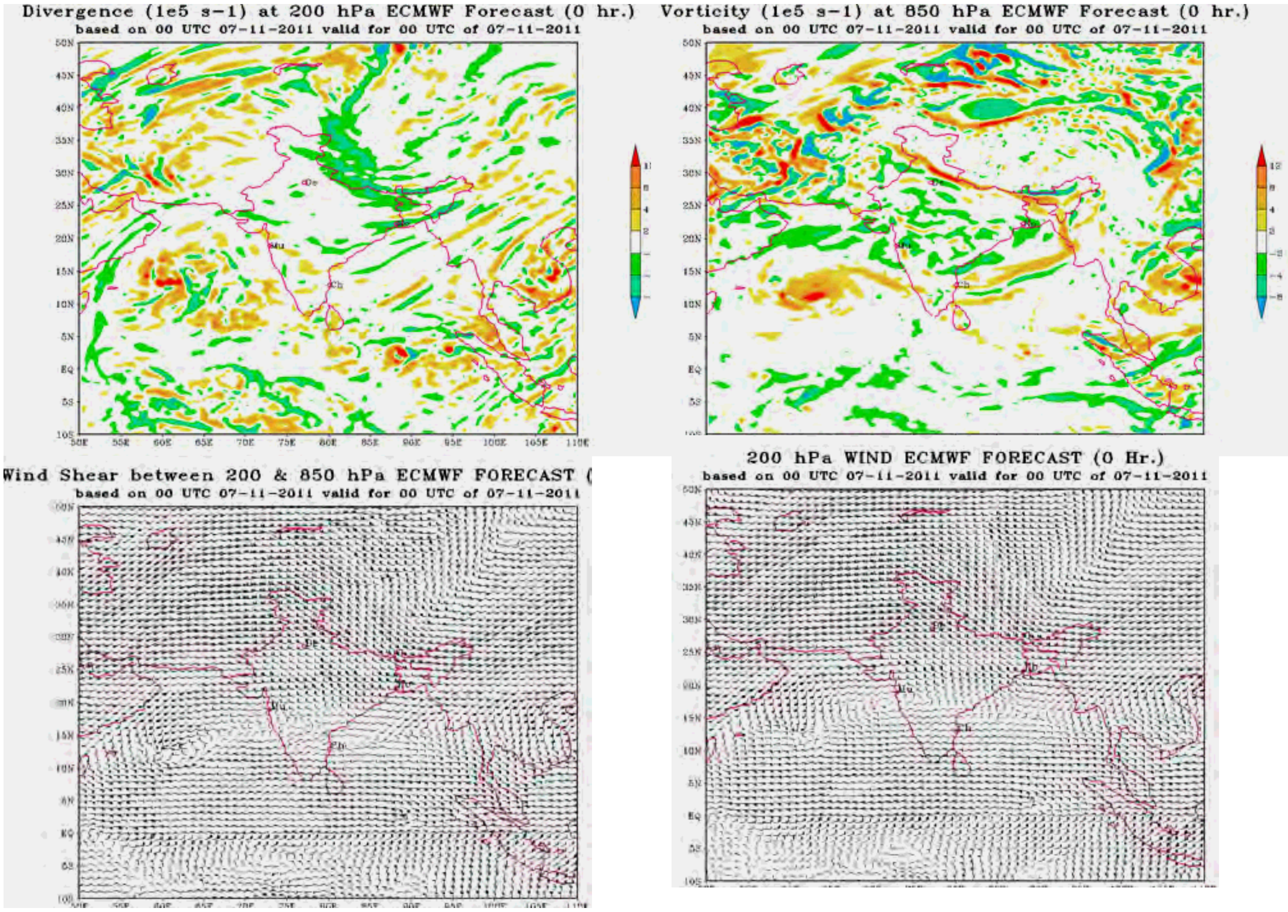


Fig. 2.8.2 (c) (i) Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) vertical wind shear of horizontal wind between 200 and 850 hPa level (iv) wind at 200 hPa level based on the ECMWF model analysis of 0000 UTC of 7th November, 2011.

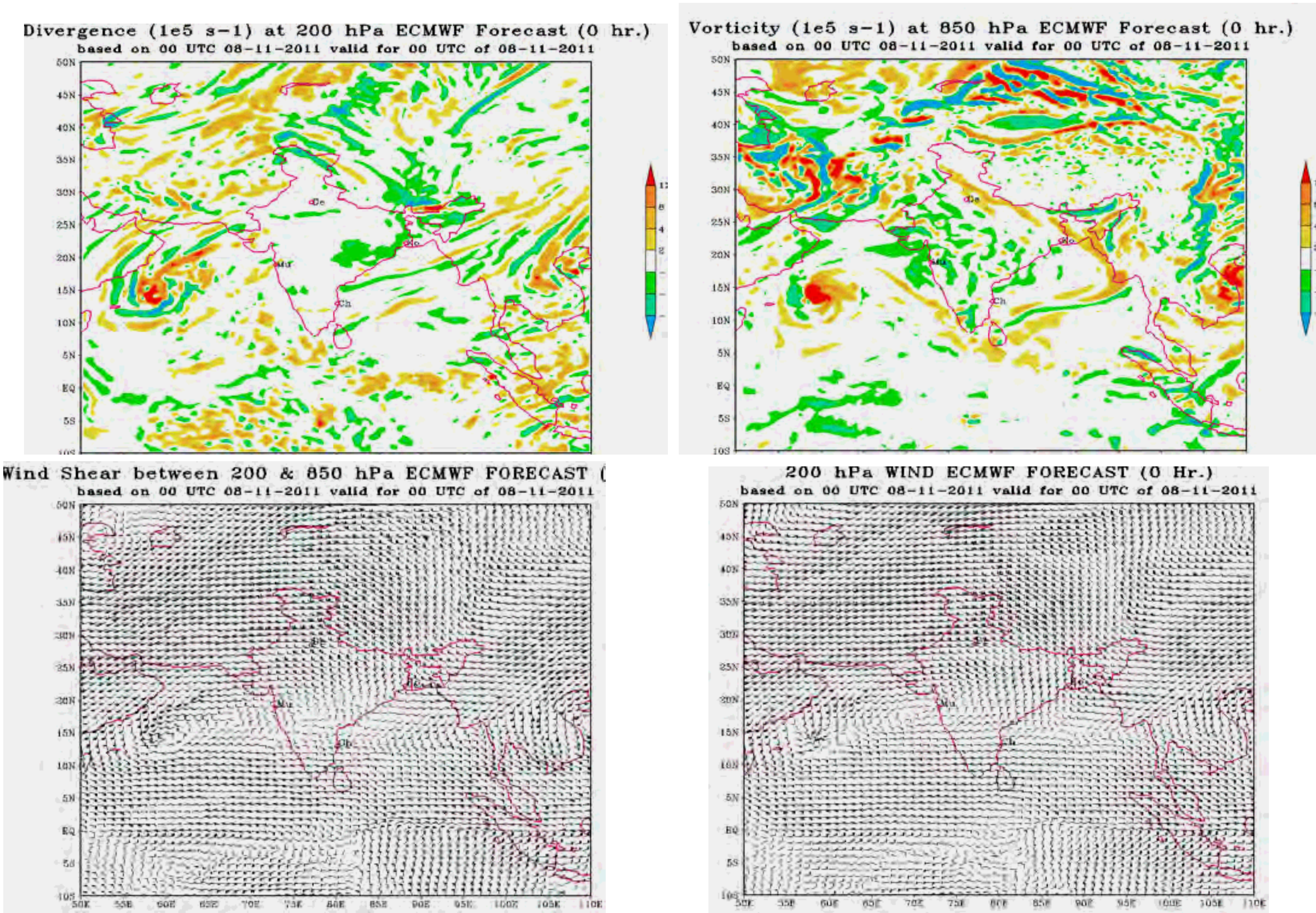


Fig. 2.8.2 (d) (i) Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) vertical wind shear of horizontal wind between 200 and 850 hPa level (iv) wind at 200 hPa level based on the ECMWF model analysis of 0000 UTC of 8th November, 2011.

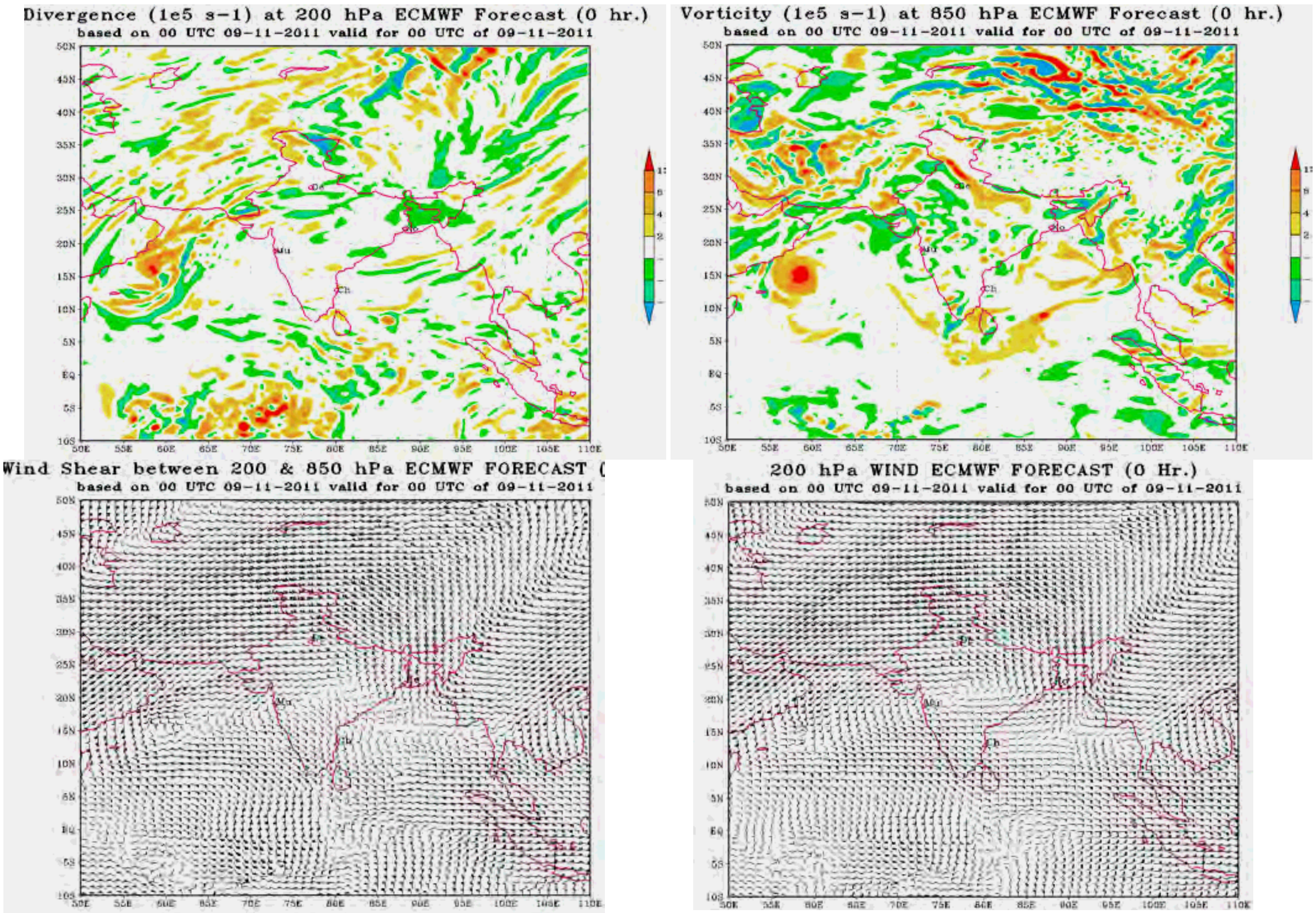


Fig. 2.8.2 (e) (i) Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) vertical wind shear of horizontal wind between 200 and 850 hPa level (iv) wind at 200 hPa level based on the ECMWF model analysis of 0000 UTC of 9th November, 2011.

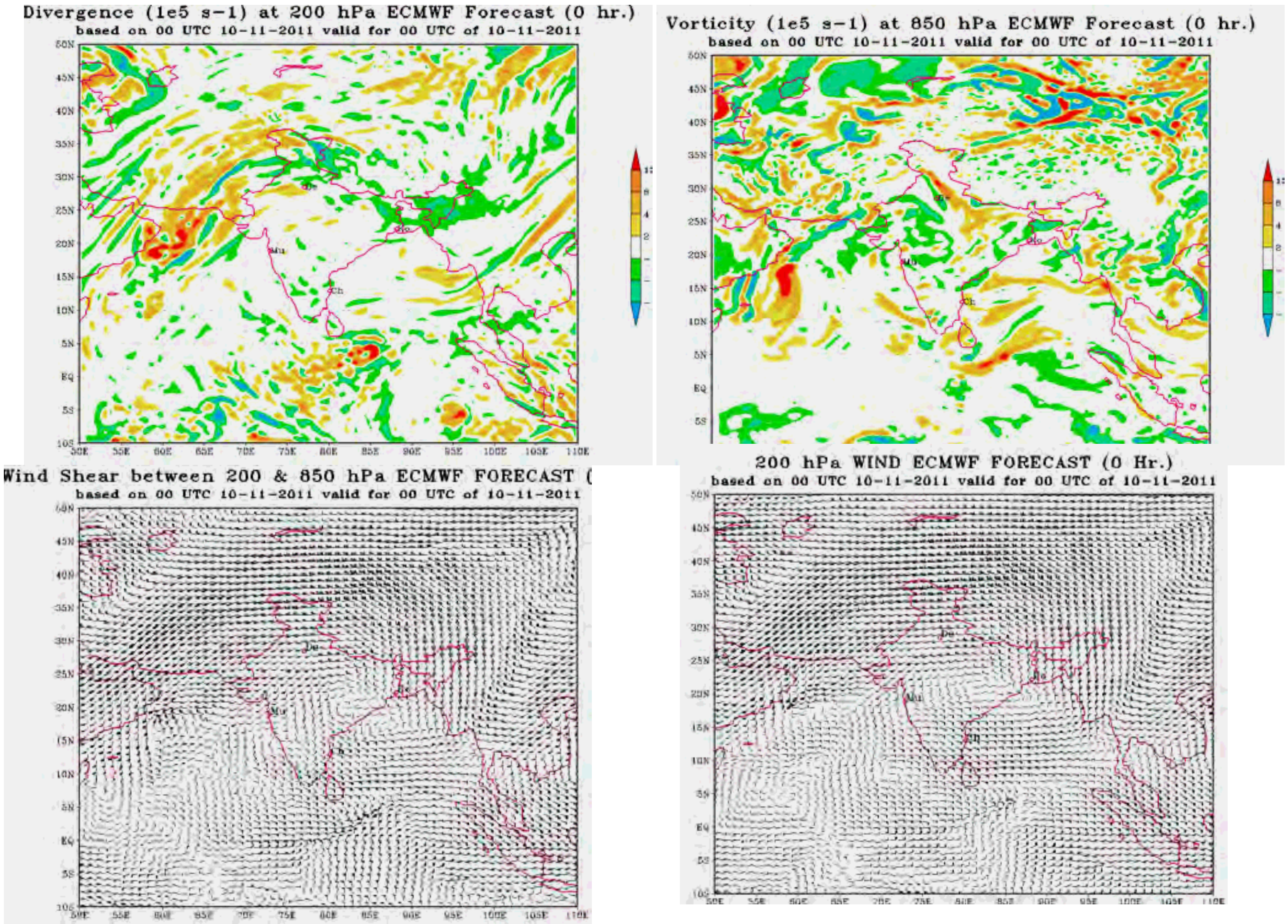


Fig. 2.8.2 (f) (i) Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) vertical wind shear of horizontal wind between 200 and 850 hPa level (iv) wind at 200 hPa level based on the ECMWF model analysis of 0000 UTC of 10th November, 2011.

2.8.4 Realised weather:

No significant weather has been reported from Oman due to this system.

2.8.5 Damage:

No damage has been reported in Oman due to this system.

2.9 Deep Depression over Arabian Sea (26 Nov to 1stDec,2011)

2.9.1 Introduction:

A depression formed over the Comorian area on 26th November. Moving west-northwestwards, it intensified into a deep depression over Lakshadweep area. It then moved northwestwards towards Oman coast. However, due to colder sea and increase in vertical wind shear it weakened and dissipated over west central Arabian Sea off Oman coast on 1st December. The detailed characteristics of this system are described below.

The cyclogenesis, intensity and location were mainly determined based on satellite imageries and products. In-situ observations from surface observatories of India and Sri Lanka and buoy and ship observations were also immense use. However, as the system entered into central Arabian Sea, satellite was the main source for determining location and intensity of the system.

2.9.2 Genesis:

Arabian Sea has been quite active in post-monsoon season (October-December), 2011. It was the third cyclonic disturbance over the Arabian Sea during this period. The higher cyclogenesis over this ocean basin could be attributed to active ITCZ and favourable large scale amplification of convection due to MJO.

Like the previous two system, this system also formed due to active ITCZ over the region. The active ITCZ roughly ran along 7.0^{0}N on 23-25 November, 2011. Under its influence, a cyclonic circulation formed over southwest Bay of Bengal off Sri Lanka and south Tamil Nadu coast on 23rd November 2011. It was seen as a low pressure area over southwest Bay of Bengal and adjoining Sri Lanka on 24th. It moved west-northwestwards and became well marked on 25th and concentrated into a depression at 0300 UTC of 26th November over the Comorian area and neighbourhood and lay centred near lat. 7.5^{0}N and long. 76.5^{0}E, about 120 km south-southwest of Thiruvanthapuram.

The favourable factors for cyclogenesis included the favourable MJO (MJO index in phase 2), warmer sea surface temperature (28-29^{0}C), higher ocean thermal energy (70-80 KJ/cm^2), higher relative vorticity and convergence at lower levels, higher upper levels divergence and low to moderate vertical wind shear (10-20 knots) between 200 and 850 hPa levels.

The best track parameters of the system are shown in Table 2.9.1. The best track is shown in Fig. 2.1. The typical satellite imageries are shown in fig. 2.9.1. The ECMWF model analysis during different phases of the system are shown in Fig 2.9.2.

2.9.3 Intensification and movement :

The depression lay to the south of the upper tropospheric ridge, which ran along 14^{0}N in association with an anticyclonic circulation over southwest peninsula of India and adjoining southwest Bay of Bengal on 26th November 2011. As the system lay far to the south of the steering ridge, it moved west-northwestwards. Also the favourable condition as mentioned in previous section continued with MJO index moving slowly to phase 3 on 27th. As a result, the depression further intensified into a deep depression and lay centred at 0000 UTC of 28th November over central Bay of Bengal near Lat 13.5^{0}N and long. 70.0^{0}E. As the a system picked gradually northerly latitude, The upper tropospheric ridge also moved northward alongwith the anticyclonic circulation. As a result, the system continued to lie in the southwestern periphery of the anticyclonic circulation in middle and upper tropospheric levels. However, the anticyclonic circulation retrograded gradually from its central location over central Bay of Bengal off Andhra Pradesh coast at 1200 UTC of 26th to north Maharashtra and south Gujarat at 0000 UTC of 1st December. The upper tropospheric ridge ran along lat. 18^{0}N on 28th morning, 19^{0}N on 29th and 20^{0}N on 30th November 2011. At the same time a trough in mid latitude westerlies in middle and upper tropospheric levels moved gradually eastwards. It ran along 40^{0}E to the north of 15^{0}N on 28th, 45^{0}E to the north of 15^{0}N on 29th and 50^{0}E to the north of 15^{0}N on 30th November 2011.

Under all these scenario, though the vertical wind shear gradually decreased being minimum and leading to intensification in deep depression, it increased after wards. Further it experienced colder sea (SST of 26-27^{0}C) and low ocean thermal energy (<50 KJ/cm^2) from 28th November onwards. All these led to gradual weakening of the system. It weakened into a depression at 1200 UTC of 29th November and lay centred near lat. 16^{0}N and long. 66.5^{0}E and further into a well marked low pressure area over west central Arabian Sea at 0600 UTC of 1st December 2011.

Under the impact of the approaching trough in westerlies in middle and upper levels and anticyclonic circulation to the northeast of the system centre, the poleward outflow from the system reached upto Karnataka coast on 28th, Maharashtra and Gujarat coast on 29th and north Pakistan and adjoining Indian region on 30th November 2011. The track of the system as changed from west-northwesterly to northwesterly on 29th and north-northwesterly on 30th November 2011.

2.9.4 Realised weather:

Heavy to very heavy rainfall occurred over Tamil Nadu, Puducherry, Kerala and Lakshadweep Island and also over Sri Lanka. Chief amount of rainfall (in cm) are follows:

27-11-2011:

Coonoor 16, Kodaikanal and Kovilpatti 13 each, Tiruttani 12, Kavaratti 11, Tuticorin, Ennore Port and Cuddalore 9 each, Chennai 8, Pechiparai, Thiruvanathpuram, Agati and Kanyakumari 7 each.

Table 2.9.1 Best Track positions and other parameter of deep depression over the Arabian Sea during 26 N0vember-01 December, 2011

Date	Time (UTC)	Centre (Lat ^{0}N/ Long ^{0}E)	C.I. No.	Estimated central Pressure (hPa)	Estimated Maximum sustained surface wind speed(Kt)	Estimated pressure drop at the centre (hPa)	Grade
26-11-2011	0300	7.5/76.0	1.5	1002	25	3	D
	0600	8.0/75.5	1.5	1002	25	3	D
	1200	8.5/75.0	1.5	1000	25	3	D
	1800	8.5/75.0	1.5	1000	25	3	D
27-11-2011	0000	9.5/74.0	1.5	1000	25	3	D
	0300	10.5/73.0	1.5	1000	25	3	D
	0600	11.0/72.5	1.5	1000	25	4	D
	1200	12.0/71.5	1.5	1000	25	4	D
	1800	12.571.0	1.5	1000	25	4	D
28-11-2011	0000	13.5/70.0	2.0	998	30	5	DD
	0300	14.0/69.5	2.0	998	30	5	DD
	0600	14.5/69.0	2.0	998	30	5	DD
	1200	15.0/68.0	2.0	998	30	5	DD
	1800	15.5/67.5	2.0	998	30	6	DD
29-11-2011	0000	15.5/67.0	2.0	998	30	6	DD
	0300	15.7/66.8	2.0	998	30	5	DD
	0600	16.0/66.5	2.0	998	30	5	DD
	1200	16.0/66.5	1.5	1000	25	4	D
	1800	16.4/65.5	1.5	1000	25	4	D
30-11-2011	0000	17.0/64.4	1.5	1000	25	4	D
	0300	17.0/64.5	1.5	1000	25	4	D
	0600	17.5/63.5	1.5	1000	25	4	D
	1200	18.0/63.5	1.5	1000	25	3	D
	1800	19.0/62.5	1.5	1000	25	3	D
01-12-2011	0000	19.5/62.5	1.5	1002	25	3	D
	0300	19.5/62.5	1.5	1002	25	3	D
	0600	19.5/62.5	Weakened into a well marked low pressure area over westcentral Arabian Sea.				

2.9.5 Damage

Sri Lanka:
(i) Number of human deaths: 19
(ii) Number of home damaged: 5700
India and Oman:
No damage has been reported due to this system.

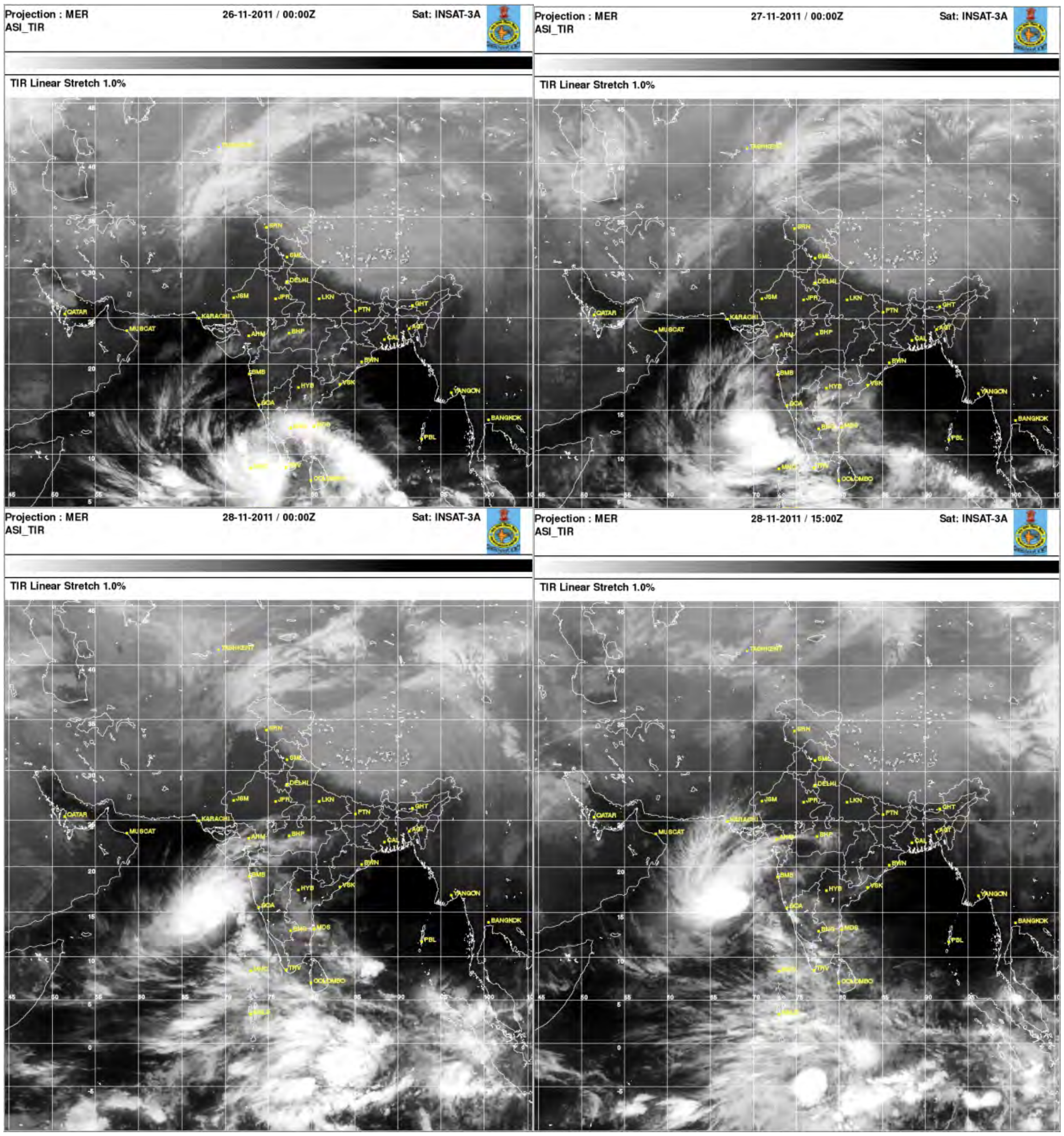


Fig. 2.9.1 The typical satellite imageries showing the intensification and movement of the system.

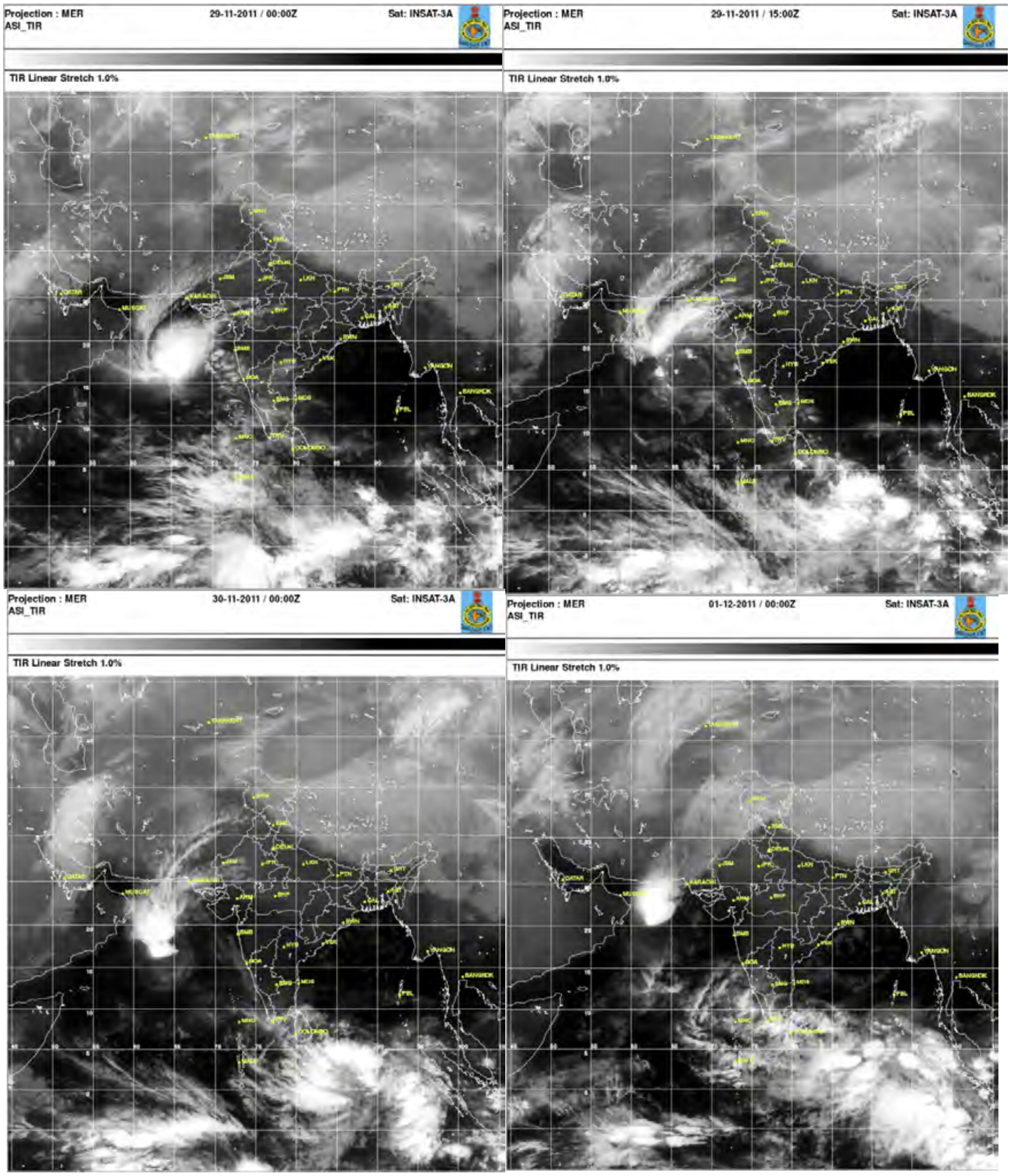


Fig. 2.9.1 (contd) the typical satellite imageries showing the intensification, movement and weakening of the system.

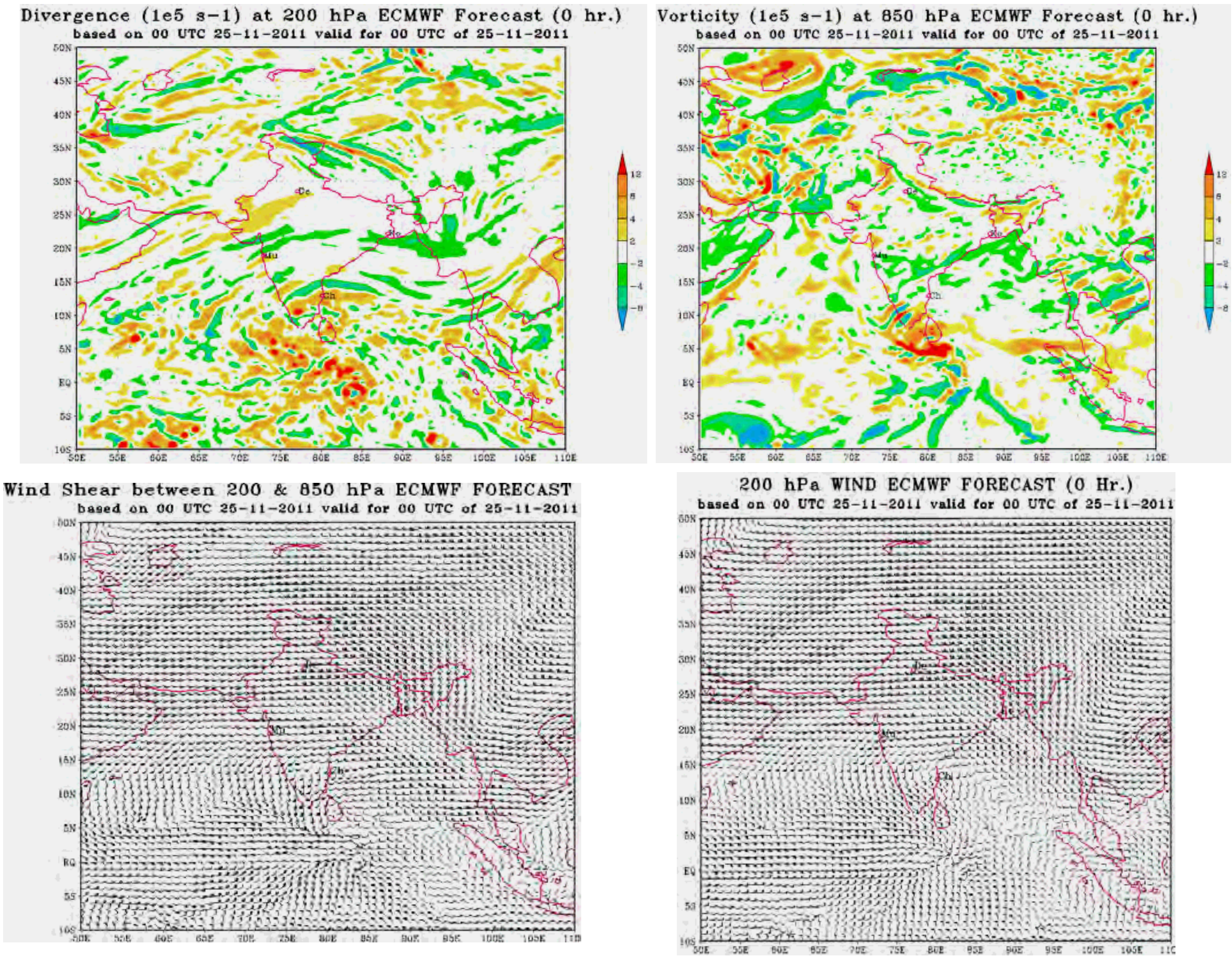
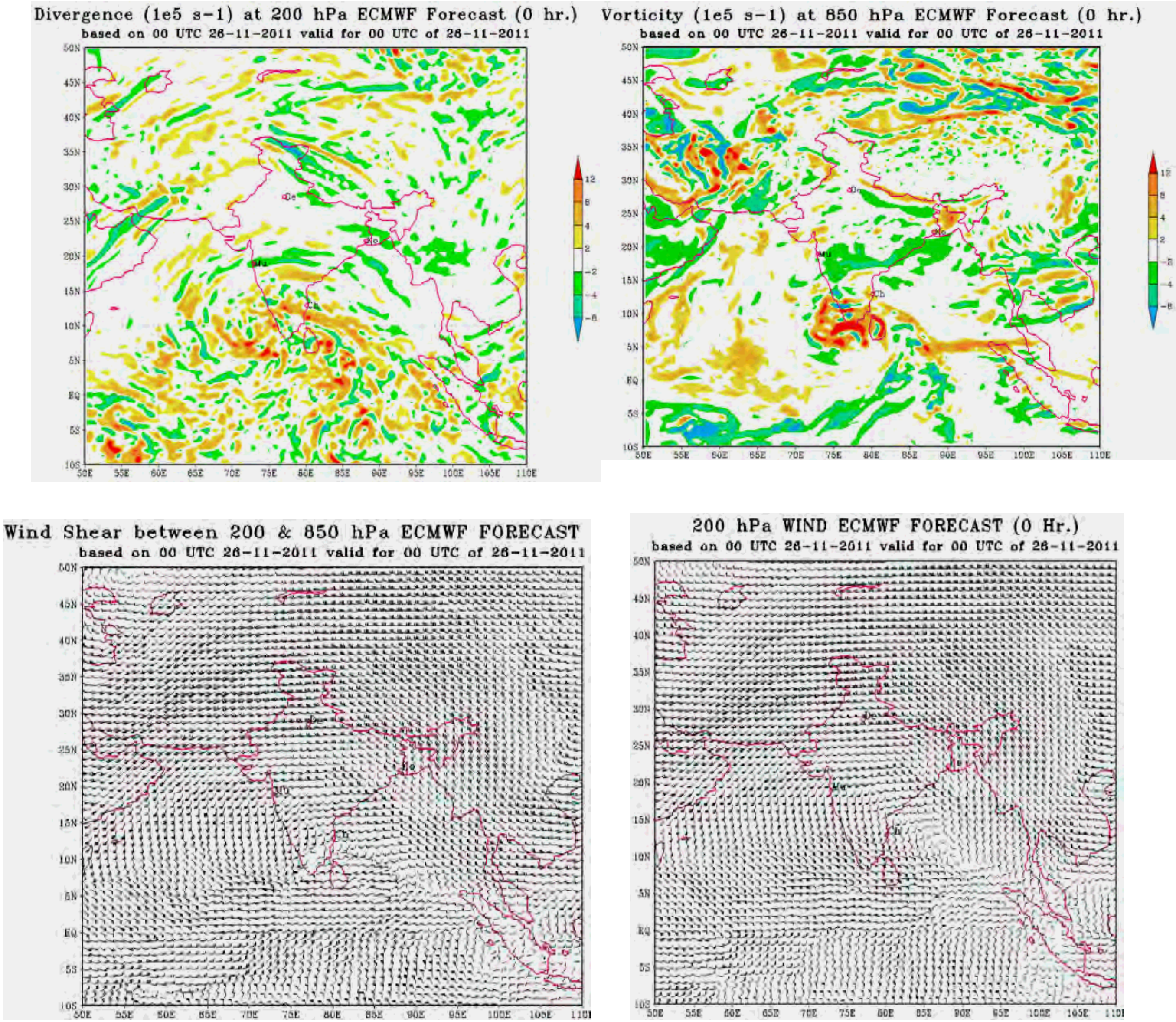


Fig. 2.9.2 (a) (i) Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) vertical wind shear of horizontal wind between 200 and 850 hPa level (iv) wind at 200 hPa level based on the ECMWF model analysis of 0000 UTC of 25th November, 2011.



