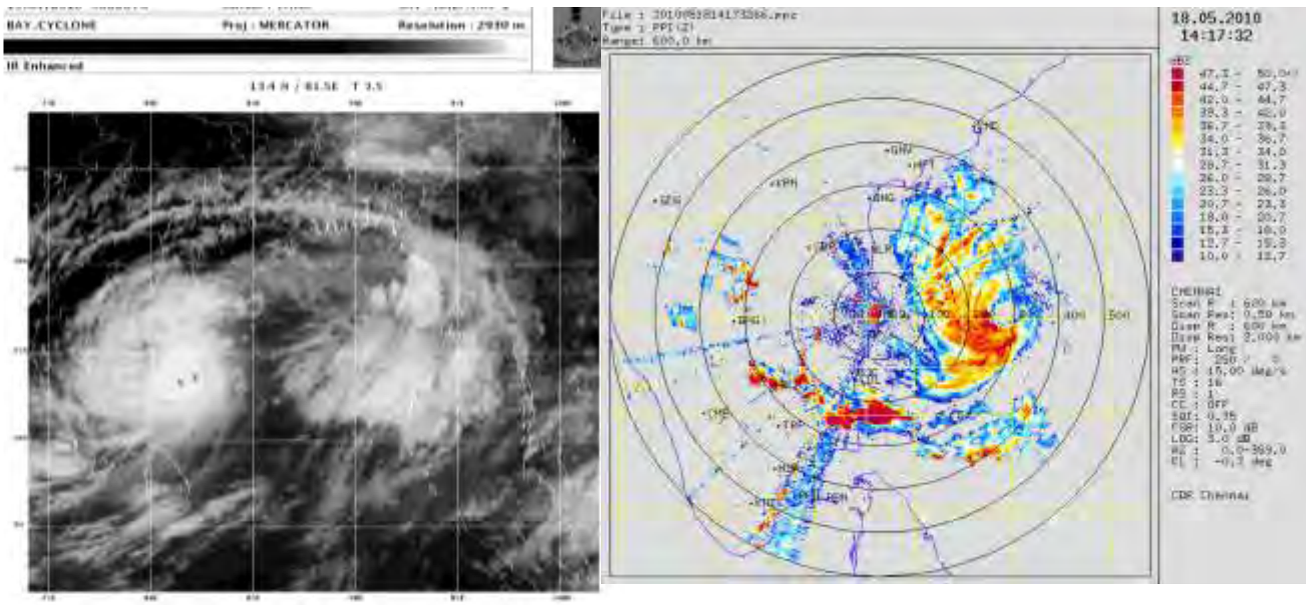
World Meteorological Organisation

India Meteorological Department

RSMC- Tropical Cyclone Report No. 1/2011

REPORT ON CYCLONIC DISTURBANCES OVER NORTH INDIAN OCEAN DURING 2010



Satellite and DWR imageries of severe cyclonic storm, LAILA

RSMC-TROPICAL CYCLONES, NEW DELHI

JANUARY 2011

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INDIA METEOROLOGICAL DEPARTMENT

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17	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 2010. 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.
18	Key words	Cyclogenesis, intensity, track, landfall, NWP model, forecast verification

CONTENTS

INTRODUCTION

Regional Specialized Meteorological Centre (RSMC) - Tropical Cyclones, New Delhi, which is co-located with Cyclone Warning Division has the responsibility of issuing Tropical Weather Outlook and Tropical Cyclone Advisories for the benefit of the countries in the World Meteorological Organization (WMO)/ Economic and Social Co-operation for Asia and the Pacific (ESCAP) Panel region bordering the Bay of Bengal and the Arabian Sea, namely, Bangladesh, Maldives, Myanmar, Pakistan, Sultanate of Oman, Sri Lanka 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, 26 names have been utilized till the end of year 2010.

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 3km and upper wind up to 9 km above Sea level. The performance of the instrument is being monitored.

1.3.3. Radar

1.3.3.1 Cyclone Detection Radars

There are 11 S-Band Radars for Cyclone Detection located at Kolkata, Chennai, Visakhapatnam, Machilipatnam, Sriharikota, Paradip, Karakikal, Kochi, Goa, Mumbai and Bhuj (Fig.1.2) 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 (DWR) 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. The radar at Mumbai is being replaced by DWR. The Radars at Goa, Paradip, Karaikal, Bhuj and Kochi have also become old/obsolete, these radars are under the process of replacement.

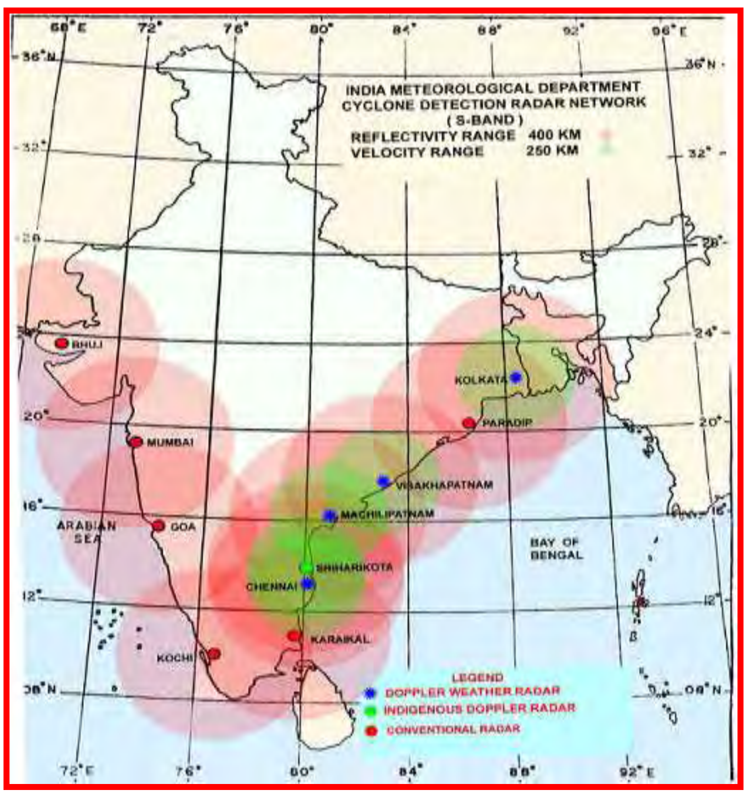


Fig. 1.2. S-Band Cyclone Detection Radar Network

DWRs Provide vital information on radial velocity and spectral width, in addition to reflectivity which is also available from conventional (analog type) of Radars. Reflectivity estimates obtained from these radars are more accurate in comparison to those from conventional radars as the DWRs have capability for correcting the values for clutters, partial beam filling, beam blockage and bright band. The DWRs generate various derived products in addition to primary PPI and RHI displays. Surface Rainfall Intensity (second level product derived from reflectivity) and other hydrological products like Precipitation Accumulation (PAC), Vertical Integrated Liquid (VIL) are very important for issuing warnings for heavy rain, fresh flood and hail. The algorithms for generation of these products employ some adaptable parameters which depend on drop size distribution (DSD) present in the precipitation. The 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 12^{th} 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 $1^0 \times 1^0$ grid intervals from all Kalpana-I data on half hourly /daily /weekly/monthly basis.
- Outgoing Longwave Radiation (OLR) are computed at $0.25^0 \times 0.25^0$ grid intervals from all Kalpana-I data on half hourly /daily /weekly/monthly basis.
- Quantitative Precipitation Estimation (QPE) is generated at $1^0 \times 1^0$ 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 emmissivity
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 CDR and DWR stations 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.

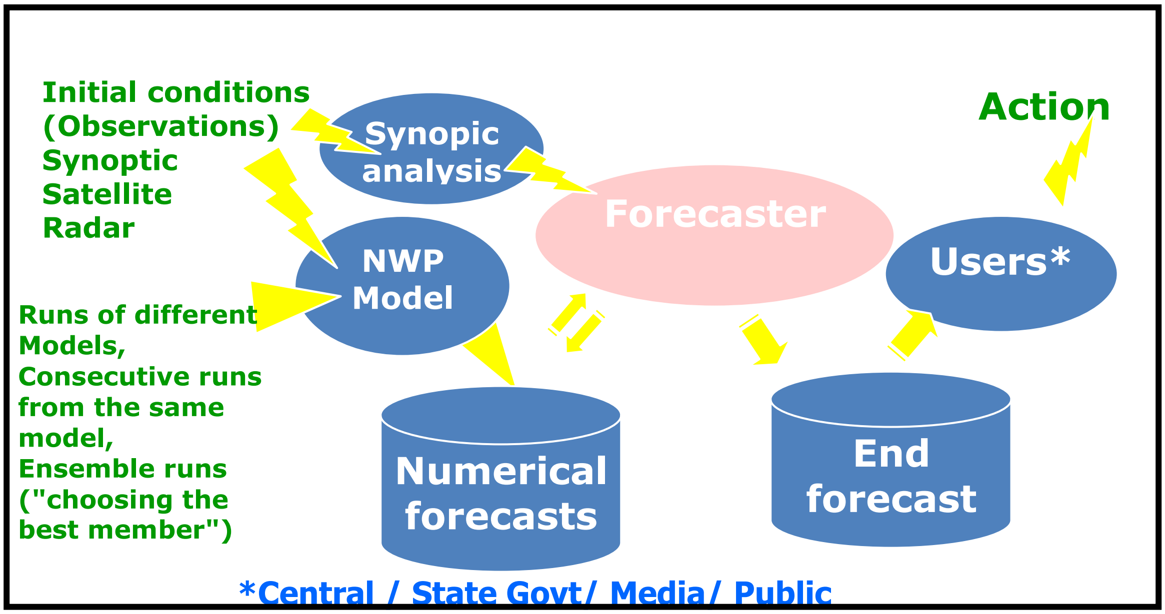


Fig.1.3.. Strategy adopted for cyclone analysis and forecasting

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. Prediction Models in operational use during the year 2010

1.5.1. Global Forecast System

With the commissioning of High Performance Computing System (HPCS), National Centre for Environmental Prediction (NCEP) based Global Forecast System (GFS T382) has been made operation at the H/Q of IMD, incorporating Global Statistical Interpolation (GSI) scheme as the global data assimilation for the forecast up to 7 days. Currently, it runs twice in a day (00 UTC and 12 UTC).

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 derived based on global model (T-80 and T-254) forecasts obtained online from the National Centre for Medium Range Weather Forecasting (NCMRWF), India. 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 WRF(NMM), MM5 and Quasi-Lagrangian Model (QLM) for short-range prediction during cyclone condition. MM5 model is run at the horizontal resolution of 45 km with 23 sigma levels in the vertical and the integration is carried up to 72 hours over a single domain covering the area between lat. 30^{o} S to 45^{o} N long 25^{o} E to 125^{o} E. WRF (NMM) is run 4 times a day at the horizontal resolution of 27 km.

1.5.3.1. Non-hydrostatic Meso-scale Model MM-5 (Version 3.6)

The non-hydrostatic model MM-5 is being run on operational basis daily once based on 00 UTC initial conditions for the forecast upto 72 hours. The horizontal resolution of the model is 45 km with 23 sigma levels in the vertical. The domain of integration covers the area between lat. 25.0^{o} S to 45.0^{o} N and long. 30^{o} E to 120.0^{o} E. National Centre for Environmental Prediction (NCEP) analysis and six hourly forecasts are used as initial and boundary conditions to run the model. During cyclone situations, the model is run by including Holland vortex scheme. The forecast products are disseminated as a WWW activity of RSMC, New Delhi.

1.5.3.2. Non-hydrostatic mesoscale model WRF

The meso-scale forecast system Weather Research and Forecast (WRF-ARW) with 3DVAR data assimilation is being operated daily twice, at 27 km and 9 km horizontal resolutions for the forecast up to 3 days using initial and boundary conditions from the IMD GFS-382. The WRF (ARW) 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, the outer model domain covers the area between lat. 25^o S to 45^o N long 40^o E to 120^o E. At ten other regional centres, very high resolution mesoscale models (WRF at 3 km resolution) are made operational. The performance of the model is found to be reasonably skilful for cyclone genesis and track prediction.

IMD has the plan to implement latest version of NCEP HWRF 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. Multi-model ensemble (MME) technique

The multi model ensemble (MME) technique is based on a statistical linear regression approach. The predictors (shown in Table 1.1) 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, IMD WRF model is also included as an ensemble member. 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 MM5, 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.

1.5.5. Statistical Dynamical model for Cyclone genesis and intensity Prediction

A statistical-dynamical model has been implemented for real time forecasting of cyclone genesis and intensity. The approach consists of (a) analysis of genesis potential parameter (GPP) and (b) 12 hourly intensity prediction for forecasts up to 72 hours. The model parameters are calibrated based on model analysis fields of past cyclones. For the real-time forecasting, model parameters are derived based on the forecast fields of MM5 model. The method is found to be promising for the operational use.

1.5.6. Storm Surge Model

For the operational storm surge prediction, IMD uses both nomograms developed by IMD and Dynamical Storm Surge Model developed by Indian Institute of Technology (IIT), Delhi. The nomograms are based on the numerical solution to the hydrodynamical equations governing motion of the Sea. The nomograms are prepared relating peak surge with various parameters such as pressure drop, radius of maximum wind, vector motion of the cyclone and offshore bathymetry. The dynamical model of IIT Delhi is fully non-linear and is forced by wind stress and quadratic bottom friction following the method of numerical solution to the vertically integrated mass continuity and momentum equations. The updated version of the model currently in operational use covers an analysis area lying between lat. 2.0^0 N and 22.25^0 N and long. 65.0^0 E & 100.0^0 E. The method uses a conditionally stable semi-implicit finite difference stair step scheme with staggered grid for numerical solution of the model equation. The bottom stress is computed from the depth-integrated current using conventional quadratic equation. The bathymetry of the model is derived from Naval Hydrographic charts applying cubic spline technique. The storm surge models developed by IIT, Delhi for different Panel member countries have been installed at RSMC, New Delhi. RSMC, New Delhi is providing storm surge guidance to member countries in tropical cyclone advisory bulletin since April, 2009 (with effect from cyclone BIJLI).

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 lies 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., max 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.

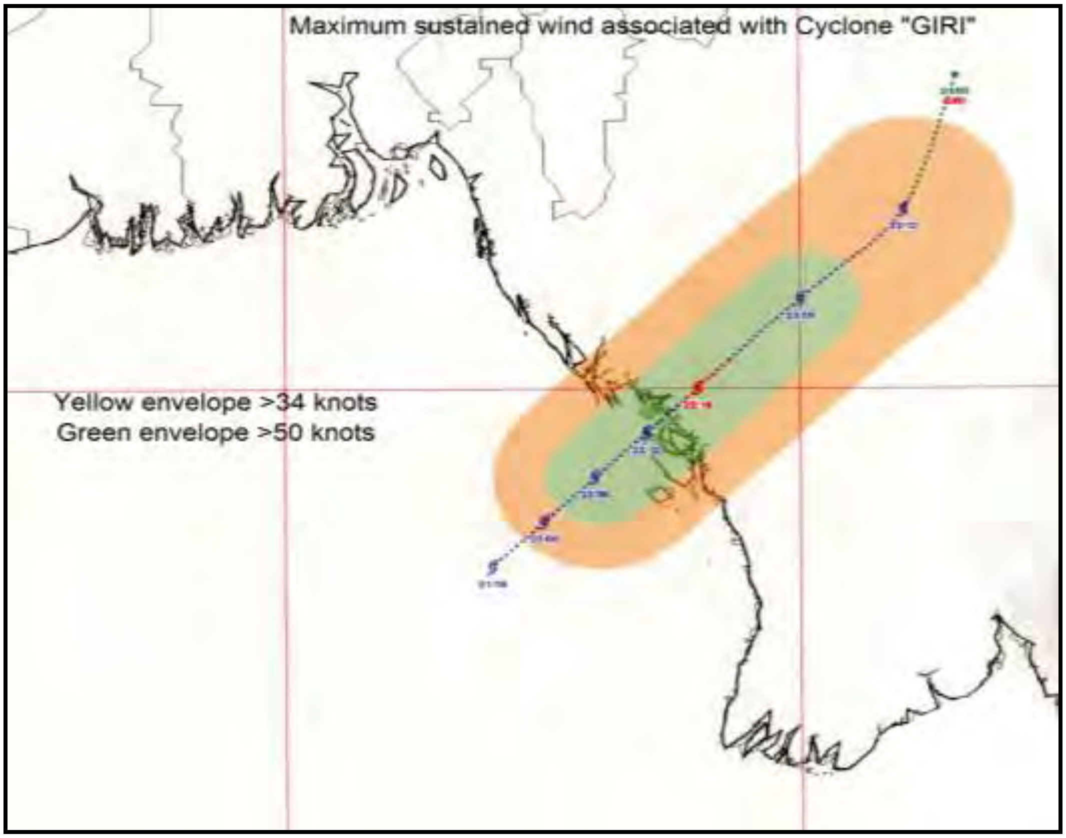


Fig.1.4. A typical graphical presentation of cyclone wind forecast during cyclone, GIRI

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.

1.6.7. Introduction of new 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, specially for PWS of cyclone. An example of product generated from this system is shown in Fig.1.5.

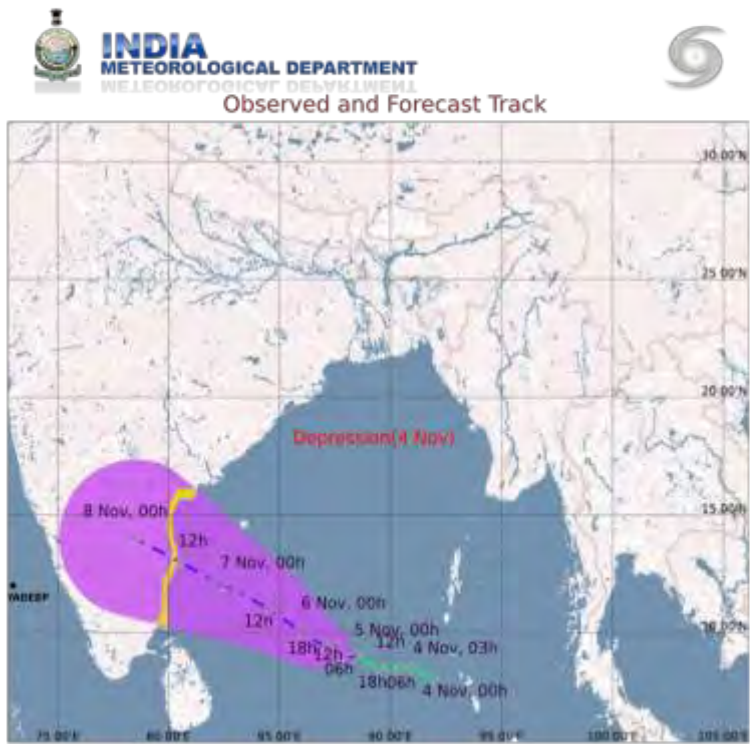


Fig.1.5. A typical example of observed and forecast track of depression which later on became the severe cyclonic storm, „JAL'

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. 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) Field phase : Oct-Nov. 2010,
(iii) Final phase : Oct-Nov 2011, 2012

During pre-pilot phase **(15 Oct- 30 Nov. 2010),** several national institutions participated for joint observational, communicational & NWP activities, like during 2008 and 2009. However there was improved observational campaign with the observation from Sea with the help of Sagarkanya cruise. There was intense observation period for 10 days during the field phase 2010 in association with a deep depression over Bay of Bengal and cyclone GIRI and JAL. The daily reports prepared during this period will be helpful to find out the characteristics of genesis, intensification and movement of the systems over the Bay of Bengal during 15 Oct. to 30 Nov., 2010.

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 are as follows.

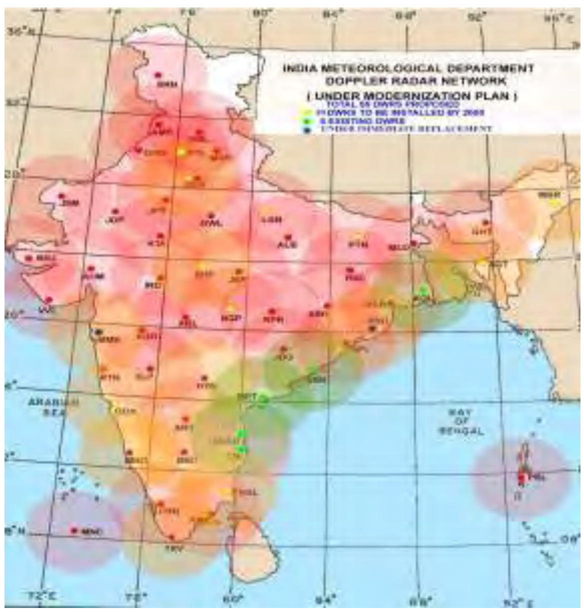


Fig. 1.6. Enhancement of Doppler Weather Radar (DWR) Network

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 2010

The north Indian Ocean witnessed the formation of eight cyclonic disturbances during 2010. Out of eight disturbances six cyclonic disturbances formed over the Bay of Bengal and two over the Arabian Sea. Out of the six cyclonic disturbances over the Bay of Bengal, one intensified upto the stage of very severe cyclonic storm (GIRI), two upto the stage of severe cyclonic storm (LAILA & JAL), one upto the stage of deep depression and rest two upto the stage of depression. Out of two cyclonic disturbances formed over the Arabian Sea, one intensified upto the stage of very severe cyclonic storm (PHET) and the other upto the stage of cyclonic storm (BANDU). Tracks of the cyclonic disturbances formed over the north Indian Ocean during the period is shown in Fig 2.1.