2.9.2 (b) (i) Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) vertical wind shear of horizontal wind between 200 and 850 hPa level (iv) wind at 200 hPa level based on the ECMWF model analysis of 0000 UTC of 26th November, 2011.

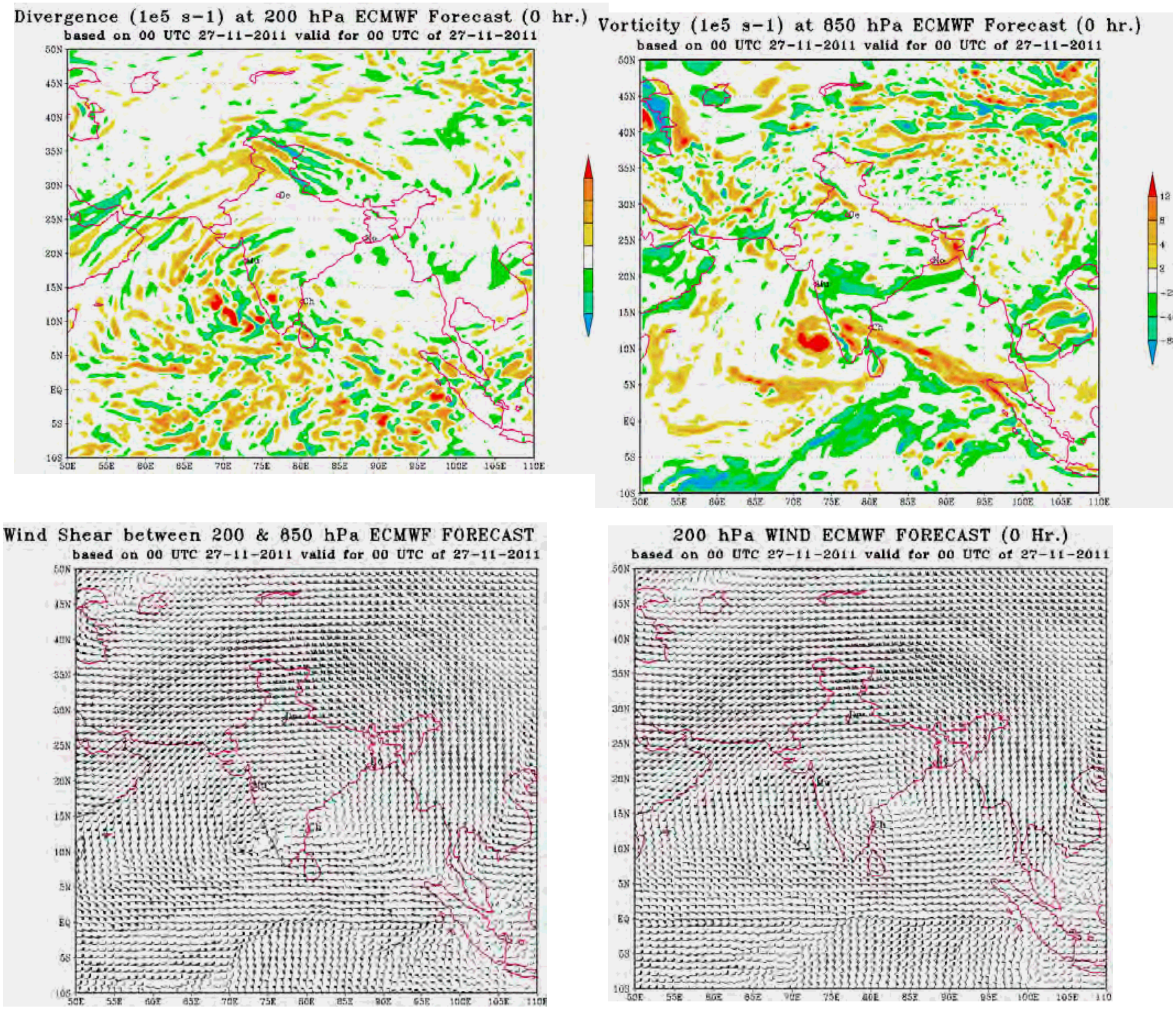


Fig. 2.9.2 (c) (i) Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) vertical wind shear of horizontal wind between 200 and 850 hPa level (iv) wind at 200 hPa level based on the ECMWF model analysis of 0000 UTC of 27th November, 2011.

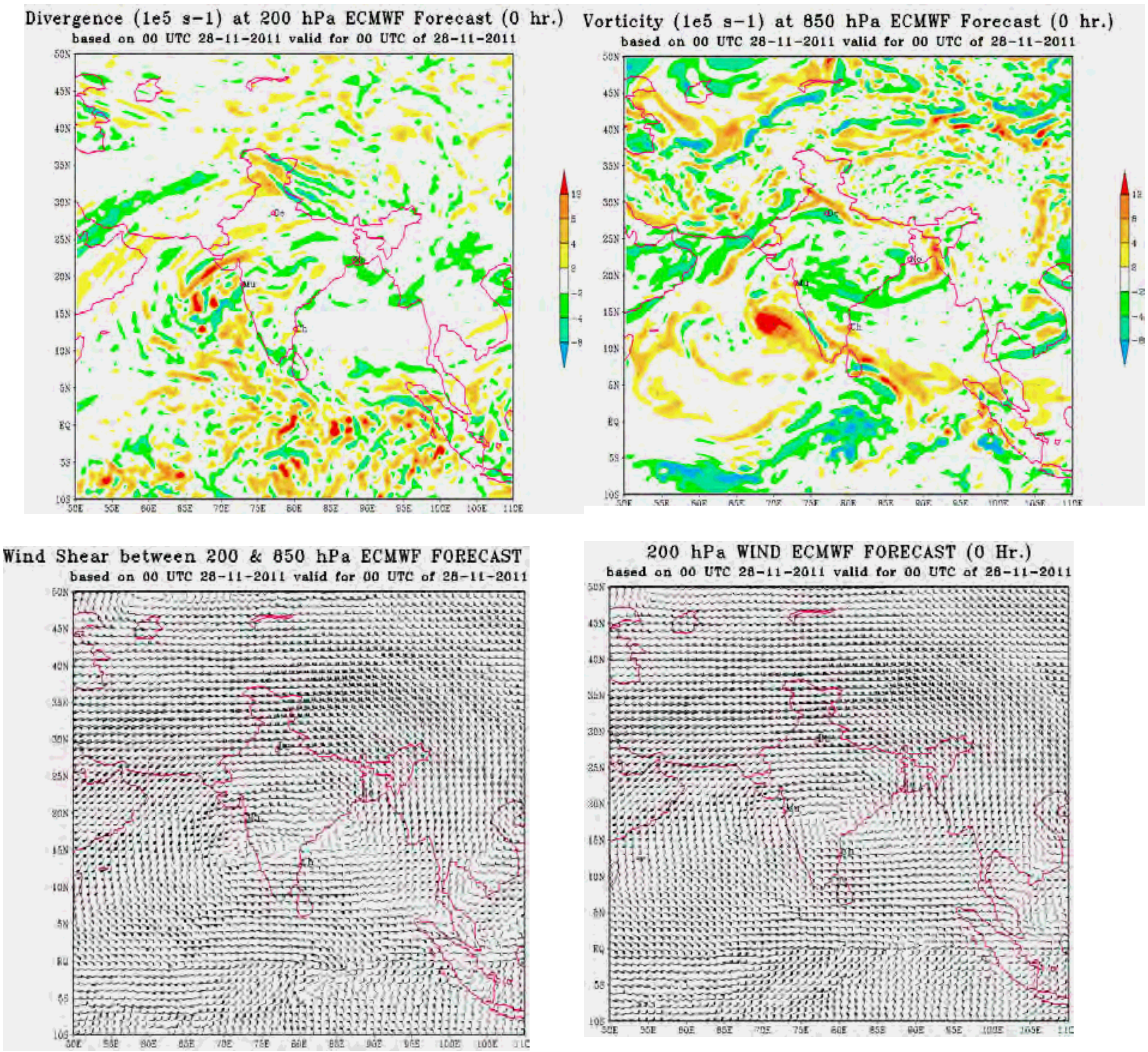


Fig. 2.9.2 (d) (i) Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) vertical wind shear of horizontal wind between 200 and 850 hPa level (iv) wind at 200 hPa level based on the ECMWF model analysis of 0000 UTC of 28th November, 2011.

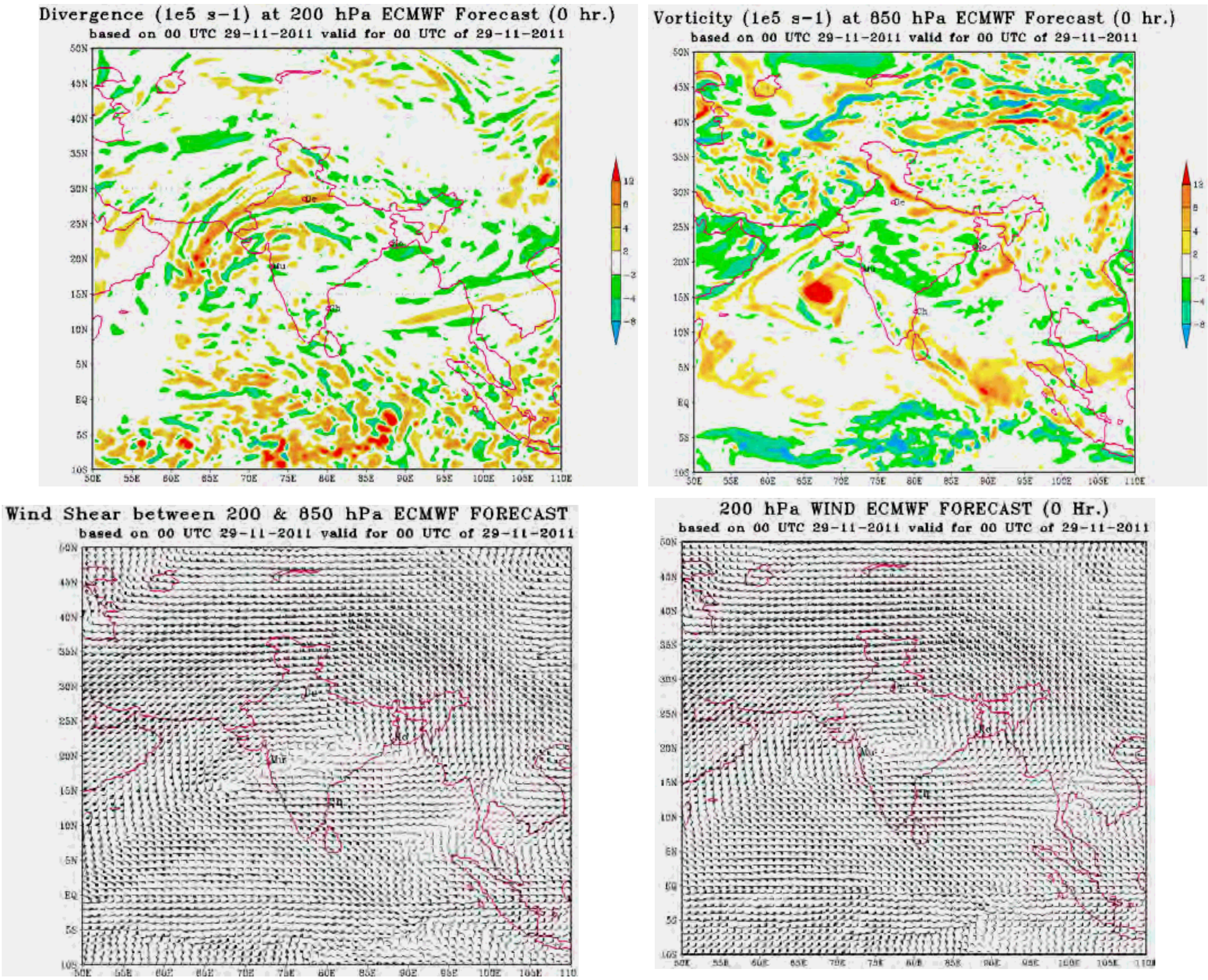


Fig. 2.9.2 (e) (i) Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) vertical wind shear of horizontal wind between 200 and 850 hPa level (iv) wind at 200 hPa level based on the ECMWF model analysis of 0000 UTC of 29th November, 2011.

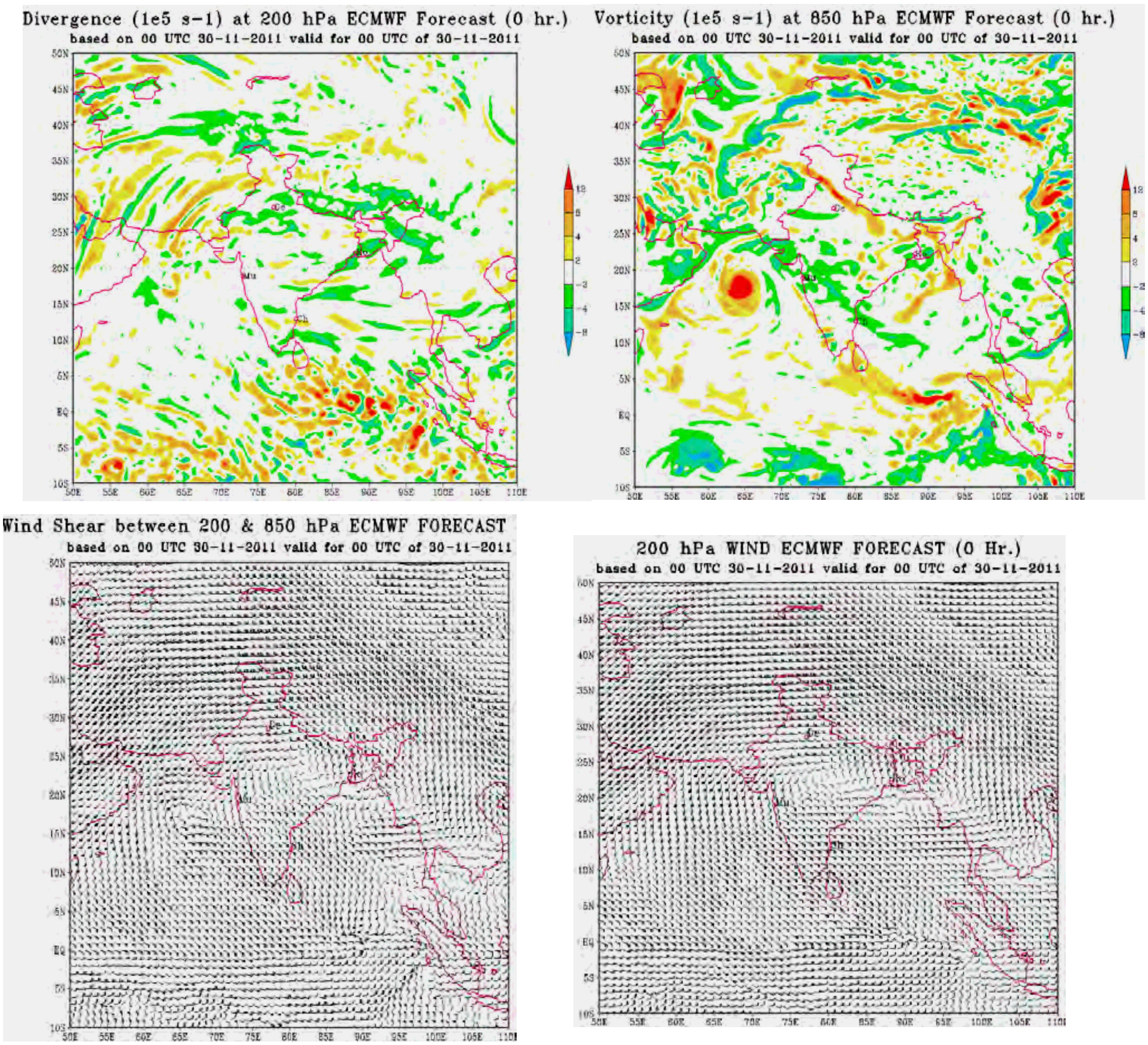


Fig. 2.9.2 (f) (i) Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) vertical wind shear of horizontal wind between 200 and 850 hPa level (iv) wind at 200 hPa level based on the ECMWF model analysis of 0000 UTC of 30th November, 2011.

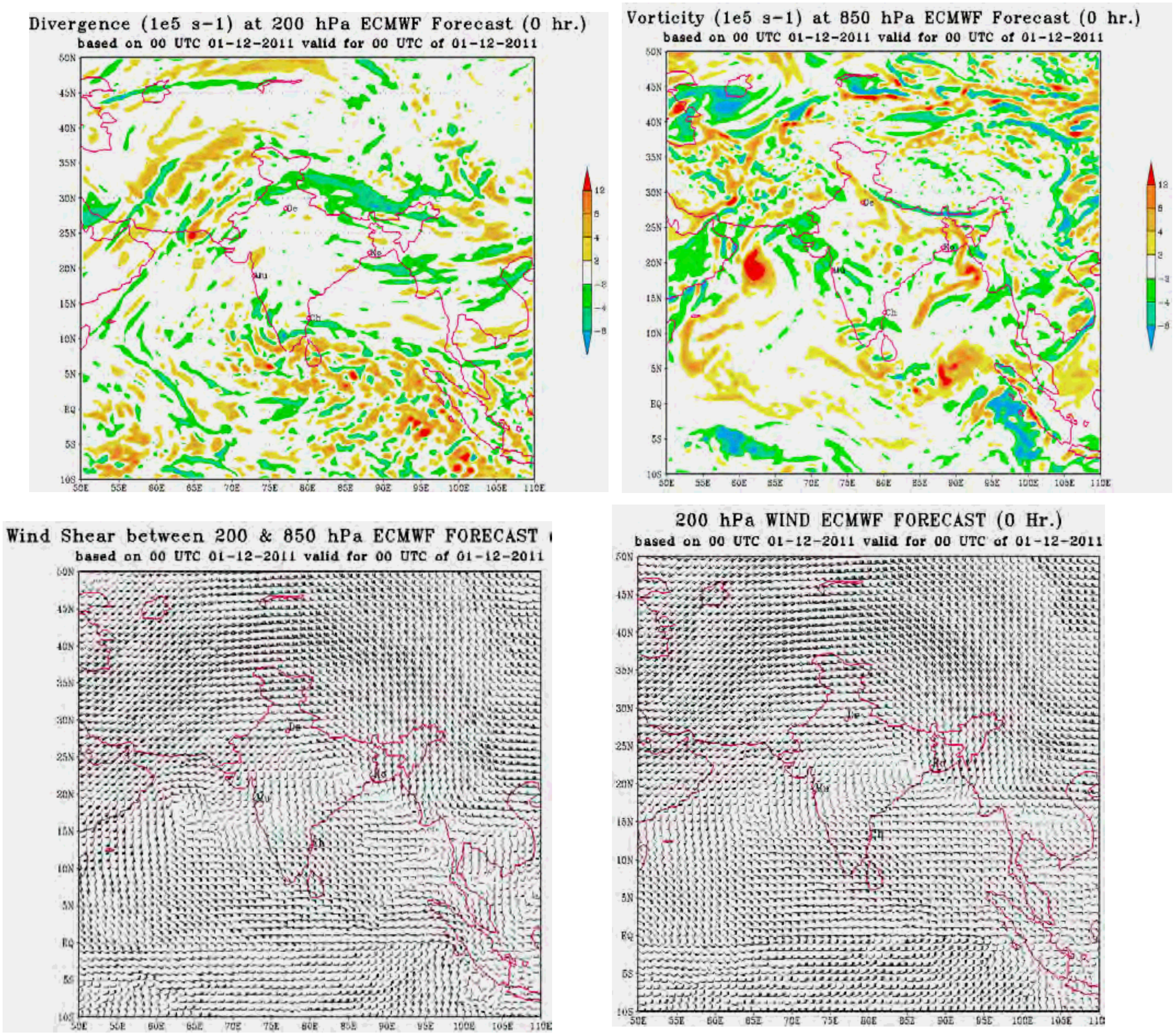


Fig. 2.9.2 (g) (i) Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) vertical wind shear of horizontal wind between 200 and 850 hPa level (iv) wind at 200 hPa level based on the ECMWF model analysis of 0000 UTC of 01st December, 2011.

2.10 Very Severe Cyclonic Storm "THANE" over Bay of Bengal (25-31 December, 2011)

2.10.1 Introduction:

A very severe cyclonic storm crossed Tamil Nadu coast on 30th December morning causing to life and property in north coastal areas of Tamil Nadu and Puducherry. About 48 people died due to this cyclone. The loss could be minimized due to accurate early warning and active disaster management by the Govt. of Tamil nadu and Puducherry. The very severe cyclonic storm 'THANE' was mainly monitored by Satellite during its genesis and early stage. When the system came within radar range, it was tracked by Doppler Weather Radar (DWR), Chennai (from 28th December evening till landfall). The system was also tracked by the available ships and buoy observations as well as hourly coastal observations from conventional synoptic network and AWS network. The characteristic features associated with the genesis, intensification, movement and landfall are described in the following sections.

2.10.2 Genesis:

In association with an active ITCZ, a cyclonic circulation formed over southeast Bay of Bengal on 23rd December 2011. It was associated with scattered convective cloud cluster over the region. Gradually the convective clusters deepened and came closer to each other and a low pressure area formed over the southeast Bay of Bengal on 24th morning with T1.0. It became well marked over the same region in the evening of 24th December 2011. Considering the environmental features, the sea surface temperature (SST) was about 27-28^{0} C. over southeast Bay of Bengal, Andaman Sea and adjoining southeast and central Bay of Bengal. It was relatively less towards Tamil Nadu and Sri Lanka coast becoming 26-27^{0}C. The ocean thermal energy was about 50-80 KJ/cm^{2} over southeast Bay of Bengal and neighbourhood. However, it was about 50 KJ/cm^{2} near Tamil Nadu and north Sri Lanka coasts. The Madden Julian Oscillation (MJO) index lay over phase 5 witch is favourable for cyclogenesis over the Bay of Bengal. The upper tropospheric ridge at 200 hPa level ran along 10^{0}N and provided required poleward outflow for intensification of the system. As a result, the lower level convergence and upper level divergence were favourable for intensification. The vertical wind shear of horizontal wind was moderate (15-20 knots) around the low pressure area. It increased towards coast of Sri lanka and Tamil nadu becoming moderate to high (20-30 knots).

Due to all the above favourable features, the well marked low pressure area concentrated into a depression and lay centred at 1200 UTC of 25th Dec. 2011 near lat. 8.5^{0}N and long. 88.5^{0}E. The intensity of the system was T1.5 as per Dvorak's technique. The lowest cloud top temperature was -77^{0}C. Associated intense to very intense convection lay over the Bay of Bengal, south of lat.15.5^{0}N and east of long. 82.0^{0}E. The poleward outflow was distinctly visible in satellite imageries. The maximum sustained surface wind was about 25 knots and the estimated central pressure was about 1000 hPa.

Table 2.10.1 Best track positions and other parameters of very severe Cyclonic storm THANE over the Bay of Bengal during 25-31 December, 2011

Date	Time (UTC)	Centre lat. N/long. E	C.I NO.	Estimated Central Pressure (hPa)	Estimated max. sustained Surface wind(Kt)	Estimated Pressure drop at the Centre(hPa)	Grade
25.12.2011	1200	08.5/88.5	1.5	1000	25	3	D
	1800	09.0/88.0	1.5	1000	25	3	D
26.12.2011	0000	09.5/87.5	2.0	998	30	4	DD
	0300	09.5/87.5	2.0	998	30	4	DD
	0600	10.0/87.5	2.0	998	30	4	DD
	1200	10.5/87.5	2.0	998	30	5	DD
	1800	11.0/87.5	2.5	996	35	7	CS
	2100	11.0/87.5	2.5	996	35	7	CS
27.12.2011	0000	11.5/87.5	2.5	994	40	8	CS
	0300	12.0/87.0	2.5	994	40	8	CS
	0600	12.0/87.0	2.5	994	40	8	CS
	0900	12.2/86.7	2.5	992	40	10	CS
	1200	12.5/86.5	2.5	992	40	10	CS
	1500	12.5/86.5	3.0	992	45	10	CS
	1800	12.5/86.0	3.0	992	45	12	CS
	2100	12.5/86.0	3.0	992	45	12	CS
28.12.2011	0000	12.5/85.5	3.0	992	45	12	CS
	0300	12.5/85.5	3.0	987	45	14	CS
	0600	12.5/85.0	3.0	988	45	14	CS
	0900	12.5/85.0	3.5	986	55	16	SCS
	1200	12.5/84.5	4.0	982	65	20	VSCS
	1500	12.5/84.0	4.0	980	65	22	VSCS
	1800	12.5/84.0	4.0	978	65	24	VSCS
	2100	12.5/83.5	4.0	976	65	26	VSCS
29.12.2011	0000	12.3/83.0	4.0	974	70	28	VSCS
	0300	12.0/82.5	4.5	976	75	30	VSCS
	0600	12.0/82.0	4.5	972	75	30	VSCS
	0900	12.0/81.7	4.5	972	75	30	VSCS
	1200	12.0/81.3	4.5	972	75	30	VSCS
	1500	12.0/81.0	4.5	970	75	30	VSCS
	1800	11.8/80.6	4.5	970	75	30	VSCS
	2100	11.8/80.3	4.5	969	75	30	VSCS
30.12.2011	0000	11.6/79.9	4.5	969	75	30	VSCS
	The system crossed the Tamil Nadu coast close to south of Cuddalore between 0100 and 0200 UTC of 30th December, 2011.						
	0300	11.6/79.5	--	986	55	16	SCS
	0600	11.6/79.0	--	998	30	5	DD
	1200	11.6/78.2	--	1000	25	3	D
31.12.2011	0000	The system weakened into a well marked low pressure area over north Kerala and neighbourhood.					

2.10.3 Intensification and movement:

In association with the favourable conditions as discussed in the previous section, the depression moved initially northwestwards and further intensified into a deep depression at 0000 UTC of 26th and lay centred near lat. 9.5^0N and long. 87.5^0E. The best track of the system is shown in Fig. 2.1. The best track parameters are shown in Table 2.10.1. Some Crucial observations reported by Puducherry and Cuddalore are shown in Table 2.10.2. The typical satellite imageries of the system are shown in fig. 2.10.1.The DWR Chennai imageries are shown in Fig. 2.10.2. The NWP model analysis of IMD-GFS model are shown in Fig. 2.10.3.

Continuing its north-northwestwards movement, the deep depression intensified into a cyclonic storm 'THANE' at 1800 UTC of 26th December 2011 near lat. 11.0^0N and long. 87.5^0E. It then moved west-northwestwards and intensified into a severe cyclonic storm over southwest and adjoining southeast Bay of Bengal at 0900 UTC of 28th Dec. near lat. 12.5^0N and long. 85.0^0E about 500 km east-southeast of Chennai. It further moved westwards, intensified into a very severe cyclonic storm at 1200 UTC of 28th December near lat. 12.5^0N and long. 84.5^0E, about 450 km east-southeast of Chennai.

The very severe cyclonic storm 'THANE' then moved west-southwestwards and lay centred at 0300 UTC of 29th December 2011 near lat. 12.0^0N and long. 82.5^0E, about 270 km east of Puducherry. It continued to move west-southwestwards and crossed north Tamil Nadu & Puducherry coast, close to the south of Cuddalore (near lat. 11.6^0 N) between 0100 and 0200 UTC of 30th December, 2011. It crossed as a very severe cyclonic storm with an estimated wind speed of 120-140 kmph and estimated central pressure of 969 hPa. After the landfall, the system moved westwards and weakened into a severe cyclonic storm at 0300 UTC of 30th December 2011 over north coastal Tamil Nadu. It further weakened into a deep depression at 0600 UTC near lat. 11.6^0N and long. 79.0^0E and into a depression at 1200 UTC of 30th December near Salem(Tamil Nadu). The depression moved further westwards and weakened into a well marked low pressure area over north Kerala and neighbourhood at 0000 UTC of 31st December 2011. It then emerged into Arabian Sea and lay as a low pressure area over southeast Arabian Sea at 1200 UTC 31st December 2011. It became less marked on 1st January 2012.

2.10.4. Size of the system, diameter of eye and central pressure

Rainfall reports and survey reports indicate that the system would have been of the size of 300 to 400 km length wise and 100-150 km breadth wise during landfall. During the survey around Marakkanam, Puducherry, Cuddalore, Parengipettai, Chidambaram, Kurinjipadi, Neyveli, Pantrui, Arasur, and Villupuram area it was understood that the lull period was experienced by the people from nine km south of Cuddalore to eight km north of Parengipettai in western sector up to Neyveli. The lull period lasted for a period of half an hour to one hour, suggesting that the eye diameter would be of the order of 20 to 25 kms range at the time of land fall. The DWR Chennai radar pictures show that the system had circular-open eye. The exact valve of the central pressure is not available. However the lowest pressure 969.4 hPa was recorded at MO Cuddalore at 0050 UTC of 30 December 2011 with a pressure fall of 35.6 hPa. Thereafter the pressure increased sharply and rapidly. The pressure gradient force was more on the northern side [20 hPa / 20 km] with more prominent closed isobars in the northern western sector of the system. i.e. north &

northwest of Cuddalore and up to Puducherry. Less densely packed isobars from Cuddalore to Parengipettai was seen in the southern direction of the system. At Cuddalore the fall of pressure during 2200 UTC of 29th to 0030 UTC of 30th December [991.3-971.5 hPa] was 19.8 hPa/3hour i.e the surface pressure decreased by 6.6 hPa per hour towards south during this period. The barograph of Cuddalore is shown in Fig.2.10.4.

2.10.5. Landfall point and time

The extensive survey of the cyclone affected areas and with available information gathered from various cross section of the people, their weather experience on 29/30 Dec 2011 and the direction of fallen trees in those areas indicated that the probable location of land fall is at Thiyagavalli [Lat: $11^{o}.37^{'}$ N / Log: $79^{o}.44^{'}$E], about fourteen km south of Cuddalore (Fig.2.10.5).

Table 2.10.2 Crucial observations reported by Puducherry (PDC) and Cuddalore (CDL) observatories of IMD

Date	Time	Station	Pressure (hPa)	Pressure fall in 24 hrs (hPa)	Surface wind Speed (knot)
29.12.11	0600	PDC (43331)	1004.3	- 2.8	NW/10 kt
29.12.11	1200	PDC(43331)	1003.7	- 4.0	NNW/10kt
29.12.11	1500	PDC (43331)	1003.7	- 4.0	NNW/10kt
29.12.11	1800	PDC (43331)	1005.5	- 7.6	N/25kt
29.12.11	2100	PDC (43331) CDL (43329)	0997.8 0996.6	- 9.4 - 10.8	NNW/35kt NNW/23kt
30.12.11	0000	PDC (43331) CDL (43329)	0991.7 0997.6	- 15.2 - 32.9	ENE/68kt NNW/62kt

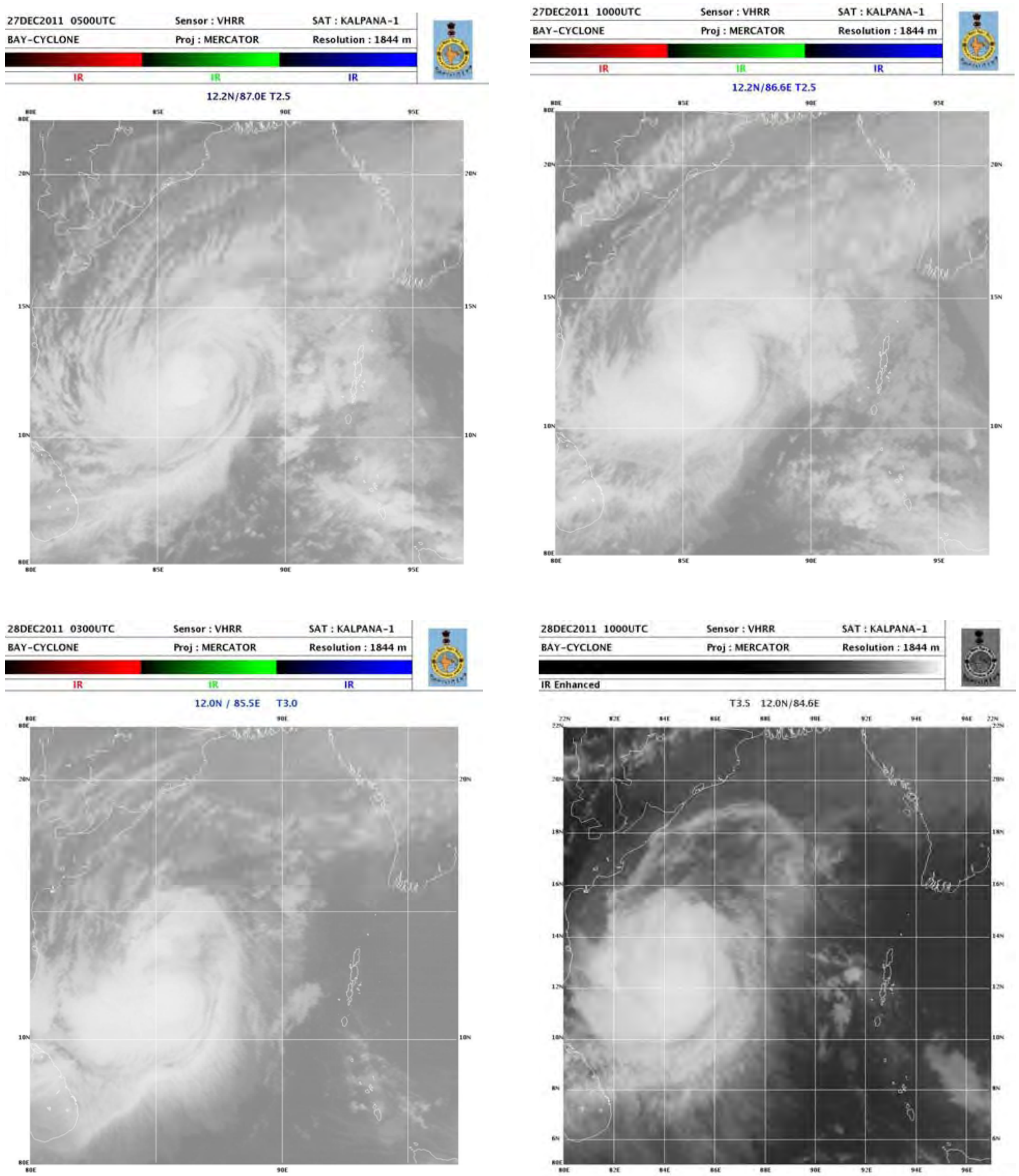


Fig.2.10.1. The typical satellite imagery showing intensification and movement of the system

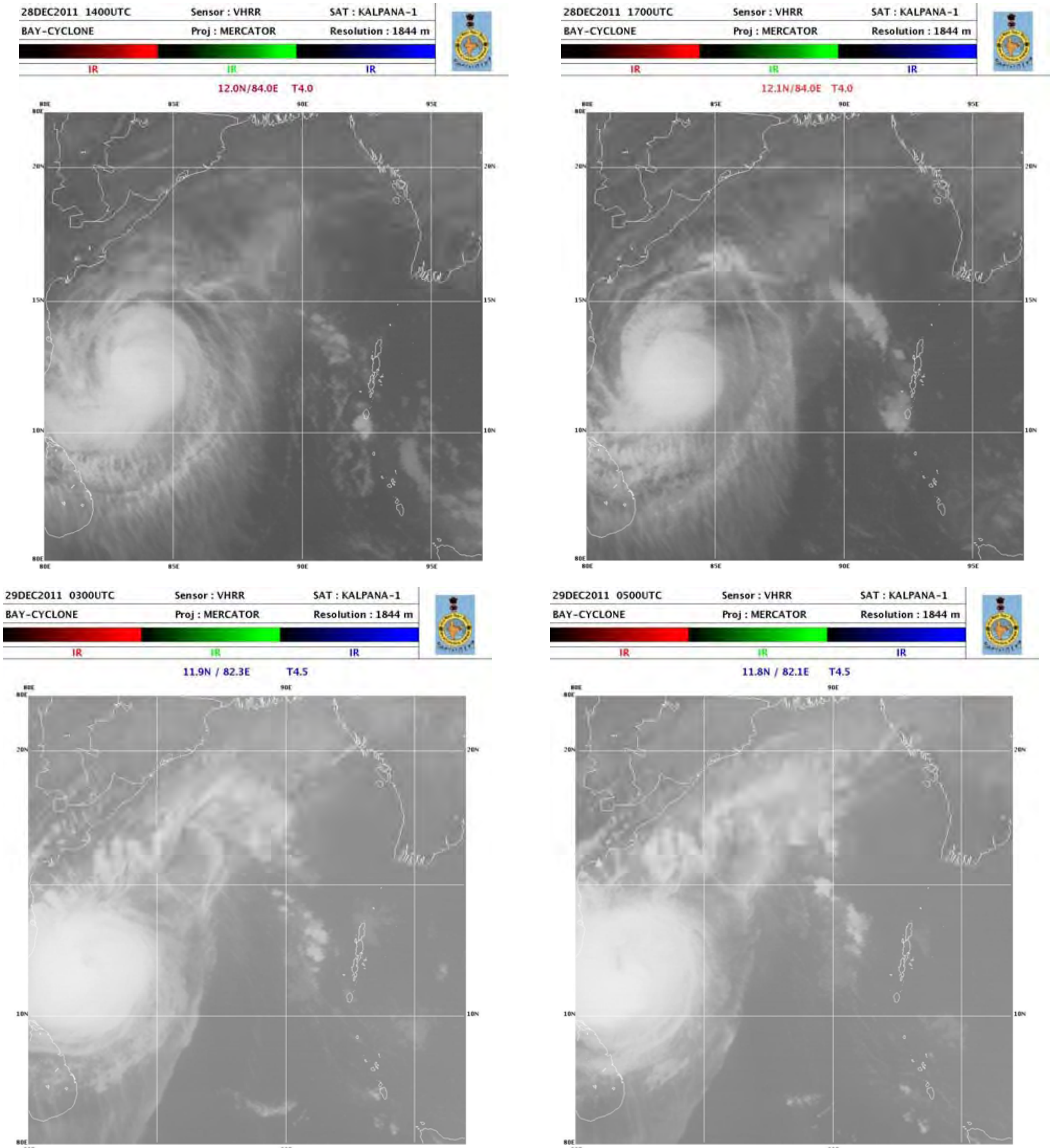


Fig.2.10.1(contd). The typical satellite imagery showing intensification and movement of the system

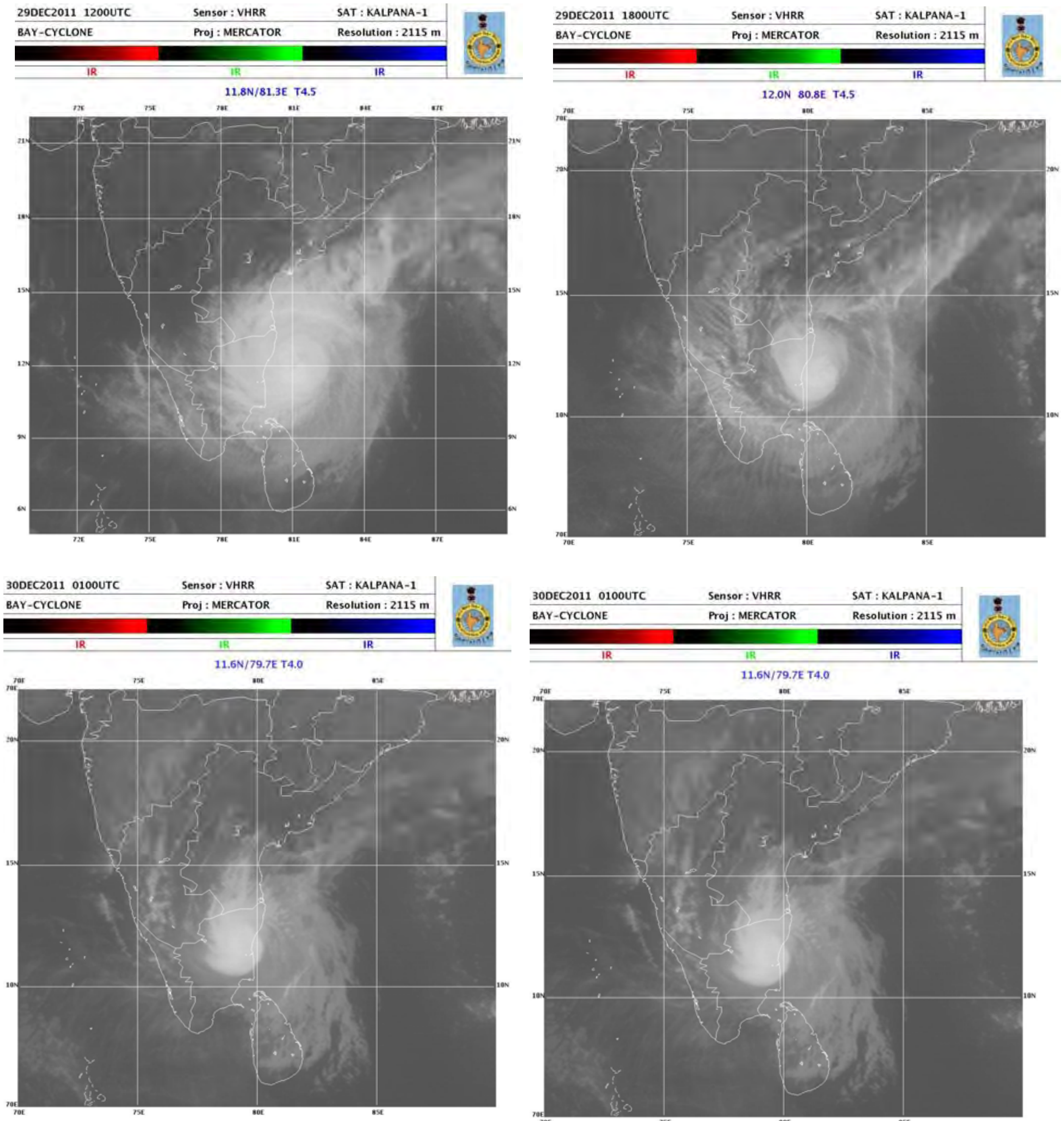


Fig.2.10.1(contd). The typical satellite imagery showing intensification and movement of the system

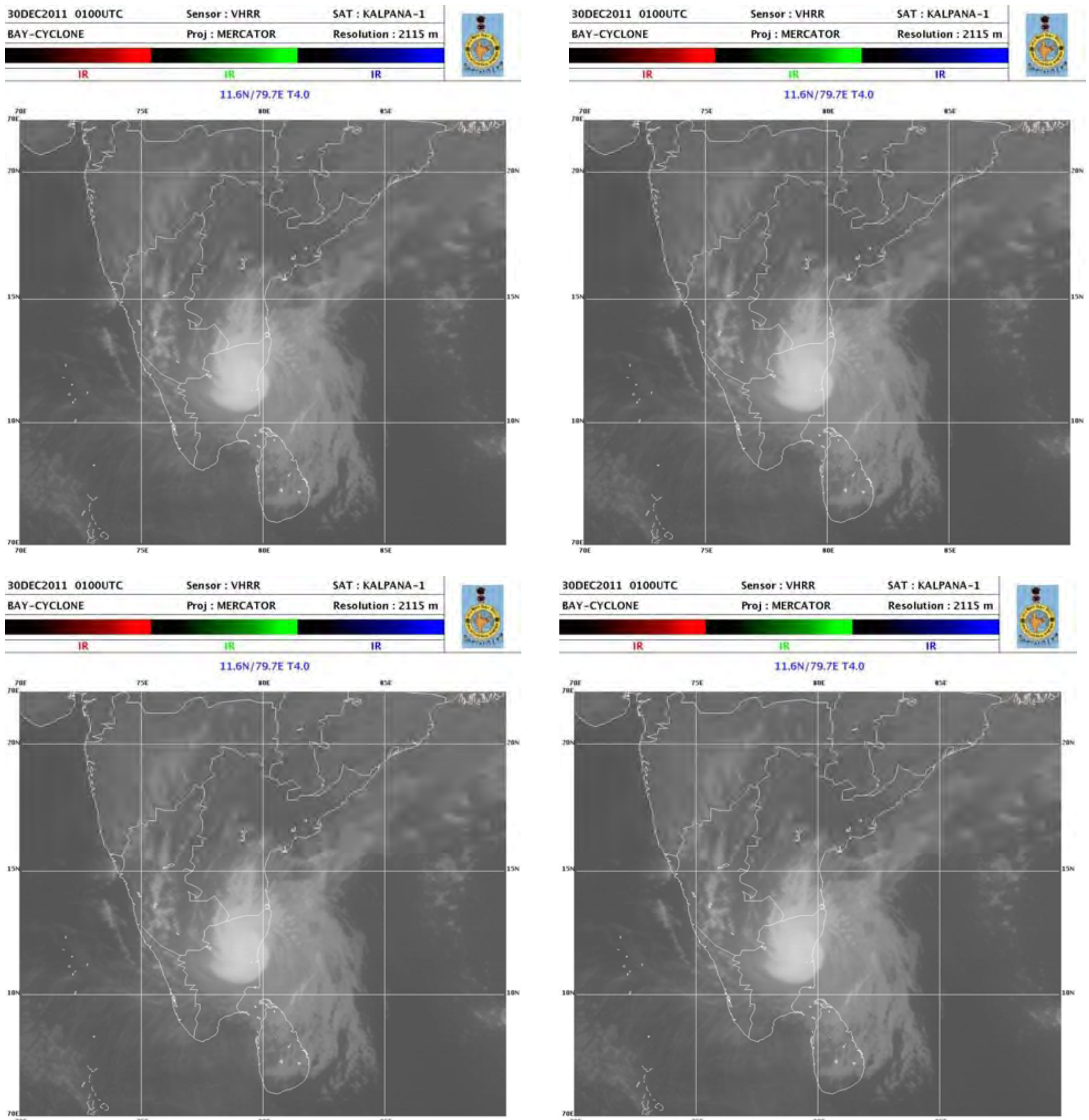


Fig.2.10.1(contd). The typical satellite imagery showing intensification and movement of the system

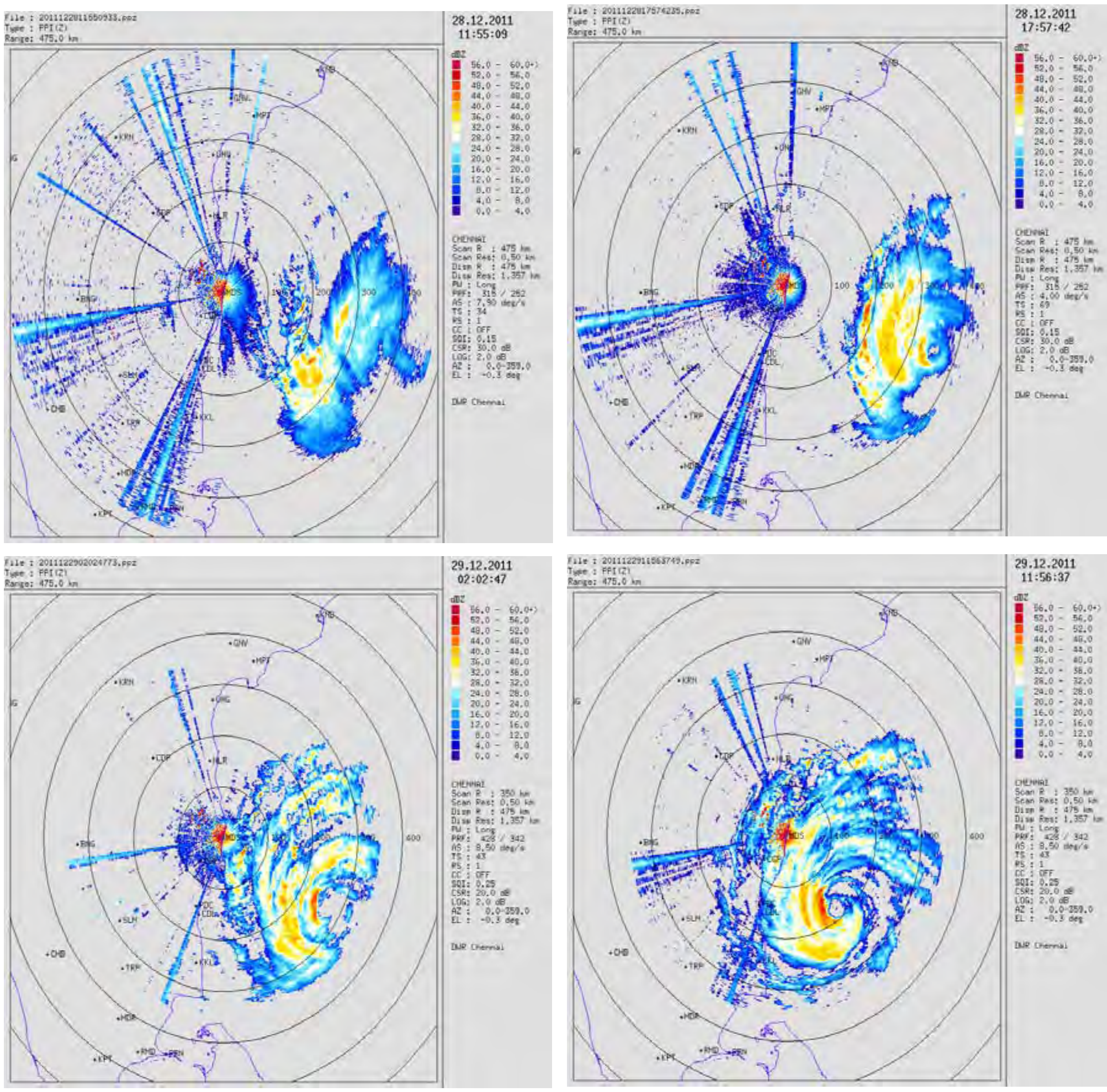


Fig.2.10.2. Doppler Weather Radar (DWR), Chennai imagery of very severe cyclonic storm, THANE showing the intensification of the system.

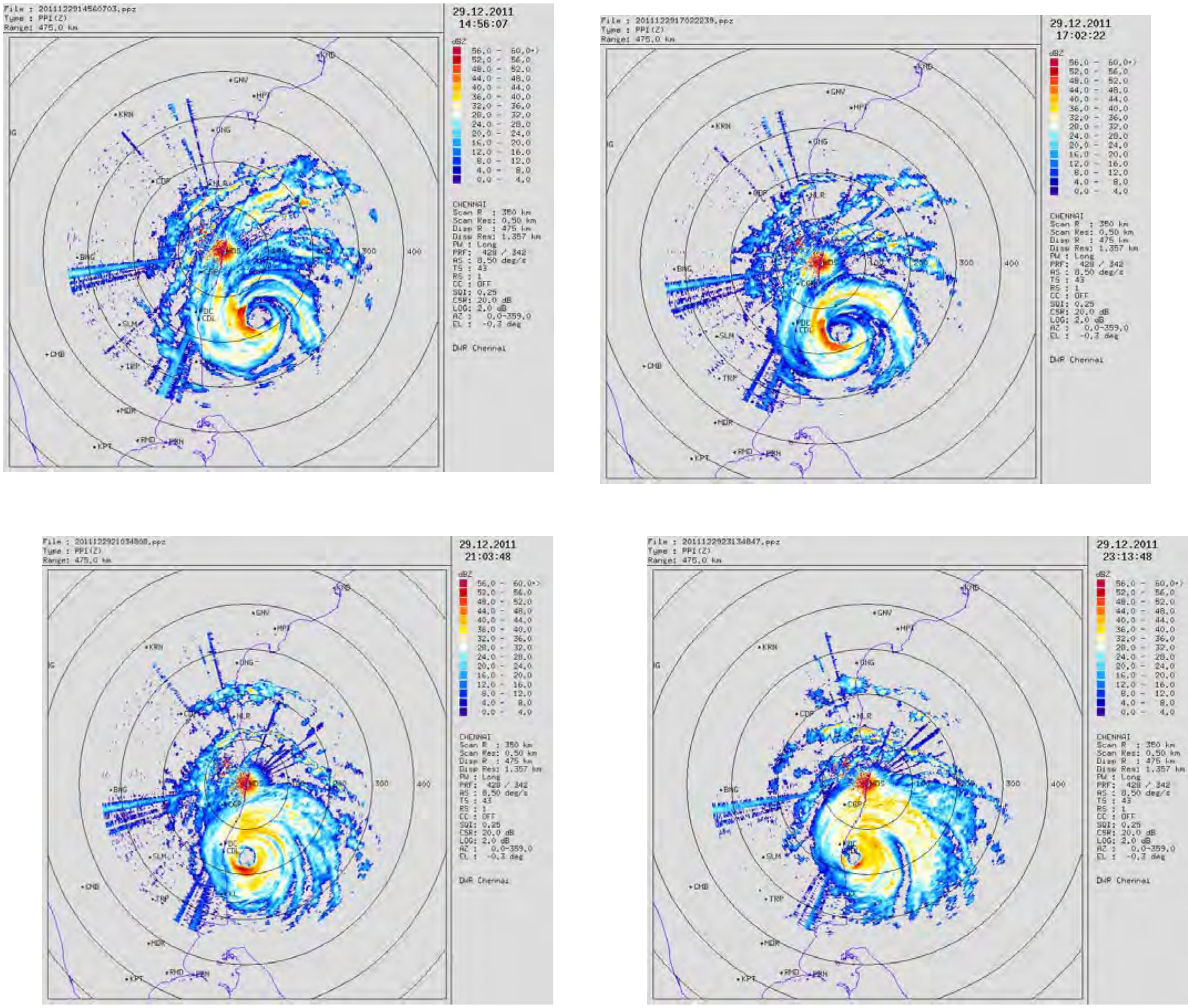


Fig.2.10.2(contd). Doppler Weather Radar (DWR), Chennai imagery of very severe cyclonic storm, THANE showing the intensification and movement of the system.

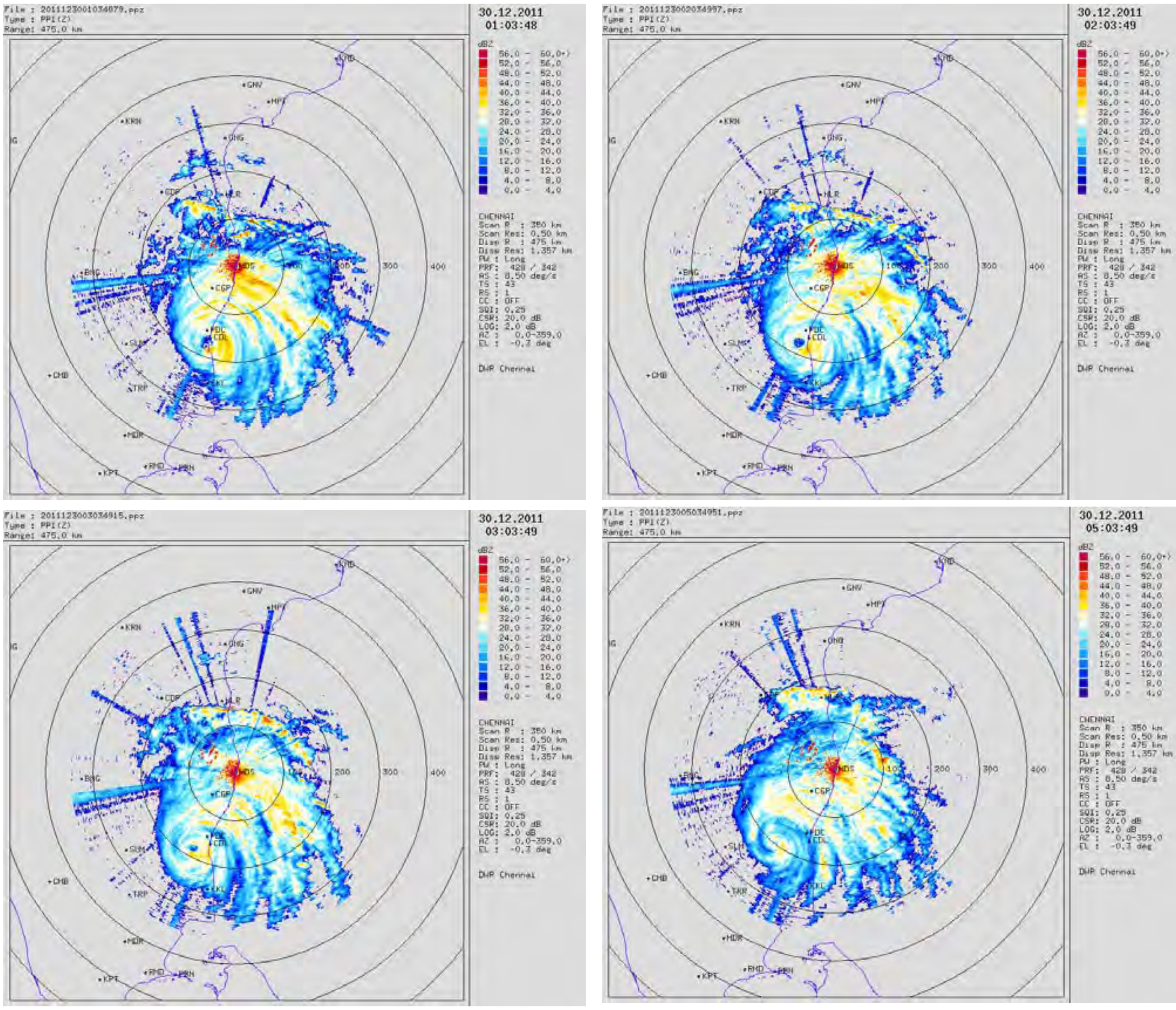


Fig.2.10.2(contd). Doppler Weather Radar (DWR), Chennai imagery of very severe cyclonic storm, THANE at the time of landfall.

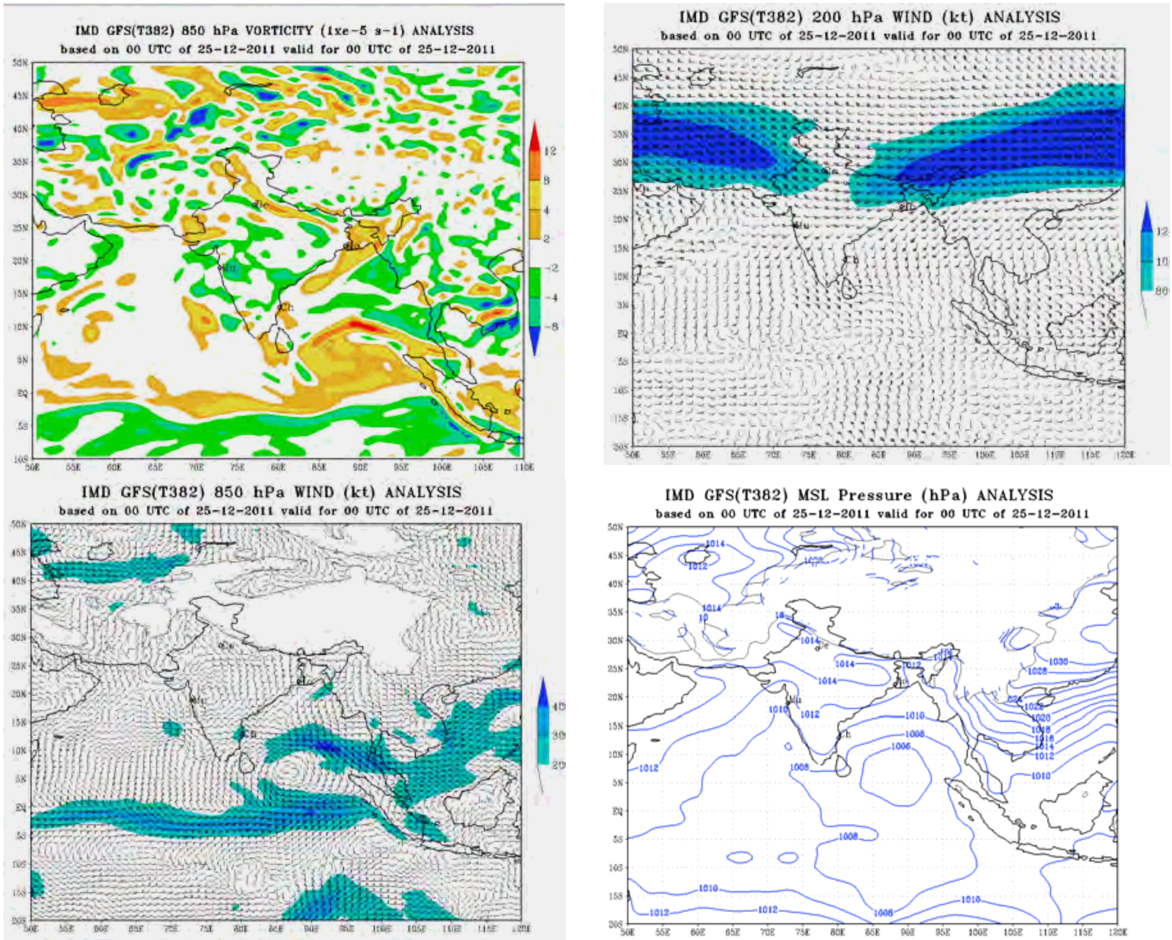


Fig. 2.10.3(a) (i) Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) wind at 200 hPa level (iv) MSLP based on the IMD GFS model analysis of 0000 UTC of 25th December, 2011.

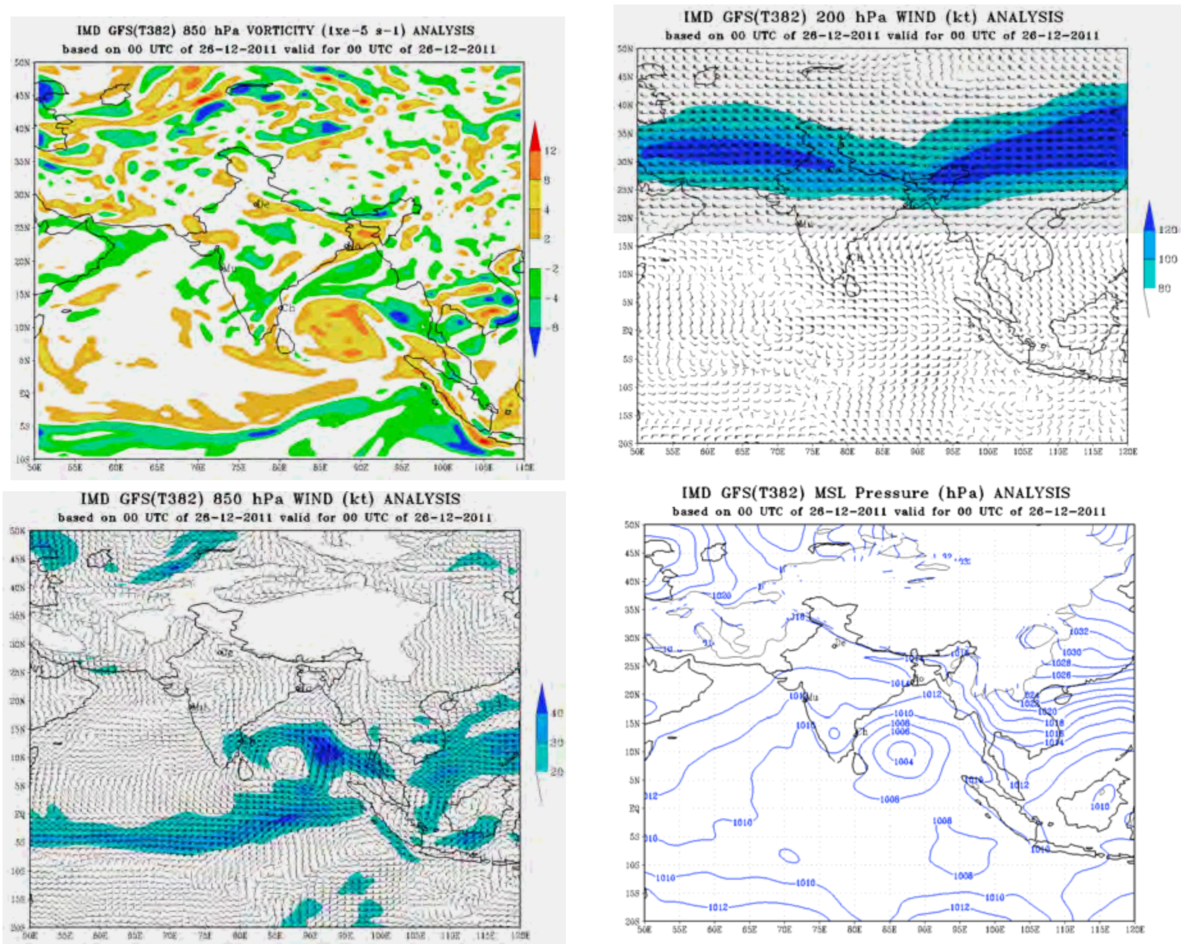


Fig. 2.10.3(b) (i) Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) wind at 200 hPa level (iv) MSLP based on the IMD GFS model analysis of 0000 UTC of 26th December, 2011.

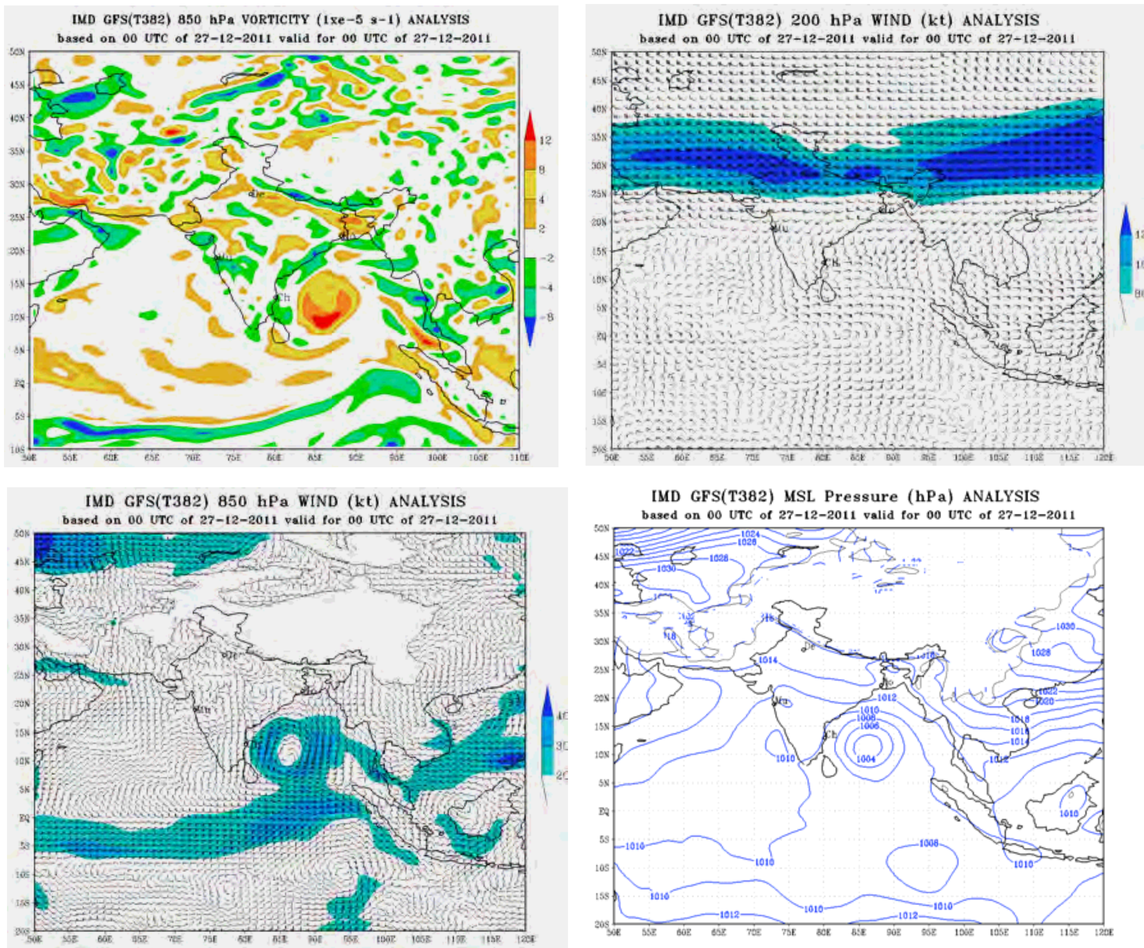


Fig. 2.10.3(c) (i) Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) wind at 200 hPa level (iv) MSLP based on the IMD GFS model analysis of 0000 UTC of 27th December, 2011.