The salient features of the cyclonic disturbances during 2010 were as follows:

- The number of total cyclonic disturbances (depression and above) during the year was far below normal, as only 8 cyclonic disturbances formed during 2010 against the normal of 13 cyclonic disturbances. However, five cyclones formed during the year which is the first such year after 1998 when six cyclones formed.
- Out of five cyclones, three cyclones made landfall with atleast cyclonic storm intensity.
- There were no cyclonic disturbances formed over the north Indian Ocean during monsoon season (June-Sep.). Comparing with past records (1891-2009), there was only one such year viz. 2002. On an average, 7 cyclonic disturbances formed over the north Indian Ocean during the monsoon season. While the year 2002 was an all India drought year, the year 2010 was a normal rainfall year. It was mainly because of the fact that the absence of cyclonic disturbances was compensated by the number of low pressure areas over the region. There were 13 low pressure areas during the season against the normal of 6. Considering low pressure systems including lows and cyclonic disturbances (depression and above), about 13.5 such systems develop normally during monsoon season.
- The cyclone „Phet' over the Arabian Sea had the rarest of the rare track with two landfall points over Oman and Pakistan and longest track in recent years.

(a) Severe Cyclonic Storm, “LAILA” over the Bay of Bengal (17-21 May, 2010.

A low pressure area developed over the southeast Bay of Bengal on 15 May 2010. It concentrated into a depression at 0600 UTC of 17 May over the southeast Bay of Bengal. It moved in a northwesterly direction and intensified into a severe cyclonic storm **„LAILA’**. Moving in a west-northwesterly direction towards Andhra Pradesh coast. It crossed Andhra Pradesh coast near Bapatla between 1100 and 1200 UTC of 20 May 2010 as a severe cyclonic storm. It caused moderate damage over Andhra Pradesh with death of six persons. The special features of the storm are as follows:

- It was one of the rarest track in recent years, as the cyclone developed over southeast Bay of Bengal on 17 May, moved initially in a west-northwesterly direction towards south Andhra Pradesh and adjoining north Tamil Nadu coast till 19 May morning and then moved in a northwesterly to northerly direction and crossed Andhra Pradesh coast near Bapatla (about 50 km southwest of Machilipatnam) on 20 May evening. It then recurved north-northeastwards and weakened gradually.
- The cyclone slowed down during landfall period. It lay very close to coast after landfall maintaining cyclone intensity for about 12 hrs. after landfall.
- It was the first ever severe cyclone to cross Andhra Pradesh coast after 1990 in the month of May. A very severe cyclone crossed Andhra Pradesh coast near the same area during May, 1990.

(b) Cyclonic Storm, „BANDU’ over the Arabian Sea (19-23 May 2010)

A cyclonic storm „BANDU’ formed over southwest Arabian Sea off Somalia coast on 19 May, 2010. Initially it moved northwesterwards and later westwards. Due to interaction with land surface and colder sea, it dissipated over Gulf of Aden. It caused heavy rain in Somalia and Yemen.

(c) Very Severe Cyclonic Storm, „PHET’ over the Arabian Sea(31 May-7 June 2010)

A very severe cyclonic storm, „PHET’ developed from a low pressure area formed over the central Arabian Sea on 30 May,2010. The low pressure area concentrated into a depression over the same region on 31 May, 2010. Moving initially in a northwesterly direction, the system intensified into a cyclonic storm „PHET’ on 1 June and attained maximum intensity of very severe cyclonic storm with maximum sustained wind speed of 85 kts on 2 June. It weakened gradually since 3 June, moved northwards and crossed Oman coast as a severe cyclonic storm with the wind speed of about 65 kts near latitude 21.5^0N on 4 June 2010. It then continued to move northwards, emerged into northwest Arabian Sea and then recurved eastwards and weakened gradually. It moved parallel to but close to Makaran coast and crossed Pakistan coast as a depression, close to south of Karachi on 6 June. It then moved east-northeastwards across south Pakistan and Rajasthan and weakened gradually into a well marked low pressure area over east Rajasthan and adjoining northwest Madhya Pradesh on 7 June. The salient features of this system are as follows.

- It was the rarest of the rare track in Arabian Sea as per the recorded history during 1877-2009. It was one of the longest tracks in recent years. The life period of the cyclone was also longer.
- As a result of such unique track, the system affected three countries, viz. Oman, Pakistan and India(Gujarat and Rajasthan). While there was loss of life and property in Oman due to both heavy rain and gale wind, the loss of life and property in Pakistan was mainly due to heavy rain and there was no significant adverse impact in India, though there was heavy rain over Gujarat and Rajasthan.

(d) Very Severe Cyclonic Storm, „GIRI' over the Bay of Bengal (20-23 October, 2010)

A low pressure area formed over the east central Bay of Bengal on 19 October. It concentrated into a depression on 20 October over the same area. It intensified into a cyclonic storm, **GIRI** at 0600 UTC of 21 October. It then moved slowly northeastwards and intensified into a severe cyclonic storm at 0300 UTC of 22 October and into a very severe cyclonic storm at 0600 UTC of the same day. It then moved relatively faster in the same direction and crossed Myanmar coast between Sittwe and Kyakpyu around 1400 UTC of 22 October 2010 with estimated sustained maximum wind speed of about 105 kts. After the landfall, it continued to move northeastwards and weakened gradually. It caused loss of life and property in Myanmar due to heavy rain, gale wind and storm surge. The salient features of cyclone „Giri' are given below:

- Cyclone, Giri rapidly intensified from associated sustained maximum wind speed of 45 kts at 1200 UTC of 21 to 105 kts at 0900 UTC of 22 October 2010.
- No severe cyclone crossed Arakan coast prior to cyclone, GIRI during the month of October, as evident from the data of 1891-2009.
- The genesis and intensification of the system could be predicted by ECMWF model to a large extent. It predicted lowest estimated central pressure of 970 hPa well in advance with landfall near 20^0N and 93^0E between 1200 and 1800 UTC of 22 October 2010 well in advance against the lowest estimated central pressure of 950 hPa and landfall near 20^0N and 93.5^0E around 1400 UTC of 22 October 2010.

(e) Severe Cyclonic Storm, „JAL' (04-08 November,2010)

A severe cyclonic storm, JAL (4-8 November 2010) developed over the Bay of Bengal from the remnant of a depression which moved from northwest Pacific Ocean to the Bay of Bengal across southern Thailand. It moved west-northwestwards and intensified upto severe cyclonic storm on 6 November. However as the severe cyclonic storm, JAL moved to the southwest Bay of Bengal closer to India coast, it entered into a region of lower ocean thermal energy and moderate to high vertical wind shear in association with the strong easterlies in the upper tropospheric level. The high wind shear led to westward shearing of the convective clouds form the system centre and lower Ocean thermal energy led to unsustainability of convection over the region. Due to these two factors, the severe cyclonic storm, JAL weakened gradually into a deep depression and crossed north Tamilnadu – south Andhra Pradesh coast, close to the north of Chennai near 13.3^0N and 80.3^0E around 1600 UTC of 07 November 2010. It continued to move west-northwestwards and further weakened into a well marked low pressure area. Its salient features are as follows.

- The severe cyclonic storm, JAL weakened into a deep depression over the Sea before the landfall.
- The convective clouds were sheared to the west to a large extent on the date of landfall (7 November,2010). As a result, more rainfall occurred over the interior parts than the coastal regions.

RSMC, New Delhi mobilized all its resources, both technical and human, to track these tropical disturbances that formed over the north Indian Ocean and issued timely advisories to WMO / ESCAP Panel member countries and to the national agencies.

Table 2.1: Cyclonic disturbances formed over north Indian Ocean and adjoining land areas during 2010

1.	Severe Cyclonic Storm, „LAILA' over the Bay of Bengal 17-21 May 2010.
2.	Cyclonic Storm, „BANDU" over the Arabian Sea 19-23 May, 2010
3.	Very Severe Cyclonic Storm „PHET' over the Arabian Sea 31 May -07 June, 2010
4.	Depression over the Bay of Bengal 7-9 October 2010
5.	Deep Depression over the Bay of Bengal 13-16 October 2010
6.	Very Severe Cyclonic Storm „GIRI' over the Bay of Bengal 20-23 October, 2010
7.	Severe Cyclonic Storm, „JAL' over the Bay of Bengal 04-08 November, 2010
8.	Depression over the Bay of Bengal 7-8 December 2010

Table 2.2: Some Characteristic features of cyclonic disturbances formed over north Indian Ocean and adjoining region during 2010

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
Severe Cyclonic Storm, "LAILA" over the Bay of Bengal (17-21 May, 2010).	17 May, 0600 UTC near 10.5/88.5	Crossed Andhra Pradesh Coast near 16.0/80.5 between 1100 &1200 UTC of 20 May	986 hPa at 0600 UTC of 19 May near 13.5/81.5	55 kt at 0600 UTC of 19 May near 13.5/81.5	T-3.5
Cyclonic Storm, "BANDU" over the Arabian Sea (19-23 May , 2010)	19 May, 0900 UTC near 10.5/54.0	Weakened into a well marked low pressure area over the Gulf of Aden at 0000 UTC of 23 May.	994hPa at 1200 UTC of 21 May near 12.5/51.5	40 kt at 1200 UTC of 21 May near 12.5/51.5	T- 2.5
Very Severe Cyclonic Storm, "PHET" over the Arabian Sea (31 May- 07 June, 2010)	31 May, 0600 UTC near 15.0/64.0	Crossed Oman coast near lat. 21.5^{0}N between 0000 & 0200 UTC of 4 June and again crossed Pakistan coast, close to south of Karachi near 24.7/67.2 between 1230 and 1330 UTC of 6 June	964 hPa at 1200 UTC of 02 June near 18.0/60.5	85 kt at 1200 UTC of 02 June near 18.0/60.5	T- 4.5
Depression over the Bay of Bengal (07-09 October, 2010)	07 October 0300 UTC near 16.5/84.5	Crossed West Bengal-Bangladesh Coast near long. 88.5 between 0500 & 0600 UTC of 08 October.	996 hPa at 1200 UTC of 07 October, near 18.5/85.0	25 kt at 0300 UTC of 07October .	T- 1.5
Deep Depression over the Bay of Bengal (13-16 October, 2010)	13 October 0600 UTC near 17.5/90.0	Crossed Orissa coast near Gopalpur between 1500 & 1600 UTC of 15 October.	995 hPa at 1200 UTC of 15 October near 19.5/85.5	30 kt at 0300 UTC of 15 October.	T- 2.0

Very Severe Cyclonic Storm „GIRI' over the Bay of Bengal (20-23 October 2010)	20 October, 1200 UTC near 17.5/91.5	Crossed Myanmar coast near lat 20.0^0N/93.5^0E about 70 km east-southeast of Sittwe around 1400 UTC of 22 October.	950 hPa at 0900 UTC of 22 November near 19.5/93.5	105 kt at 0900 UTC of 22 November near 19.5/93.5.	T- 5.5
Severe Cyclonic Storm „JAL' over the Bay of Bengal (04-08 November 2010)	04 November, 0000 UTC near 8.0/92.0	Crossed north Tamil Nadu and south Andhra Pradesh coast close to north of Chennai near 13.3/80.2 around 1600 UTC of 07 November.	988 hPa at 1200 UTC of 06 November near 11.0/84.5	60 kt at 1200 UTC of 06 November near 11.0/84.5 .	T-3.5
Depression over the Bay of Bengal 07-08 December	07 December 0300 UTC near 14.0/82.0	Crossed south Andhra Pradesh coast near Baptla around 2000 UTC of 07 December near	1000 hPa at 0300 UTC 07 December near 14.0/82.0	25 kt at 0300 UTC 07 December	T-1.5

Table 2.3: Statistical data relating to cyclonic disturbances over the north Indian Ocean during 2010

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												

↔ Peak intensity of the system

B) Life time of cyclonic disturbances during 2010 at different stages of intensity

S.No	Type	Life Time in (Days)
1.	D	10.11
2.	DD	3.11
3.	CS	6.37
4.	SCS	3.87
5.	VSCS	2.61
6.	SuCS	--
Total Life Time in (Days)		26.07

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	8	6	5	4	4	2	2	1

D) Basin-wise distribution of cyclonic disturbances

Basin	Number of cyclonic disturbances
Bay of Bengal	6
Arabian Sea	2
Land depression	-

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	-	2	1	0	6
	ARB	-	-	1	-	1	0	2
	LAND	0	0	0	0	0	0	0
	Total							**8**

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

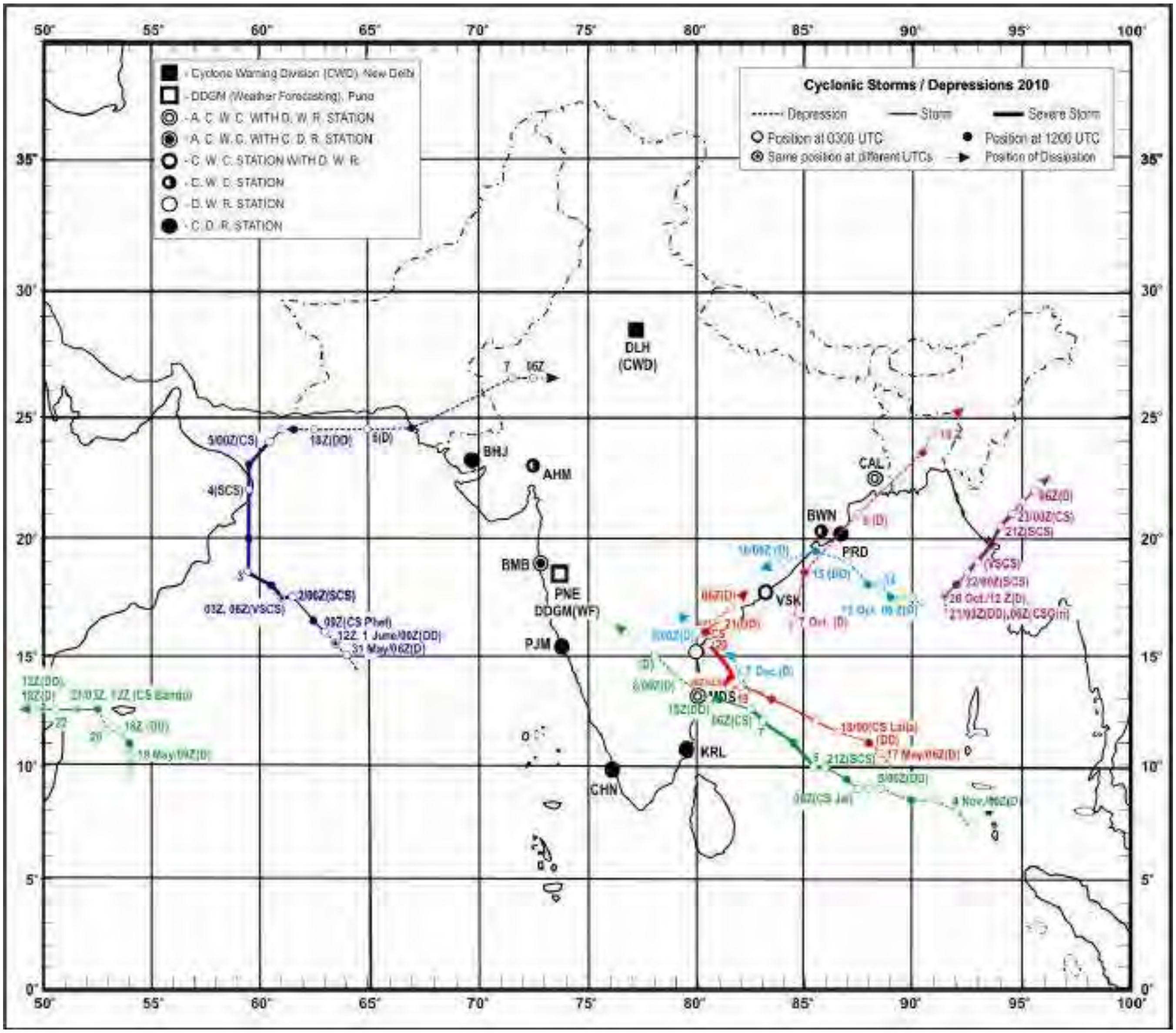


Fig. 2.1 Tracks of the cyclonic disturbances formed over the north Indian Ocean during the year, 2010

2.1 Cyclonic Storm' LAILA' over the Bay of Bengal (17-21 May, 2010)

2.1.1. Introduction:

A severe cyclonic storm, „LAILA' crossed Andhra Pradesh coast near Bapatla between 1100 and 1200 UTC of 20 May,2010. It caused wide spread rainfall with scattered heavy to very heavy rainfalls and isolated extremely heavy rainfalls (≥25 cm) over coastal Andhra Pradesh leading to flooding in low lying areas. Gale winds speed reaching 90-100 kmph were reported by the meteorological observatories in the coastal regions of Andhra Pradesh. The storm surge of 2 to 3 meters inundated the low lying areas of Guntur, Prakasham, West & East Godavari districts. The salient features of this cyclone are as follows.

(i) It was one of the rarest track in recent years, as the cyclone developed over southeast Bay of Bengal on 17 May, moved initially in a west-northwestwards and crossed Andhra Pradesh coast near Bapatla and then recurved north-northeastwards.

(ii) The cyclone slowed down during landfall period. It lay very close to coast after landfall maintaining cyclone intensity for about 12 hrs after landfall.

(iii) It was the first ever severe cyclone to cross Andhra Pradesh coast after 1990 in the month of May. A very severe cyclone crossed Andhra Pradesh coast near the same area during May, 1990.

The genesis, intensification, movement and characteristic features like pressure and wind are presented and discussed below along with the weather associated with system and damage caused thereof.

2.1.2 Genesis:

Southwest monsoon set in over Andaman Sea and adjoining south Bay of Bengal on 17 May,2010. Under its influence, the southerly surge over the region increased. It resulted in increase in the horizontal pressure gradient and the north-south wind gradient over the region. Hence, the lower level horizontal convergence and relative vorticity increased gradually over the southeast Bay of Bengal. According to INSAT imageries, a low level circulation appeared over southeast Bay adjoining south Andaman Sea at 1500 UTC of 15 May. It intensified into a vortex at 1200 UTC of 16 May with center near 9.0N/90.5E with intensity T 1.0. It led to the development of the low pressure area with at 1200 UTC of 16 May over the southeast Bay of Bengal and associated convective cloud clusters persisted over the region. It concentrated into a depression and lay centered at 0600 UTC 17 May near Lat. 10.5ºN/Long 88.5º E about 1000 kms southeast of Machilipatnam. The track of the system is shown in Fig.2.1. The best track parameters of the system are shown in Table 2.1.1. The INSAT imagery of the system at the stage of depression is shown in Fig. 2.1.1.

It was the shear pattern at the time of cyclogenesis with maximum convection lying to the southwest of the system centre. The lowest cloud top temperature was about -70 deg. C.

Considering the environmental factors for cyclogenesis, the sea surface temperature (SST) was warmer (about 28-30^0 C) over the Bay of Bengal, according to SST estimated by TMI. The ocean heat content was also favourable for genesis and intensification, as it was more than 100 KJ/cm^2. The wind shear between the layers (150-300) hPa & (700-925) hPa was low (05-10 knots) on 16 and 10-15 knots on 17 May according to METEOSAT observations. There was favourable lower level convergence and upper level divergence along with the lower level relative vorticity around the system centre. The system could gain upper level divergence as the upper tropospheric ridge roughly ran along 12-14^{0}N in association with an anti-cyclonic circulation located to the northeast of the system centre. The available ship observations suggested 30 knots wind to the southwest of the system centre at 0000 UTC of 17 May. The windsat observations also indicated 25-30 knots wind on 17 May in association with the system. The wind speed was relatively stronger in the southern sector due to strong southerly surge of the monsoon current. All these observations indicate that the environmental factors were favourable for genesis and further intensification of the system (Fig.2.1.2).

Table 2.1.1. Best track positions and other parameters of the severe cyclonic storm “LAILA” over the Bay of Bengal during 17-21 May, 2010

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
17-05-2010	0600	10.5/88.5	1.5	1004	25	3	D
	1200	11.0/88.0	2.0	1000	30	5	DD
	1800	11.5/87.5	2.0	998	30	5	DD
18-05-2010	0000	11.5/86.5	2.5	998	35	6	CS
	0300	12.0/85.5	2.5	996	40	6	CS
	0600	12.5/84.5	3.0	992	45	8	CS
	0900	13.0/84.0	3.0	992	45	8	CS
	1200	13.0/83.5	3.0	990	45	10	CS
	1500	13.0/83.0	3.0	990	45	10	CS
	1800	13.0/82.5	3.0	990	45	10	CS
	2100	13.0/82.0	3.0	990	45	10	CS
19-05-2010	0000	13.5/82.0	3.0	990	45	10	CS
	0300	13.5/82.0	3.0	990	45	10	CS
	0600	13.5/81.5	3.5	986	55	15	SCS

	0900	14.0/81.5	3.5	986	55	15	SCS
	1200	14.0/81.5	3.5	986	55	15	SCS
	1500	14.0/81.5	3.5	986	55	15	SCS
	1800	14.5/81.0	3.5	986	55	15	SCS
	2100	14.5/81.0	3.5	986	55	15	SCS
	0000	15.0/81.0	3.5	986	55	15	SCS
	0300	15.5/80.5	3.5	986	55	15	SCS
	0600	15.7/80.5	3.5	986	55	15	SCS
	0900	15.8/80.5	3.5	986	55	15	SCS
20-05-2010	Severe cyclonic storm „LAILA’ crossed Andhra Pradesh coast near Bapatla (16.0^0 N/80.5^{0}E) between 1100-1200 UTC.						
	1200	16.0/80.5	-	990	45	12	CS
	1500	16.0/80.5	-	990	45	12	CS
	1800	16.0/80.5	-	990	45	10	CS
	2100	16.0/80.7	-	990	40	10	CS
	0000	16.2/80.8	-	990	35	10	CS
	0300	16.5/81.0	-	995	30	5	DD
21-05-2010	0600	17.0/81.5	-	999	20	3	D
	1200	Weakened into a well marked low pressure area over coastal Andhra Pradesh and adjoining area.					

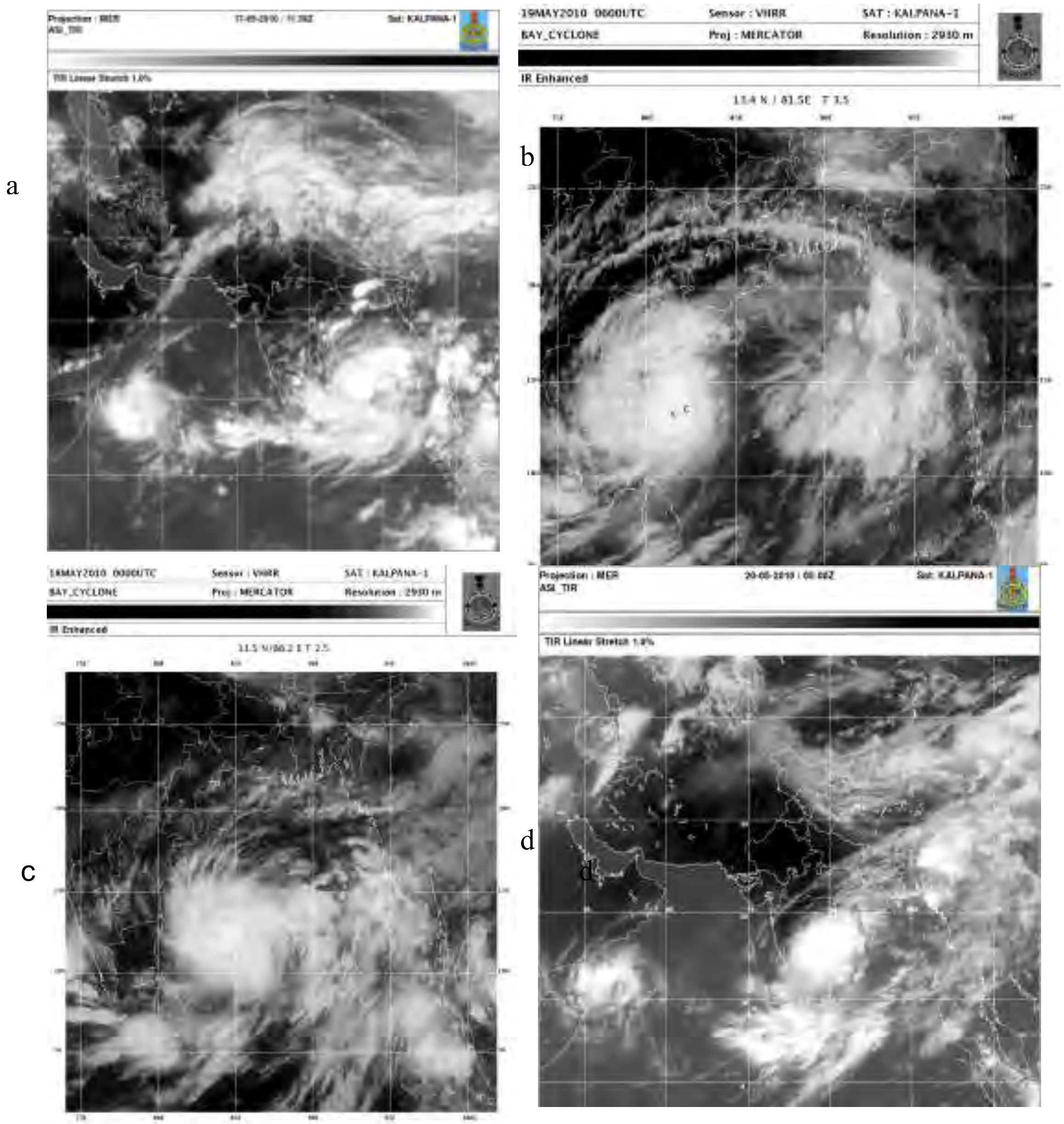


Fig.2.1.1. INSAT imageries of SCS, LAILA at different stages of intensification (a) Depression, (b) cyclonic storm, (c) severe cyclonic storm and (d) severe cyclonic storm prior to landfall

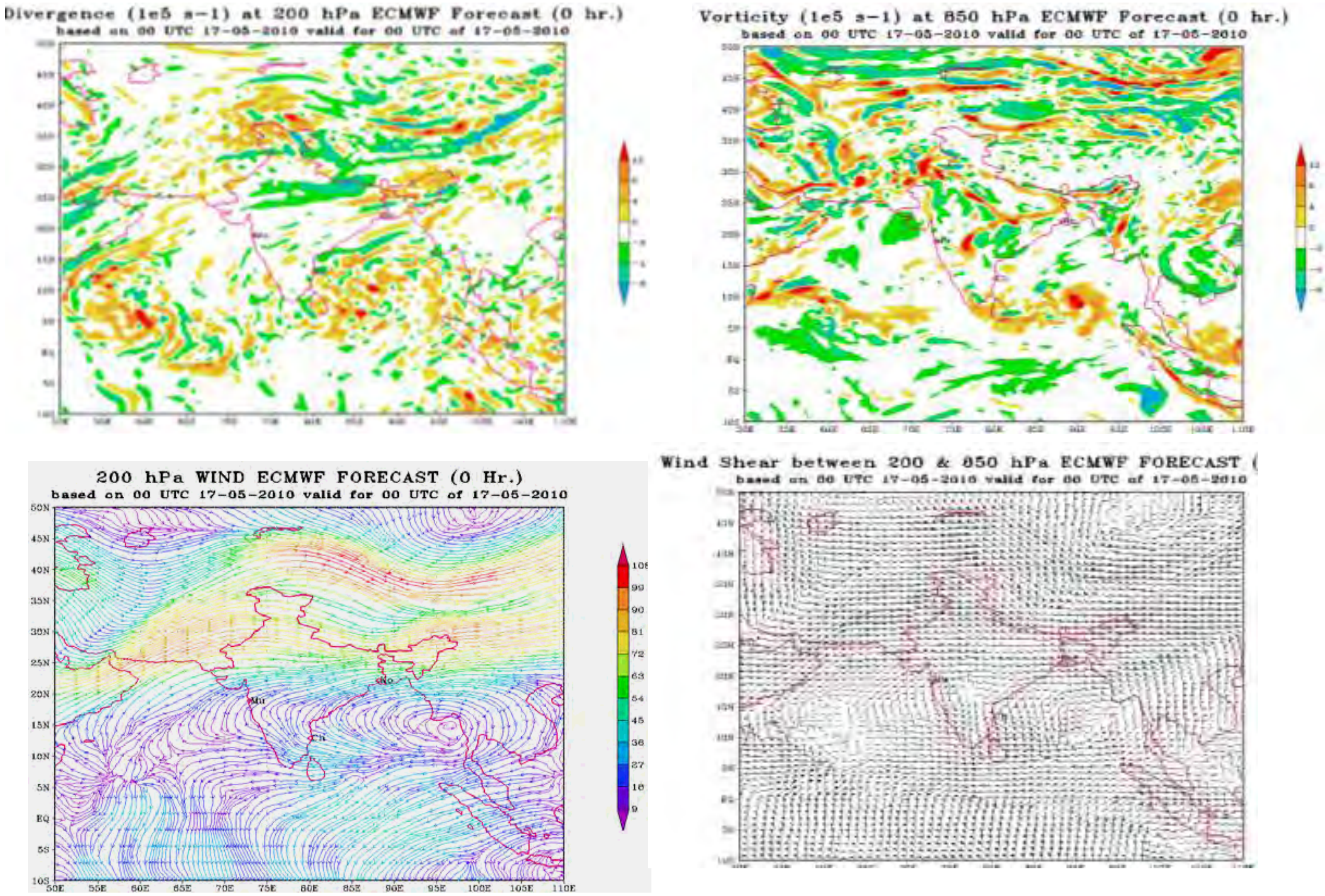


Fig.2.1.2. ECMWF analyses (a) Divergence at 200 hPa level, (b) Vorticity at 850 hPa level, (c) wind at 200 hPa level and (d) Vertical wind shear between 200 and 850 hPa level at 0000 UTC of 17 May 2010

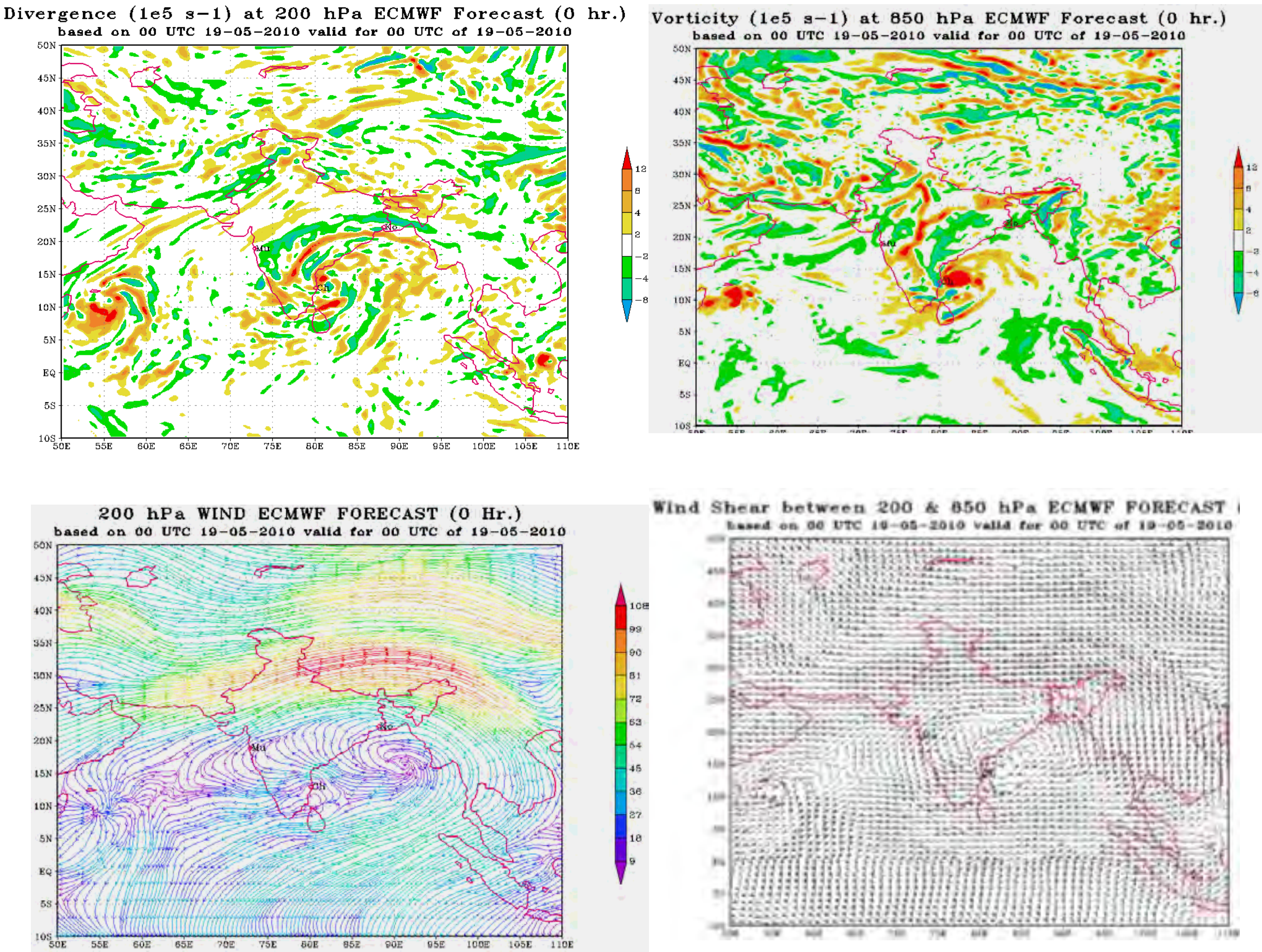


Fig.2.1.3. ECMWF analysis (a) Divergence at 200 hPa level, (b) Vorticity at 850 hPa level, (c) wind at 200 hPa level and (d) Vertical wind shear between 200 and 850 hPa level at 0000 UTC of 19 May 2010

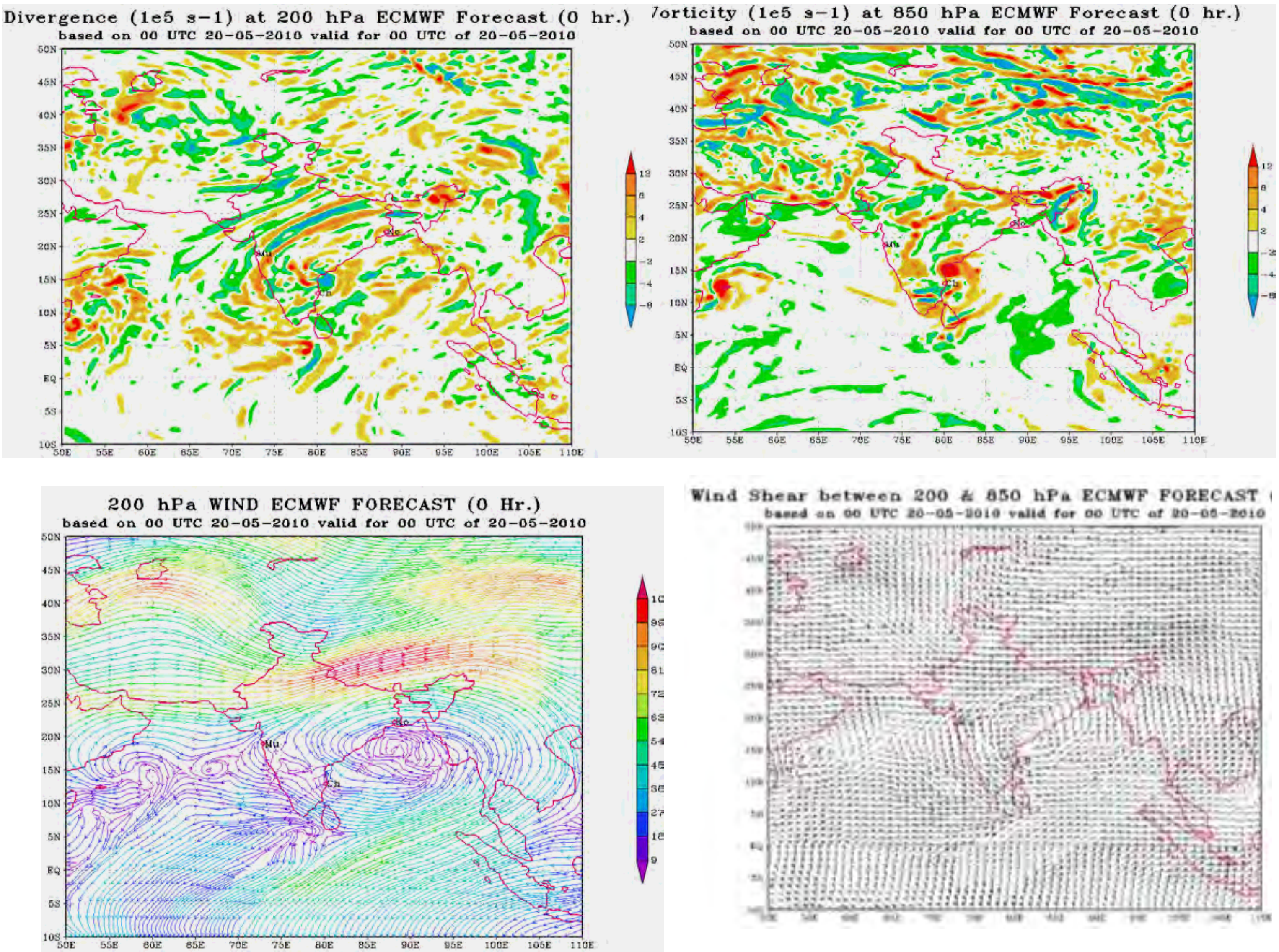


Fig.2.1.4. ECMWF analysis (a) Divergence at 200 hPa level, (b) Vorticity at 850 hPa level, (c) wind at 200 hPa level and (d) Vertical wind shear between 200 and 850 hPa level at 0000 UTC of 20 May 2010

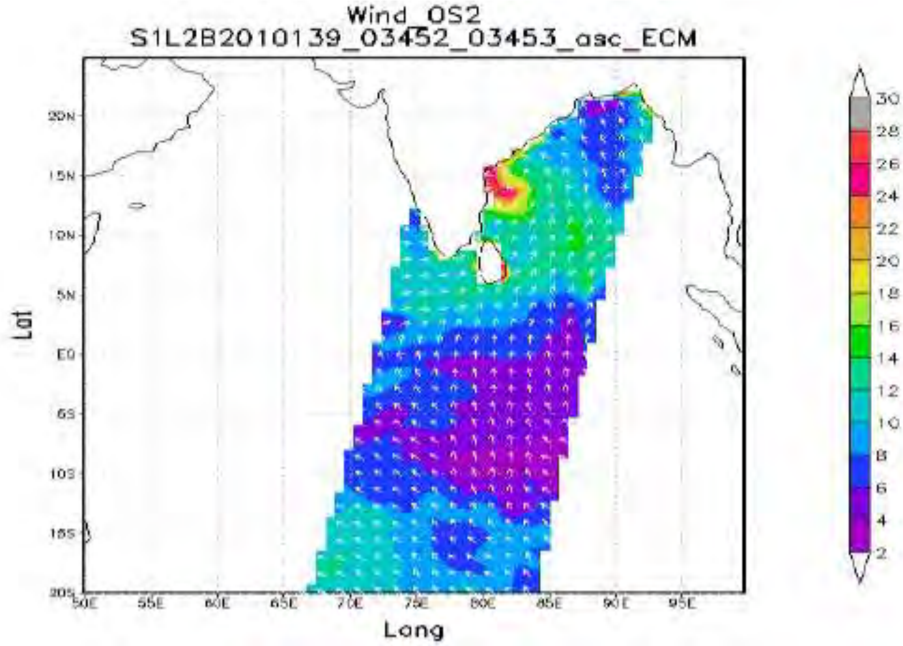


Fig.2.1.5. Laila Cyclone captured by Oceansat-2 Scatterometer at 0700 UTC of 19-05-2010(winds in metre per second)

2.1.3. Intensification and movement

The development of the system was very fast as the system intensified into a deep depression at 1200 UTC of 17 May with Dvorak's T number as T2.0 while moving northwestwards. Wind shear and shear tendency at this stage was between 10-20 kts and –10 kts respectively indicating further intensification. The system then moved west-northwestwards and gradually intensified into a cyclonic storm, LAILA at 0000 UTC of 18 May, 2010 over southeast and adjoining southwest Bay of Bengal, about 700 km east-southeast of Chennai.

It then moved northwestwards and intensified into a severe cyclonic storm at 0600 UTC of 19 May, 2010 over southwest and southeast Bay of Bengal about 150 km east-northeast of Chennai and 300 km south-southeast of Machilipatnam. It then moved slowly northwestwards to northwards direction and lay centred at 0300 UTC of 20 May over westcentral Bay of Bengal, about 50 km south of Bapatala. It moved then northwards very slowly and crossed coast near Bapatla between 1100 and 1200 UTC of 20 May. It weakened into a cyclonic storm after the landfall and lay over coastal Andhra Pradesh close to Bapatla at 1200 UTC of 20 May, 2010. Its motion continued to be slow in the north-northeasterly direction after the landfall and it further weakened into a deep depression at 0300 UTC of 21 May, 2010 near about 50 km north of Machilipatnam. Continuing its north-northeastwards movement, it further weakened into a depression at 0600 UTC and into a well marked low pressure area over coastal Andhra Pradesh and adjoining Telangana at 1200 UTC of the same day.

According to INSAT observation, at 2100 UTC of 19 May indication of slight weakening of the system was observed and its intensity was assigned as T

3.0 with center near lat.14.6N and long.81.1E.The system crossed Andhra Pradesh coast near lat.15.7N and long.80.1E at 0500 UTC of 20 May with intensity T 3.0 (Fig.2.1.1).

The cyclone, LAILA tracked along the southwestern periphery of the middle level sub-tropical ridge and hence in a west-northwesterly to northwesterly direction till 18 May. It moved in a north-northwesterly to northerly direction as the sub-tropical ridge in association with the anti-cyclonic circulation oriented itself in response to the approaching mid-latitude short wave westerly trough on 19 May. It subsequently moved in a north-northeasterly direction on 20 May onwards under the influence of the mid-latitude trough in westerlies and the anti cyclonic circulation over the Bay of Bengal. The ECMWF analysis at 0000 UTC of 17, 19,and 20 May 2010 explaining the above in upper level divergence lower level vorticity, 200 hPa level wind and vertical wind shear are shown in Fig, 2.1.3-2.1.4.

2.1.4. Structure and other parameters

The structure of the system was curved band except for one or two cases when it was observed as Central Dense Overcast (CDO) type with intensity of T3.5. The depth of intense convection was very high through out life period of the system with lowest cloud top temperatures ranging from -80 to -95 deg. C. It was maximum at 2100 UTC of 19 May, 2010.