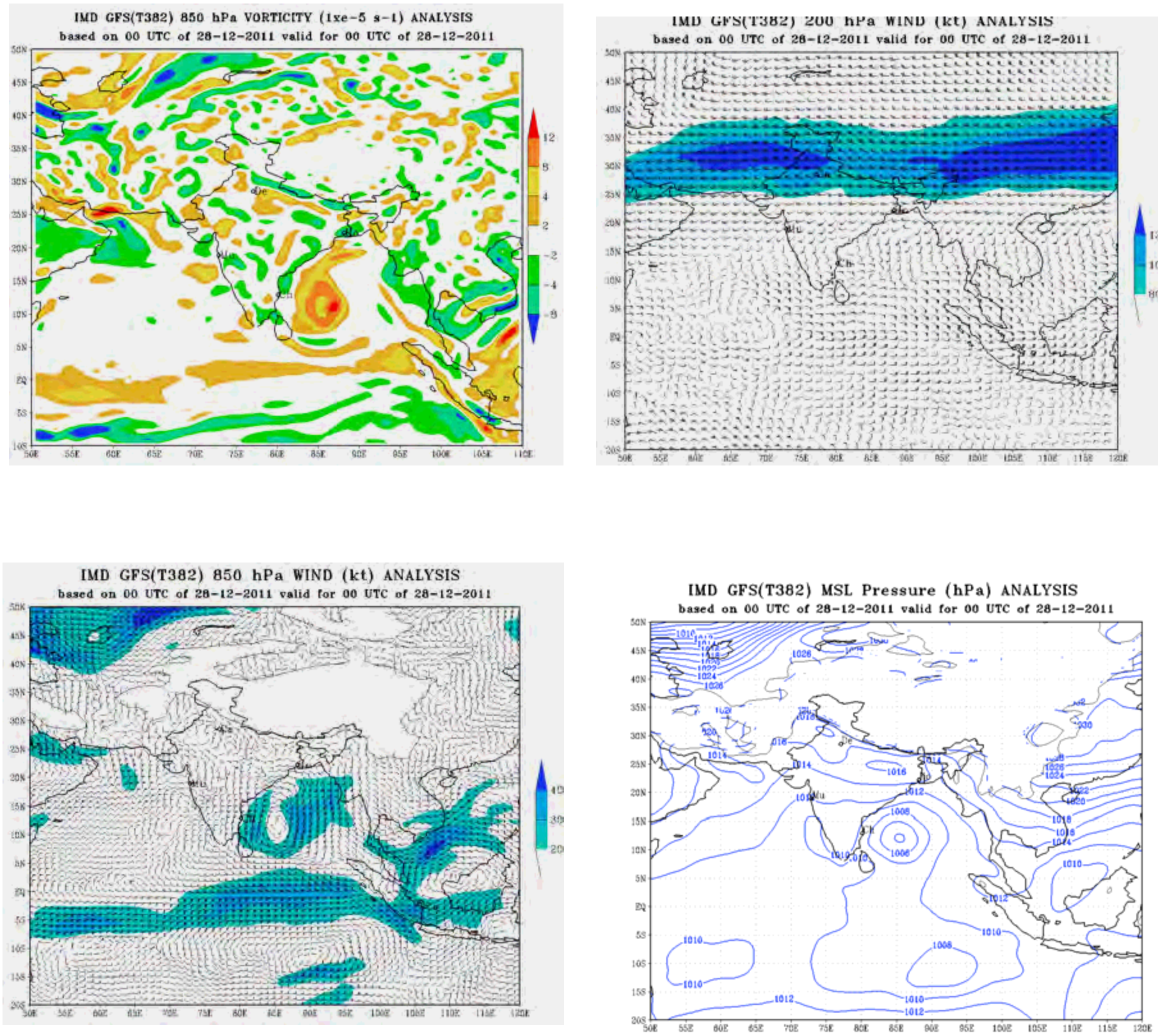


Fig. 2.10.3(d) (i) Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) wind at 200 hPa level (iv) MSLP based on the IMD GFS model analysis of 0000 UTC of 28th December, 2011.

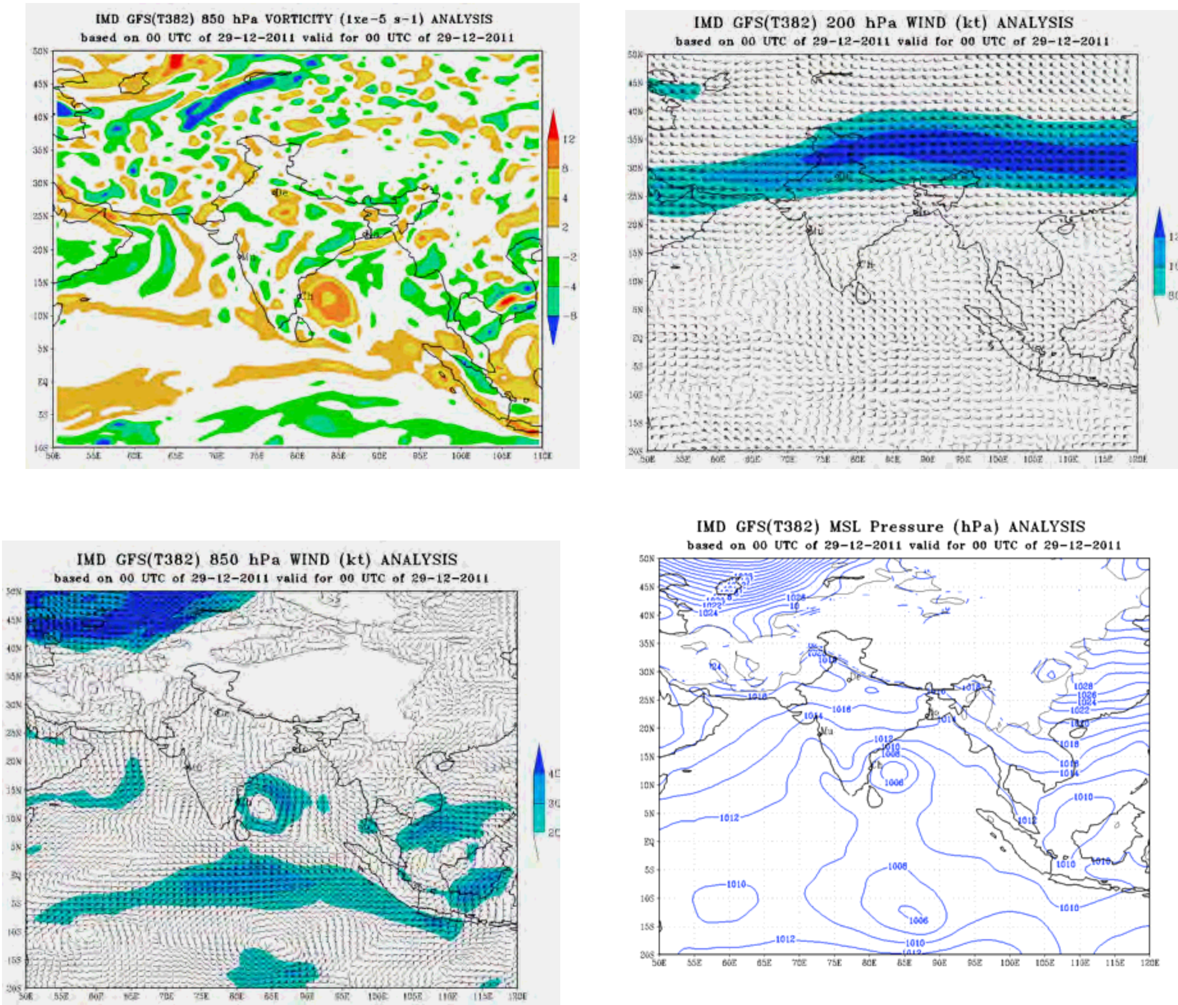


Fig. 2.10.3(e) (i) Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) wind at 200 hPa level (iv) MSLP based on the IMD GFS model analysis of 0000 UTC of 29th December, 2011.

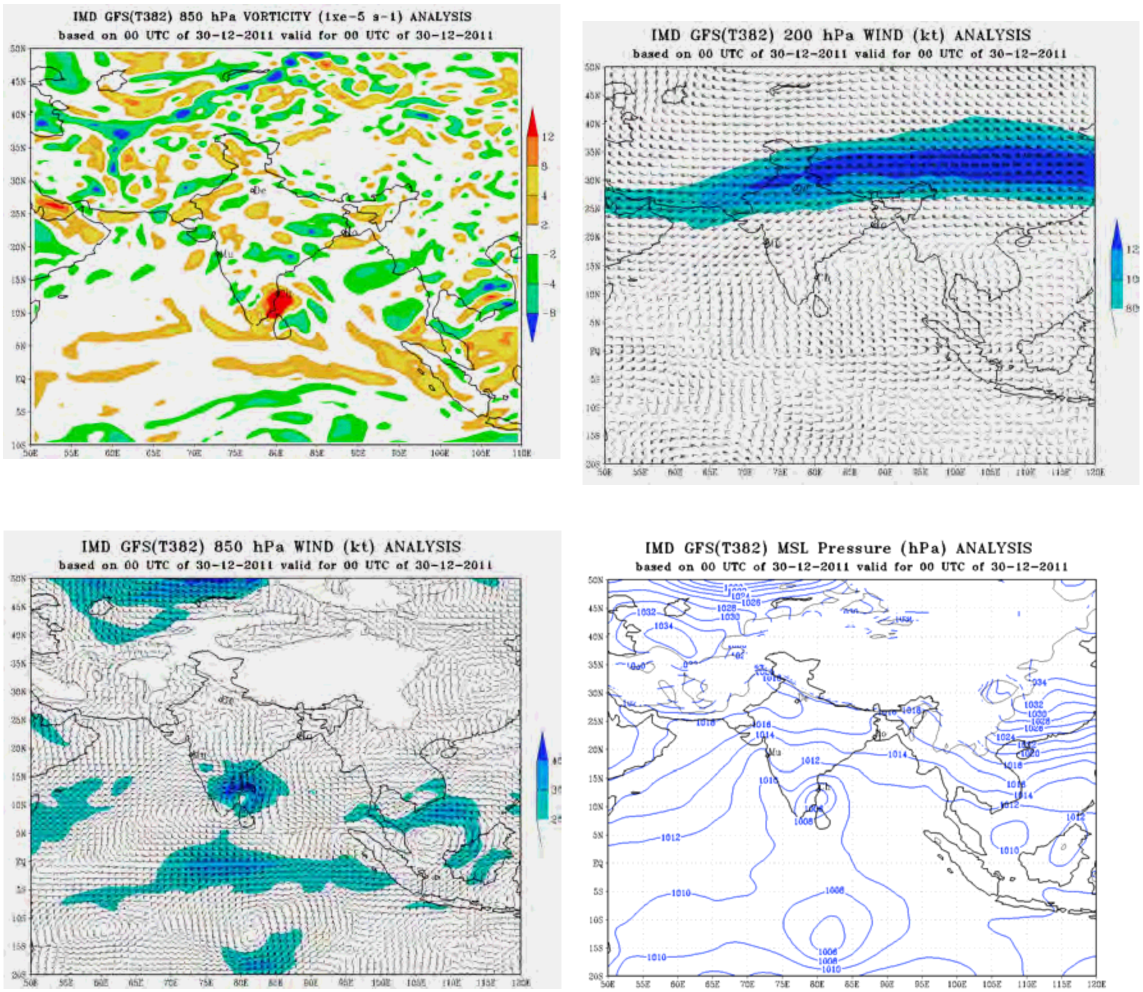


Fig. 2.10.3(f) (i) Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) wind at 200 hPa level (iv) MSLP based on the IMD GFS model analysis of 0000 UTC of 30th December, 2011.

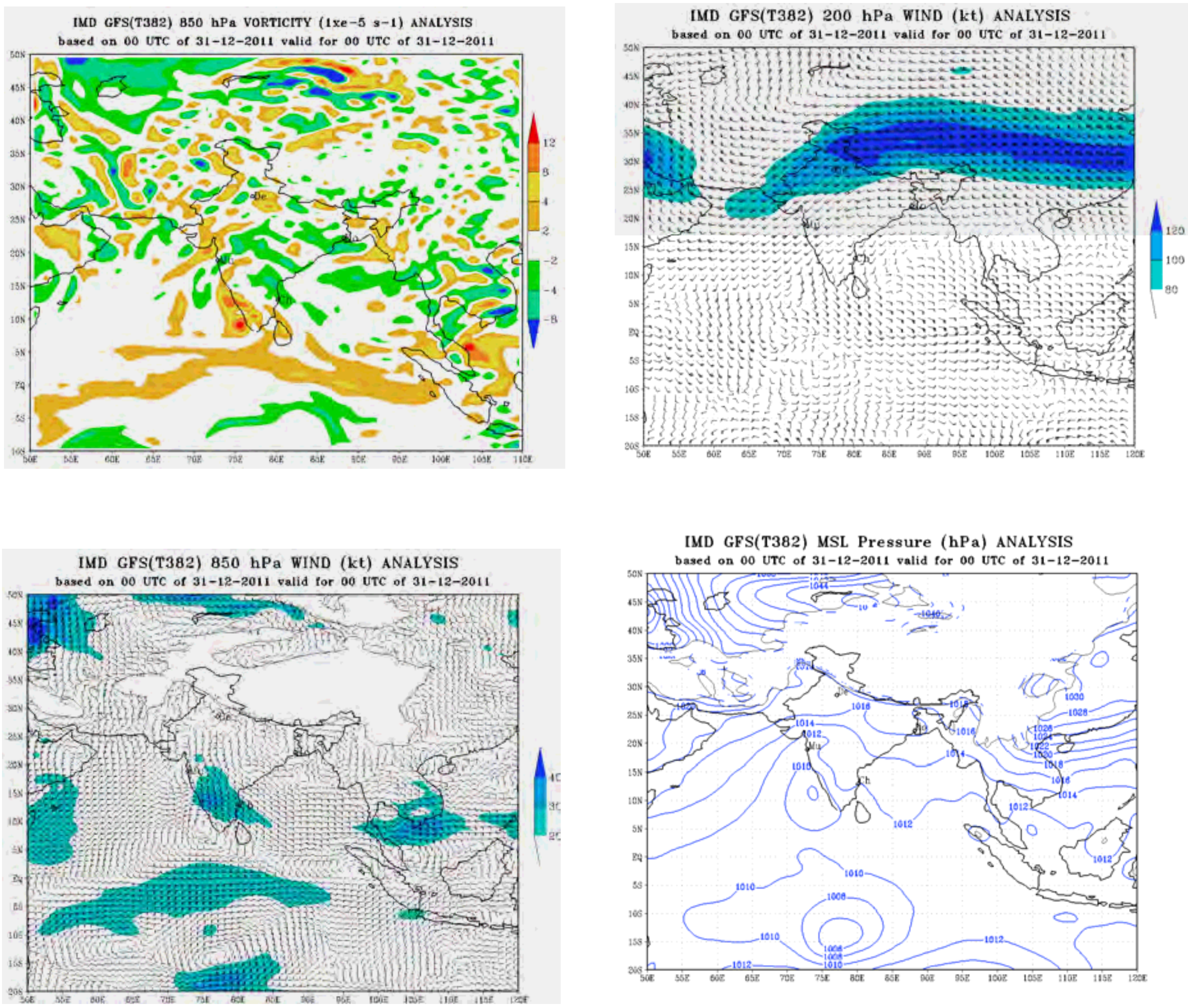


Fig. 2.10.3(g) (i) Upper level divergence at 200 hPa level (ii) low level relative vorticity at 850 hPa level (iii) wind at 200 hPa level (iv) MSLP based on the IMD GFS model analysis of 0000 UTC of 31st December, 2011.

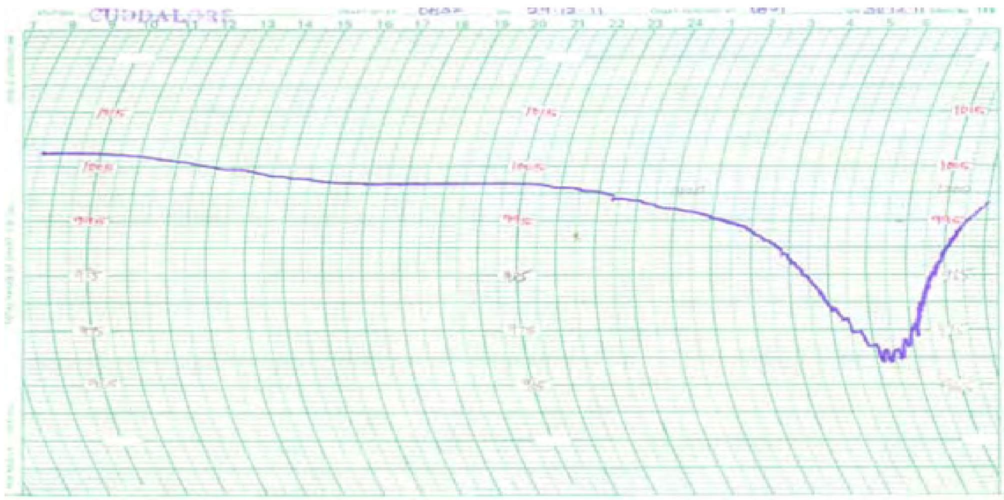


Fig.2.10.4(a) . Barograph of Cuddalore during 29-30th December 2011

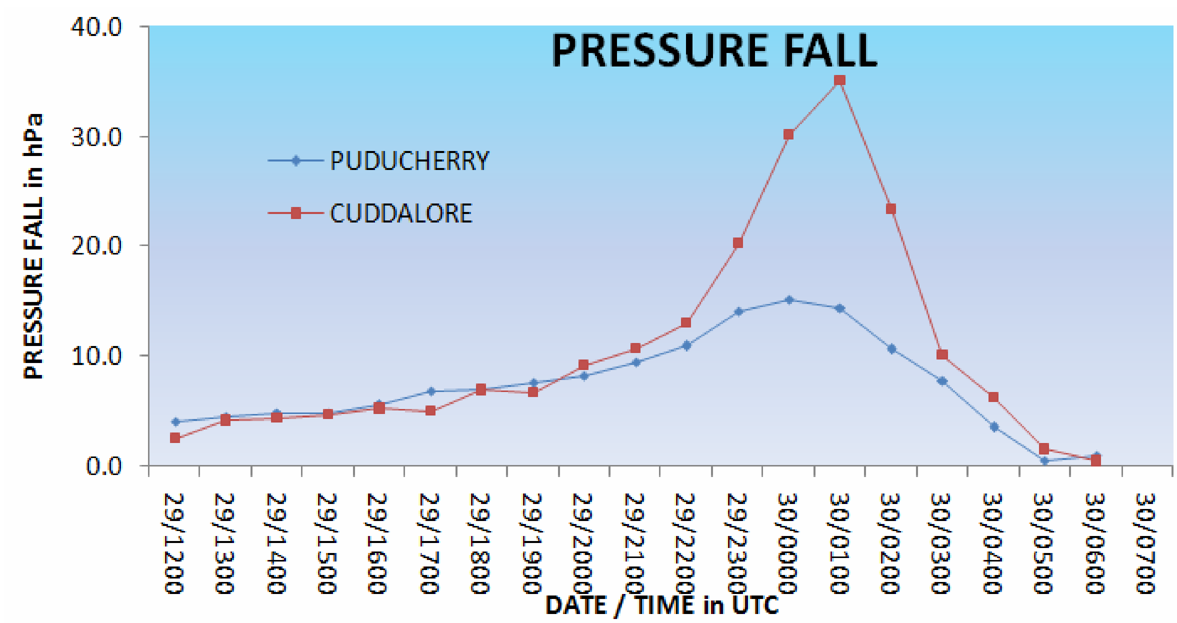


Fig.2.10.4(b) . 24 hr pressure fall of Puducherry and Cuddalore during 29-30th December 2011

2.10.5 Realised Weather

(a) Heavy Rainfall

Heavy to very heavy rainfall occurred at a few places over north Tamil Nadu and Puducherry on 30th and 31st December. Isolated heavy rainfall also occurred over south Tamil Nadu, south coastal Andhra Pradesh, Rayalaseema during this period and over Kerala on 31st December.The following stations recorded past 24 hrs heavy rainfall (7 centimeters or more) at 0830 hrs IST of 30th and 31st December 2011.

30 December 2011

Puducherry : Puducherry airport 15,

Tamil Nadu : Kalpakkam and Kelambakkam (both Kanchipuram dt) 10 each, Cuddalore, Maduranthagam and Uthiramerur (both Kanchipuram dt) 9 each, Chengalpattu and Mahabalipuram (both Kanchipuram dt) 8 each and Chennai airport, Tiruvallur and Chidambaram (Cuddalore dt) 7 each.

Andhra Pradesh : Rapur (Nellore dt), Puttur (Chittoor dt) 7 each,

31 December 2011

Kerala : Haripad (Alapuzha dt) 22, Tiruvananthapuram 18, Nedumangad (Tiruvanathapuram dt) 16, Kayamkulam (Alapuzha dt) 15, Thiruvalla (Pattanamthitta dt) 14, Chengannur (Alapuzha dt) 12, Neyyatinkara (Tiruvananthapuram dt) 11, Mavelikara (Alapuzha dt) 10, Konni (Pattanamthitta dt), Kanjirapally (Kottayam dt), Kottayam, Alapuzha 9 each, Varkala (Tiruvananthapuram dt), Kozha (Kottayam dt) 7 each,

Puducherry: Puducherry airport 10

Tamil Nadu : Kallakurichi (Villupuram dt) 18, Gingee (Villupuram dt) 16 each, Sankarapuram (Villupuram dt), Mylaudy and Nagerkoil (both Kanyakumari dt) 14 each, Uthiramerur (Kanchipuram dt) and Kuzhithurai (Kanyakumari dt) 13 each, Virudhachalam (Cuddalore dt), Cheyyar (Tiruvannamalai dt) 12 each, Mancompu (Alapuzha dt), Tozhudur (Cuddalore dt), Tirukoilur (Villupuram dt), Polur, Vanthavasi and Sathanur Dam (all Tiruvannamalai dt) 11 each, Kanchipuram, Maduranthagam (Kanchipuram dt), Arani (Tiruvannamalai dt) 10 each, Chengalpattu (Kanchipuram dt), Chembarambakkam (Tiruvallur dt), Ulundurpet (Villupuram dt) and Tiruvannamalai 9 each, Punalur, Tiruvallur, Boothapandy (Kanyakumari dt), Kanyakumari, Chengam (Tiruvannamalai dt) and Sholingur (Vellore dt) 8 each and Chennai airport, Cheyyur, Kelambakkam and Sriperumpudhur (all Kanchipuram dt), Poonamalli, Ramakrishnarajupet and Tiruvalangadu (all Tiruvallur dt), Tiruttani, Sethiyathope (Cuddalore dt) and Tindivanam (Villupuram dt), Kumbakonam (Thanjavur dt), Arakonam and Kaveripakkam (both Vellore dt), Vellore, Attur (Salem dt), Coonoor, Jayamkondam (Ariyalur dt) and Padallur (Perambalur dt) 7 each.

The daily cumulative rainfall on 30th and 31st December 2011 at recorded at 0300 UTC are shown in Fig.2.10.5. The SRRG chart of Meteorological Observatory, Puducherry is shown in Fig.2.10.6

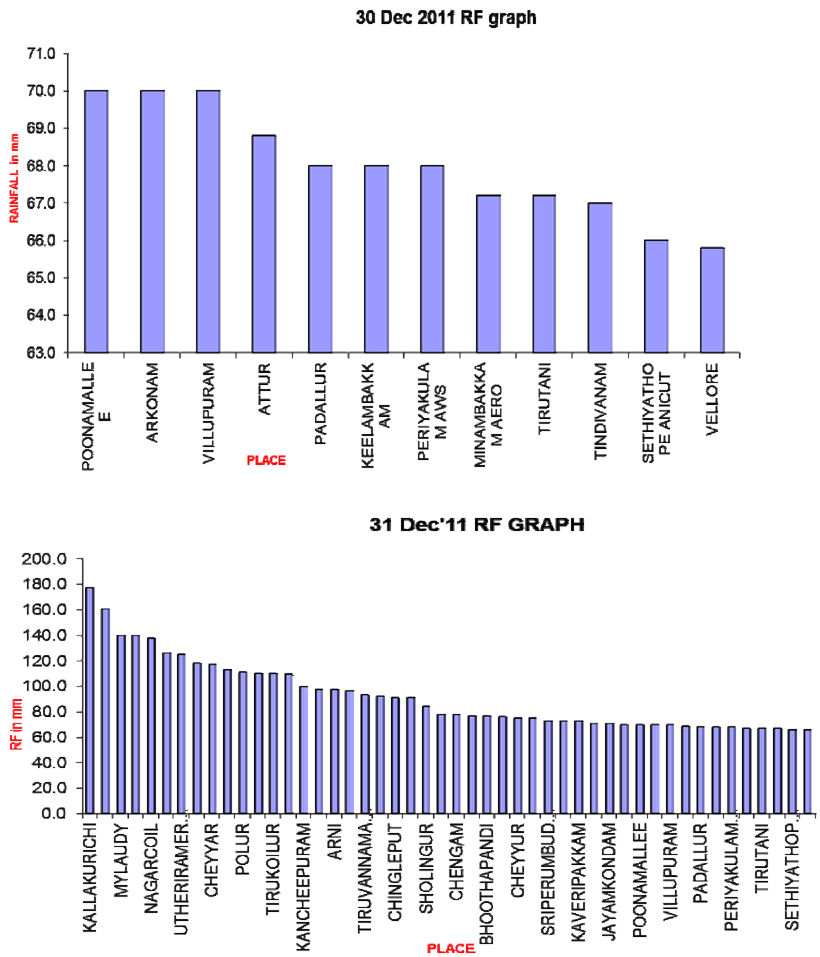


Fig.2.10.5. Daily cumulative rainfall on 30th and 31st December 2011 at recorded at 0300 UTC along the coast of Tamil Nadu and Puducherry

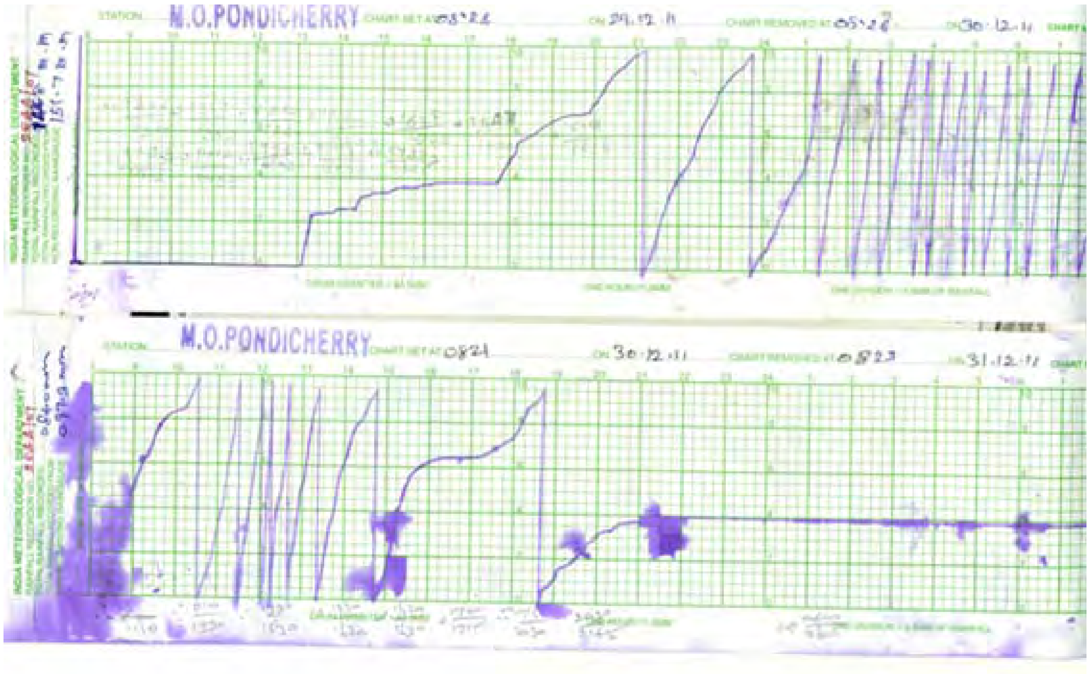


Fig.2.10.6. SRRG chart of Meteorological Observatory, Puducherry

(b) Gale wind

Gale wind speed reaching 120-140 kmph prevailed along and off north Tamil Nadu and Puducherry coast. Puducherry reported maximum wind of 68 knots (125 kmph) and Cuddalore reported maximum wind of 76 knots (140 kmph) at the time of landfall. The area affected by gale wind due to Thane is shown in Fig.2.10.7.

(c) Storm surge

As per post-cyclone survey conducted by IMD, the storm surge of about 1 metre height inundated the low lying coastal areas of Cuddalore, Puducherry and Villuparam districts at the time of landfall of the cyclone, THANE.

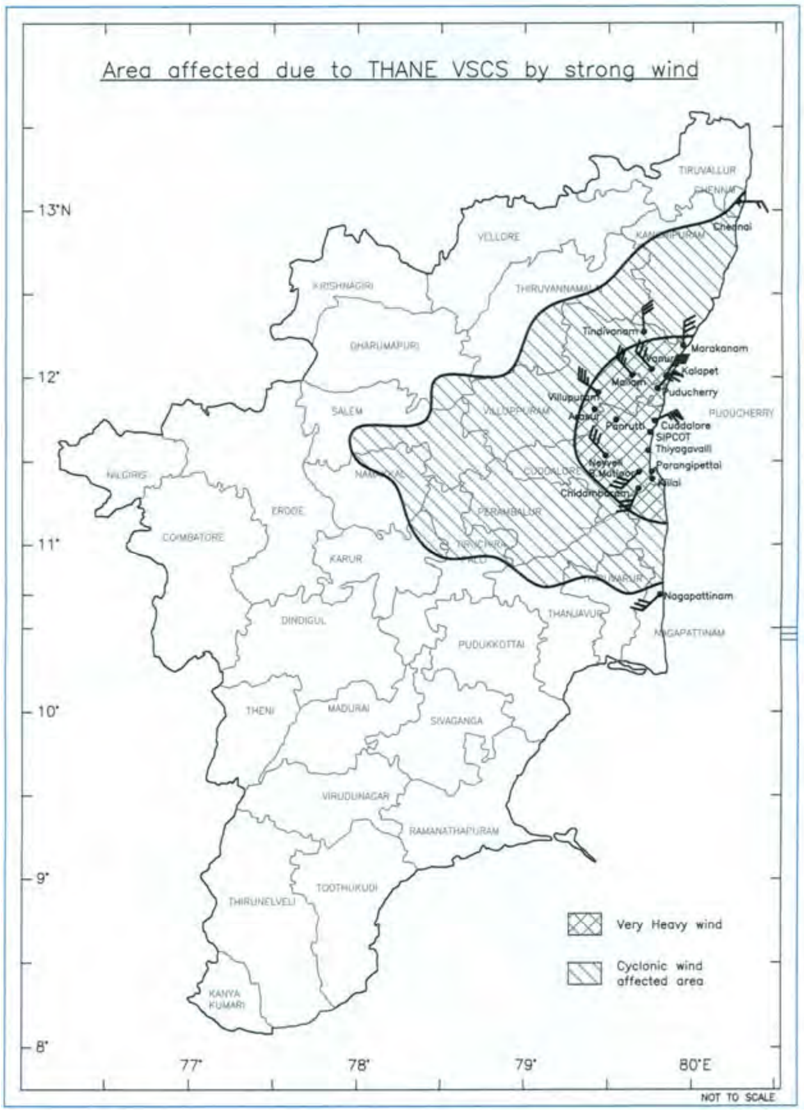


Fig.2.10.7. Area affected by gale wind due to Thane.

2.10.6. Damage:

As per media /Govt reports, 46 persons died due to the VSCS “Thane” in Tamil Nadu and Puducherry.

The samba crop grown in 1700 hectares in Thanjavur district; 2000 hectares in Tiruvarur district; Paddy crop in Cuddalore, Nagapattinam, Villupuram, Kanchipuram, parts of Thanjavur, Tiruvarur and Thiruvallur were affected besides sugarcane in 6000 hectares and coconut in about 500 hectares. In Salem district, many acres of tapioca, betel nuts, and banana crops were also affected.

When the storm crossed the coast, heavy rains accompanied by squally winds speed reaching 140 Kmph uprooted trees, electric posts, disrupted power supply and transport services in Cuddalore district and Puducherry.

Due to wind and rain, 793 trees more than 35 years old in the roadside were uprooted In the cyclone affected coastal areas.

Around 6000 persons in Cuddalore, Villupuram, and Nagapattinam, Tiruvallur and Kancheepuram districts and low level areas were shifted to shelters. Besides, the supply of water, milk, diesel and kerosene has been affected and essential commodities go scarce in Cuddalore district and Puducherry. In Puducherry the storm has caused considerable loss to the Tourism Industry and the Silver beach in Cuddalore has been reduced to a strip as sea erosion caused the coast leaving little space for the sand.

About 73292 thatched houses were fully damaged and 94633 houses were partially damaged by wind and rain in the various affected districts of the state.

In agricultural sector, paddy crop in 58,200 hectares; sugarcane in 5,752; groundnut in 1,402; black gram in 945; coconut in 490 hectares were damaged in the entire cyclone affected areas. In horticultural sector, cashew in 23,500 hectares; banana plantation in 2,860; Jackfruit in 340; vegetables in 320; Mango trees in 317; Guava in 270; flowers in 250; betel nuts in 128; tuber in 73; amla in 12 hectares were damaged.