Initially, the shape of the isobar was elliptical with its major axis along the horizontal when the system was in depression/deep depression stage and moving in a west-northwesterly/ northwesterly direction. It became circular at 0000 UTC of 18 May, when the system intensified into a cyclonic storm. It further changed shape to elliptical with major axis oriented from south-southwest to north-northeast on 19^{th} indicating recurvature of the system. The scatterometry wind as observed by OCEANSAT-II on 19 May, 2010 is shown in Fig.2.1.5.

The estimated central pressure of the system gradually decreased from 1002 hPa at 0600 UTC of 17^{th} to 986 hPa at 0600 UTC of 19^{th} May (Table 2.1.1). It then started increasing after 0900 UTC of 20 May. The pressure drop at the centre was maximum (15 hPa) during the same period.

Considering the hourly coastal observations, the lowest pressure of 990.9 hPa was recorded over Machilipatnam at 0000 UTC of 21 May followed by 991.1 hPa over Ongole at 0800 UTC of 20 May and 992.3 hPa over Bapatla at 0100 UTC of 20 May, 2010. The 24 hr pressure fall was maximum (-10.1 hPa) over Bapatla at 0300 UTC of 20 May.

The estimated sustained maximum wind at the surface was 55 knots during 0600 UTC of 19 to 0900 UTC of 20 May, 2010. The hourly coastal observations indicated that maximum wind of about 35 knots was reported by coastal observatory stations in Andhra Pradesh.

2.1.5. Performance of AWS

Fall of station level pressure recorded at Kavali, Narsapur and Nellore AWS in Andhra Pradesh is shown is Fig.2.1.6. The lowest pressure of about 992 hPa was recorded by AWS stations at Nellore, Kavali (to the southwest of Machilipatnam) at about 0100 UTC of 20 May. It was about 996 hPa at 0000 UTC of 21 May over Narsapur as it lay to the northeast of Machilipatnam and the system moved north-northeastwards after landfall. The lowest pressure of 983 hPa was recorded over Darsi AWS (about 100 km west of Bapatla) at about 0100 UTC of 20 May, which does not seem to be correct as the system was still over the sea at that time.

Considering surface wind measured by coastal AWS, maximum wind of about 30 knots was reported by Bapatla in the forenoon of 20 May(Fig. 2.1.7).

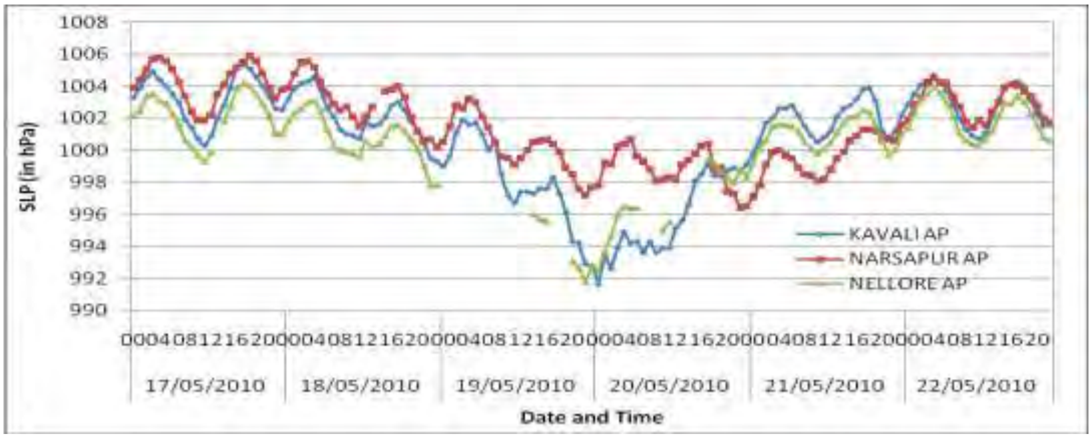


Fig.2.1.6: Variation of sea level pressure (SLP) recorded at AWS as the cyclone "LAILA" approached the coast.

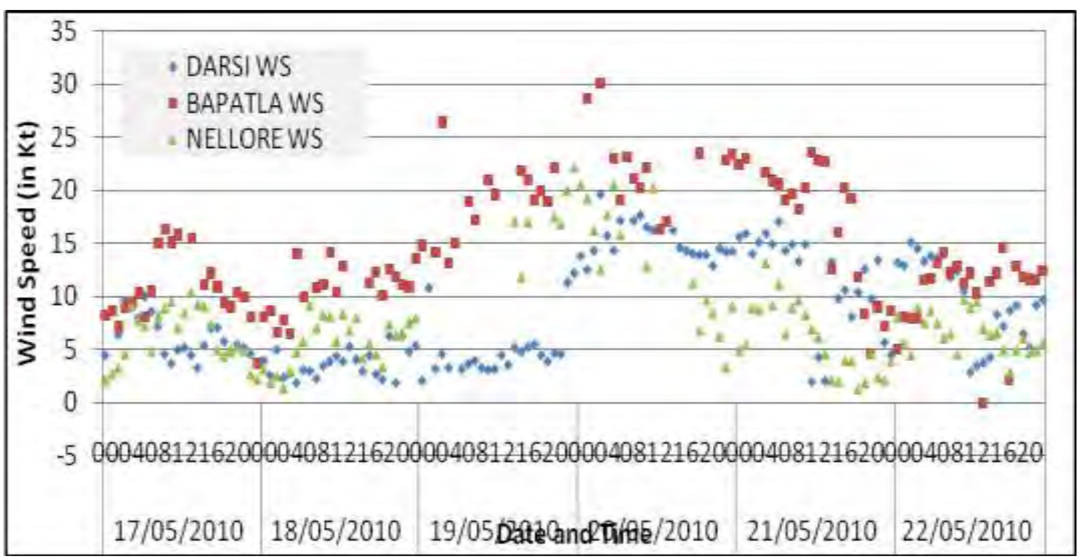


Fig. 2.1.7(a): Variation in wind speed recorded by AWS as cyclone "LAILA" approached the coast.

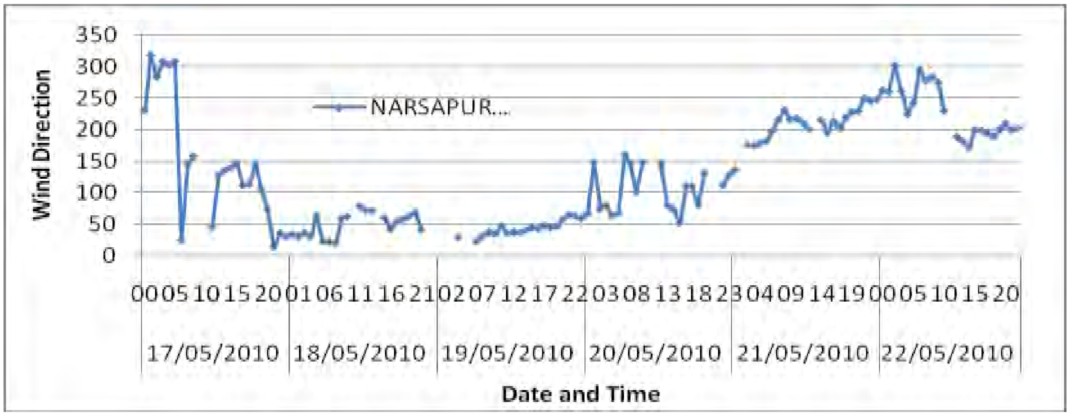


Fig. 2.1.7(b). Variation in Wind Direction recorded at Narsapur AWS as cyclone LAILA approached the coast.

The AWS network responded well during cyclonic storm LAILA except a few problems. The data reception from a few stations was intermittent. The variation of station level pressure, wind speed and wind direction and rainfall do not seem to be correct for a few stations.

2.1.6. Salient features of the system as seen by the DWR, Chennai:

i. **Reflectivity field**

Areal extent of reflectivity field in excess of 30 dBZ (~3 mm/hr) was relatively less (average radius ~ 300km), though detached bands of higher reflectivity could be seen occasionally in the southwest sector of the system. Vertical extent of reflectivity of 30 dBZ and higher was seen generally below 10 km above ground level. Reflectivity in excess of 50 dBZ (~50 mm/hr) were seen over the eye region and spiral bands. Eye of the cyclone with varying features (closed, circular, elliptical, ill defined etc) could be seen during the course of the system within the radar range. The radar based features and fixes from DWR, Chennai are shown in Table2.1.2. The typical DWR imageries are shown in Fig. 2.1.8-2.1.9.

ii. Velocity field

Maximum radial velocity recorded during the course of the system was around 48 mps at the height of 1 to 2 km agl, during the period around 06 to 09 UTC on 19th. As the arc of maximum wind was insufficient, radius of maximum wind could not be estimated with confidence. Analysis of Vertical time-section of wind over the radar station reveals that wind speed of the order of 65 knots prevailed above 1km to 4 km agl. Below 1km, speed gradually reduced and seen to be ~ 30 knots at 100 agl. The typical Volume Velocity Processing (VVP) imagery from DWR, Chennai is shown in Fig. 2.1.10.

Table 2.1.2. Cyclonic Storm LAILA - 18 to 20 May 2010: Radar based Features and Fixes (DWR, Chennai)

Date/ UTC	Estimated Centre				Radial wind		Motion speed	Remarks
	AZ deg	Range Km	LAT deg	LONG deg E	height km	Speed mps		
18/0900	090	390	13.052	83.910	-	30	---	
1000	090	370	13.054	83.725	-	30	---	
1 100	87.7	340	13.181	83.444	-	33	W /25	
1200	89.1	330	13.105	83.353	-	33	W /20	
1300	88.0	300	13.157	83.074	-	33	W/25	Irregular Eye
1400	88.0	285	13.153	82.934	-	38	W/23	Irregular Closed Eye
1500	87.5	270	13.171	82.794	-	36	W/20	Irregular Closed Eye
1600	91.0	260	13.024	82.704	-	36	W/18	Circular E e
1700	90.4	245	13.052	82.565	3.5	42	W/16	Circular Open Eye
1800	93.0	235	12.957	82.469	3.5	43	W/16	Elliptical Open Eye
1900	91.4	218	13.021	82.314	3.4	43	W/14	Elliptical Open Eye
2000	91.9	206	13.008	82.202	3.2	43	W/18	Elliptical Open Eye
2100	89.5	206	13.086	82.023	2.8	43	W/1 I	Circular Open Eye
2200	87.5	200	13.149	82.145	2.8	43	W/10	Circular Open Eye
2300	83.5	190	13.266	82.043	2.7	42	NW/09	Irregular Open Eye
19/0000	80.0	183	13.359	81.964	2.3	42	NW/09	Irregular Open Eye
0100	79.0	187	13.394	81.995	2.4	36	NW/05	Irregular Open Eye
0200	72.0	175	13.561	81.836	1.8	30	NW/12	Elliptical Open Eye
0300	66.0	160	13.662	81.648	1.7	38	NW/14	Circular Closed Eye
0400	57.4	156	13.833	81.511	1.6	43	NW/17	Irregular Open Eye
0500	66.0	144	13.603	81.512	1.5	43	NW/I1	Irregular Open Eye
0600	63.0	130	13.608	81.366	1.4	43	NW/12	Irregular Open Eye
0700	60.0	134	13.680	81.368	1.4	45	NW/12	Irregular Open Eye
0800	60.0	134	13.680	81.368	0.9	40	NW/10	Eye ill defined Confidence poor
0900	59.0	133	13.696	81.348	0.9	42	NW/05	Eye ill defined
1000	53.4	149	13.877	81.402	1.1	42	NW/02	Eye ill defined Confidence poor
1 100	51.6	151	13.922	81.390	1.5	36	NW/05	Eye ill defined Confidence poor
1200	49.5	156	13.990	81.393	1.9	30	N/07	Eye ill defined Confidence poor
1300	46.9	169	14.118	81.437	2.5	30	N/08	Eye ill defined Confidence poor
1400	42.4	174	14.236	81.380	2.2	36	N/10	Eye ill defined Confidence poor
1500	System features as seen in Radar image are insufficient to attempt centre fix							
2100	18.0	181	14.632	80.811	2.1	Eye ill defined, confidence poor.		

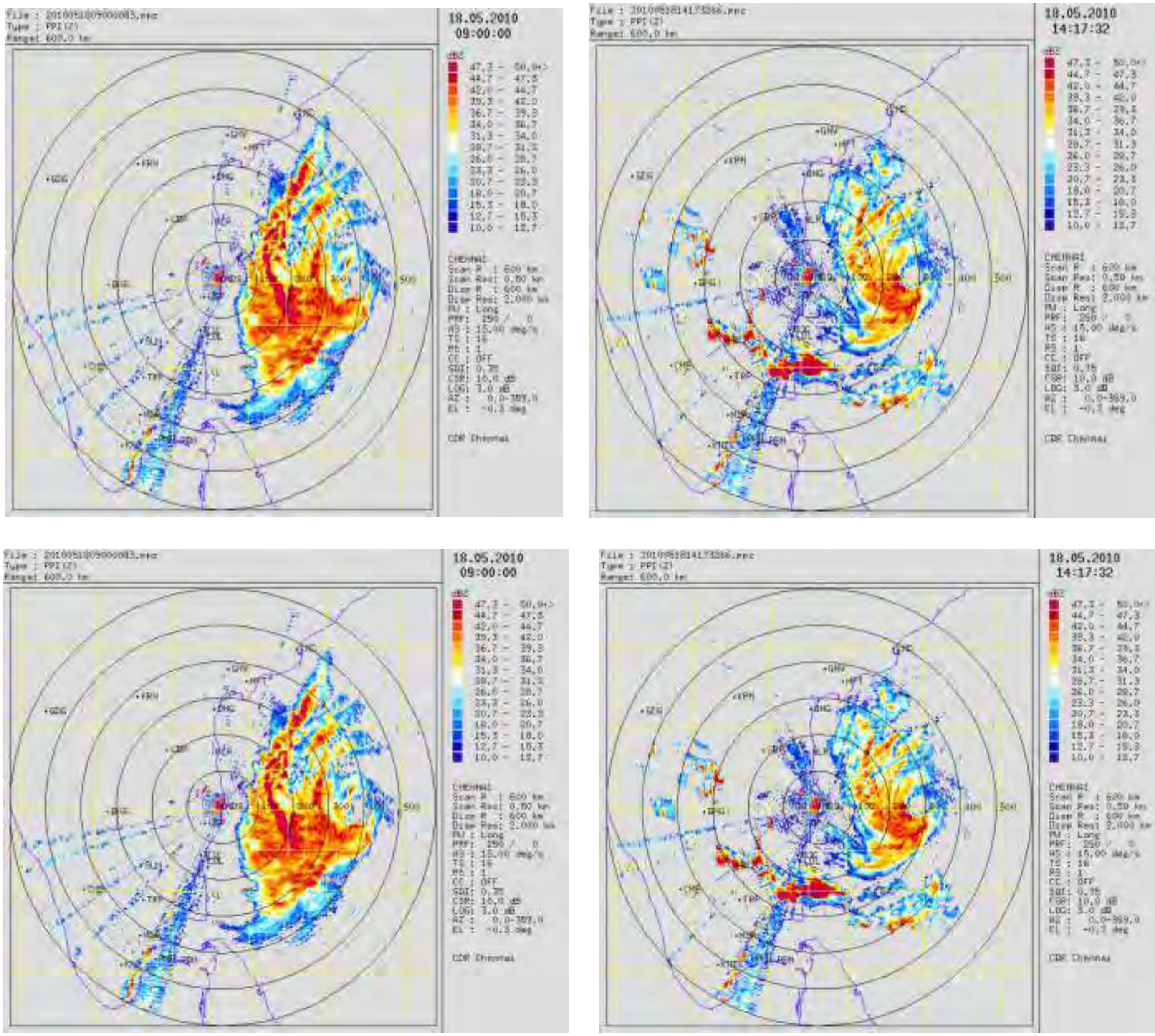


Fig. 2.1.8. Typical PPI(Z) imageries of SCS LAILA as observed by DWR Chennai

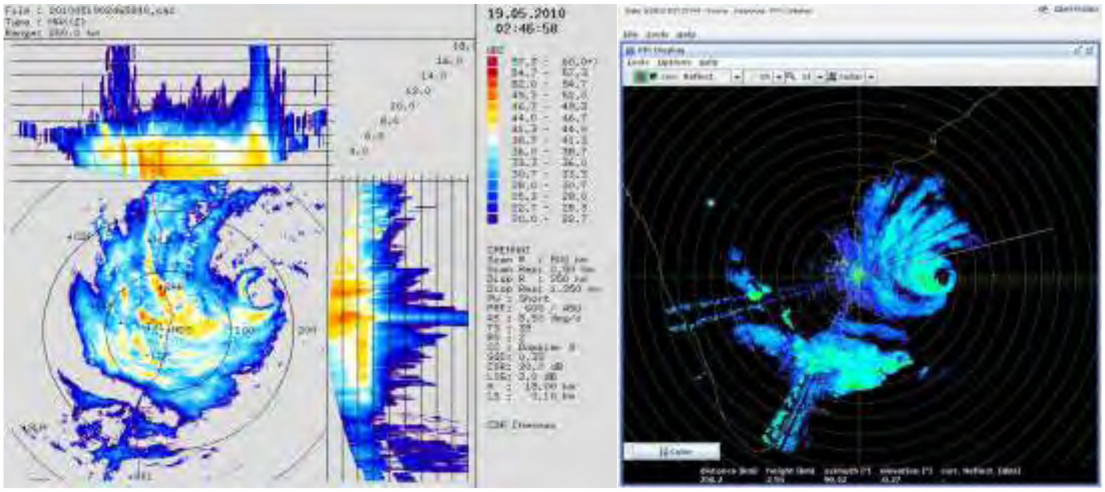


Fig.2.1.9. Typical Max(Z) and PPI imageries of SCS LAILA as observed by DWR Chennai

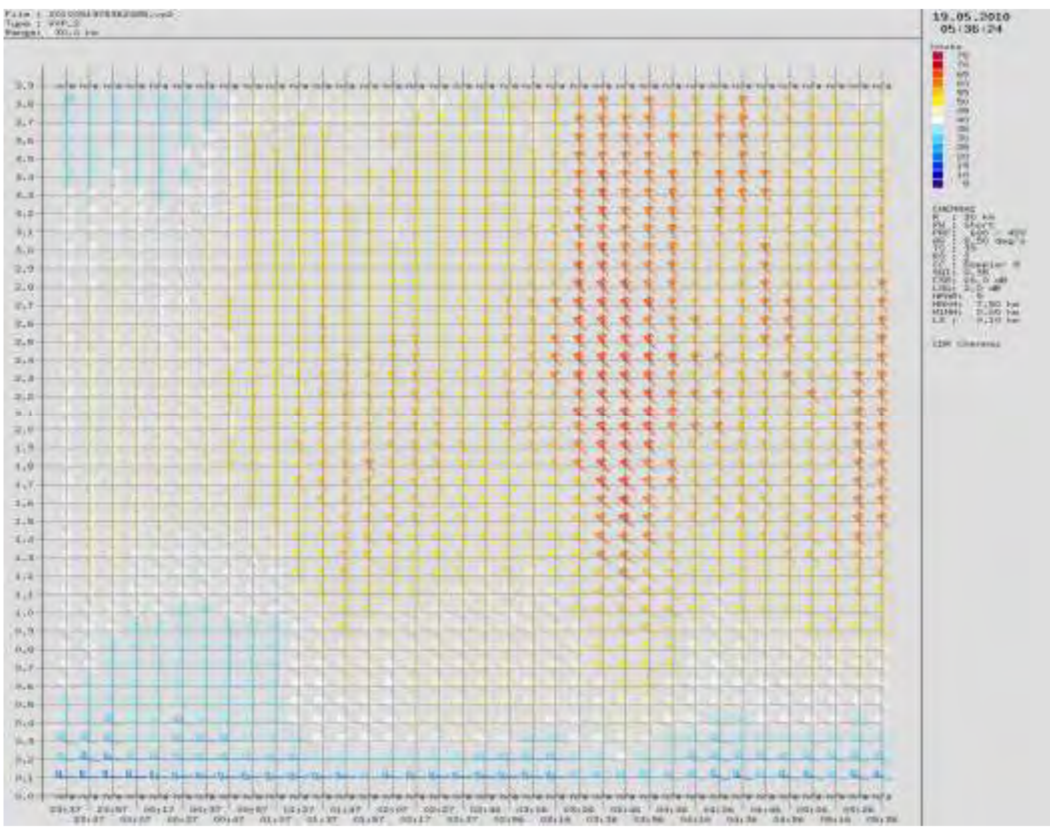


Fig. 2.1.10. Typical VVP imagery of SCS LAILA as observed by DWR, Chennai

2.1.7. Realised weather

(i) Heavy rain

Scattered heavy to very heavy rainfall with isolated extremely heavy rainfall occurred over coastal Tamil Nadu and Coastal Andhra Pradesh. Isolated heavy to very heavy falls also occurred over Orissa during 21-24 May, 2010. The chief amounts of rainfall (≥ 7 cm) as recorded at 0300 UTC of date are mentioned below. The spatial distributions of rainfall over Andhra Pradesh are shown in Fig.2.1.11.

19-05-2010

Tamil Nadu and Puducherry

Thozhudur (Cuddalore dt) 9 Chennai and Chennai airport 8 each, Anna University and DGP Office (both Chennai dt), Thiruvarur and Musiri (Thiruchirapalli dt) 7 each.

20-05-2010

Tamil Nadu and Puducherry:

Ponneri (Tiruvallur dt) 17, Cholavaram (Tiruvallur dt) 13, Chennai, Anna University (Chennai dt) and Tamaraipakkam (Tiruvallur dt) 11 each, DGP Office (Chennai dt) 10, Tiruvallur and Poondi (Tiruvallur dt) 9 each, Chennai Airport 8, Poonamally and Chembarambakkam (both Tiruvallur dt),Tiruttani and Arakonam (Vellore dt) 7 each.

Coastal Andhra Pradesh:

Kothapatnam 35, N.G.Padu 34, Ongole 32, Atchampet(G) 27, Maddipadu 26, Tangutur 22, chimakurthy 20, S. Konda 19, Narsapur 18, Tanuku & Tada 15 each, Sullurput 14, Pangalur & Amalapuram 13 each, Kandukur, Bhimavaram, Machilipatnam & Inkollu 12 each, Avanigadda, Chinaganjam, Konepi, Kaikalur, Kakinada Ulavapadu & Vetapalem 11 each, Bapatla, Chirala, Korisapadu, Koderu, Repalle , Kavali & Tadepalligudem 10 each, Nagram, Gudur, S.N.Padu, Vendatagiri Twon, Addanki & Bhattiprodu 9 each, Parchur, Karamchedu, Yaddanapudi, Gudlur, Gudivada , Nakirekallu, Kollurru, Darsi, Guntur & Rajahmundary 8, each Anakapalle, Elamanchili, Magalur, Panalur, Prathipadu, Tuni 7, Nellore 7, Peddapuram 7 each.

Rayalaseema:

Satyavedu 9, Trippathi AP 8, Rayadurg 8, Puttur 8, Srikalahasti 7

21-05-2010

Coastal Andhra Pradesh:

Addanki 52, Maadipadu 28 Chimakurthy, Nurendla, S.N. Padu 27 each, Tallur & Kothapatnam 26 each, Vinulonda 25, Savalyapuram 23, Bollapalli 20, Machavaram 19, Rompicherla, Tadepalle & Darsi 18 each, Nakirekkallu & N.G.

Padu 17 each, Kondepi 16, Manglagiri, Korisapadu, Zarugumalli, Kurichedu 15 each, Muundlamur, Tangulur. S. Konda & Ongole 14 each, Visakhapatnam AP, Elamanchili, Piduguralla, Bhimunipatnam, Bellamkonda & Duggirala 13 each, Pidugupalla, Vijayawada AP, Kandukur ,J. Pangulur & Donakonda 12 each, Vinjamur, Vizianagaram, karempudi, Ballikurava, Utavapadu, Pedakakani & Rajupalem 11 each, Podili, Narsipatnam, Visakhapatnam, Anakapalle, Dachepalli, Podili, Nadendila, Chebrolu & Thollur 10 each, Srungavarapukota, Cheepurupalli, Chodavaram, Bhimadole, Polavaram, Tiruvuru, Atchampet(G), Koyyalagudem & Tenali 9 each, Nandigama, Patapatnam, Chintalapudi, Guntur, Ranasthalam 8 each, Amalapuram,Sattenapalli, Paderu, Prathipsdu, Sompeta, Kalingapatanam, Tuni 7 each.

Rayalaseema:
Penukonda 10, Holagunda 7.

Orissa:
Paralachemundi 9.

22-05-2010
Coastal Andhra Pradesh:
Tiruvuru 25, Nuzvid 15, Palasa 11, Ichapuram 10, Chintalapudi 10, Salur 10, Sompeta 9, Mandasa, Tekkali 7 each.

Telngana:
Madhira 12, Yellandu 10, Venkatapuram 10, Bhadrachalam 9, Eturnagaram 7.

Orrisa:
Gopalpur 10, Berhmpur 9, Chhatrpur 8, Purushottampur 7, Krishnaprasad 7, Umarkote 7.

23-05-2010
Orissa:
Gopalpur 14, Athagarh 13, Dhenkanal & Berhmpur 10 each, Tikabali, Purushottampur & Chhatrpur 8 each, Rajkishorenagar & Krishnaprasad 7 each.

24-05-2010.
Orissa:
Jaipur & Gopalpur 9 each, Nilgiri & Berhmpur 8.

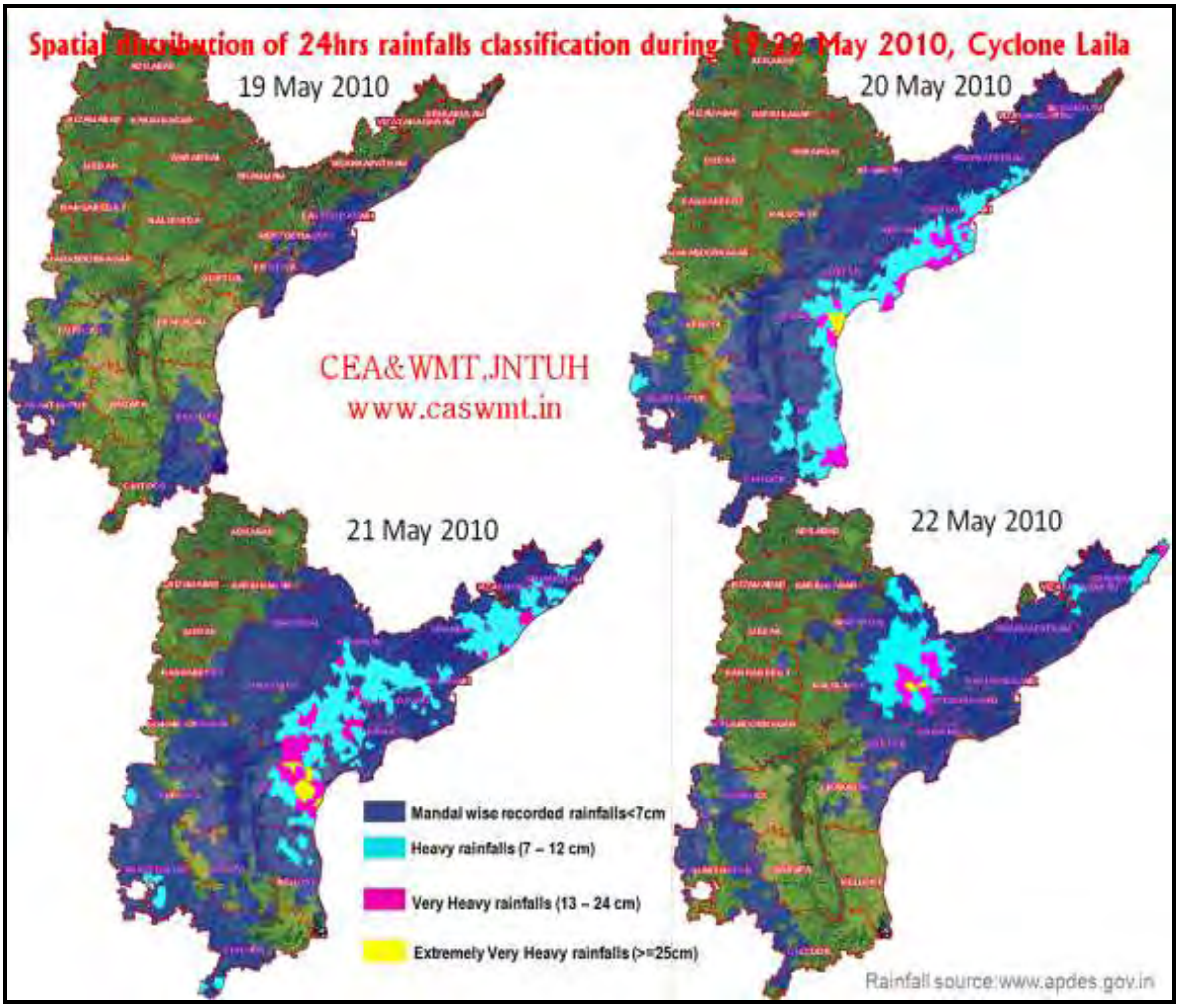


Fig. 2.1.11. Spatial distribution of rainfall over Andhra Pradesh due to SCSLAILA

(ii) Wind

Gale winds speed reaching 90-100 kmph were reported by the meteorological observatories of IMD. The damage caused by the cyclone suggests the wind speed of 90-100 kmph along coastal Andhra Pradesh at the time of landfall. The maximum wind of 53 kt was reported by Surya Lanka India Air Force (IAF) station near Bapatla. The high wind speed recorder at Machilipatnam recorded maximum surface wind of 59 knots

(iii) Storm surge

The storm surge of 2 to 3 meters inundated the low lying areas of Guntur, Prakasham, West & East Godavari districts.

2.1.8. Damage

- Number of human deaths : 06

Following are the damages over Andhra Pradesh due to cyclone, according to sources of Andhra Pradesh Government. Two typical photographs showing damage/ loss are shown in Fig. 2.1.12.

Agriculture department

- 11,351 Ha of agricultural crop are damaged so far as per the preliminary reports.
    - Prakasam 6320
    - Krishna 4000
    - Prakasam – 800
    - Kadapa – 396
    - Nellore – 347
    - East Godavari - 288

Horticulture department

- 7949 Ha of horticulture crop are damaged so far as per the preliminary reports.
    - Nellore 3383
    - Prakasam – 2220
    - Kadapa – 830
    - Guntur 604
    - Krishna 560
    - West Godavari -315
    - Ananthapur – 32
    - East Godavari – 4

Fisheries department

2 Fishermen missing in Krishna district.

416 **boats lost** worth Rs 87.25 lakhs.

- 260 in Prakasham
- 155 Krishna
- 1 Vizianagaram

Total 1643 **boats damaged** worth Rs 139.59 lakhs

- 679 in Krishna
- 355 in Nellore
- 540 Prakasham
- 30 Guntur
- 20 Visakhapatnam
- 16 srikakulam
- 3 Vizianagarm

Total 3648 **nets lost** worth Rs 297.83 lakhs.

- 1545 Krishna
- 1200 Prakasham

- 615 Guntur
- 245 Nellore
- 23 Vizianagaram
- 17 Visakhapatnam
- 3 Srikakulam

762 Ha of brackish water culture ponds inundated worth Rs 547 lakhs.
181.20 Ha of fresh water culture ponds inundated worth Rs 28.50 lakhs.

Energy department

- 58 electric substations (33 KV) affected. Electricity is affected in 692 villages.

Irrigation department

- 5 Minor Irrigation tanks damaged (3 in Prakasham, 1 in Nellore, 1 Chittoor).
- In East Godavari, Chagalnadu lift irrigation project canal is breached for 7 meters.

Housing department

- 172 houses damaged fully and 265 partly damaged so far.

Roads & Buildings department

- 3 overflows. Traffic restored at one location at KM 253/0 of D-O section of NH 214 A. Traffic interruption is still there at two other locations i.e. 209/6 and 226/0 of D-O section of NH-214 A as overflow is yet to recede.
- One R & B road breached at Prakasham district.
- 2 roads damaged (9.7 KM) in West Godavari.
- 300 meters of R&B road is damaged in Nellore district.

Animal husbandry department

- 367 domestic animals including 60 cows, 302 sheep and goat worth Rs 24.65 lakhs died.
- 57 Veternary buildings damaged worth Rs 285 lakhs.
- 475 Metric Tonnes of fodder damaged in Krishna worth Rs 11.87 lakhs.

Fig.2.1.12 Damage over Andhra Pradesh Due to cyclone LAILA during 17-21, May 2010

2.2 Cyclonic Storm, „BANDU' (19-23 May, 2010)

2.2.1. Introduction:

A cyclonic storm, „BANDU' developed over the southwest Arabian Sea on 19 May. Moving in a west northwesterly direction, it dissipated over the Gulf of Aden before landfall, mainly due to colder Sea. The characteristic features of the system are discussed below.

2.2.2. Genesis

During onset phase of monsoon, a low pressure area formed over the southwest Arabian Sea on 18 May in association with persistent convection over the region. A low level cyclonic circulation was observed in the INSAT imagery on that day. Due to favourable conditions like warmer SST, higher Ocean thermal energy and favourable modulation of convection by the Madden Julian Oscillation (MJO), the low level circulation concentrated into a vortex (T1.0)over the same region on 18 May evening (1200 UTC) and in the surface chart, the low pressure area became well marked.. The well marked low pressure area concentrated into a depression with T1.5 at 0900 UTC of 19 May 2010 over southwest Arabian Sea near lat. 10.5^0N and long. 54.0^0E (Table 2.2.1). The genesis of the system was captured also by the Ocean surface wind as derived from Oceansat-II satellite (Fig.2.2.1).

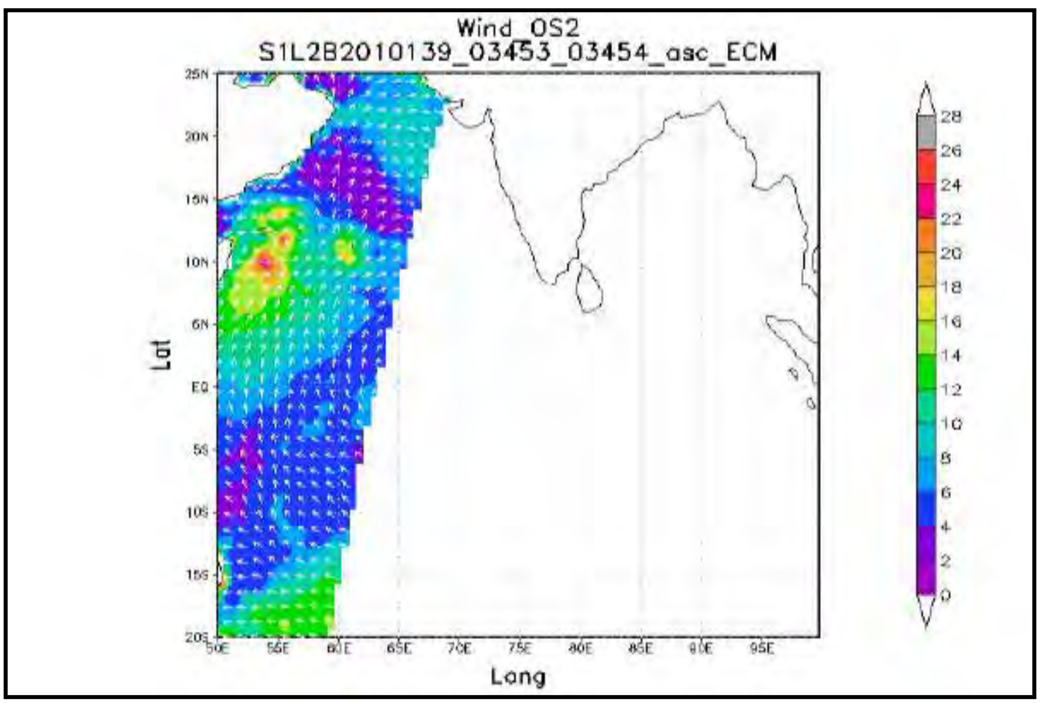


Fig.2.2.1. Genesis of cyclone, „BANDU' as captured by Oceansat-II (wind speed in metre per second) at 0850 UTC of 19 May 2010

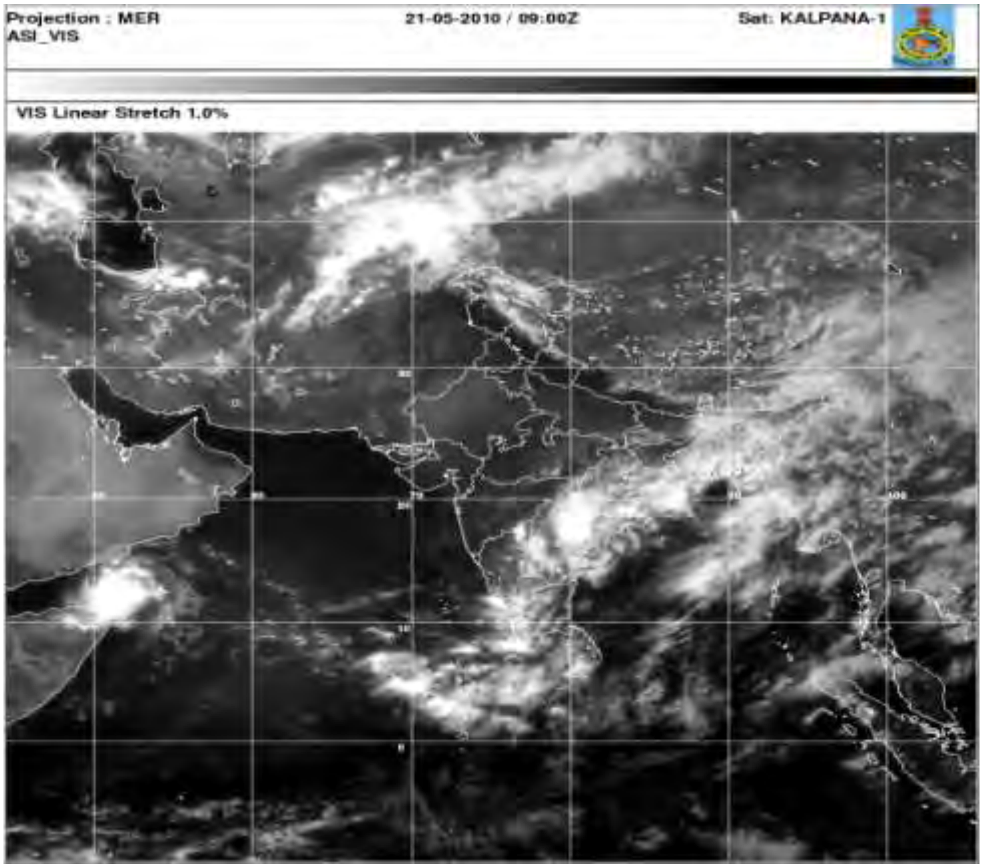


Fig. 2.2.2. Kalpana-1 imagery of BANDU: 21 May of 2010(0900 UTC)

2.2.3. Intensification and Movement

Due to continued favourable environmental conditions, the depression moved northwestwards and intensified into a deep depression over southwest Arabian Sea, near lat. 11.5^0N and long. 53.5^0E at 1800 UTC of 19 May. It then moved west-northwestwards and gradually intensified into a cyclonic storm, „BANDU' over westcentral Arabian Sea near 12.5^0N and long. 51.5^0E at 1200 UTC of 21 May 2010. However, due to interaction with land surface and colder Sea, it gradually weakened and dissipated over Gulf of Aden. It weakened into a deep depression at 1200 UTC and into a depression at 1800 UTC of 22 May. Further, it weakened into a low pressure area at 0000 UTC of 23 may 2010. The track of the system is shown in Fig.2.1. The best track parameters are shown in Table 2.2.1. The typical satellite imageries of cyclone, Bandu is shown in Fig.2.2.2.

Table 2.2.1. Best track positions and other parameters of the cyclonic storm BANDU" over the Arabian Sea during 19-23 May, 2010

Date	Time (UTC)	Centre lat.^{0} N/ long. ^{0} E	C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
19.05.2010	0900	10.5/54.0	1.5	1002	25	3	D
	1200	11.0/54.0	1.5	1002	25	3	D
	1500	11.5/53.5	1.5	1002	25	4	D
	1800	11.5/53.5	2.0	1000	30	5	DD
	2100	11.5/53.0	2.0	1000	30	5	DD
20.05.2010	0000	11.5/53.0	2.0	1000	30	5	DD
	0300	11.5/53.0	2.0	999	30	5	DD
	0600	11.5/53.0	2.0	999	30	5	DD
	0900	12.0/53.0	2.0	999	30	5	DD
	1200	12.5/52.5	2.0	999	30	5	DD
	1800	12.5/51.5	2.0	999	30	5	DD
21.05.2010	0000	12.5/51.5	2.0	998	30	5	DD
	0300	12.5/51.5	2.0	998	30	5	DD
	0600	12.5/51.5	2.0	998	30	5	DD
	0900	12.5/51.5	2.0	996	30	6	DD
	1200	12.5/51.5	2.5	994	40	8	CS
	1500	12.5/51.5	2.5	994	40	8	CS
	1800	12.5/51.5	2.5	994	40	8	CS
	2100	12.5/51.0	2.5	994	40	8	CS
22.05.2010	0000	12.5/50.5	2.5	994	40	8	CS
	0300	12.5/50.5	2.5	994	40	8	CS
	0600	12.5/50.5	2.5	994	40	8	CS
	0900	12.5/50.0	2.5	996	35	7	CS
	1200	12.5/50.0	2.0	998	30	5	DD
	1800	12.5/50.0	1.5	1000	25	3	D
23.05.2010	0000	Weakened into a well marked low pressure area over the Gulf of Aden					

The dynamic parameters based on 0000 UTC ECMWF analysis of 21 May 2010 indicating favourable upper level divergence, lower level vorticity, upper air wind at 200 hPa level and vertical wind shear are shown in Fig 2.2.3. Similar parameters on 22 and 23 May 2010 suggesting weakening of the system are shown in Fig. 2.2.4 and 2.2.5.