In Cuddalore district alone 4500 electric poles, 4500 transformer, 27 electric towers were damaged. Electric wire in 10,500 Km length was damaged. The damages are worked out to be 1300 to 1500 crores.

In fishing sector, in the coastal villages of Cuddalore and Puducherry, 240 country boats; 67 numbers motorized boats; 58 catamarans and four mechanized boats were fully damaged.

In the cyclone affected coastal areas, 1,430 catamarans; 106 motor boats; 101 mechanised boats and 16 country boats were partially damaged. Apart from this damage 1,94,000 fishing nets and 1262 engines were damaged. In animal husbandry sector, 47 Cows; 32 Calves; 9 Buffaloes; 5 Buffaloes calves and 4 Bullocks were dead. About 52,938 Chickens; 6200 Kadai; 1000 ducks and 246 goats also perished.

A few damage photographs are shown in Fig.2.10.8

(a) Broken electrical post and submerged fishing boat at Cudallore

(b)Twisted cell phone tower at Cuddalore and blown up fishing boats at Cudallore

(c) Damages at Puducherry and fishing hamlet Puducherry coastal line.

(d) Up rooted trees Pondy Assembly campus and Damaged District Collectorate, Cudallore

Fig. 2.10.8 Some damage photograph due to the cyclone THANE in Cudallore district Puducherry.

CHAPTER – III

Performance of operational NWP models for tropical cyclones during the year 2011

3.1 Introduction:

NWP Division of India Meteorological Department (IMD) operationally runs three regional models WRF (ARW), WRF (NMM) and Quasi-Lagrangian Model (QLM) for short-range prediction and one Global model (T382L64) for medium range prediction (7 days). The upgraded version of the GFS (*GSI 3.0.0 and GSM 9.1.0*) model at T574L64 (~ 25 km) resolution has been also operated in the experimental mode since 1 June 2011 and real-time outputs are made available to the national web site of IMD (www.imd.gov.in). The WRF-VAR model is run at the horizontal resolution of 27 km and 9 km with 38 Eta levels in the vertical and the integration is carried up to 72 hours over three domains covering the area between lat. 25^o S to 45^o N long 40^o E to 120^o E. Initial and boundary conditions are obtained from the IMD Global Forecast System (IMD GFS) at the resolution of 35 km. The boundary conditions are updated at every six hours interval. The QLM model (resolution 40 km) is used for cyclone track prediction in case of cyclone situation in the north Indian Ocean. IMD also makes use of NWP products prepared by some other operational NWP Centres like, ECMWF (European Centre for Medium Range Weather Forecasting), GFS (NCEP), JMA (Japan Meteorological Agency), UKMO etc. A multimodel ensemble (MME) for predicting the track of tropical cyclones for the Indian Seas is developed. The MME is developed applying multiple linear regression technique using the member models WRF, QLM, GFS (NCEP), ECMWF and JMA. NWP division also provides 12 hourly intensity forecasts and genesis potential inputs during cyclone conditions. In this report Cyclone track prediction skill of these models is presented and discussed here.

3.2. Tropical cyclone "KEILA" over Arabian Sea (29 Oct.-04 Nov. 2011)

3.2.1 GENESIS POTENTIAL PARAMETER (GPP):

The GPP forecast for 00UTC of 2^{nd} November, based on observations of 28^{th}, 29^{th}, 30^{th}, 31^{st} Oct. and 1^{st} Nov.,2011 are shown in fig.3.2.1.

The forecast of Genesis Potential Parameter (GPP) values valid for 00UTC of 02-11-11 for CS 'KEILA' on the basis of real time model analysis fields (28^{th} Oct.- 2^{nd} Nov.) clearly indicated that the system had enough potential (>30, the threshold value) to intensify into a cyclonic storm .

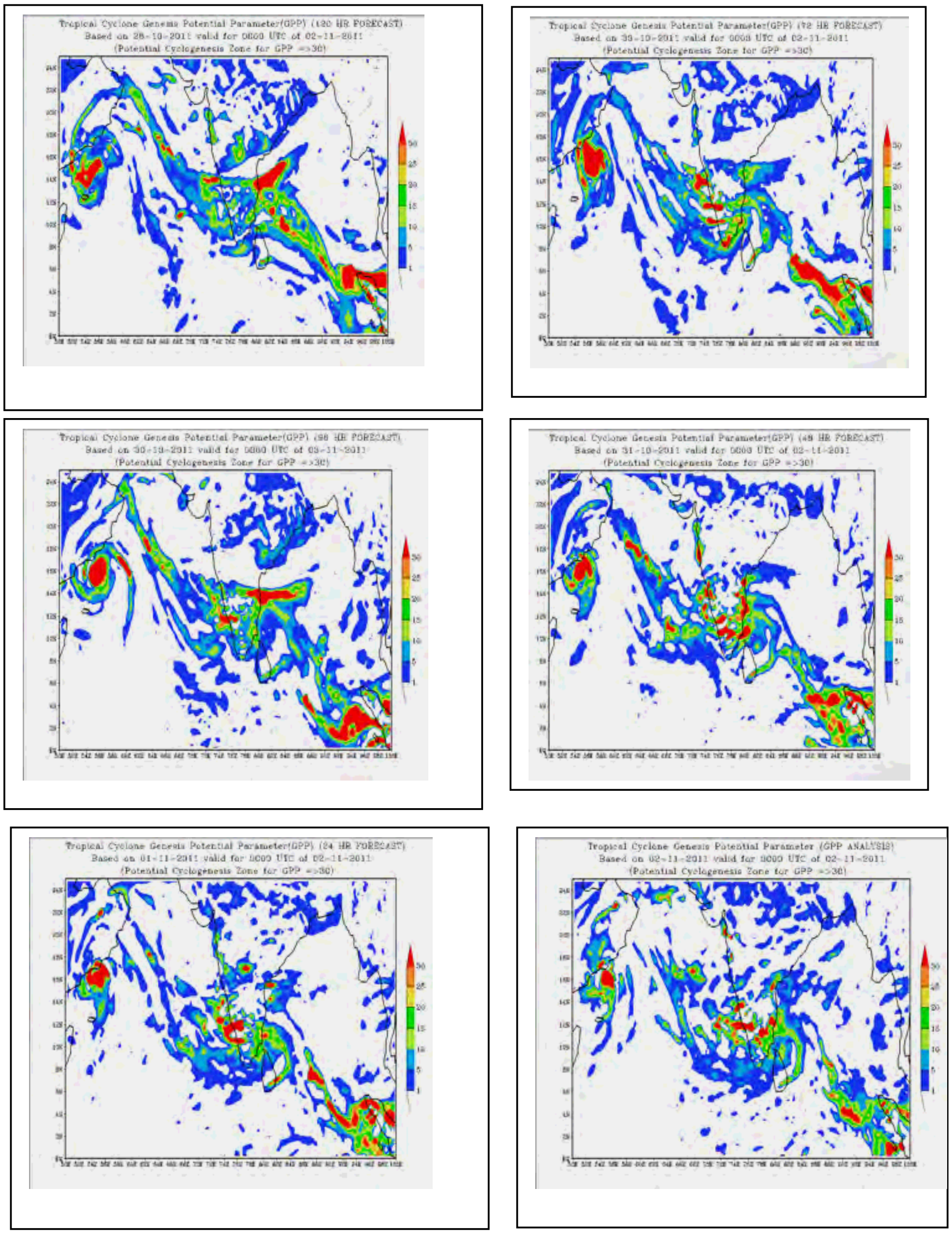


Fig.3.2.1: GPP forecast valid for 00 UTC 2nd Nov.based on 28th Oct to 2nd Nov.observations

3.2.2 TRACK:

Fig.3.2.2 (a-e) display the forecast track of CS 'KEILA' by various NWP models with the initial conditions of 0000UTC of 29th, 30th , 31st Oct. and 1st ,2nd Nov.,2011respectively. Based on initial condition of 0000UTC of 29th October, the predicted tracks were very erratic in nature, none showing landfall and there was no agreement among the models about the movement.

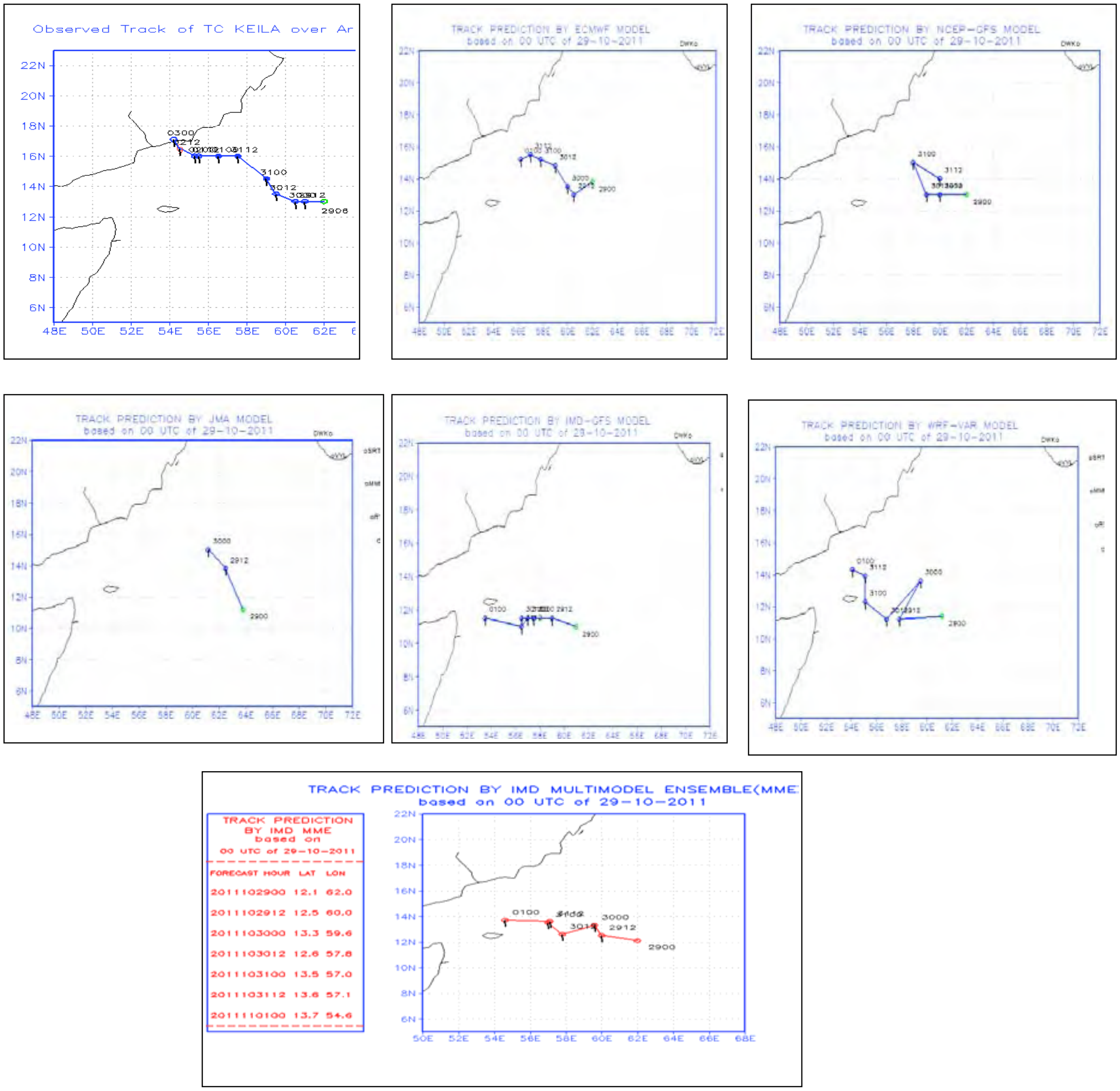


Fig. 3.2.2(a) TRACK FORECAST BASED ON 00 UTC OF 29-10-2011

Based on 00 UTC of 30th October 2011, none of the models predicted landfall on Oman coast and there was no consistency in the forecast track by various models. However, ECMWF model indicated movement towards Oman coast, whereas NCEP-GFS indicated recurvature towards north and other models indicated movement towards Gulf of Aden.

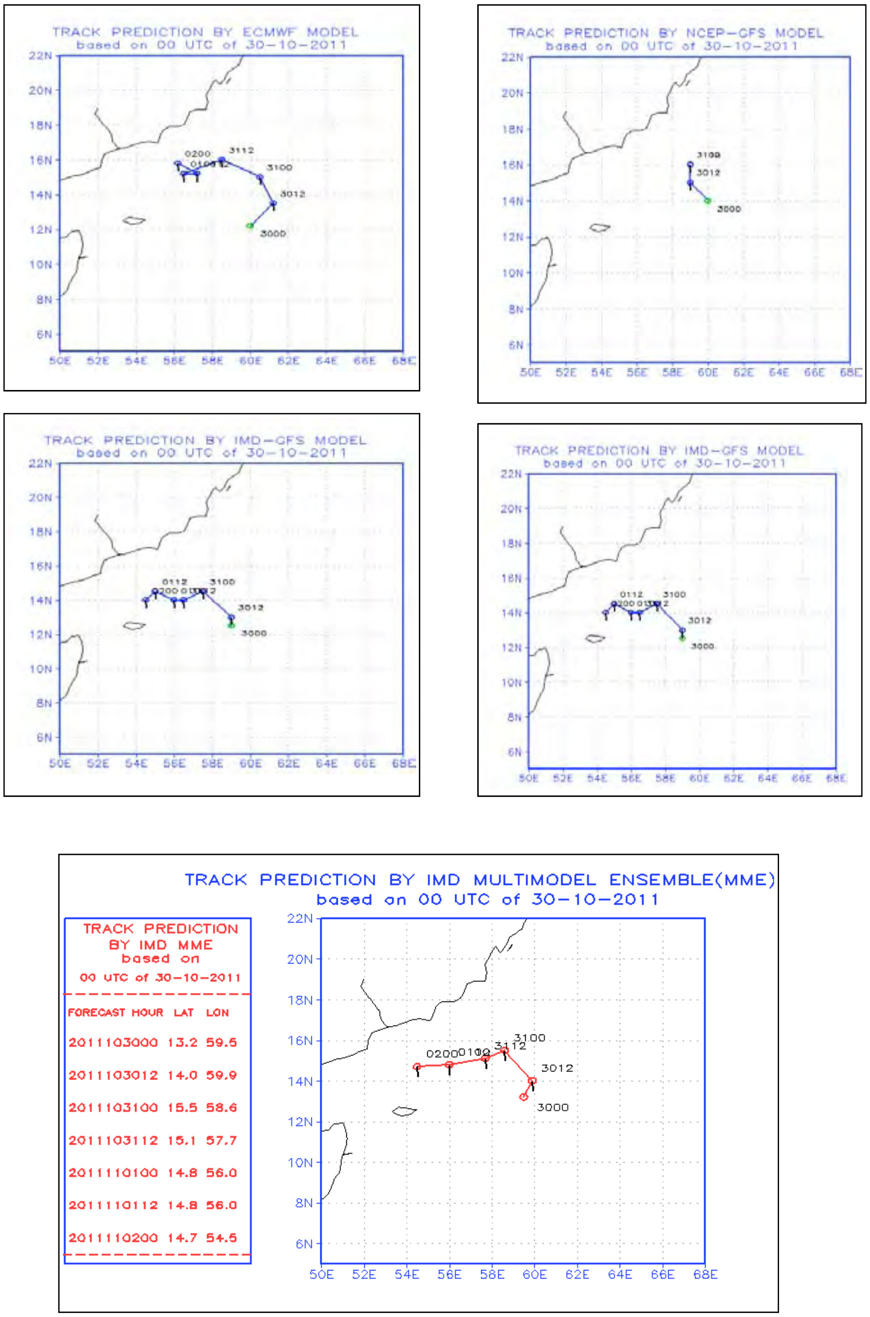


Fig.3.2.2(b) TRACK FORECAST BASED ON 00 UTC OF 30-10-2011

Based on 00UTC of 31st Oct. only QLM and MME models predicted landfall over Oman coast. The track prediction by other models was highly erratic.

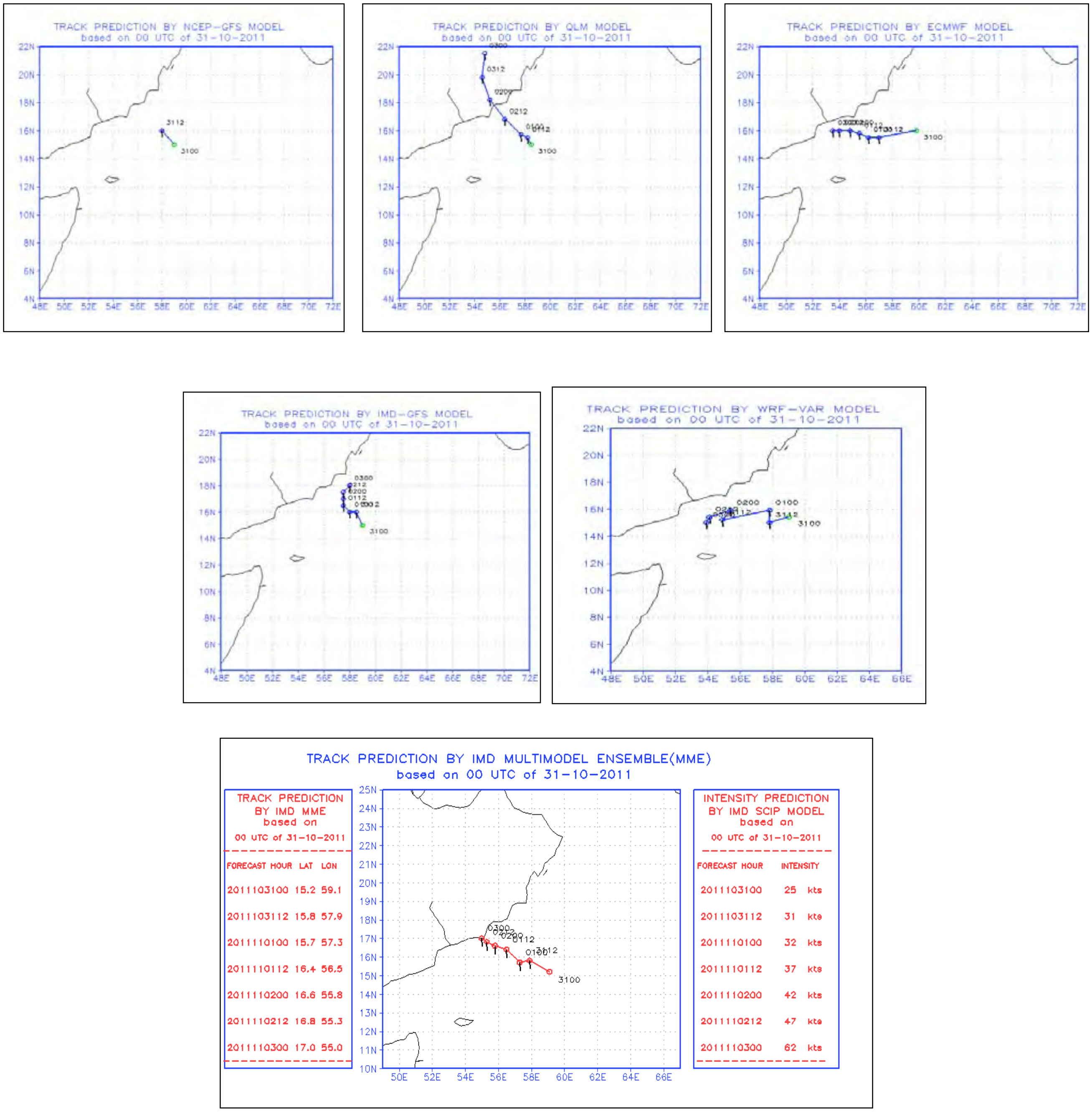


Fig.3.2.2(c)TRACK FORECAST BASED ON 00 UTC OF 31-10-2011

Even on 1st of Nov. most of the models predicted zigzag or looping track. Only QLM model showed landfall over Oman coast. However, it failed to predict the looping of the cyclone after landfall like previous forecasts.

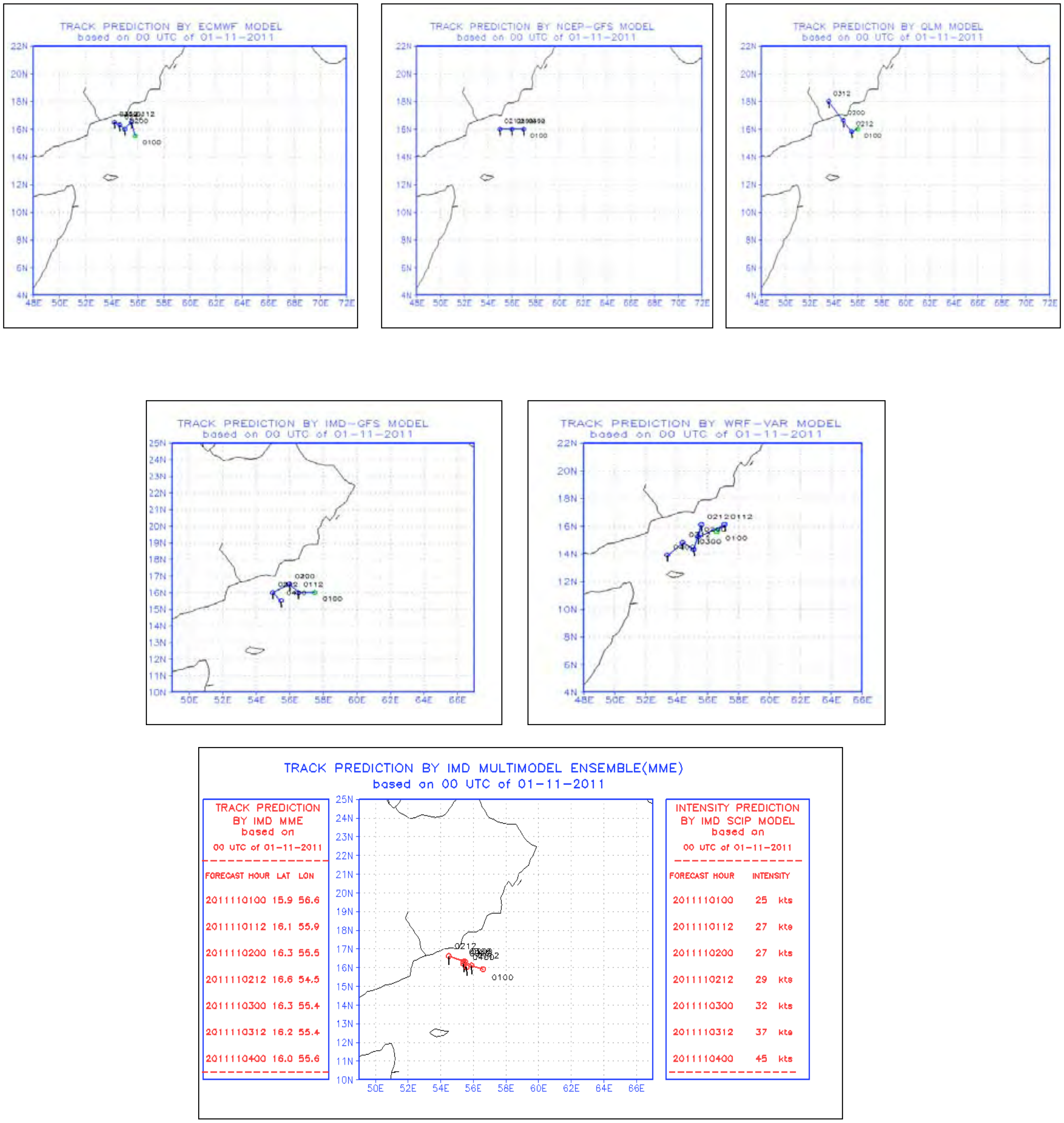


Fig.3.2.2(d). TRACK FORECAST BASED ON 00 UTC OF 01-11-2011

Based on 00 UTC of 2nd Nov. ECMWF and QLM model predicted the landfall of the system and ECMWF model only predicted the looping of the system near the coast. The track predictions by our models were highly inconsistent.

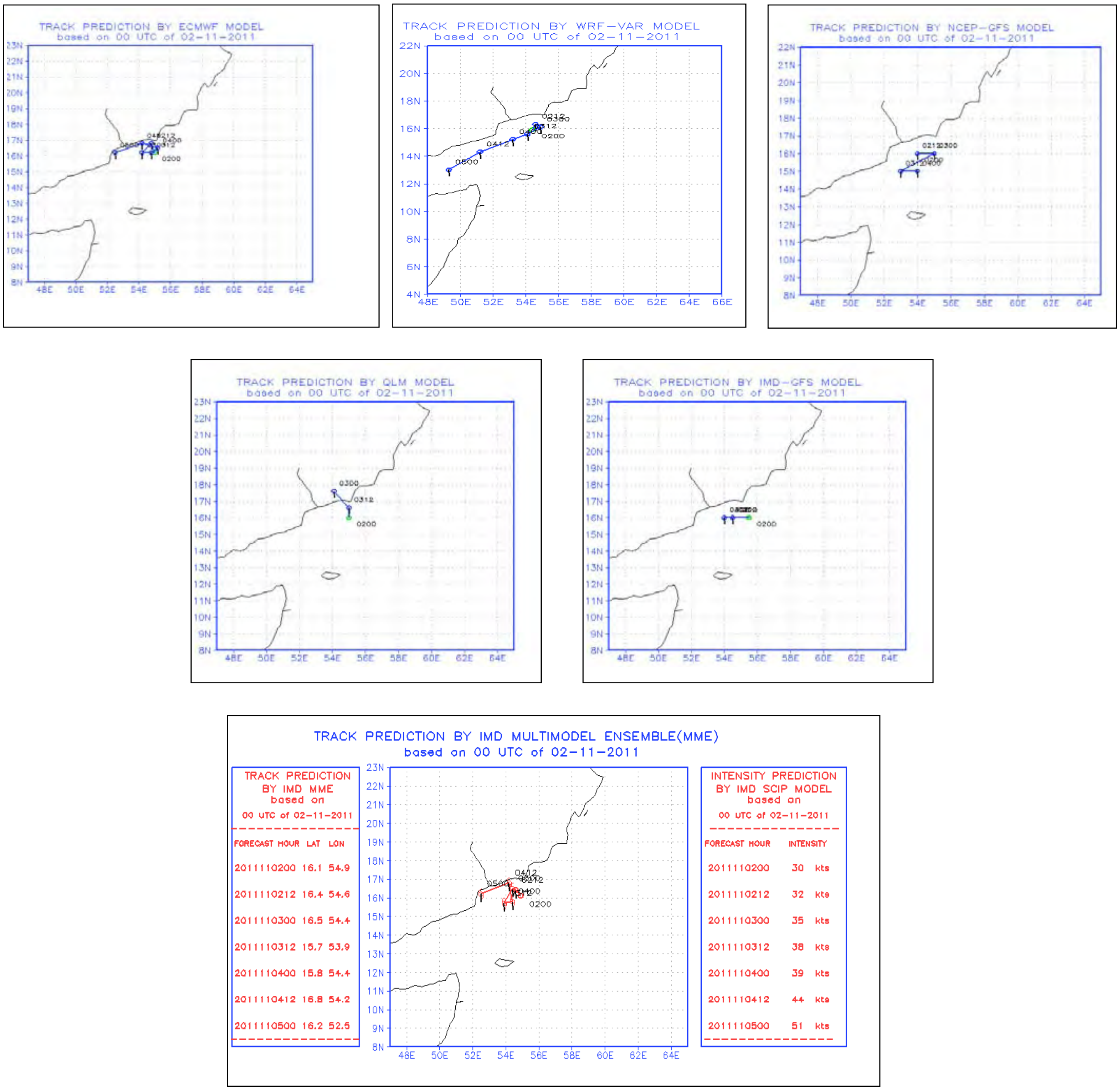


Fig. 3.2.2(e). TRACK FORECAST BASED ON 00 UTC OF 02-11-2011

The average track forecast errors of member models based on different initial conditions are summarized in table 3.2.1. The track forecast errors were very high. The forecast error by ECMWF followed by MME model was less. The forecast error by QLM model was less for 24 hr. lead time only.

Table 3.2.1 AVERAGE TRACK FORECAST ERRORS OF TC KEILA (DIRECT POSITION ERROR IN KM)

	Lead time →					
Models	**12 hr**	**24 hr**	**36 hr**	**48 hr**	**60 hr**	**72 hr**
ECMWF	83	89	77	90	119	112
GFS (NCEP)	93	111	105	174	348	-
JMA	185	235	-	-	-	-
QLM (IMD)	57	91	161	245	367	493
MME (IMD)	60	85	110	169	185	222
GFS (IMD)	124	181	235	272	360	416
WRF(IMD)	145	159	249	263	219	309

3.2.3 INTENSITY (by SCIP)

The 12 hourly intensity forecasts valid upto 72 hrs show that mean model forecast errors for this cyclone varied between 4 knots to 32 knots as shown in table 3.2.2.

Table 3.2.2. Mean intensity forecast error (KEILA)

Forecasts hours →			12 hr	24 hr	36 hr	48 hr	60 hr	72hr
KEILA	00/31.10.11	Error (knots)	+6	+7	+7	+12	+12	+32
	00/01.11.11	Error (knots)	-3	-3	-6	2	-	-
	00/02.11.11	Error (knots)	-3	5	-	-	-	-
Average Absolute Error(AAE) (knots)			**4**	**5**	**7**	**7**	**12**	**32**

3.3. DEEP DEPRESSION OVER ARABIAN SEA (06 Nov-11 Nov 2011)

3.3.1 GENESIS POTENTIAL PARAMETER (GPP)

The forecast of Genesis Potential Parameter (GPP) values valid for 00UTC of 8th Nov. on the basis of real time model analysis fields indicated that the system had enough potential (>30, the threshold value) to intensify into a cyclonic storm. The GPP forecast valid for 00UTC of 8th Nov. based on initial conditions of 5th -8th Nov. are shown in fig.3.3.1. However, the system intensified upto the stage of deep depression and dissipated over sea before landfall as other factors for cyclogenesis were not favourable.

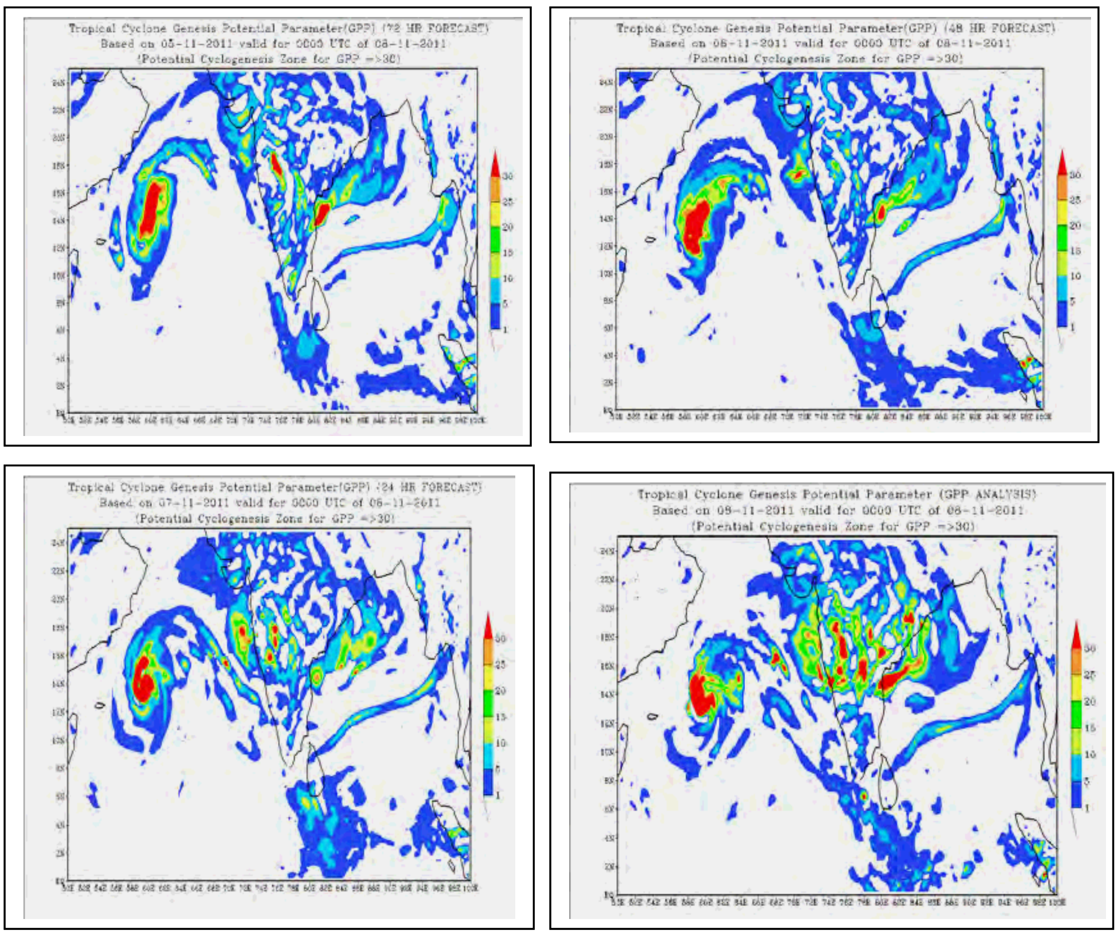


Fig.3.3.1 GPP forecast valid for 00 UTC 8th Nov. based on 5th -8th Nov.observations

3.3.2 TRACK

Fig.3.3.2 (a-d) display the forecast track of Deep Depression over Arabian Sea by various NWP models with the initial conditions of 00UTC of 6th -9th Nov.,2011 respectively. NCEP GFS model forecast was more close to the observed track. Except NCEP-GFS and ECMWF, none predicted the recurvature of the system on 9th November. Similar was the case based on 0000UTC of 7th November except that the ECMWF forecast was closer to observed track instead of NCEP-GFS forecast. The model forecasts deteriorated on 8th and 9th with no model forecast track being closer to forecast track.