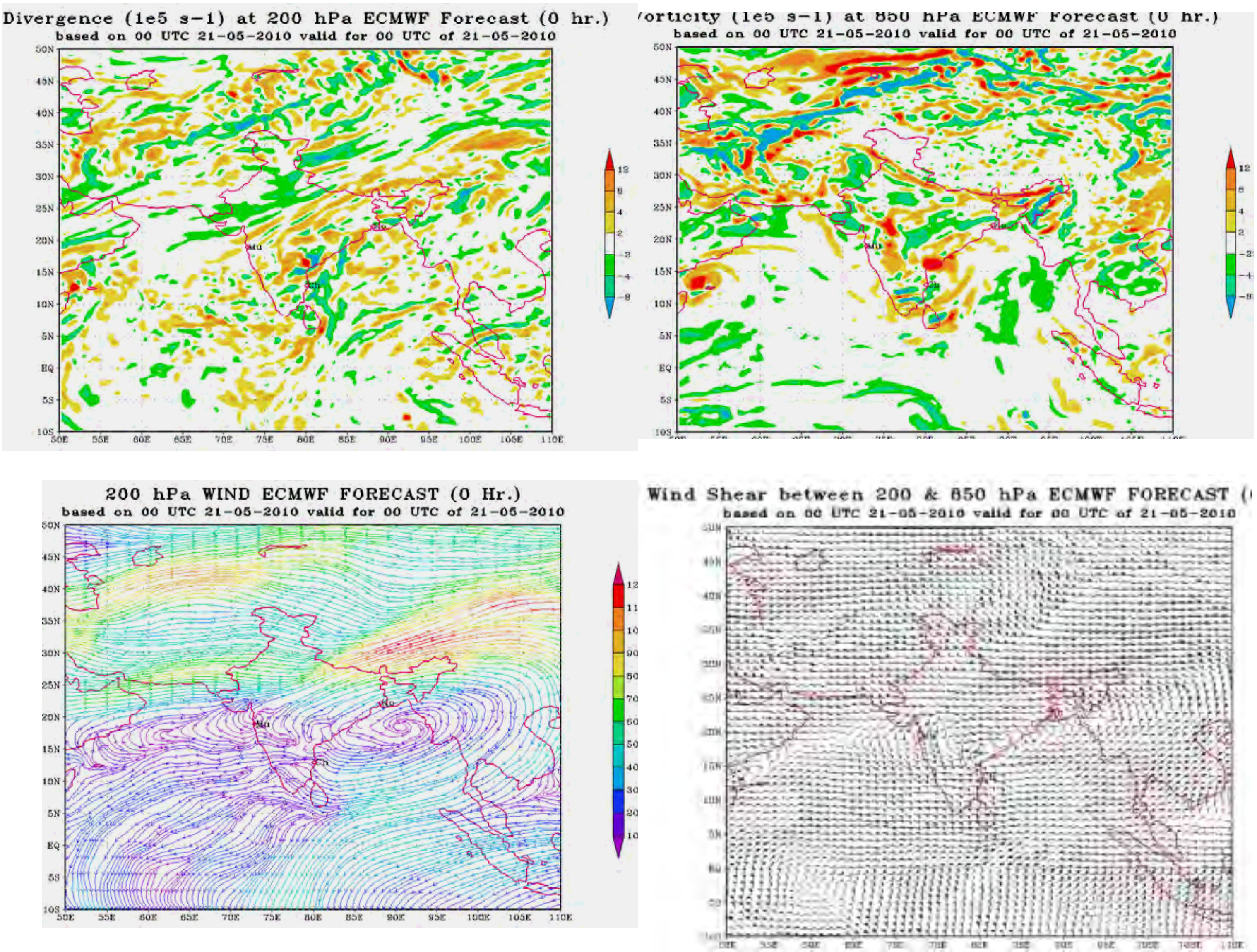


Fig. 2.2.3. ECMWF analysis (a) Divergence at 200 hPa level, (b) Vorticity at 850 hPa level, (c) wind at 200 hPa level and (d) Vertical wind shear between 200 and 850 hPa level at 0000 UTC of 21 May 2010

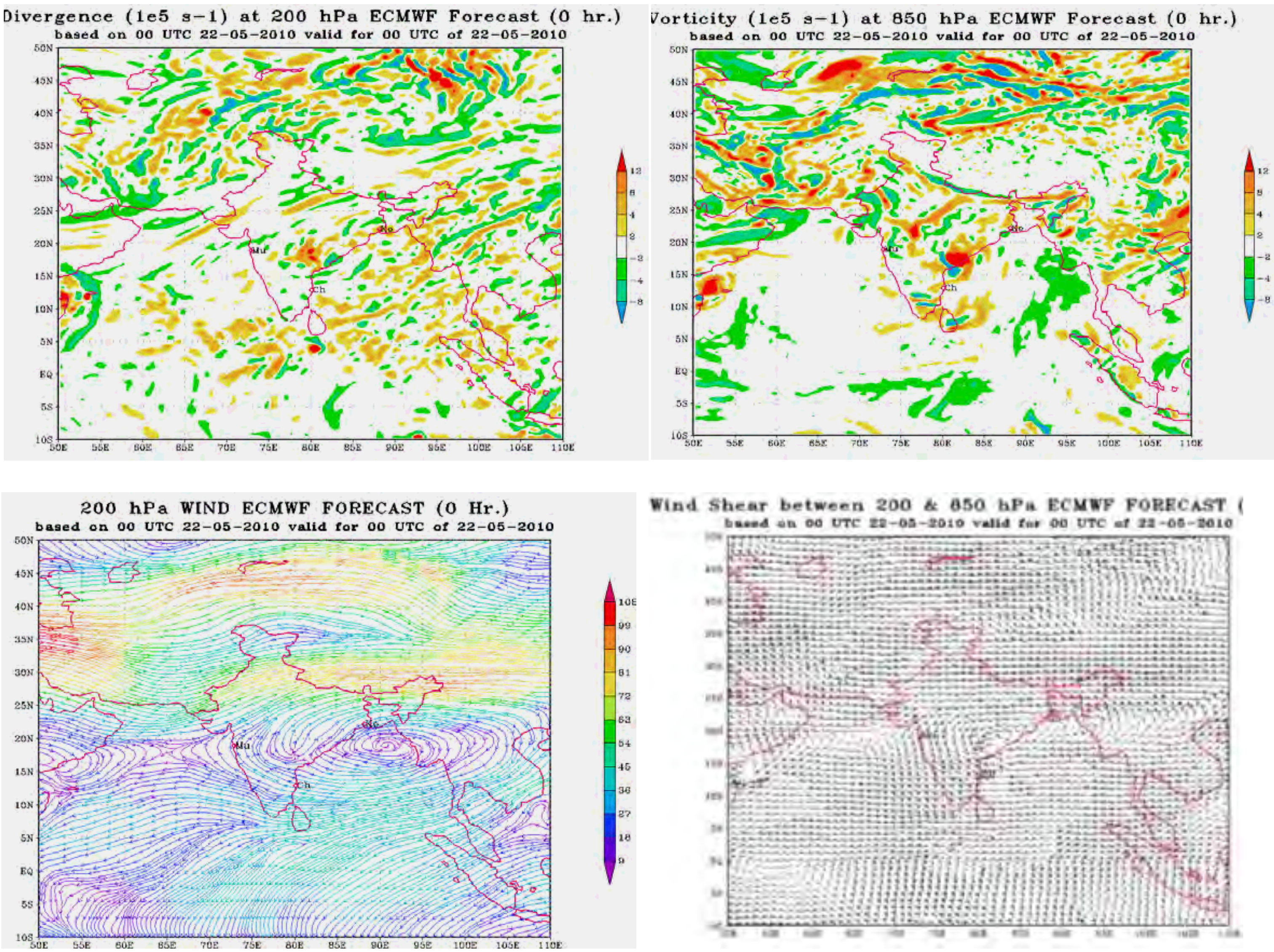


Fig. 2.2.4. ECMWF analysis (a) Divergence at 200 hPa level, (b) Vorticity at 850 hPa level, (c) wind at 200 hPa level and (d) Vertical wind shear between 200 and 850 hPa level at 0000 UTC of 22 May 2010

2.2.4. Structure

The lowest ECP of the system was 994 hPa with pressure drop of 8 hPa. The The maximum wind was estimated to be about 40 knots. According to satellite imagery, the structure of the system was curved band type with intensity of T2.5. The depth of intense convection was very high during cyclonic storm stage with lowest cloud top temperatures ranging from -75 to -85 deg. C. It was maximum at 2100 UTC of 21 May 2010.

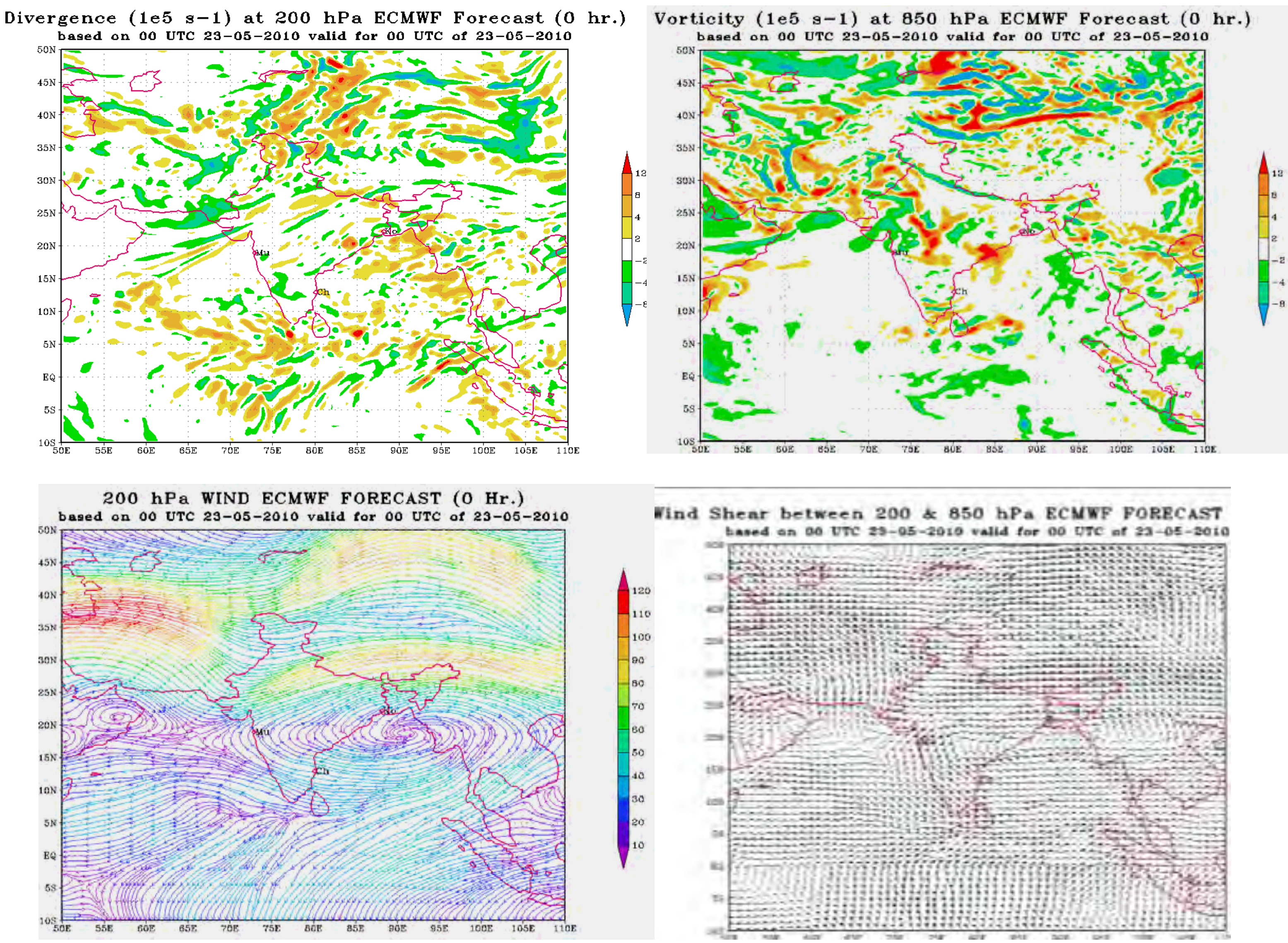


Fig. 2.2.5. ECMWF analysis (a) Divergence at 200 hPa level, (b) Vorticity at 850 hPa level, (c) wind at 200 hPa level and (d) Vertical wind shear between 200 and 850 hPa level at 0000 UTC of 23 May 2010

2.2.5. Realised weather:

The system caused heavy rain in Somalia and Yemen.

2.2.6. Damage

As the system weakened over the Sea, there was no damage over these countries due to wind and tidal wave.

2.3. Very severe cyclonic storm, „PHET' over the Arabian Sea (31 May – 07 June 2010)

2.3.1. Introduction

A very severe cyclonic storm, „PHET' developed over the Arabian Sea and crossed Oman coast with the wind speed of about 65 kt (125 kmph) near latitude 21.5^{0}N between 0000 and 0200 UTC of 4 June 2010. It then continued to move northwards, emerged into northwest Arabian Sea and then recurved eastwards and weakened gradually. It moved parallel to but close to Makaran coast and crossed Pakistan coast as a depression, close to south of Karachi between 1230 and 1330 UTC of 6 June. The salient features of this system are as follows.

- It was the rarest of the rare track in Arabian Sea as per the recorded history during 1877-2009.
- It was one of the longest tracks in recent years. The life period of the cyclone was also longer, as it was 8 days against the normal of 4-5 days.
- It had two landfall and affected three countries, viz., Oman, Pakistan and India
- The system weakened before landfall and crossed Oman as a severe cyclonic storm and Pakistan as a depression.

2.3.2. Genesis

In association with the southerly surge of monsoon during its onset phase, solid convective cloud cluster persisted over southeast and adjoining eastcentral Arabian Sea for a considerable period of time. At 0600 UTC of 30 May, it was assigned a low level circulation and at 1200 UTC of the same day, it was declared as a vortex centered at lat. 14.0^{0}N and long. 65.0^{0}E with intensity of T1.0 according to Dvorak's scale. Accordingly, it was declared as a low pressure area on 30 May, 2010. The low pressure area moved in a northwesterly direction and concentrated into a depression over the same region at 0300 UTC of 31 May 2010 with centre near lat. 15.0^{0}N and long. 64.0^{0}E. The track of the system is shown in Fig.2.1. The best track parameters are shown in Table 2.3.1.

Considering the environmental features; the SST was warmer (30-32^{0}C) and the tropical cyclone heat potential was more than 100KJ/cm^2 (Fig.2.3.1) over the region with depth of 26^{0}C isotherm extending upto more than 100 metres. The upper level divergence and lower level relative vorticity were also favourable for cyclogenesis and suggested further intensification as shown in Fig.2.3.2. There was deep convection in association with the system as the lowest CTT was -75$^{0\ C}$ at the time of formation of depression. There was moderate vertical wind shear favouring the genesis of the system

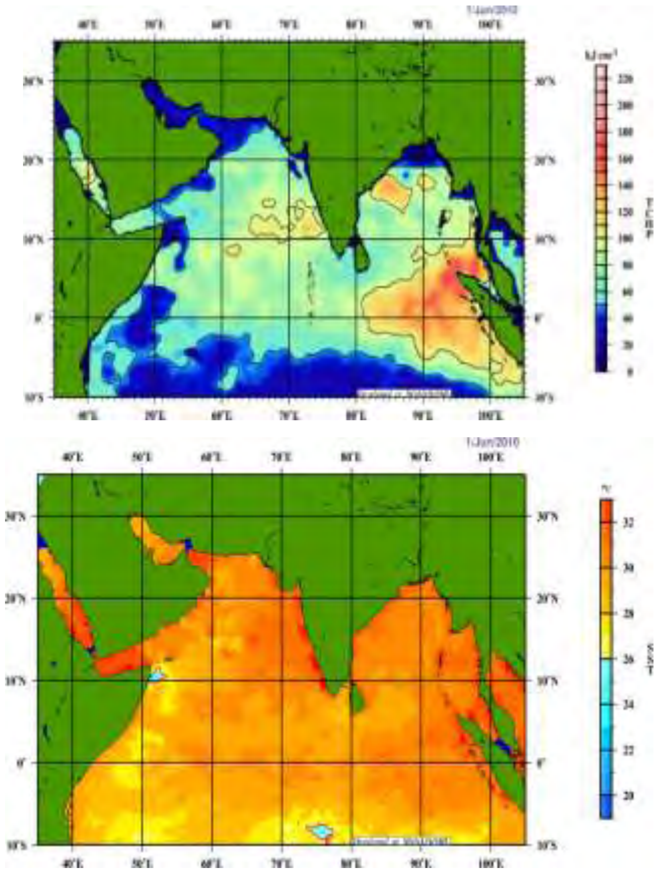


Fig.2.3.1. Tropical Cyclone Heating Potential (TCHP) and Sea Surface Temperature (SST) during genesis of cyclone, „PHET'.

2.3.3. Intensification and movement

As the favourable conditions as discussed above with reduction of vertical wind shear (Fig.2.3.3 & 2.3.5) and increase in deep convection (lowest CTT=-80^0 C), the depression at 0000 UTC of 1 June, it intensified into a deep depression . At 0600 UTC of 1 June, when the system was centred near lat. 16.0^0N/long. 63.0^0E, the signs of rapid intensification were observed. It intensified into a cyclonic storm, PHET at 0900 UTC of 1 June with T2.5 and center near lat. 16.0^0N/long. 63.0^0E. The system intensified into a severe cyclonic storm at 0000 UTC of 2 June, when its eye was visible and the center was located near lat 17.5^0N/long. 61.0^0E. It further intensified into a very severe cyclonic storm with T4.0 at 0600 UTC of 2 June remaining practically stationary over the region. The intensity was increased to T4.5 with center at 18.0N/60.5E. The system was slowly moving north-westwards. At 0000 UTC of 3 June, signs of weakening were observed in the system and the intensity was decreased to T4.0. It maintained its north-westwards movement with intensity T4.0 and crossed Oman coast between 0000 & 0200 UTC of 3 June near lat. 21.5^{0}N. After crossing over to land, it assumed north/north-easterly movement. At 1200 UTC of 4 June it again entered into Sea with intensity T3.5. At 2300 UTC of 4 June signs of rapid weakening of the system were observed and the system weakened into a cyclonic storm with T3.0 at 0000 UTC of 5 June. Again its intensity was decreased to T2.5 at 0300 UTC of 5 June. It crossed the Pakistan coast close to south of Karachi between 1230 and 1330 UTC of 6 June 2010. . It then moved east-northeastwards across south Pakistan and Rajasthan and weakened gradually into a well marked low pressure area over east Rajasthan and adjoining northwest Madhya Pradesh in the evening of 7 June. It was the rarest of the rare track in Arabian Sea as per the recorded history during 1877-2009. It was one of the longest tracks in recent years. The life period of the cyclone was also longer.

Table 2.3.1. Best track positions and other parameters of the Very Severe Cyclonic Storm (VSCS) "PHET" over the Arabian Sea during 31 May – 7 June, 2010

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
31-05-2010	0600	15.0/64.0	1.5	1001	25	3	D
	1200	15.5/63.5	1.5	1001	25	3	D
	1800	15.5/63.5	1.5	999	25	4	D
01-06-2010	0000	15.5/63.5	2.0	998	30	5	DD
	0300	15.5/63.5	2.0	998	30	5	DD
	0600	16.0/63.0	2.0	996	30	5	DD
	0900	16.0/63.0	2.5	995	35	7	CS
	1200	16.5/62.5	2.5	994	35	7	CS
	1500	16.5/62.5	2.5	992	40	8	CS
	1800	17.0/62.0	3.0	990	45	10	CS
	2100	17.0/62.0	3.0	990	45	10	CS
02-06-2010	0000	17.5/61.5	3.5	986	55	15	SCS
	0300	17.5/61.0	3.5	984	60	18	SCS
	0600	17.5/61.0	4.0	978	70	24	VSCS
	0900	18.0/60.5	4.5	968	80	32	VSCS
	1200	18.0/60.5	4.5	964	85	36	VSCS
	1500	18.5/60.0	4.5	964	85	36	VSCS
	1800	18.5/60.0	4.5	966	85	36	VSCS
	2100	18.5/60.0	4.5	970	80	32	VSCS
03-06-2010	0000	18.5/59.5	4.0	974	75	28	VSCS
	0300	18.5/59.5	4.0	974	75	28	VSCS
	0600	19.0/59.5	4.0	978	70	24	VSCS

	0900	19.5/59.5	4.0	978	70	24	VSCS
	1200	20.0/59.5	4.0	978	70	24	VSCS
	1500	20.0/59.5	4.0	978	70	24	VSCS
	1800	20.5/59.5	4.0	980	65	22	VSCS
	2100	21.0/59.5	4.0	980	65	22	VSCS
04-06-2010	0000	21.5/59.5	4.0	980	65	22	VSCS
	The system crossed Oman coast near lat. 21.5^0 N between 0000 & 0200 UTC.						
	0300	22.0/59.5	--	982	60	18	SCS
	0600	22.0/59.5	--	984	60	18	SCS
	0900	22.5/59.5	--	984	60	18	SCS
	1200	23.0/59.5	3.5	984	60	18	SCS
	1500	23.0/59.5	3.5	986	55	16	SCS
	1800	23.0/59.5	3.5	988	55	14	SCS
	2100	23.5/60.0	3.5	990	50	12	SCS
05-06-2010	0000	24.0/60.5	3.0	990	45	10	CS
	0300	24.5/61.0	2.5	992	40	8	CS
	0600	24.5/61.0	2.5	992	40	8	CS
	0900	24.5/61.0	2.5	992	40	8	CS
	1200	24.5/61.5	2.5	992	40	8	CS
	1500	24.5/62.0	2.5	994	35	7	CS
	1800	24.5/62.5	2.0	994	30	5	DD
	2100	24.5/63.0	2.0	994	30	5	DD
06-06-2010	0000	24.5/64.0	2.0	994	30	5	DD
	0300	24.5/65.0	1.5	994	25	4	D
	0600	24.5/66.0	1.5	994	25	4	D
	0900	24.5/66.5	1.5	994	25	4	D
	1200	24.5/67.0	1.5	993	25	4	D
	The system crossed Pakistan coast, close to south of Karachi (near 24.7 ^{0}N and 67.2^{0}E between 1230 and 1330 UTC.						
	1500	25.0/68.0	--	993	25	4	D
	1800	25.0/69.0	--	991	25	5	D
07-06-2010	0000	26.5/71.0	--	993	25	5	D
	0300	26.5/71.5	--	993	25	5	D
	0600	26.5/72.5	--	995	20	3	D
	1200	Weakened into a well marked low pressure area over east Rajasthan and adjoining northwest Madhya Pradesh					

The dynamical parameters suggesting weakening of the system from 4 June onwards are shown in Fig.2.3.6-8. The INSAT imageries at different stages of intensity are showing Fig. 2.3.9.