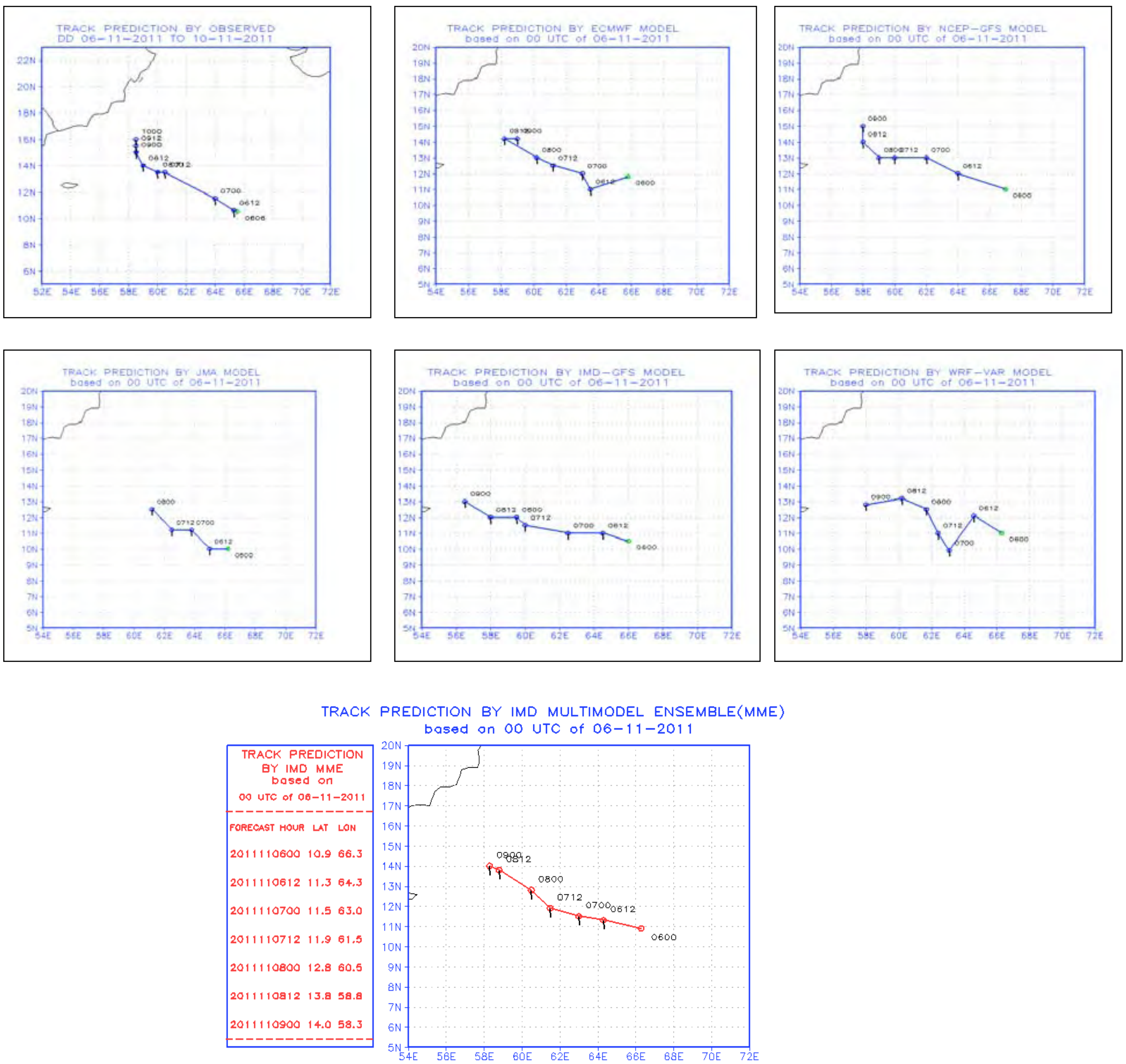


Fig.3.2.2(a) TRACK FORECAST BASED ON 00 UTC OF 06-11-2011

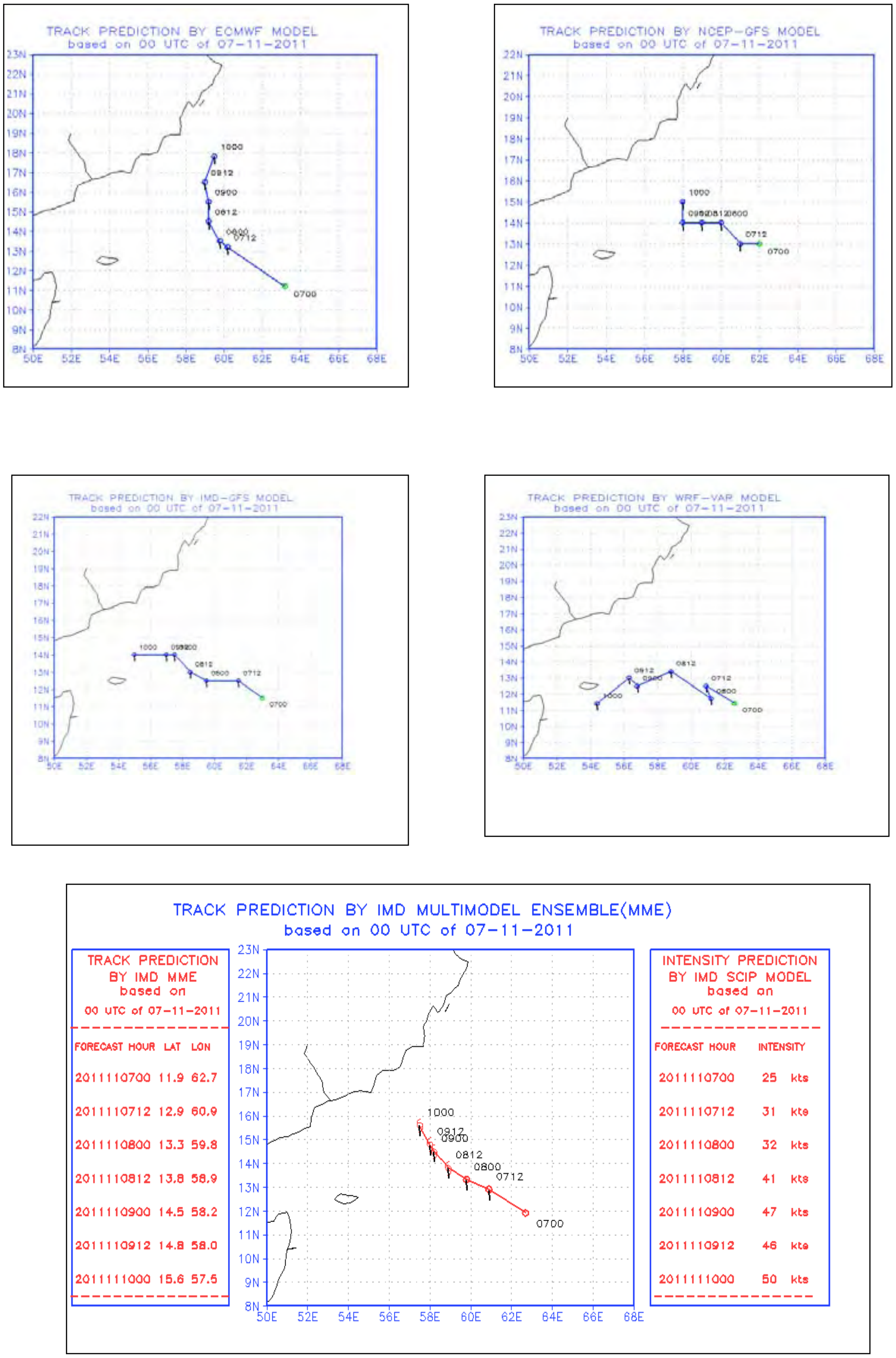


Fig.3.2.2(b) TRACK FORECAST BASED ON 00 UTC OF 07-11-2011

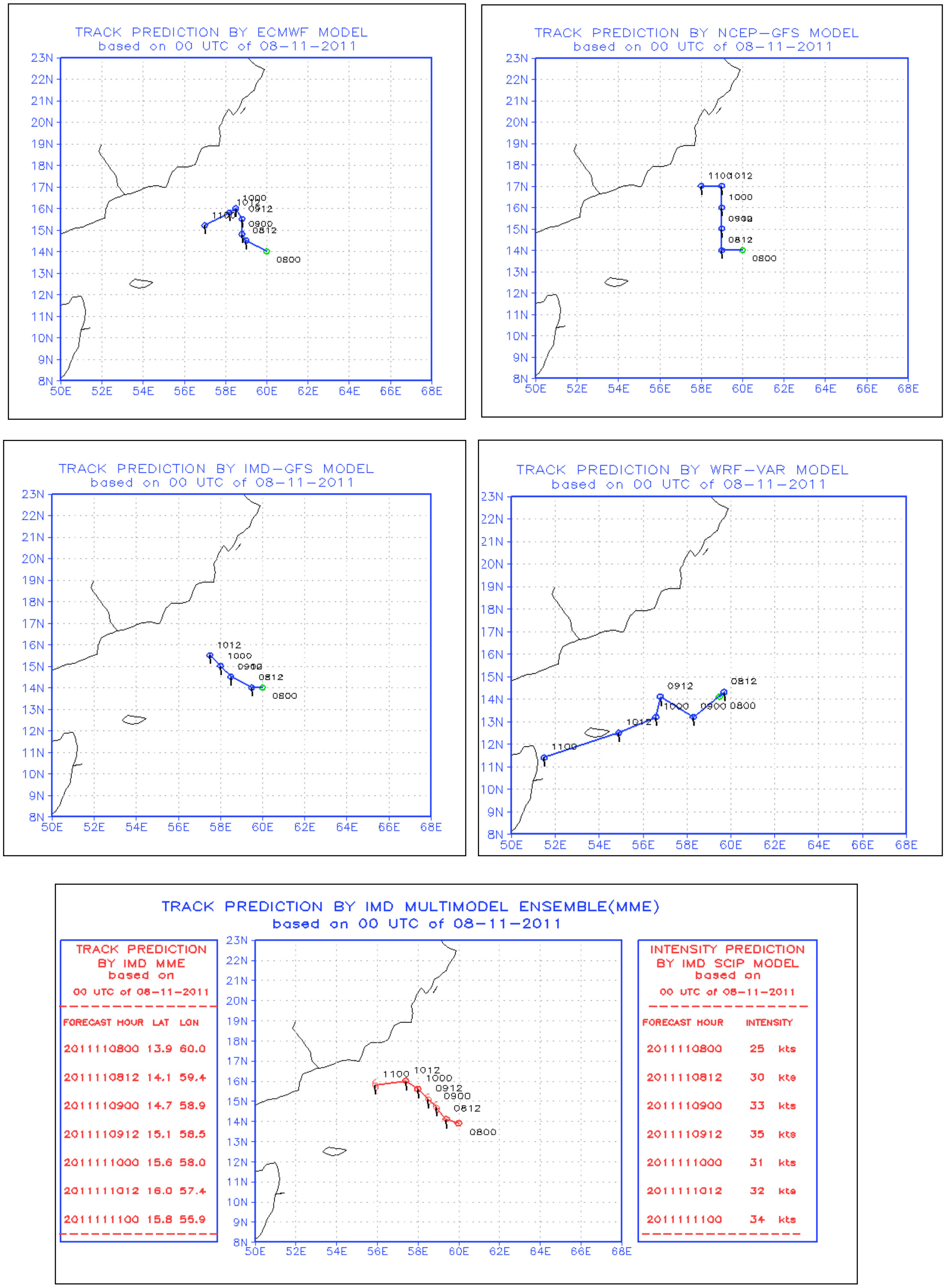


Fig.3.3.2(c) TRACK FORECAST BASED ON 00 UTC OF 08-11-2011

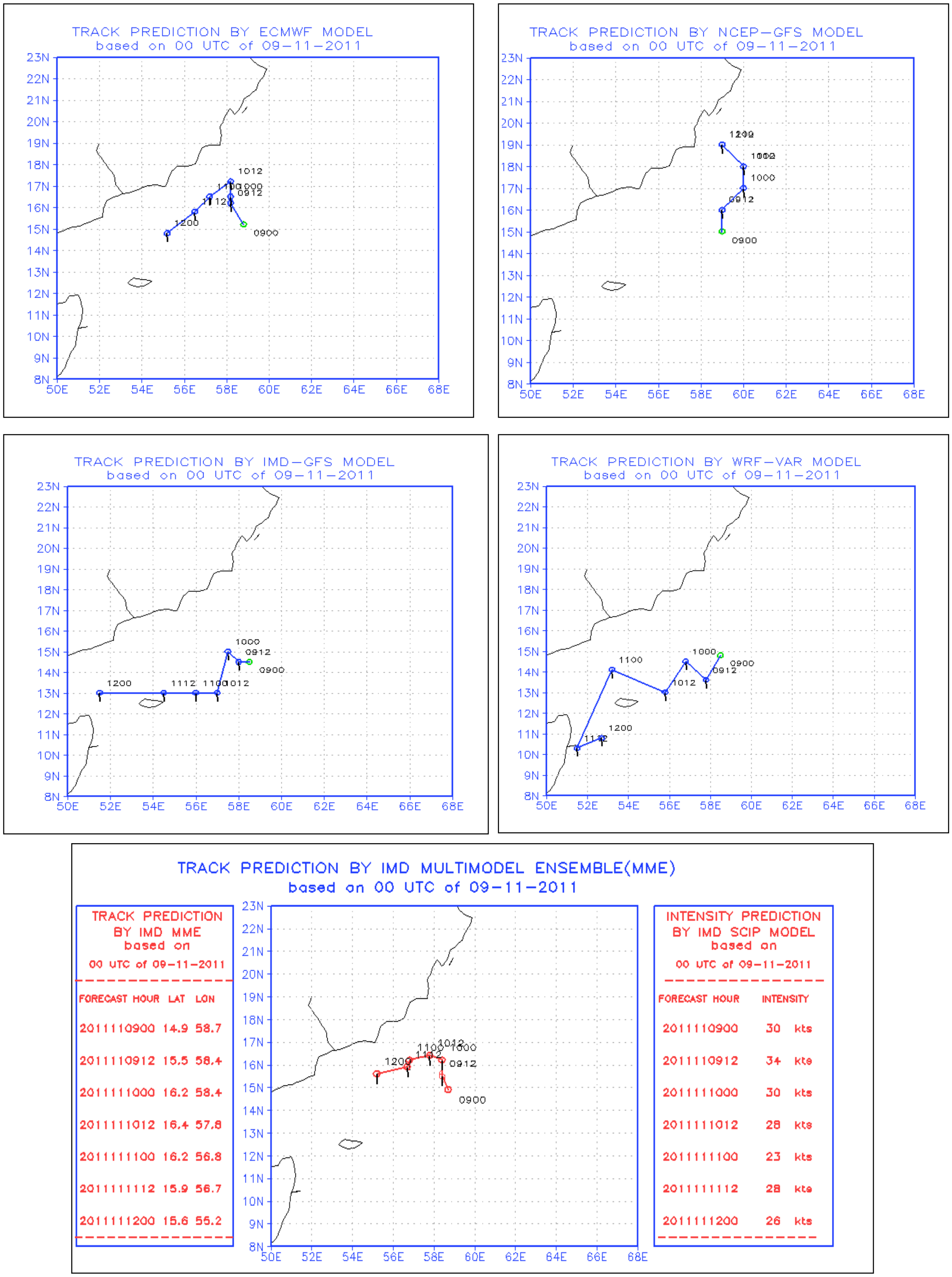


Fig.3.3.2(d) TRACK FORECAST BASED ON 00 UTC OF 09-11-2011

The average track forecast errors of member models based on different initial conditions are summarized in table 3.3.1. The performance of NCEP-GFS, ECMWF and MME models were relatively better.

Table 3.3.1: Deep depression over Arabian Sea (06 Nov.-11 Nov. 2011)- Average track forecast errors of Deep Depression (direct position error in km)

	Lead time →					
Model	**12 hr**	**24 hr**	**36 hr**	**48 hr**	**60 hr**	**72 hr**
ECMWF	97	61	75	76	106	104
GFS (NCEP)	91	128	52	123	141	54
JMA	74	40	335	171	-	-
QLM (IMD)	66	93	89	-	-	-
MME (IMD)	67	65	92	79	63	113
GFS (IMD)	108	117	154	165	240	310
WRF(IMD)	152	214	219	274	261	250

3.3.3 INTENSITY (by SCIP)

The 12 hourly intensity forecasts valid upto 72 hrs show that mean model forecast errors for this system varied between 5 knots to 25 knots as shown in table 3.3.2.

Table 3.3.2: Mean intensity forecast error(knots)

Forecasts hours →			12 hr	24 hr	36 hr	48 hr	60 hr	72hr
DEEP DEPRESSION	00/07.11.11	Error	+6	+7	+11	+17	+21	+25
	00/08.11.11	Error	0	+3	+10	+6	-	-
	00/09.11.11	Error	+9	+5	-	-	-	-
Average Absolute Error(AAE) (knots) →			**5**	**5**	**11**	**12**	**21**	**25**

3.4. DEEP DEPRESSION OVER ARABIAN SEA (26 Nov.-01 Dec. 2011)

3.4.1 GENESIS POTENTIAL PARAMETER (GPP)

The forecast of Genesis Potential Parameter (GPP) values valid for 00UTC of 28th Nov. for the Deep Depression over Arabian Sea on the basis of real time model analysis fields (25th Nov.- 28th Nov.) indicated that the system had enough potential (>30, the threshold value) to intensify into a cyclonic storm .The GPP forecast for 00UTC of 28th Nov. based on initial conditions as on 25th -28th Nov. are shown in fig.3.4.1. However, the maximum intensity was that of a deep depression and as other parameters for cyclogenesis were not favourable, the system gradually dissipated into a low on 1st Dec over the sea.

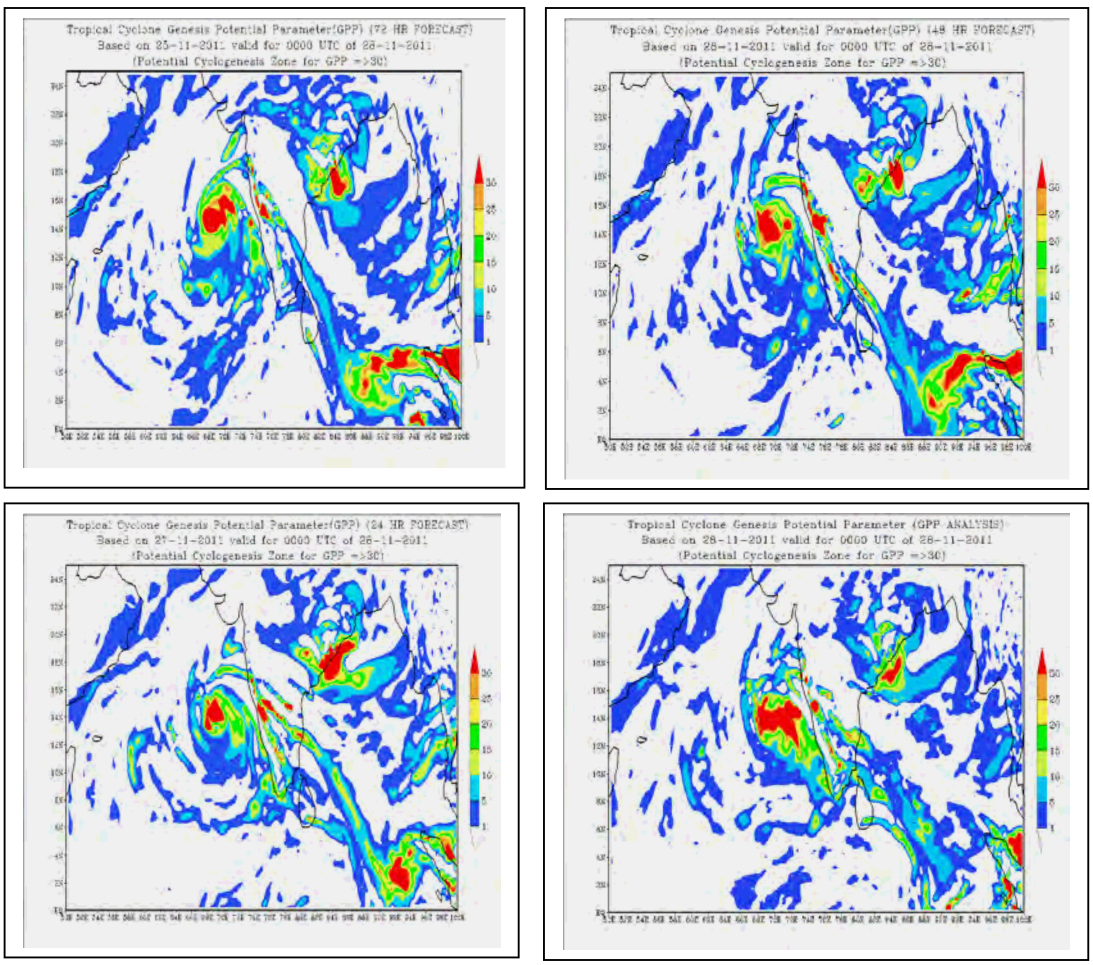


Fig.3.4.1 GPP forecast valid for 00 UTC 28th Nov. based on 255th -28th Nov.observations

3.4.2 TRACK

Track of the system was best forecast by ECMWF model. ECMWF model showed west-northwestward movement and rest of the models showed north northwestward movement initially. Fig.3.4.2 (a-e) display the forecast track of Deep Depression over Arabian Sea by various NWP models with the initial conditions of 00UTC of 26th -30th Nov., 2011 respectively. While all the models except JMA showed northwestward track, the JMA model indicated southwestward movement on day-3 forecast. The forecast performance of the models improved on 6th for all the models except QLM, which showed a northerly track. Though there was large variation in the track forecast by various models on subsequent days, all were in agreement on the dissipation of the system over the sea.

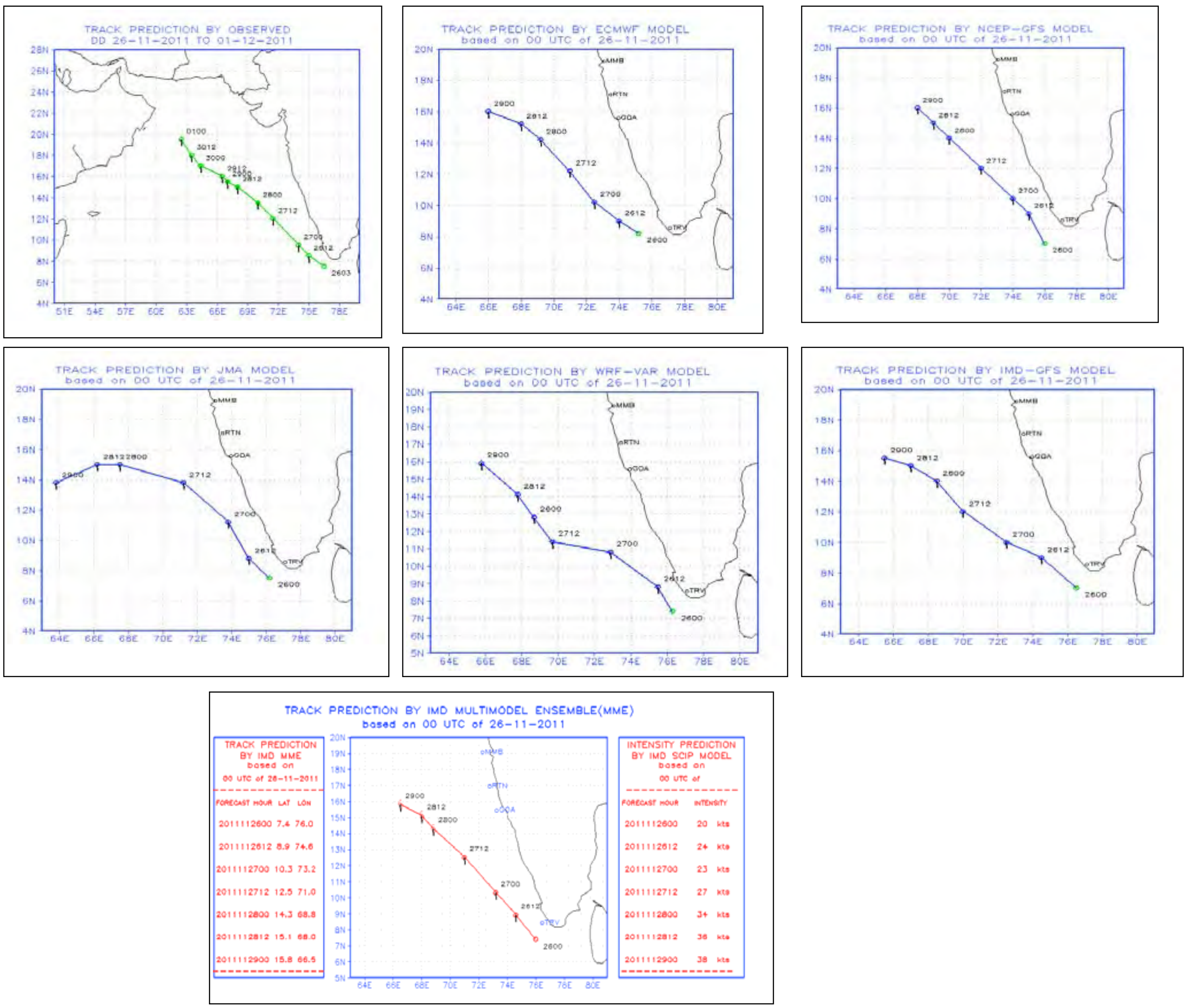


Fig.3.4.2(a) TRACK FORECAST BASED ON 00 UTC OF 26-11-2011

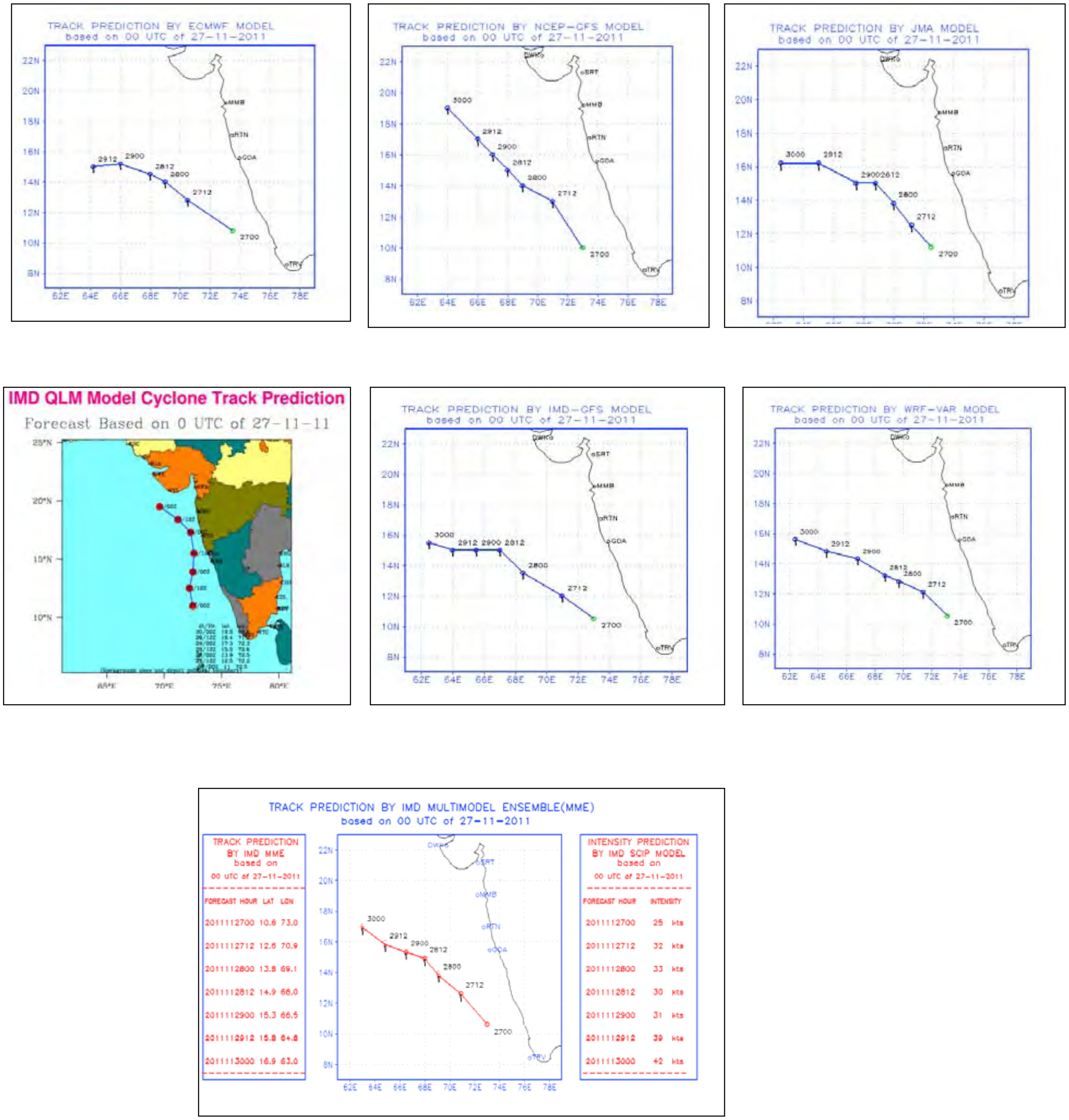


Fig.3.4.2(b) TRACK FORECAST BASED ON 00 UTC OF 27-11-2011

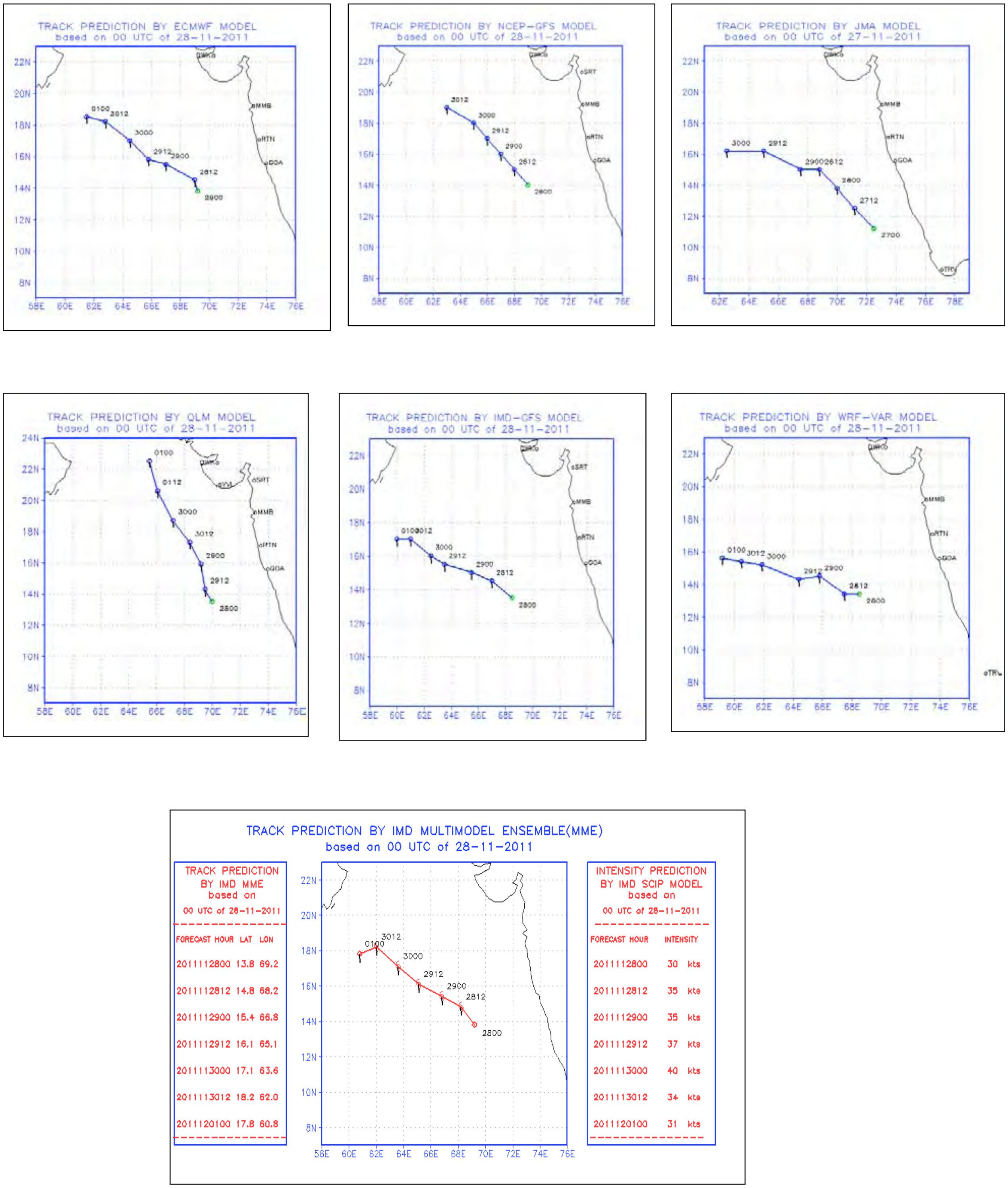


Fig.3.4.2(c) TRACK FORECAST BASED ON 00 UTC OF 28-11-2011

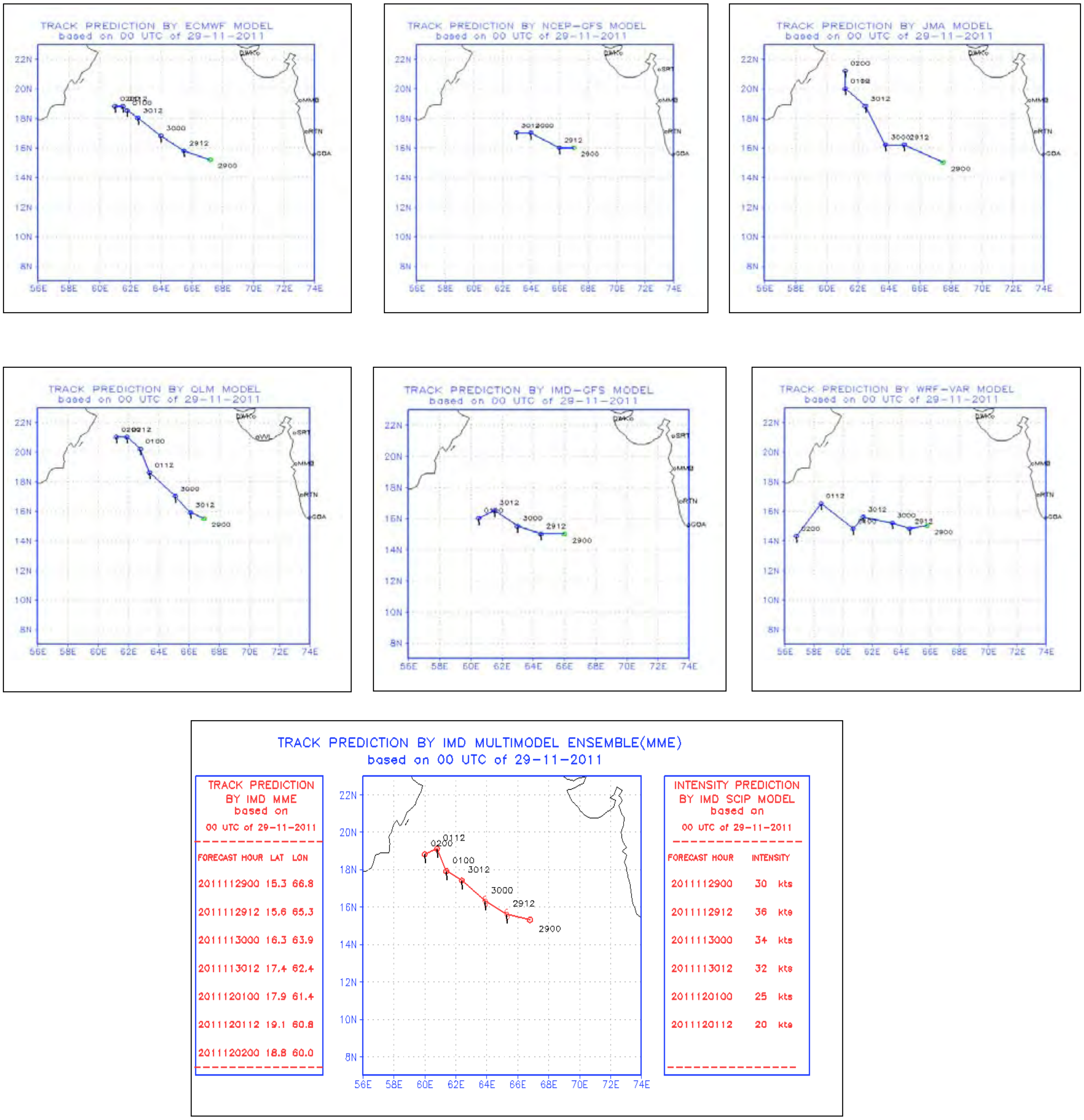


Fig.3.4.2(d) TRACK FORECAST BASED ON 00 UTC OF 29-11-2011

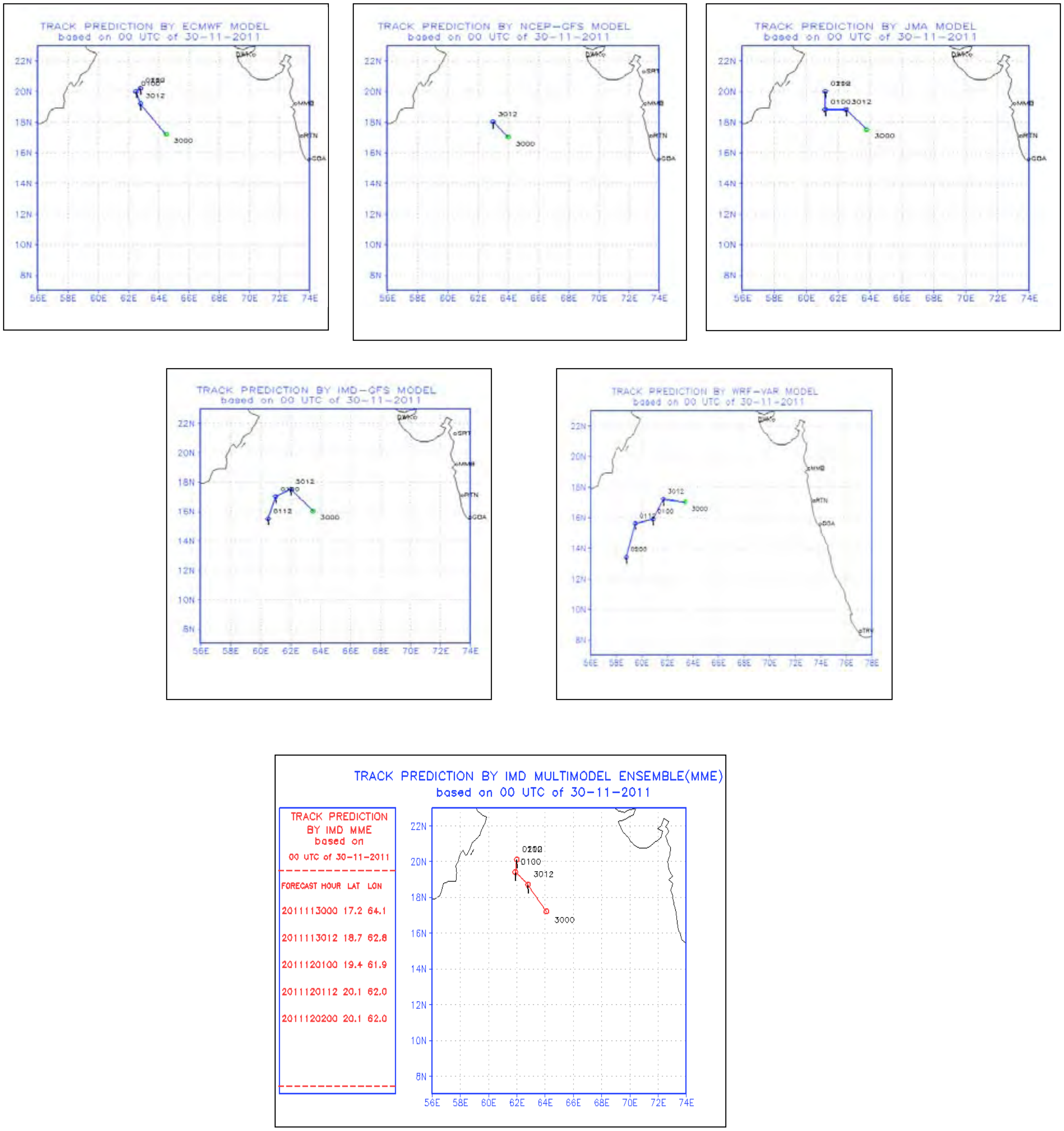


Fig.3.4.2(e) TRACK FORECAST BASED ON 00 UTC OF 30-11-2011

Average track forecast error for 24hr, 48hr, 72hr was less (<200km) for ECMWF model, GFS (NCEP) and MME (IMD). The average track forecast errors of member models based on different initial conditions are summarized in table 3.4.1.

Table 3.4.1: Average track forecast errors (km) of deep depression over Arabian Sea (26 Nov-01 Dec 2011)

	Lead time →					
Models	**12 hr**	**24 hr**	**36 hr**	**48 hr**	**60 hr**	**72 hr**
ECMWF	129	81	74	93	123	137
GFS (NCEP)	57	69	75	80	118	173
JMA	97	113	147	187	204	307
QLM (IMD)	106	195	271	345	482	536
MME (IMD)	83	77	84	108	118	157
GFS (IMD)	133	210	216	254	228	269
WRF(IMD)	144	221	266	296	259	319

3.4.3 INTENSITY (by SCIP)

The 12 hourly intensity forecasts valid upto 72 hrs show that mean model forecast errors for this system varied between 6 knots to 10 knots as shown in table 3.4.2.

Table 3.4.2: Mean intensity forecast error (knots) for deep depression (26 Nov-01 Dec 2011)

Forecasts hours →			12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
DEEP DEPRESSION	00/26.11.11	Error	-1	-2	+2	+4	+6	+8
	00/27.11.11	Error	+7	+3	0	+1	+14	+17
	00/28.11.11	Error	+5	+5	+12	+15	+9	+6
	00/29.11.11	Error	+11	+9	+7	0	-	-
Average Absolute Error(AAE)			**6**	**5**	**5**	**5**	**10**	**10**

3.5. VSCS “THANE” OVER BAY OF BENGAL (26 -30 Dec 2011)

3.5.1 GENESIS POTENTIAL PARAMETER (GPP)

The forecast of Genesis Potential Parameter (GPP) values valid for 00UTC of 27th Nov. on the basis of real time model analysis fields indicated that the system had enough potential (>30, the threshold value) to intensify into a cyclonic storm. The GPP forecast valid for 00UTC of 27th Nov. based on initial conditions of 24th - 27th Nov. are shown in fig.3.5.1.

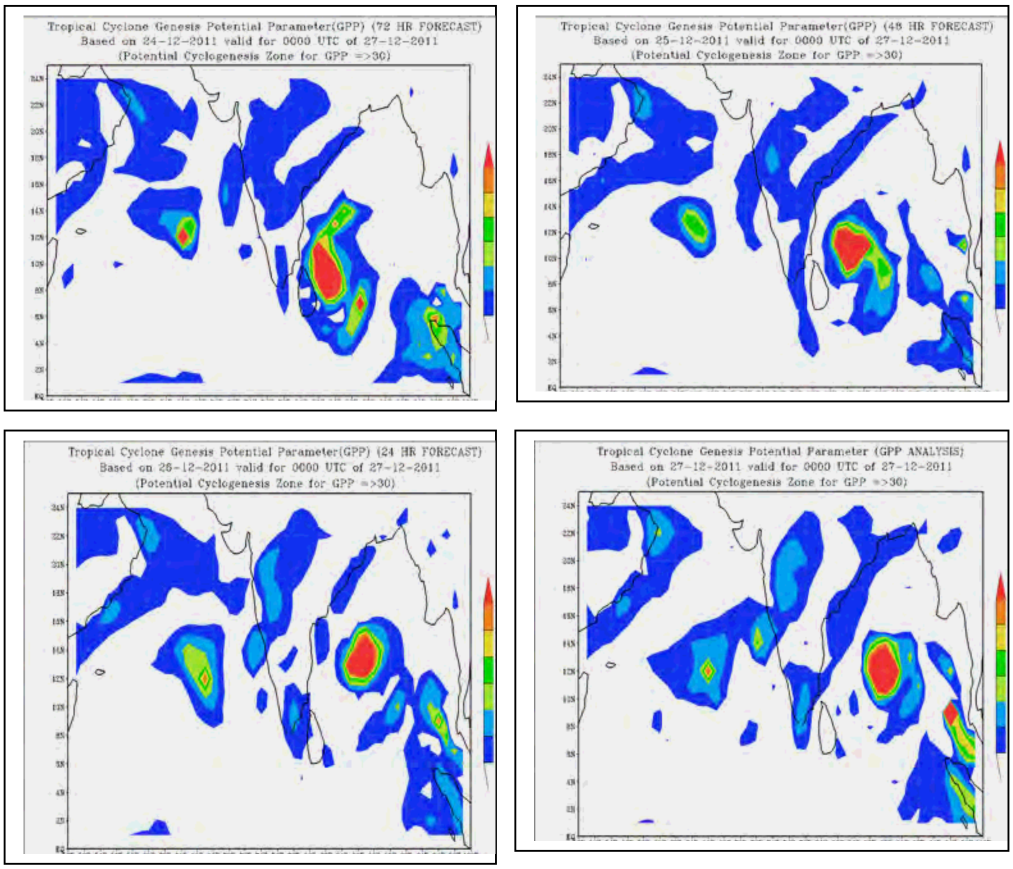


Fig.3.5.1 GPP forecast valid for 00 UTC 27th Nov. based on 24th -27th Nov.2011 observations

3.5.2 TRACK

Fig.3.5.2 (a-d) display the forecast track of VSCS THANE over Bay of Bengal by various NWP models with the initial conditions of 00UTC of 26th -30th Nov.,2011 respectively. ECMWF forecast was not available for this system. The average track forecast errors of member models based on different initial conditions are summarized in table 3.5.1. Based on initial condition of 0000UTC of 26th December, the forecast performance of NCEP-GFS and MME was better, as it could predict initial northward/north-northwestward movement and then westward movement. The landfall of the system around 0000UTC of 30th December near Cuddalore (Tamil nadu) could not be predicted by any model based on 0000UTC of 27th December, though the direction of movement could be predicted more reasonably by a few models. The forecast performance improved on 28th, most of the model showing landfall on 30th, however with about 12 hrs time lag by IMD-GFS and NCEP GFS models.

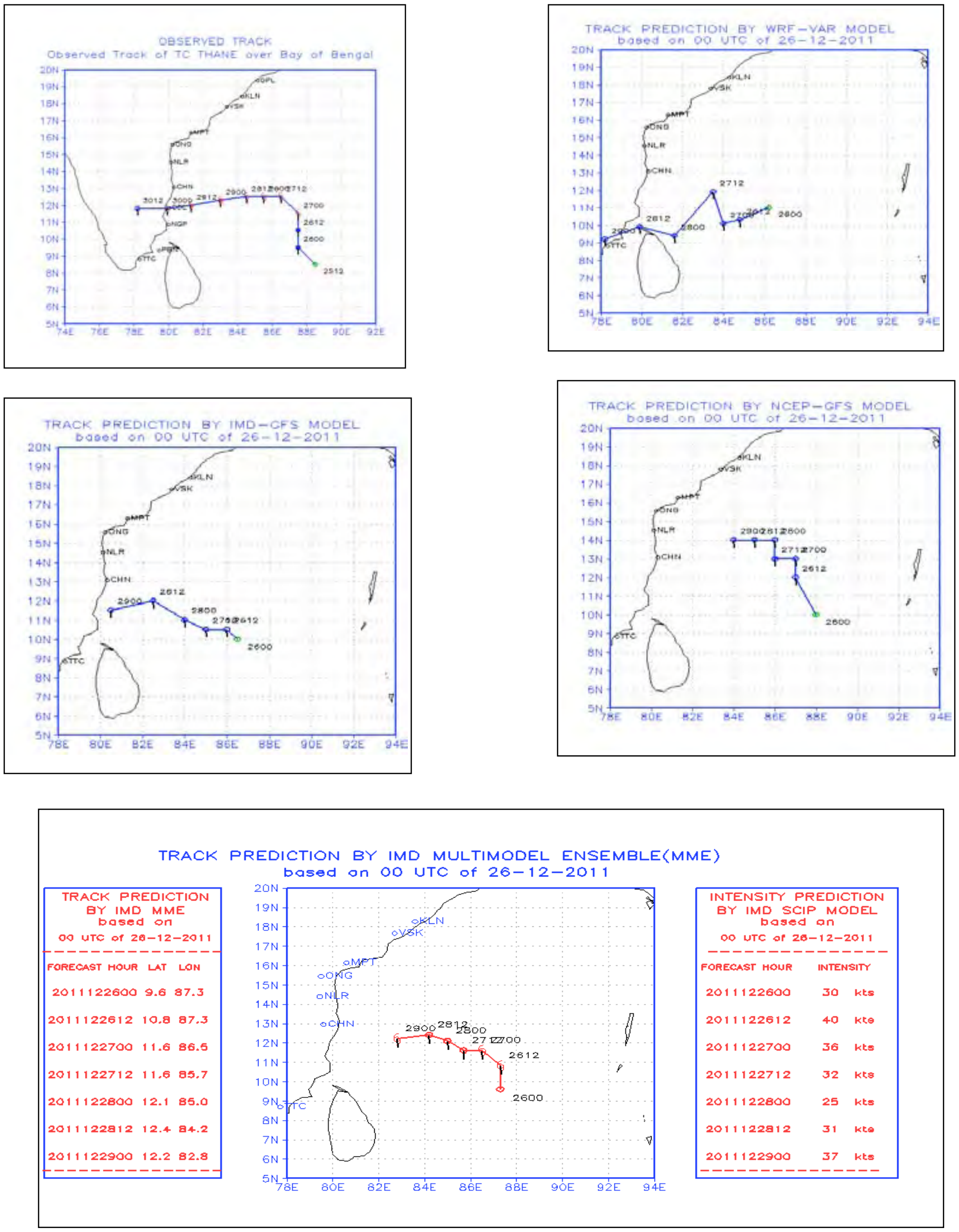


Fig.3.5.2(a) TRACK FORECAST BASED ON 00 UTC OF 26-12-2011

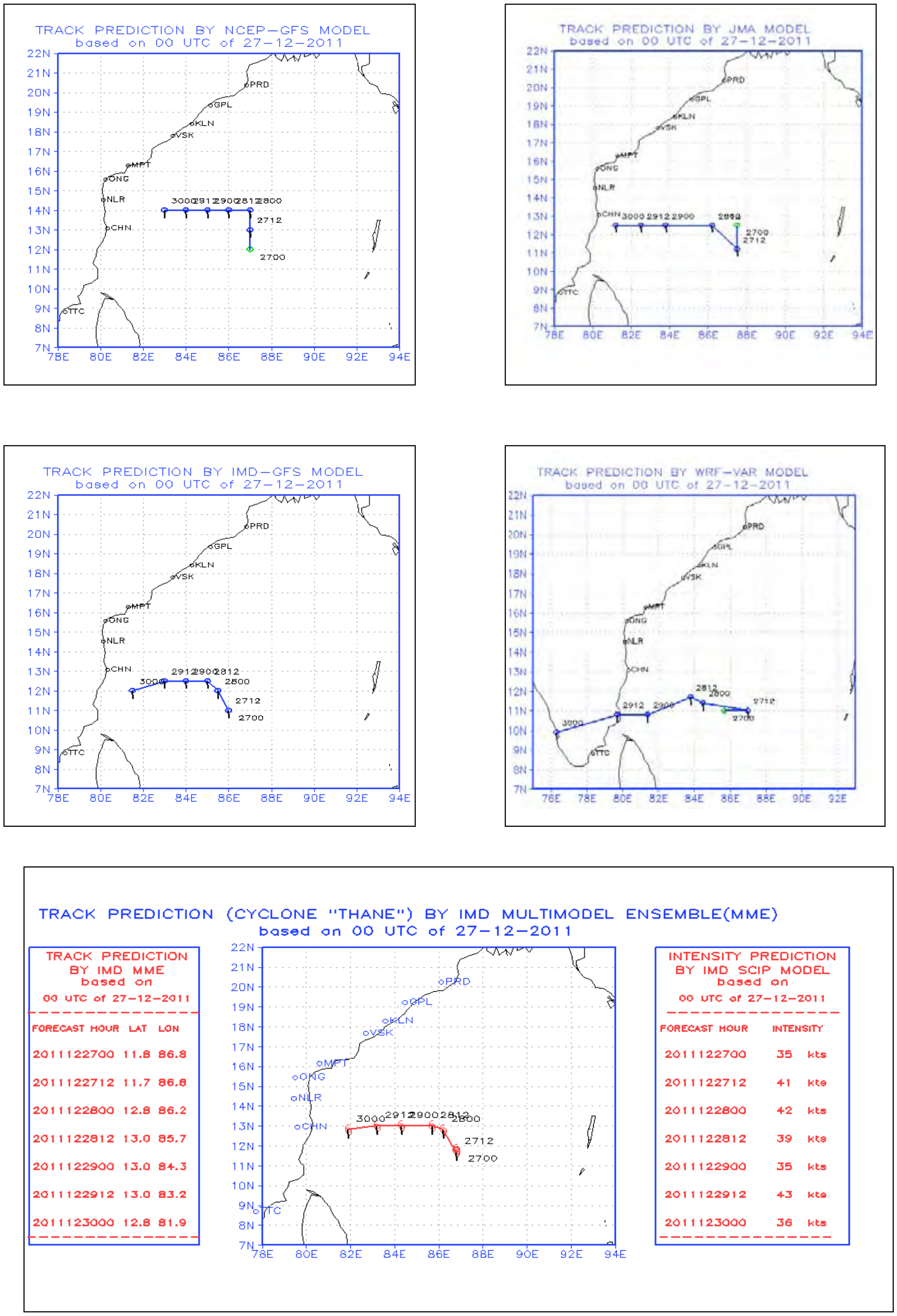


Fig.3.5.2(b) TRACK FORECAST BASED ON 0000 UTC OF 27-12-2011

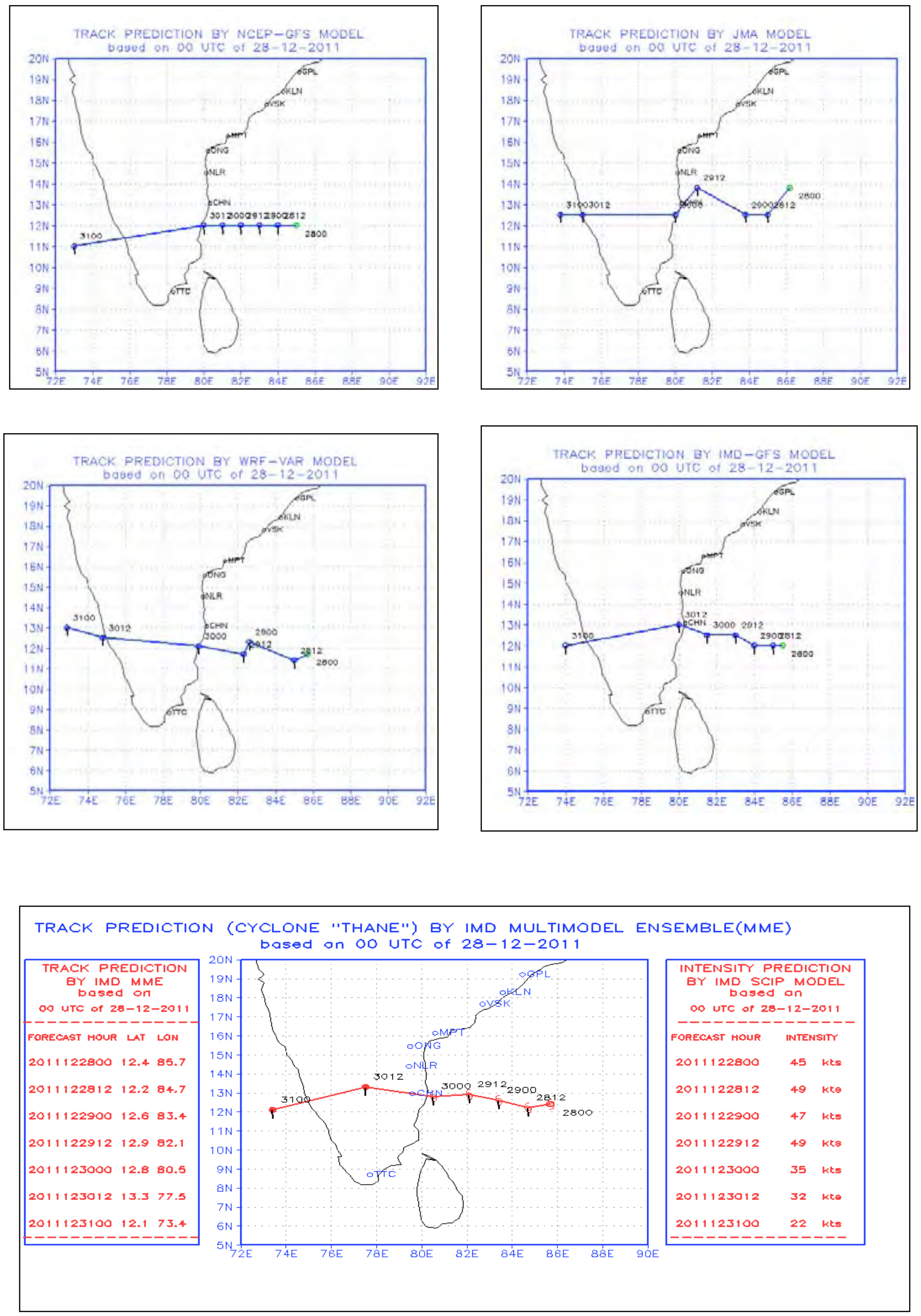


Fig.3.5.2(c) TRACK FORECAST BASED ON 0000 UTC OF 28-12-2011

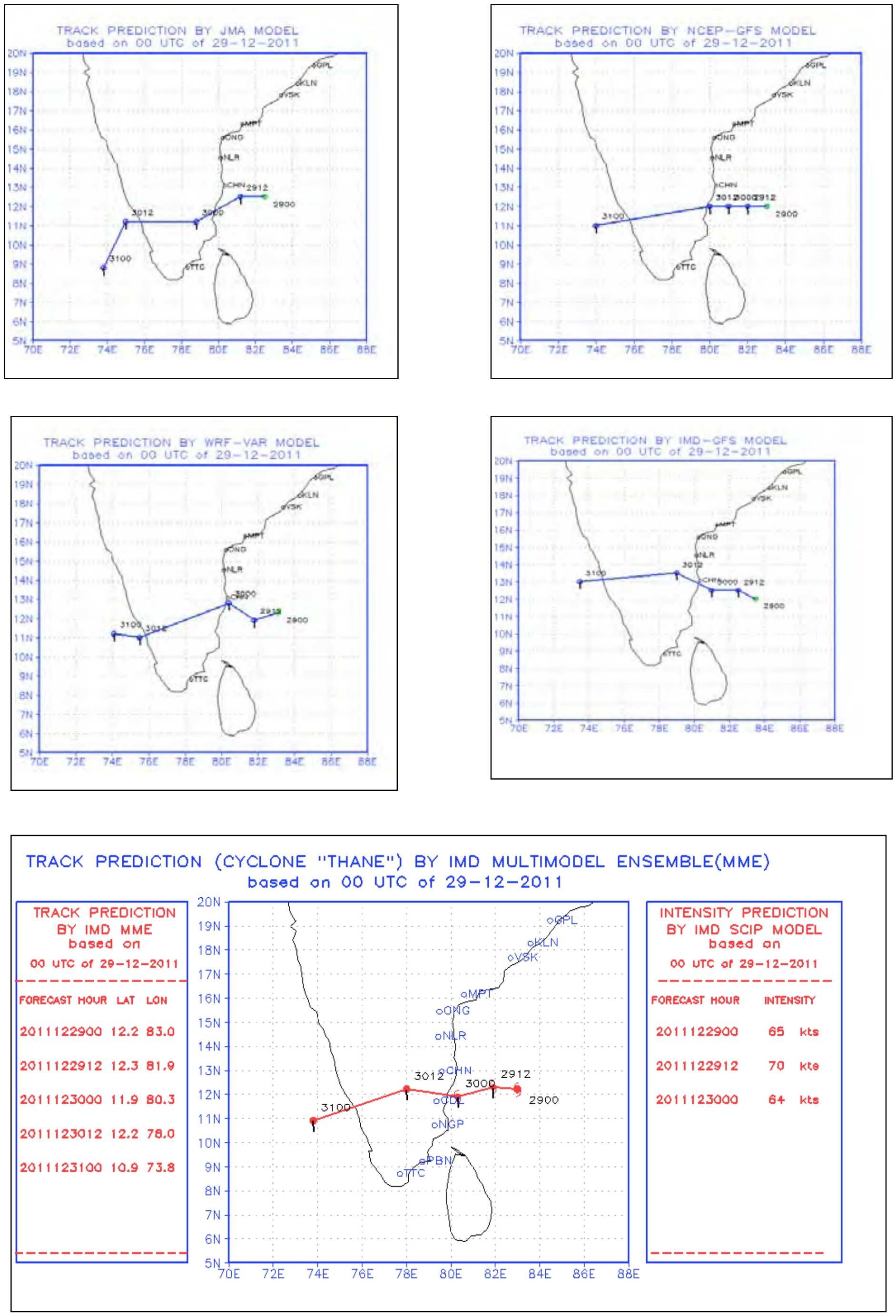


Fig.3.5.2(d) TRACK FORECAST BASED ON 0000 UTC OF 29-12-2011

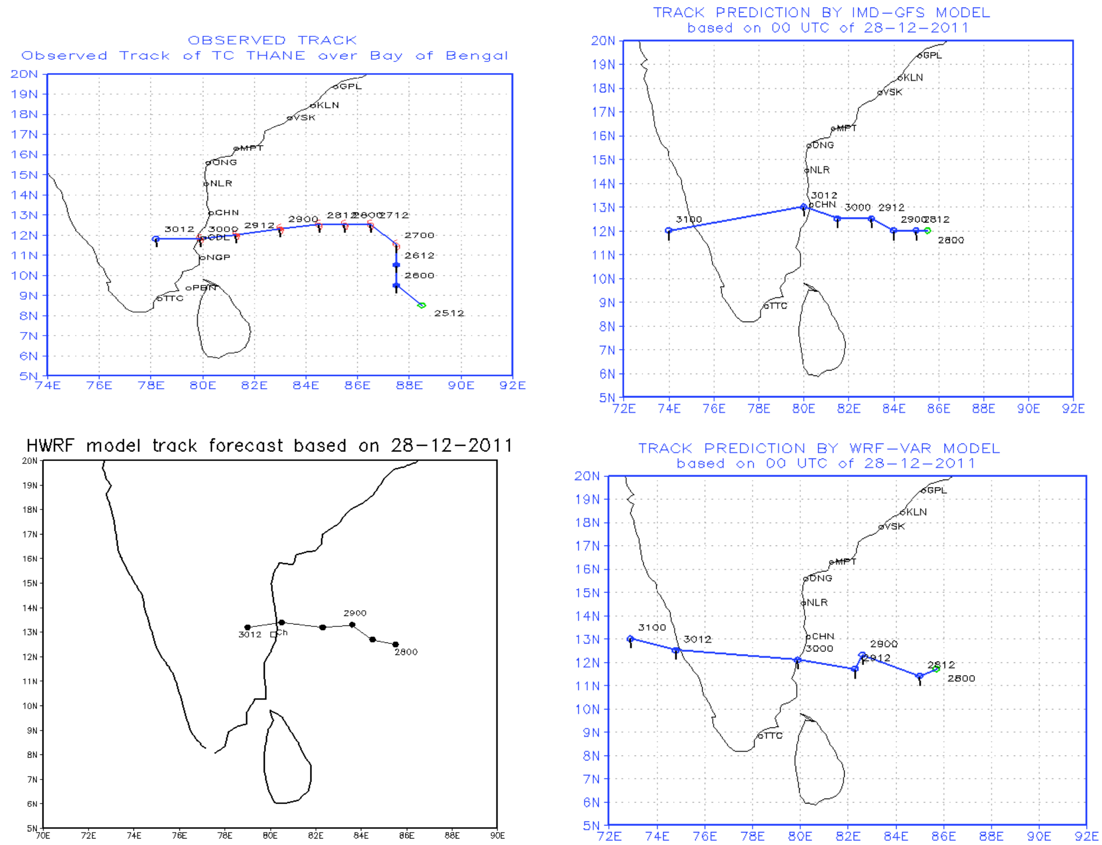


Fig.3.5.2(e): Observed, IMD-GFS, HWRF and WRF model track forecast for TC 'THANE' based on 00 UTC of 28 December 2012.

The performance of the MME and ensemble prediction by ECMWF was better compared to individual models. The ECMWF track and strike probability plot based on 26 Dec 2011/00 UTC for 120 hours forecast; Ensemble mean (ECMWF, NCEP, UKMO) TC track forecasts and Strike Probability Map of cities based on 28 Dec. 2011/00 UTC, 'THANE' 26-30 December 2011 are shown in Fig.3.5.2(f). Track prediction by T-574 model based on 00UTC of 27th Dec. & 28thDec.2011is shown in fig.3.5.2(g). The landfall based on initial conditions of 27th Dec. is close to observed landfall point but there was time lag of about 12hrs.

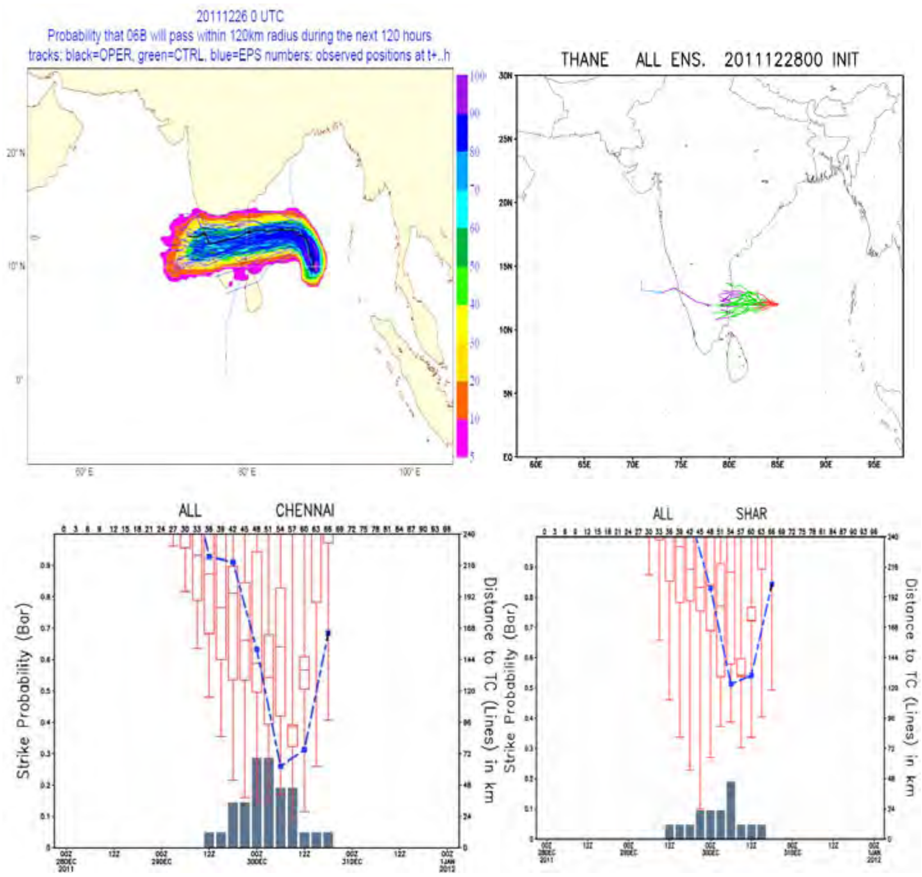


Fig.3.5.2(f). ECMWF track and strike probability plot based on 26 Dec 2011/00 UTC for 120 hours forecast; Ensemble mean (ECMWF, NCEP, UKMO) TC track forecasts and Strike Probability Map of cities based on 28 Dec. 2011/00 UTC, 'THANE' 26-30 December 2011.

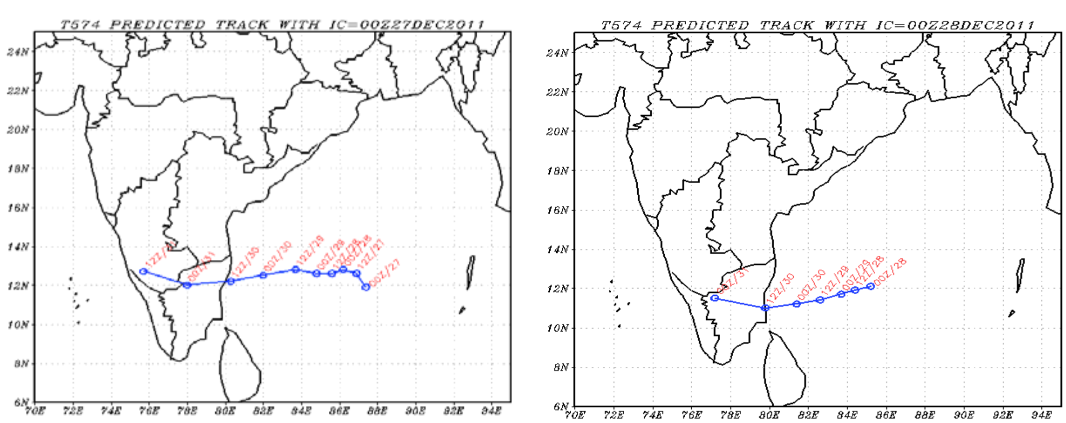


Fig.3.5.2(g) Track prediction by T-574 model based on 00UTC of 27th Dec.&28th Dec.2011

Track and Intensity forecast by IITD model based on initial conditions of 25th - 28th Dec.,2011 is shown in fig.3.5.2.(h) and fig.3.5.2.(i).