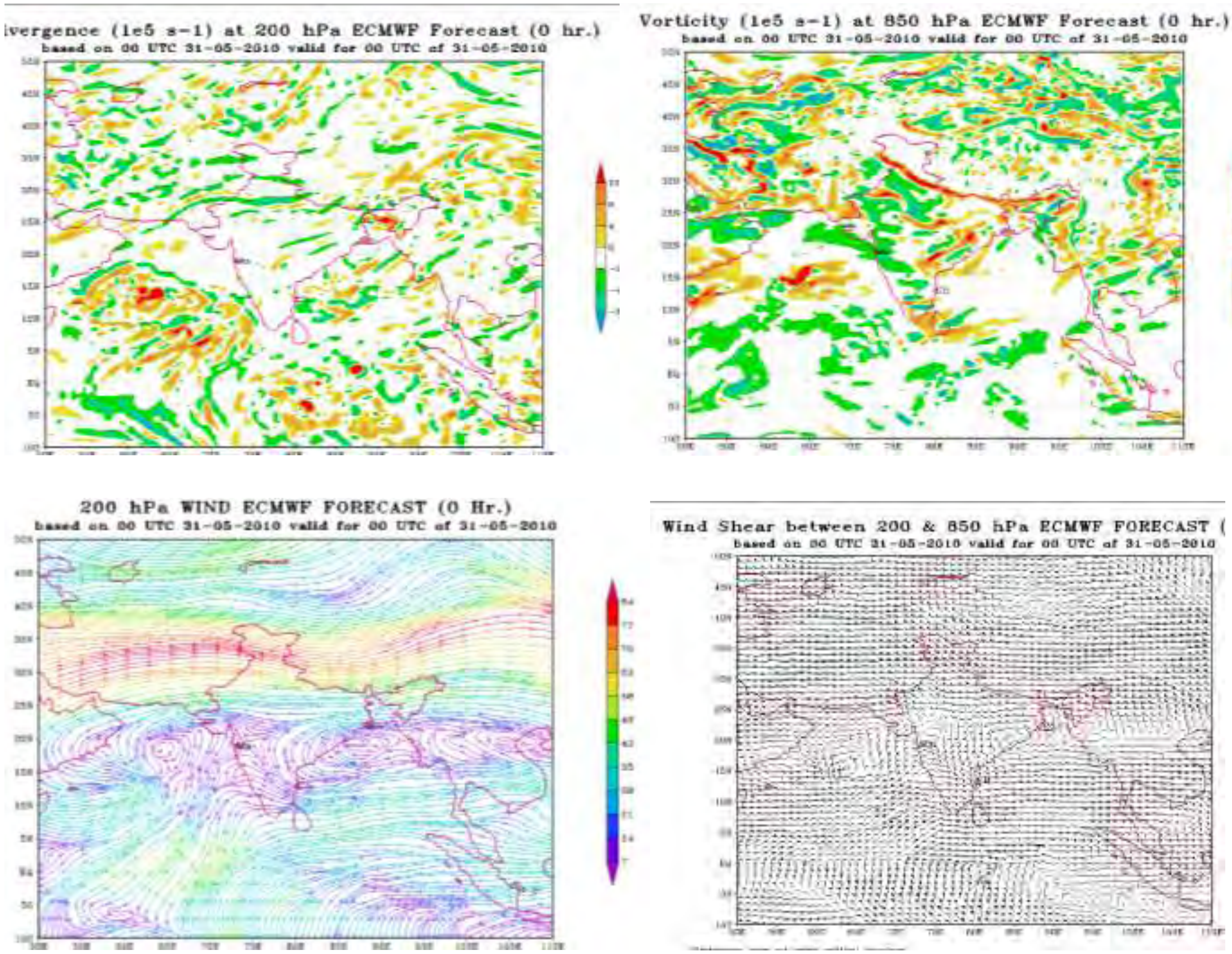


Fig.2.3.2. ECMWF analysis (a) Divergence at 200 hPa level, (b) Vorticity at 850 hPa level, (c) wind at 200 hPa level and (d) Vertical wind shear between 200 and 850 hPa level at 0000 UTC of 31 May 2010

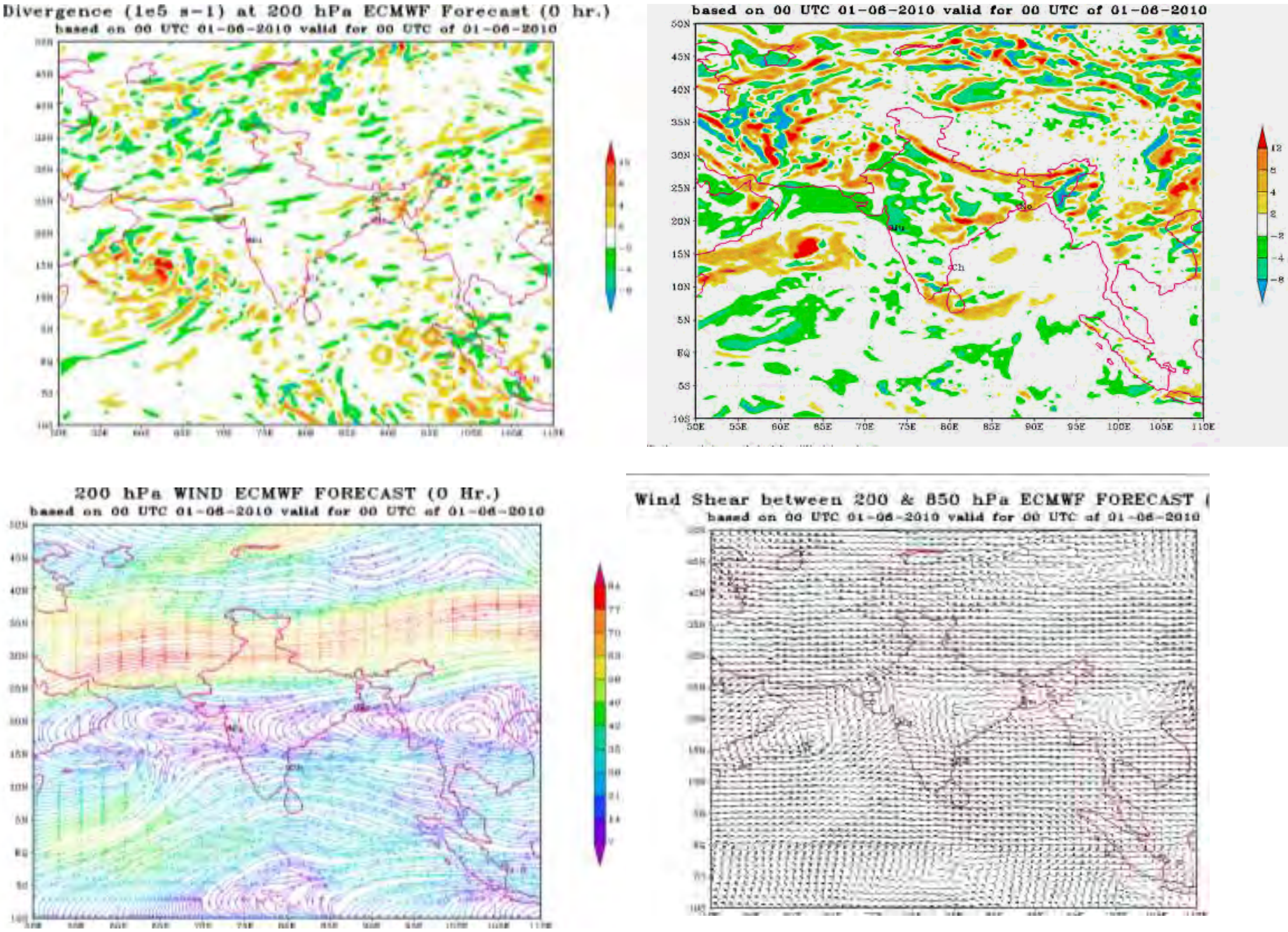


Fig.2.3.3. ECMWF analysis (a) Divergence at 200 hPa level, (b) Vorticity at 850 hPa level, (c) wind at 200 hPa level and (d) Vertical wind shear between 200 and 850 hPa level at 0000 UTC of 01 June 2010

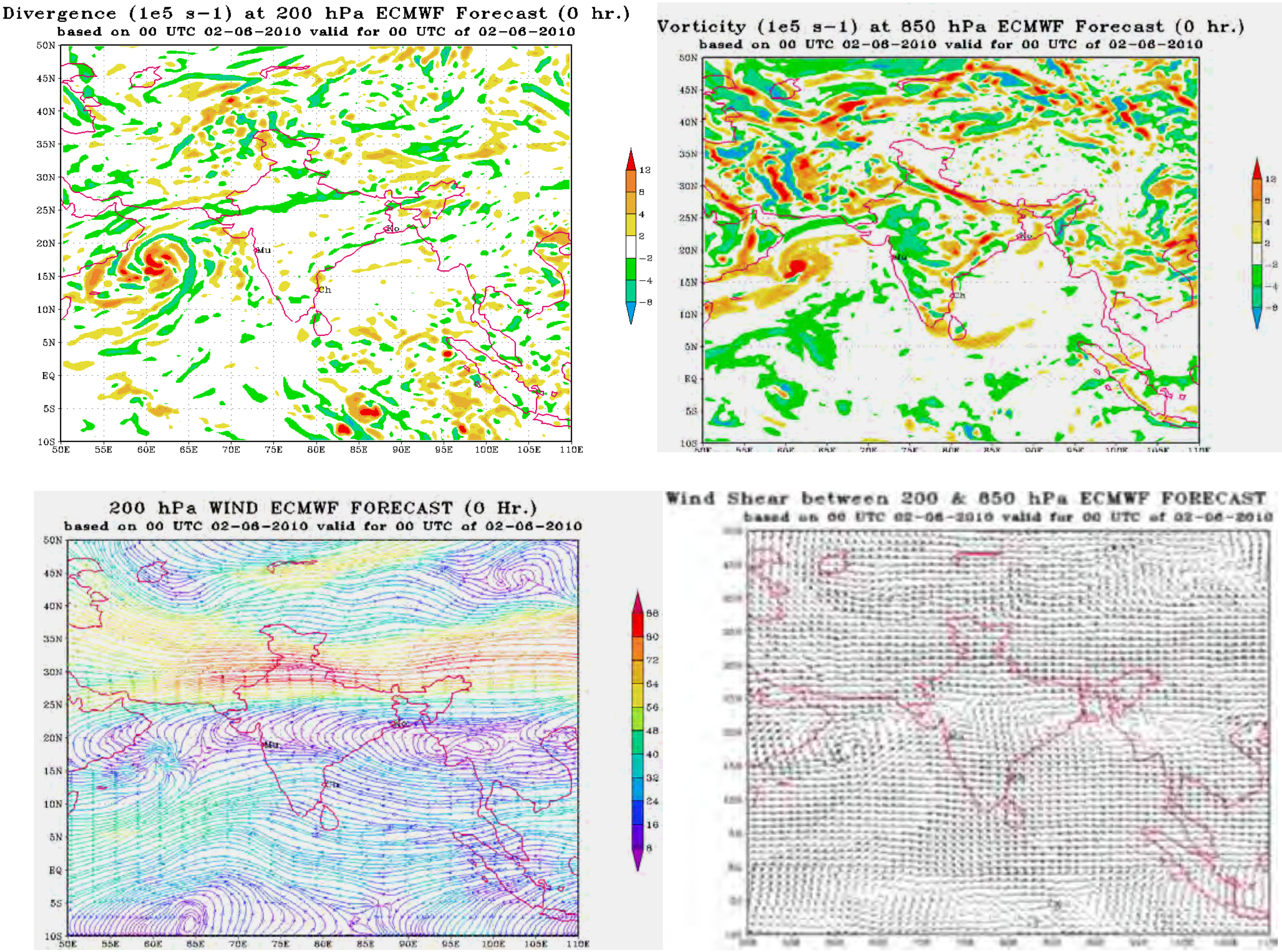


Fig.2.3.4 ECMWF analysis (a) Divergence at 200 hPa level, (b) Vorticity at 850 hPa level, (c) wind at 200 hPa level and (d) Vertical wind shear between 200 and 850 hPa level at 0000 UTC of 02 June 2010

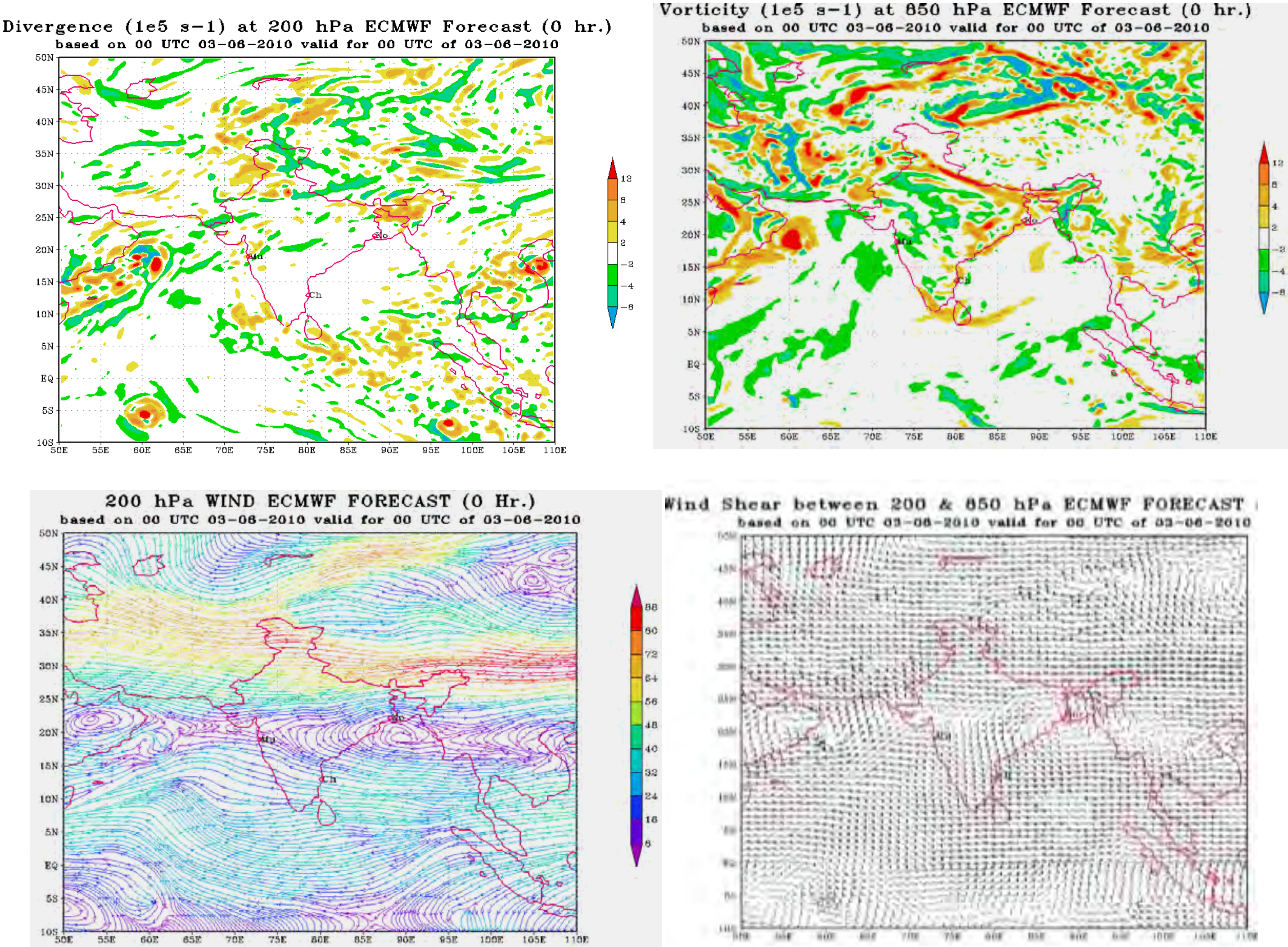


Fig.2.3.5. ECMWF analysis (a) Divergence at 200 hPa level, (b) Vorticity at 850 hPa level, (c) wind at 200 hPa level and (d) Vertical wind shear between 200 and 850 hPa level at 0000 UTC of 03 June 2010

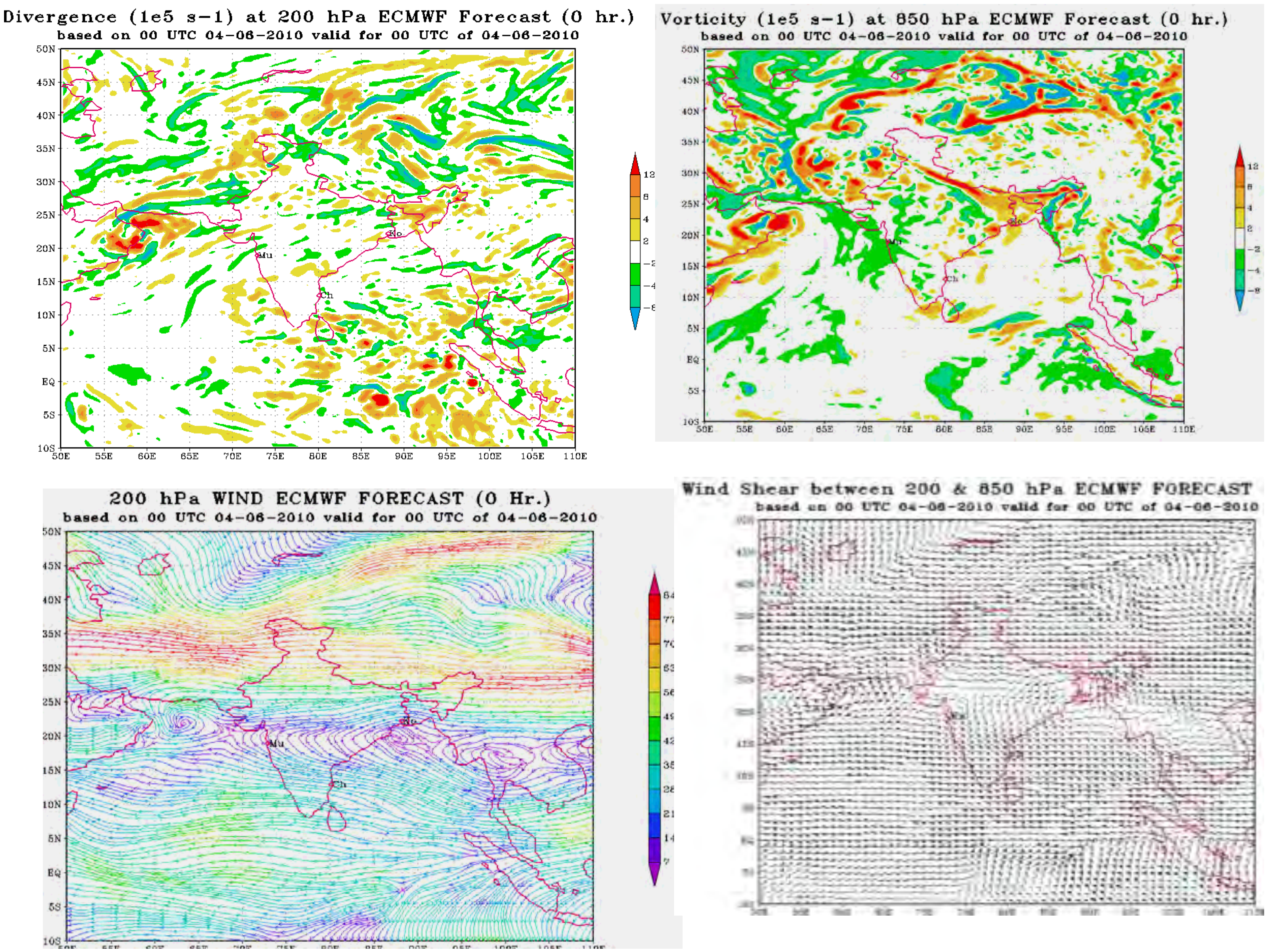


Fig.2.3.6. ECMWF analysis (a) Divergence at 200 hPa level, (b) Vorticity at 850 hPa level, (c) wind at 200 hPa level and (d) Vertical wind shear between 200 and 850 hPa level at 0000 UTC of 04 June 2010