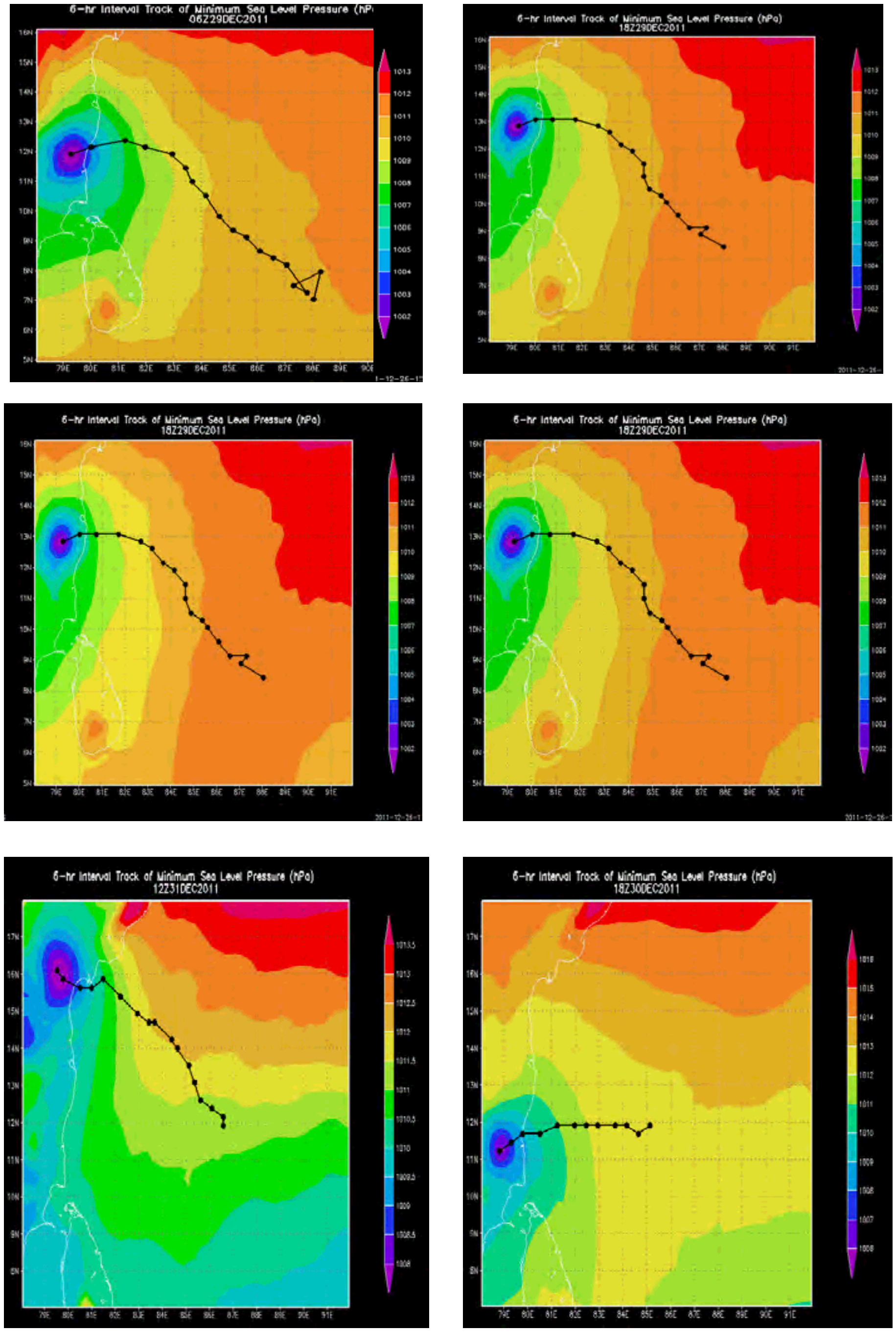


Fig.3.5.2.(h) : Track Forecast based on initial conditions of 27th and 28th Dec.,2011

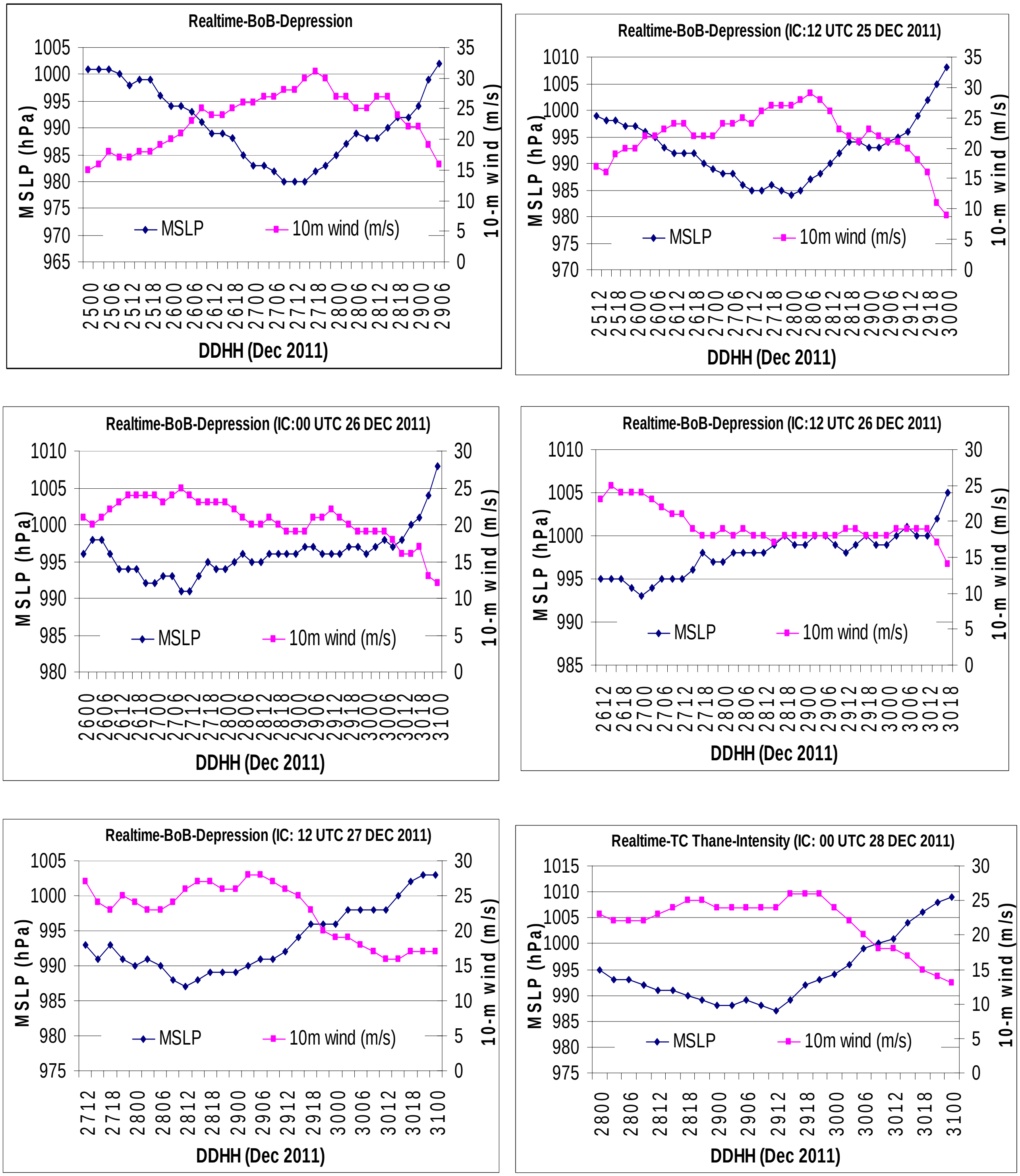


Fig.3.5.2.(i) : Intensity Forecast based on initial conditions of 27th and 28th Dec.,2011

Table 3.5.1. AVERAGE TRACK FORECAST ERRORS OF VSCS THANE (DIRECT POSITION ERROR IN KM)

	Lead time →					
Models	**12 hr**	**24 hr**	**36 hr**	**48 hr**	**60 hr**	**72 hr**
ECMWF	-	-	-	-	-	-
GFS (NCEP)	102	141	146	195	246	316
JMA	111	84	222	107	217	156
QLM (IMD)	109	244	354	557	778	1216
MME (IMD)	62	73	114	120	151	134
GFS (IMD)	140	152	183	178	218	231
WRF(IMD)	165	186	218	274	392	536

3.5.3 INTENSITY (by SCIP)

The 12 hourly intensity forecasts valid upto 72 hrs show that mean model forecast errors for this system varied between 8 knots to 36 knots as shown in table 3.5.2.

Table 3.5.2. Mean intensity forecast error (knots) in case of THANE

Forecasts hours →			12 hr	24 hr	36 hr	48 hr	60 hr	72hr
THANE	00/26.12.11	Error	+10	-4	-8	-20	-34	-33
	00/27.12.11	Error	+1	+-3	-26	-35	-32	-39
	00/28.12.11	Error	-16	-23	-26	-40	+7	-
	00/29.12.11	Error	-5	-11	-	-	-	-
Average Absolute Error(AAE)			**8**	**10**	**20**	**32**	**24**	**36**

3.6. Annual average track and intensity forecast errors of NWP models

Average Track and Intensity forecast errors for the year 2011 has been summarized in table 3.5.3 and table 3.5.4 respectively.

Table 3.5.3 AVERAGE TRACK FORECAST ERRORS (IN KM) FOR THE YEAR 2011

	Lead time →					
Models	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
ECMWF	103	77	75	86	116	118
GFS (NCEP)	86	112	95	143	213	181
JMA	117	118	235	155	211	231
QLM (IMD)	85	156	219	383	542	748
MME (IMD)	68	75	100	119	129	157
GFS (IMD)	126	165	197	217	261	306
WRF(IMD)	152	195	238	277	283	354

Table 3.5.4: AVERAGE INTENSITY FORECAST ERRORS (by SCIP) FOR THE YEAR 2011

Forecasts hours →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
Average Absolute Error(AAE) (knots) →	6	6	11	14	17	26

It is observed that the performance of ECMWF model for track forecast was better than all other individual models. However, the performance of MME was better that that of all individual models in 12 and 24 hr forecast range. The average intensity error varied from 6 to 26 knots for 12 to 72 hour forecast periods.

CHAPTER-IV

PERFORMANCE OF RSMC, NEW DELHI IN TRACK AND INTENSITY PREDICTION OF CYCLONES DURING 2011

4.1. Introduction

The Cyclone Warning Division/ Regional Specialised Meteorological Centre (RSMC)-Tropical Cyclone, IMD, New Delhi mobilised all its resources for monitoring and prediction of cyclonic disturbances over the north Indian Ocean during 2011. It issued 3 hourly warning/advisory bulletins to national disaster management agencies. It issued forecast and warning bulletins to various national and international disaster management agencies including National Disaster Management (NDM), Ministry of Home Affairs (MHA), concerned state Govts. and other users in regular intervals. It also issued advisories to World Meteorological Organisation (WMO)/Economic and Social Cooperation for Asia and the Pacific (ESCAP) Panel member countries including Bangladesh, Myanmar, Thailand, Pakistan, Oman, Srilanka and Maldives during cyclone period. As tropical cyclone advisory centre (TCAC), it also issued tropical cyclone advisories with effect from the stage of cyclone for international civil aviation purpose as per the requirement of international civil aviation organization (ICAO).

IMD continuously monitored, predicted and issued bulletins containing track & intensity forecast at +06, +12, +18, +24, +36, +48, +60 and +72 hrs or till the system weakened into a low pressure area. The above structured track and intensity forecasts were issued from the stage of deep depression onwards. The cone of uncertainty in the track forecast was also given for all cyclones. The radius of maximum wind and radius of ≥34 knots, ≥50 knots and ≥64 knots wind in four quadrants of cyclone was also issued for every six hours. The graphical display of the observed and forecast track with cone of uncertainty and the wind forecast for different quadrants were uploaded in the IMD's website regularly. The storm surge guidance was provided as and when required to the member countries of WMO/ESCAP Panel as per the recommendation of last meeting of Panel on Tropical Cyclone (PTC) held during March, 2009 at Muscat, Oman based on IITD model. The prognostics and diagnostics of the systems were described in the special tropical weather outlook and tropical cyclone advisory bulletins since 2008. The TCAC bulletin was also sent to Asian Disaster Risk reduction (ADRR) centre of WMO at Hongkong like previous year.

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 2011 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 2011

Bulletins issued during 'KEILA'
Bulletins for national disaster management agencies : 10
Bulletin for WMO/ESCAP Panel counties
(Special Tropical Weather Outlook and Tropical Cyclone Advisory) : 14
Tropical cyclone advisory for international civil aviation: 06

Bulletins issued during 'THANE'
Bulletins for national disaster management agencies : 37
Bulletin for WMO/ESCAP Panel counties
(Special Tropical Weather Outlook and Tropical Cyclone Advisory) : 28
Tropical cyclone advisory for international civil aviation : 15

Bulletins issued for all cyclones during 2011
Bulletins for Indian coast 47
RSMC bulletin for WMO/ESCAP Panel member countries
(Special Tropical Weather Outlook and Tropical Cyclone Advisory) 42
TCAC bulletin for international civil aviation 21

Bulletins issued for all cyclonic disturbances (depression and above) during 2011
Bulletins for Indian coast 141
RSMC bulletin for WMO/ESCAP Panel member countries :
(Special Tropical Weather Outlook and Tropical Cyclone Advisory) 84
TCAC bulletin for international civil aviation 21

4.3. Performance of Operational Track and landfall forecast

The performance of operational genesis, track and intensity forecasts issued by IMD, New Delhi for two cyclones and four deep depressions during 2011 are described below.

4.3.1. Deep depression over the Bay of Bengal (16-23 June, 2011)

The landfall point and time error are given in Table 4.1. While landfall point could be predicted more accurately (52 km), there was a significant error in landfall time (4.5 hrs).

Table 4.1. Landfall point and time error of deep depression (16-23 June 2011)

Lead time hours (Landfall point error in km.)				**Landfall time error (in hrs.)**		
Hours	F/C	Actual	Error (km)	F/C(UTC)	Actual(UTC)	Error
12	21.7^0N/88.5^0E	21.7^0N/89.0^0E	52	16/1500	16/1130	-4.5

4.3.2. Deep Depression 19-20 October over Bay of Bengal

4.3.2.1. Intensity:

The average intensity forecast errors for various lead time periods are shown in Table 4.2. The RMS error of wind speed was about 03 and 16 knots for 12 and 24 hr forecast period.

Table 4.2. Average Intensity forecast error

Lead Period of forecast	Intensity Error (knots)			No. of observations verified
	Average	Absolute Average	RMS	
12	2.2	2.2	2.7	3
24	16.2	16.2	16.2	1

4.3.2.2 Track and landfall:

The average track and landfall forecast errors for various lead time periods as shown in Table 4.3 and 4.4 respectively. Average track forecast errors were 43 km and 55 km in the forecast issued 12 hrs and 24 hrs in advance respectively.

Table 4.3 Average track forecast errors (Direct position error in Km)

Lead time (hours)	Direct position error (km)	Number of forecasts verified
12	43	3
24	55	1

Table 4.4 Verification of landfall forecast

Lead time hours (Landfall point error in km.)				Landfall time error (in hrs.)		
Hours	F/C	Actual	Error (km)	F/C(UTC)	Actual(UTC)	Error
12	21.4^0N /92.0^0E	21.2^0N /92.1^0E	25	191830	191300 UTC	-5.5

The 12 hr landfall forecast error was about 25 km with a time error of 5.5. hrs.

4.3.3 Cyclone KEILA 29 October to 4 November 2011

4.3.3.1 Intensity:

The average intensity forecast errors for various lead time periods as shown in Table 4.5.The RMS error of wind speed was about 05 knots for different forecast period.

Table 4.5 Average Intensity forecast error

Lead Period of forecast	Intensity Error (knots)			No. of observations verified
	Average	Absolute Average	RMS	
12	2.7	2.7	3.8	4
24	4.1	4.1	4.7	4
36	6.1	6.1	6.2	3
48	0	3.6	3.98	3
60	5.4	5.4	5.4	1

4.3.3.2 Track and landfall:

The average track, landfall forecast errors for various lead time periods as shown in Table 4.6 and 4.7 respectively. Average 24 hr track forecast error was 177 km, landfall point error was 108 km with time error of about 2 hrs. in the forecast issued 24 hrs in advance of the landfall. Landfall point/time error for the forecast was higher for 12 hrs lead period as the cyclone had slow movement before the landfall.

Table 4.6 Average track forecast errors (Direct position error in Km)

Lead time (hours)	Direct position error (Km)	Number of forecasts verified
12	89	4
24	177	4
36	260	3
48	397	3
60	336	1

Table 4.7 Verification of landfall forecast

Lead time hours (Landfall point error in km.)				Landfall time error (in hrs.)		
Hours	F/C	Actual	Error (km)	F/C(UTC)	Actual(UTC)	Error
12	16.0^0N/52.2^0E	17.1^0N/54.3^0E	254	03/1230	02/1630 UTC	-4
24	16.5^0N/53.5^0E	17.1^0N/54.3^0E	108	02/1430	02/1630 UTC	-2
36	16.5^0N/53.5^0E	17.1^0N/54.3^0E	108	02/0030	02/1630 UTC	-16
48	16.5^0N/53.5^0E	17.1^0N/54.3^0E	108	02/0000	02/1630 UTC	-16.5

4.3.4 Deep Depression 6-10 November 2011

4.3.4.1 Intensity:

The average intensity forecast errors for various lead time periods are shown in Table 4.8. The RMS error of wind speed was about 05 knots for different forecast period.

Table 4.8 Average Intensity forecast error

Lead Period of forecast	**Intensity Error (knots)**			**No. of observations verified**
	Average	**Absolute Average**	**RMS**	
12	36	3.6	3.8	3
24	4.5	4.5	5.6	3
36	5.4	5.4	6.0	2
48	0	0	0	1

4.3.4.2 Track and landfall:

The average track forecast errors for various lead time periods are shown in Table 4.9. Due to the recurving nature of the track, the track forecast error in case of this system for 48 hr forecast period was relatively higher, being about 350 km.

Table 4.9 Average track forecast errors (Direct position error in Km)

Lead time (hours)	Direct position error (Km)	Number of forecasts verified
12	69	3
24	111	3
36	238	2
48	349	1

4.3.5 Deep Depression 26 November to 1 December 2011

4.3.5.1 Intensity:

The average intensity forecast errors for various lead time periods as shown in Table 4.10. The RMS error of wind speed was about 03-06 knots for different forecast period.

Table 4.10 Average Intensity forecast error

Lead Period of forecast	**Intensity Error (knots)**			**No. of observations verified**
	Average	**Absolute Average**	**RMS**	
12	3.1	3.1	3.3	6
24	4.5	4.5	5.4	6
36	3.1	1.9	5.3	6
48	4.7	4.7	4.9	4
60	2.7	2.7	2.7	4
72	4.1	4.1	5.7	2

4.3.5.2 Track:

The average track forecast errors for various lead time periods as shown in Table 4.11. The track forecast errors were significantly less than long period average in this system, as 24, 48 and 72 hr forecast errors were 121, 174 and 245 km against the long period average of 150, 250 and 350 km respectively.

Table 4.11 Average track forecast errors (Direct position error in Km)

Lead time (hours)	Direct position error (Km)	Number of forecasts verified
12	39	6
24	121	6
36	160	6
48	174	6
60	209	4
72	245	2

4.3.6. Very Severe Cyclonic Storm “THANE” over the Bay of Bengal (25-31 December, 2011)

4.3.6.1. Genesis forecast

The genesis of depression over the southeast Bay of Bengal was predicted 36 hrs in advance, i.e. on 24th December 2011 morning.

4.3.6.2. Track, intensity & landfall forecast

The verification of intensity and track forecast issued by IMD is discussed in Table 4.12, 4.13 & 4.14. The average track forecast errors (km) for 24, 48 and 72 hrs lead time are 77, 160 & 181 km against the long period average of 150, 250 and 350 km. The average intensity forecast errors (knots) for the same lead time period are 10, 16 & 21 knots respectively.

The average intensity forecast errors for various lead time periods as shown in Table 4.12. The RMS error of wind speed was about 11-22 knots for different forecast period. It increased with increased in forecast length.

Table 4.12 Average Intensity forecast error

Lead Period of forecast	**Intensity Error (knots)**			**No. of observations verified**
	Average	**Absolute Average**	**RMS**	
12	-10.2	17.4	18.0	17
24	-1.1	10.5	11.0	15
36	-2.5	12.9	13.9	13
48	-6.1	16.0	16.4	11
60	-10.2	17.4	18.0	9
72	-8.9	21.2	22.4	7

4.3.6.3. Track and landfall:

The track forecast errors were significantly less than long period average in this system, as 24, 48 and 72 hr forecast errors were 77, 160 and 181 km (Table 4.15) against the long period average of 150, 250 and 350 km respectively.

Table 4.13 Average track forecast errors (Direct position error in Km)

Lead Time(hrs)	Average Track forecast error (km)	No. of forecast verified
12	43	17
24	77	15
36	129	13
48	160	11
60	175	9
72	181	7

Table 4.14 Landfall forecast error

Lead time hours (Landfall point error in km.)				Landfall time error (in hrs.)		
Hours	F/C	Actual	Error (km)	F/C(UTC)	Actual(UTC)	Error
12	12.0^0N/79.9^0E	11.8^0N/79.9^0E	20	30/0500	30/0700	-2
24	12.0^0N/79.9^0E	11.8^0N/79.9^0E	20	30/0600	30/0700	-1
36	12.5^0N/80.1^0E	11.8^0N/79.9^0E	80	30/0600	30/0700	-1
48	13.2^0N/80.2^0E	11.8^0N/79.9^0E	160	30/0600	30/0700	-1
60	13.1^0N/80.2^0E	11.8^0N/79.9^0E	150	30/0600	30/0700	-1
72	13.0^0N/80.2^0E	11.8^0N/79.9^0E	140	30/0600	30/0700	-1

The landfall forecast errors were also significantly less than long period average in this system, as 24, 48 and 72 hr forecast errors were 20, 160 and 140 km respectively with time error of about 1 hour each.

4.3.6.4. Heavy rainfall warning and Gale wind warning

The occurrence of heavy to very heavy rainfall over Andaman & Nicobar Islands, Tamil Nadu and Puducherry, south coastal Andhra Pradesh and Kerala could be very well predicted. However, the extremely heavy rainfall as predicted over north Tamil Nadu did not occur during this period.

The storm surge forecast was mainly based on IIT, Delhi storm surge model and the nomograms prepared by IMD. The IIT, Delhi model predicted about 1 meter storm surge above the astronomical tide at the time of landfall. IIT Delhi provided the storm surge model forecast regularly. One such forecast is shown in Fig.4.1.

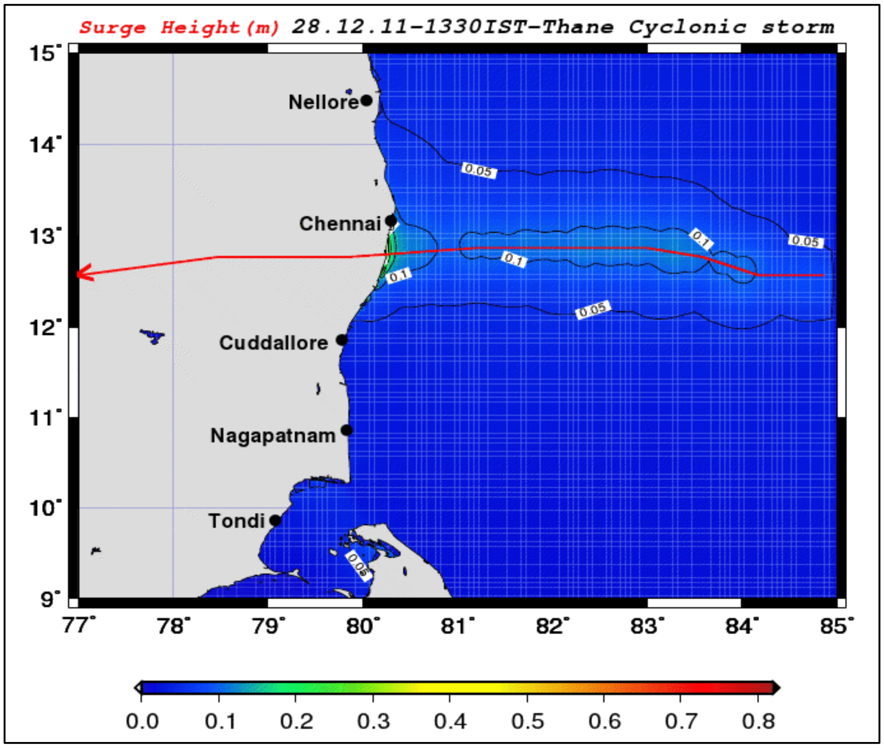


Fig.4.1 IITD Storm Surge based on 0600 UTC of 28th Dec.,2011

4.4. Annual Performance Track and intensity forecast

The performance of operational genesis, track and intensity forecasts issued by IMD, New Delhi for six disturbances (four Deep depressions and two cylones) during 2011 are described below.

4.4.1. Annual track forecast error

The average track forecast, skill and landfall forecast error of cyclonic storms during 2011 based on the forecast issued by RSMC, New Delhi are given in Table 4.15, 4.16 & 4.17. The landfall point and time forecast errors as well as track forecast errors have improved during 2011. For comparison, the 12 and 24 hr track forecast errors during 2003 and 2011 are shown in Fig.4.2. The figures clearly indicate the gradual improvement in the cyclone forecast by IMD, as the error has decreased and the skill has increased. The average landfall error was less than the long period average error for the landfalling cyclones over the north Indian Ocean. It is also very much comparable to the forecast errors over other Ocean basins including north Atlantic and Pacific Ocean basins.

Table 4.15 Average track forecast error (Direct position error in km)

Lead Time(hrs)	Average Track forecast error (km)	No. of forecasts verified
12	49	33
24	103	29
36	162	24
48	208	21
60	175	14
72	195	9

The rate of decrease in track forecast error is about 07 km per year in 24 hr forecast and 6 km per year in 12 hr forecasts based on the data of 2003-2011. The rate of improvement in skill is about 03% per year in 12 hr forecasts and 8% per year in 12 hr forecasts based on the data of 2003-2011. The rate of improvement in forecast is comparable to that over other Ocean basins.

Table 4.16. Cyclone track forecast skill (%)-2011

Lead Time(hrs)	Average Track forecast skill (%)	No. of forecasts verified
12	43	33
24	45	29
36	46	24
48	46	21
60	64	14
72	73	9

4.4.2. Gain in Skill in Track Forecast

The skill score has been calculated by comparing the IMD's forecast track errors with the forecast difficulty level. For this purpose, the IMD's forecast error has been compared with the CLIPER (climatology + persistence) model error, which is the international practice. The gain in skill in relation to CLIPER, is quantified in percentage terms by;

$$\text{Gain in skill} = \frac{\text{CLIPER DPE} - \text{DPE}}{\text{CLIPER DPE}} \times 100\%$$

4.4.3. Landfall forecast errors

The landfall forecast errors for the systems during 2011 are shown in Table 4.17 The average landfall forecast errors are about 20 and 160 km for 24 and 48 hr forecasts respectively

Table 4.17. Landfall Point and Time Forecast error (km)

Lead Time(hrs)	Average landfall error (km)	Average time error
12	88	-4.0
24	64	-1.5
36	94	-8.5
48	134	-8.7
60	150	-1
72	140	-1

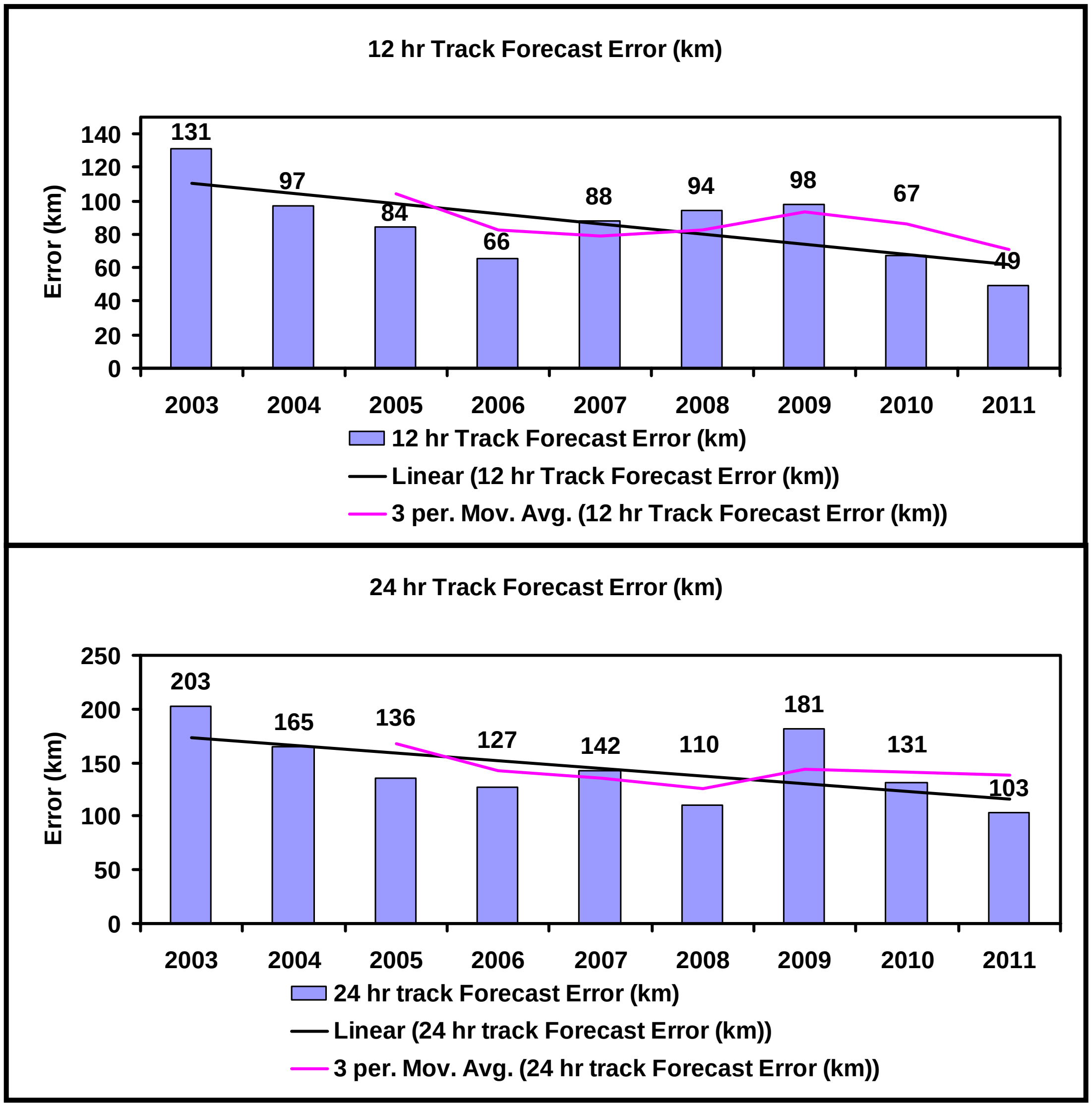


Fig. 4.2 12hr and 24 hr cyclone track forecast errors of IMD during 2003-2011.

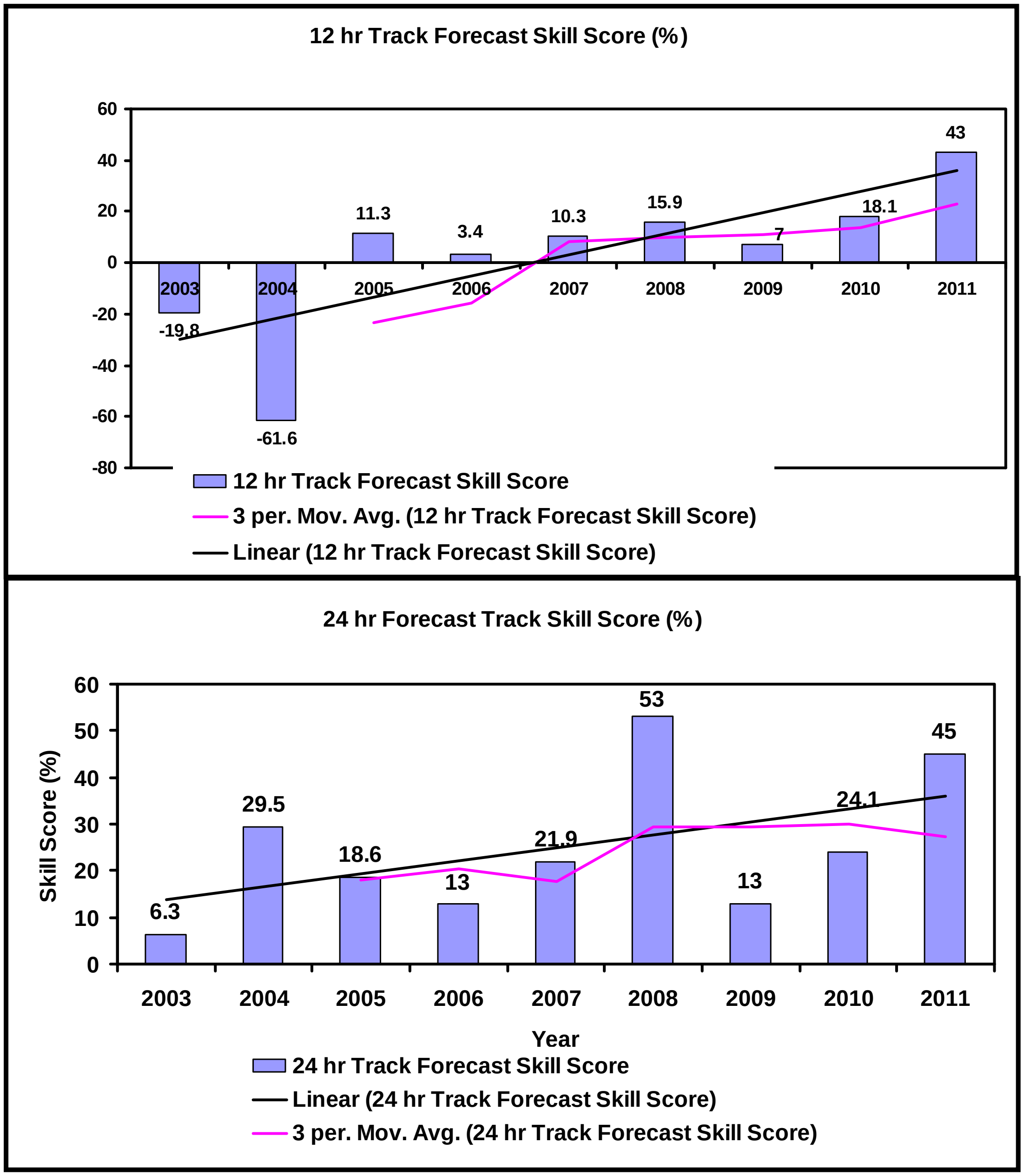


Fig.4.3. 12 hr and 24 hr cyclone track forecast skill scores of IMD during 2003-2011.

For comparison, the 12 and 24 hr track forecast skill scores during 2003 and 2011 are shown in Fig.4.3.

4.4.4. Intensity Forecast errors

The intensity forecast errors are shown in Table 4.18. The average absolute intensity forecast errors vary from 7-18 knots for 12 to 72 hrs forecasts.

Table 4.18 Average annual intensity error in 2011 expressed in wind speed

Lead Period of forecast	Intensity Error (knots)			No. of forecasts verified
	Average	Absolute Average	RMS	
12	1.1	4.9	6.1	33
24	2.0	7.9	9.2	29
36	0.9	9.3	10.7	25
48	-2.6	10.8	12.8	19
60	-5.4	12.3	14.6	14
72	-6.0	17.4	19.9	9