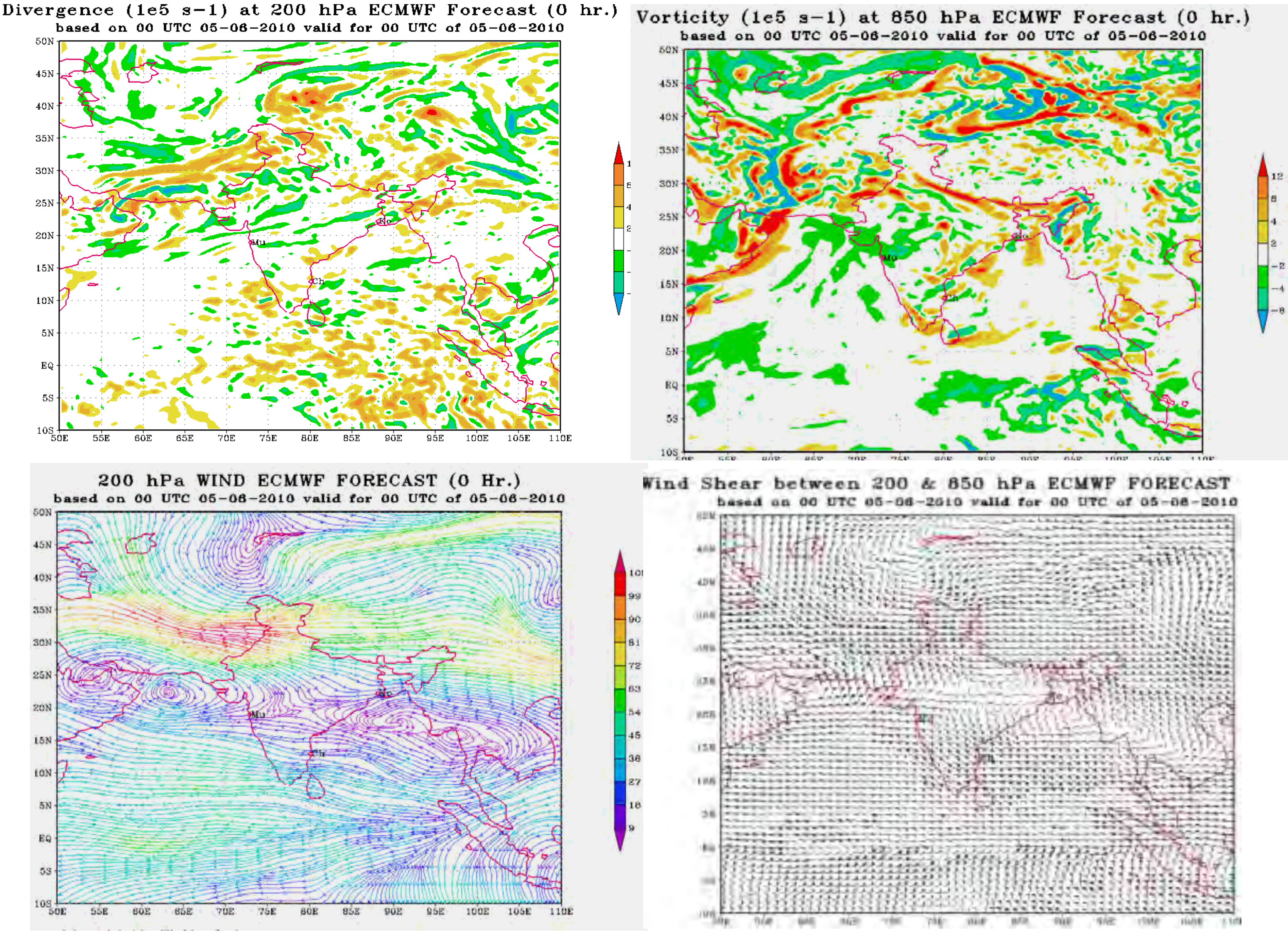


Fig.2.3.7. ECMWF analysis (a) Divergence at 200 hPa level, (b) Vorticity at 850 hPa level, (c) wind at 200 hPa level and (d) Vertical wind shear between 200 and 850 hPa level at 0000 UTC of 05 June 2010

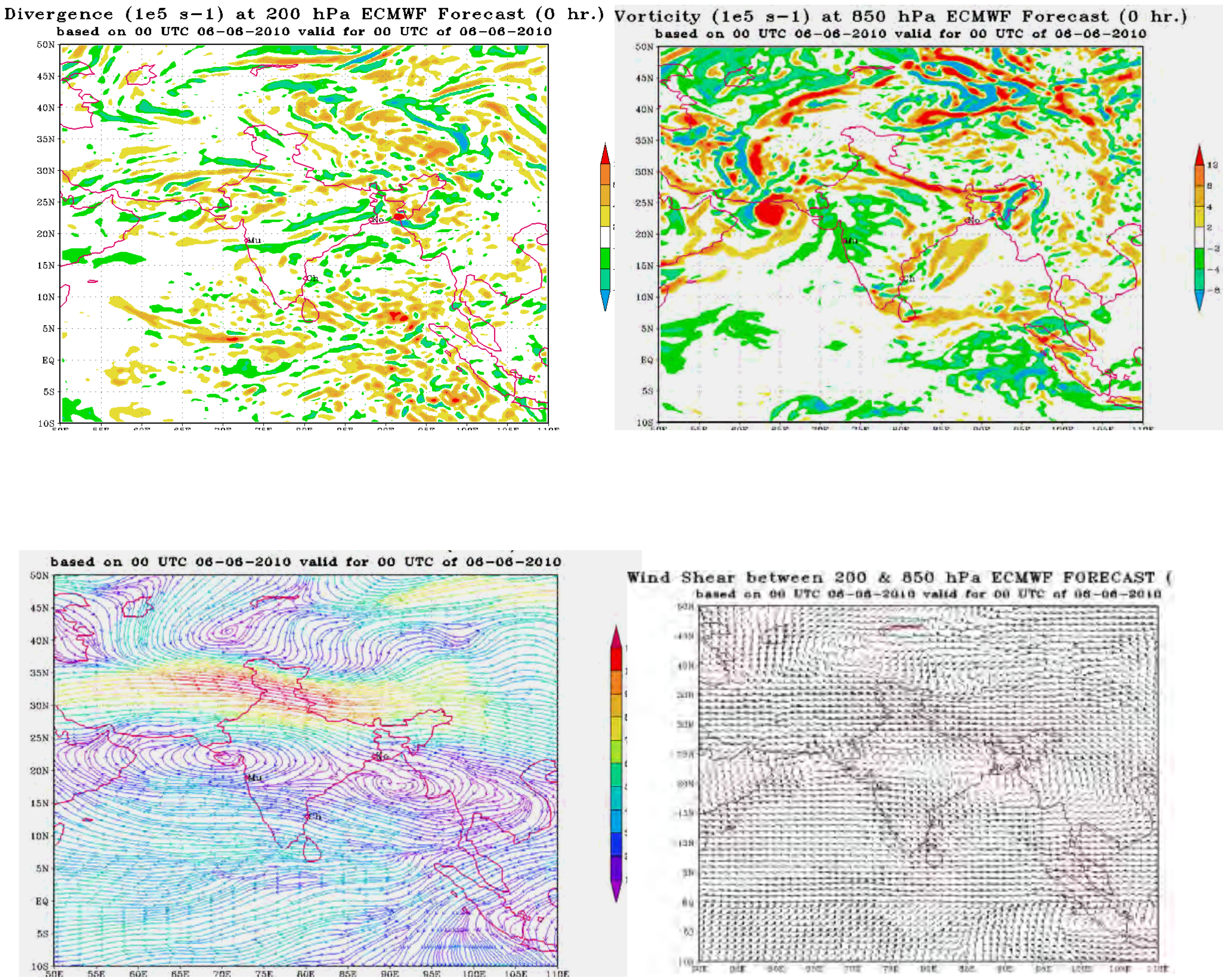


Fig.2.3.8.. ECMWF analysis (a) Divergence at 200 hPa level, (b) Vorticity at 850 hPa level, (c) wind at 200 hPa level and (d) Vertical wind shear between 200 and 850 hPa level at 0000 UTC of 06 June 2010

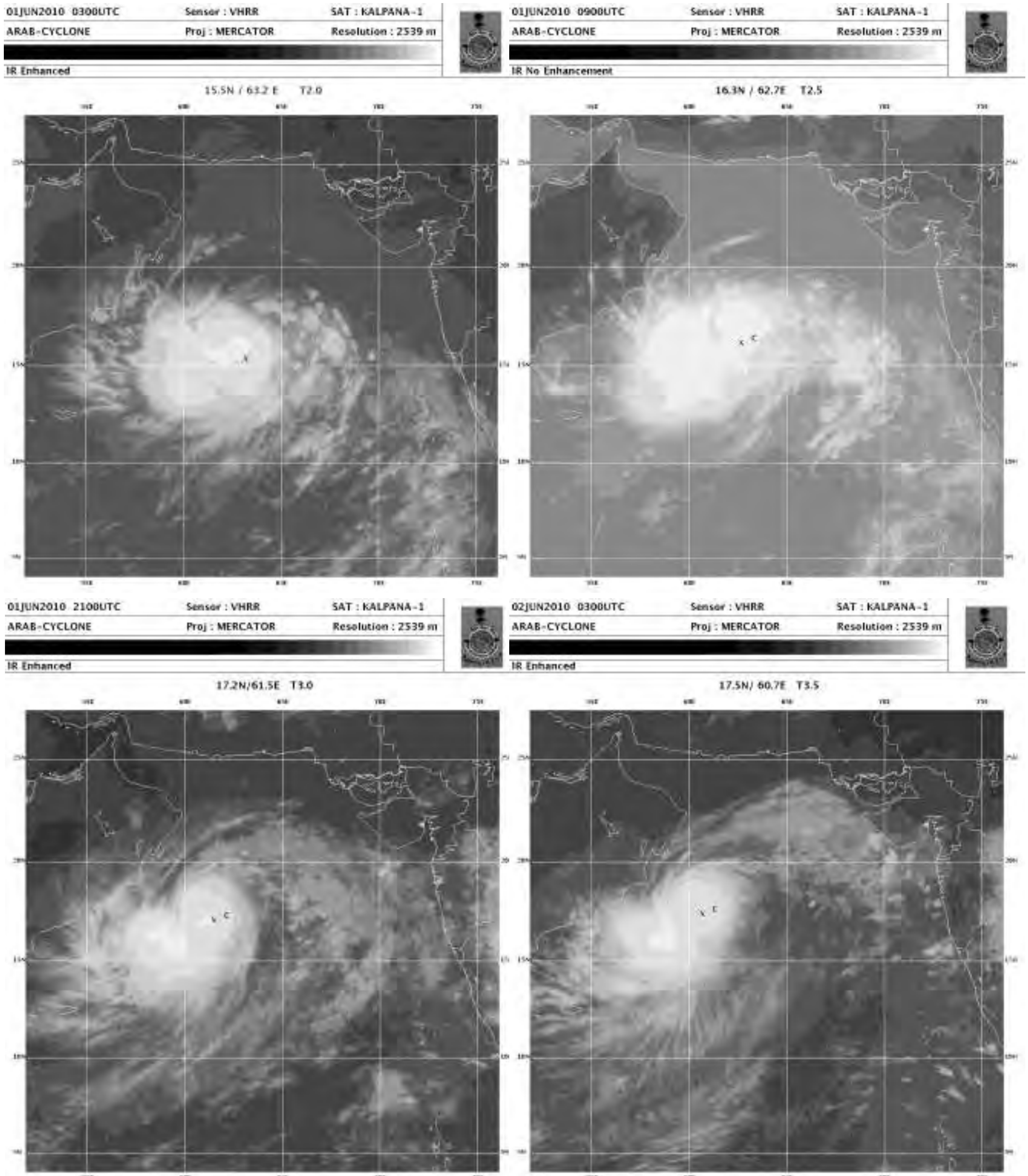


Fig.2.3.9. Kalpana imagery of cyclone, PHET showing different stages of intensity

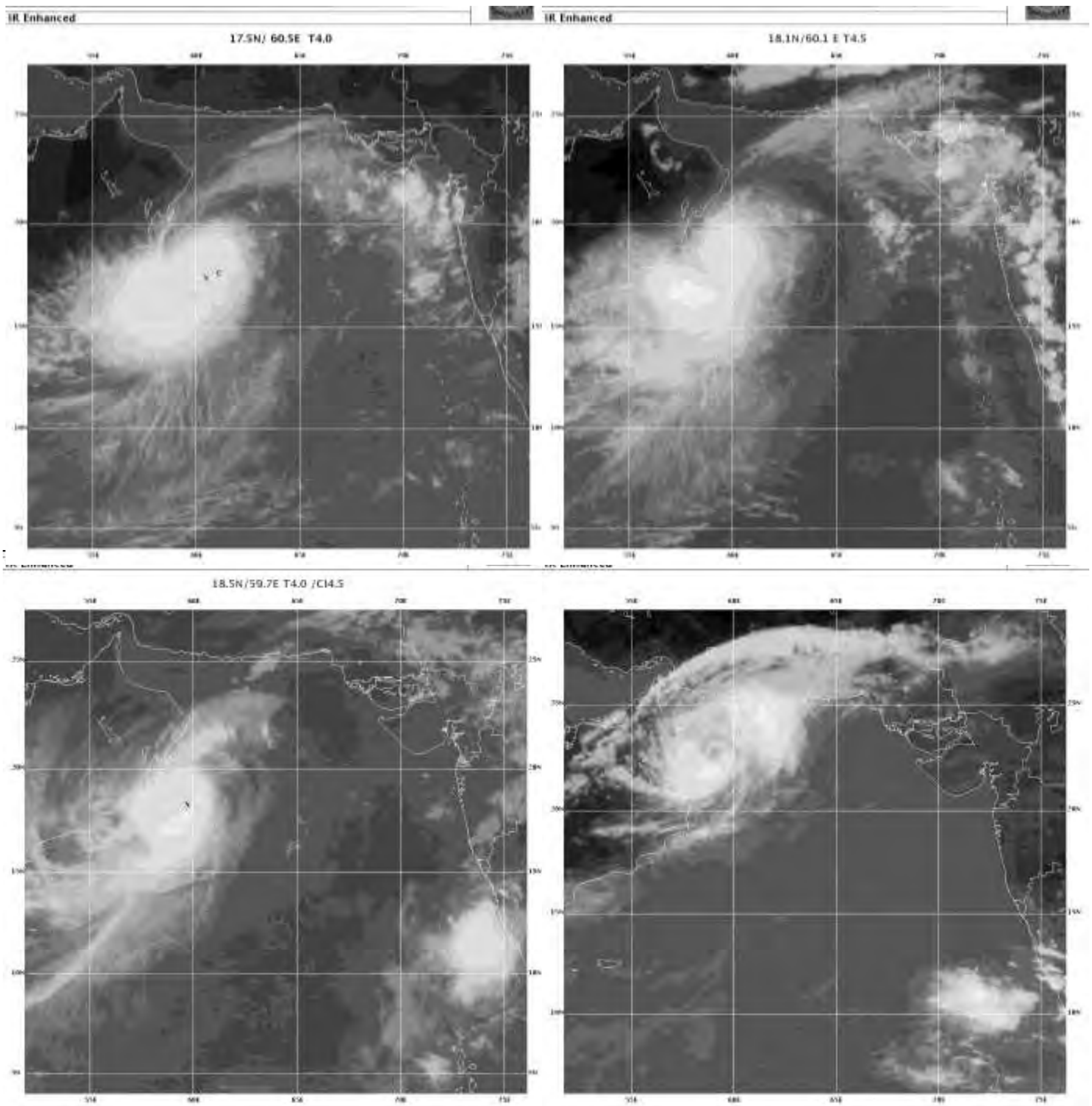


Fig.2.3.9. (contd) Kalpana imagery of cyclone, PHET showing different stages of intensity

2.3.4. Structure and other Parameters

There was rapid intensification of the system from 31 May to 01 June 2010. The satellite imagery of the storm revealed an eye on early hours of 2 June.The moderate resolution imaging spectroradiometer (MODIS) captured a visible image of PHET around 0700 UTC of 2 June and noticed an eye with a diameter of about 12 km. However, there was slight weakening of the system with disappearance of the eye in the later part of the day. The animation of the multi-spectral satellite imageries indicated that system regained 20 nm ragged eye on 3 June, that appeared to wobble as the cyclone underwent possible eye wall replacement.

At its maximum intensity, the radii of gale wind (34 knots or more) extended upto about 120 km and 64 knots wind extended upto about 55 km.

2.3.5. Realised weather

Heavy rains drenched Oman's east coast The sytem mainly moved eastwards close to but parallel to Makaran coast from 5 June onwards and weakened gradually further.Fairly widespread rainfall with isolated heavy falls occurred over west Rajasthan and Kutch region of Gujarat on 7 June. The entire western Rajasthan was badly affected by the spell of heavy rains due to Phet. The drought prone Jaislamer district of Rajasthan was hit with torrential rains. Chief amounts of rainfall are:

West Rajasthan
7 June: Jaisalmer 11, Phalodi 9.

Pakistan
6 June: Gawadar 37, Jiwani 21, Karachi Masroor 13, Pasni 13, Faisal Base 9, Karachi Sadar 8

RAJASTAN :
7 June: Pokran 12, Jaisalmer 11, Phalodi 9, Tehsil 9, Nokh -7
8 June: Lunkaransar -8, Taranagar -7, Laxmangarah -7

Gujarat Region:
7 June : Kadi -7,

Saurashtra : Kalyanpur -11, Mandvi -9, Lalpur -8, Rajkot Aero , Jamnagar Aero , Nakhatrana, Bhanwad , Naliya , Abadaga -7 each.

2.3.6. Damage

The death due to cyclone, PHET are as follows
Oman : 24
Pakistan : 15

India : 05
Total : 44

Strong winds uprooted trees and signboards in Oman, halted its oil and gas production due to bad weather as Cyclone Phet hit the small oil-producing country's coast. Jaisalmer district of Rajsthan was worst hit as 35 black bucks and 11 chinkaras were killed in Tal Chhapar wildlife sanctuary in Churu district. Chhapar sanctuary is one of the few places in India where black bucks are present in large numbers.

Typical damage photograph from Oman coast are shown in.2.3.10.

Fig.2.3.10. Damage photographs from Oman coast in association with cyclone, PHET

2.4. Depression over the Bay of Bengal (7-8 October 2010)

2.4.1. Introduction

A depression formed over the west central Bay of Bengal on 7 October during withdrawal phase of southwest monsoon. It moved north-northeastwards and crossed west Bengal and Bangladesh coast near long. 88.5^{0}E on 8 October 2010. The characteristics of this system are discussed below.

2.4.2 Genesis

An area of convection was located over southeast Bay of Bengal in association with a cyclonic circulation on 4 October, 2010. It gradually began to consolidate on the poleward side of the cyclonic circulation. It gradually moved northwestwards and lay over southwest and adjoining westcentral Bay of Bengal on 5 October, 2010 with increase in lower level cyclonic vorticity. Low vertical wind shear prevailed to the north of 15^{0}N. Under this scenario, a low pressure area formed over the region on 5 October evening. It became well marked over westcentral Bay of Bengal on 6 October morning with Dvorack T number as T1.0. The vertical wind shear continued to be weak to moderate (10-20 knots). The system lay to the south of the upper tropospheric ridge running along 18^{0}N in association with an anticyclonic circulation over Myanmar and adjoining Bay of Bengal. The sea surface temperature was 30-32^{0}C over central and north Bay of Bengal with ocean heat content being more than 100 KJ/cm$^{2.}$ Due to all these favourable conditions, the well marked low pressure area concentrated into a depression and lay centred at 0300 UTC of 7 October over westcentral Bay of Bengal near lat. 16.5^{0}N and long.84.5^{0}E, about 180 km southeast of Visakhapatnam.

2.4.3 Intensification and movements

As the system lay close to the south of the upper tropospheric ridge along 18^{0}N, the depression initially moved northwards till 0600 UTC of 7 October. At 1200 UTC of 7 October, the system lay close to the north of the upper tropospheric ridge and hence it started moving north-northeastwards and subsequently northeastwards. The Ocean heat content over the north Bay of Bengal was less which was not favourable for intensification. As a result, the system crossed West Bengal-Bangladesh coast near long. 88.5^{0}E between 0500 and 0600 UTC of 8 October as a depression. It then continued to move northeastwards and weakened into a low pressure area over Nagaland, Manipur, Mizoram, Tripura and neighbourhood at 0000 UTC of 9 October 2010.

The minimum estimated central pressure of the system was 998 hPa with maximum sustained wind speed of 25 knots. The best track parameters of the system are given in Table 2.4.1. The track of the system is shown in Fig.2.1. The typical satellite imagery of the system is shown in Fig. 2.4.1. The convection associated with the system showed shear pattern of the system. The lowest cloud temperature was about -80^{0}C on 7 October. It became -70^{0}C at 0300 UTC of 8 October when the system was still over northwest Bay of Bengal indicating decrease in deep convection before the landfall.

Table 2.4.1. Best track Positions and other parameters for depression over Bay of Bengal during 07-08 October 2010

Date	Time (UTC)	Centre lat.^{0} N/ long. ^{0} E	C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
07.10.2010	0300	16.5/84.5	1.5	998	25	4	D
	0600	17.5/84.5	1.5	998	25	4	D
	1200	18.5/85.0	1.5	996	25	4	D
	1800	19.0/85.5	1.5	996	25	4	D
08.10.2010	0000	20.0/86.5	1.5	998	25	4	D
	0300	21.0/87.5	1.5	998	25	4	D
	0600	22.0/89.0	1.5	998	25	4	D
	The system crossed West Bengal-Bangladesh coast near long. 88.5^{0}E between 0500 and 0600 UTC.						
	1200	23.5/90.5	--	1000	25	3	D
	1800	24.5/91.0	--	1002	25	3	
09-10-2010	0000	The system weakened into a low pressure area over Nagaland, Manipur, Mizoram & Tripura and neighbourhood.					

The system was tracked initially with the help of satellite cloud imageries. DWR Kolkata observed the system since 0000 UTC of 7 October at every 15 minutes interval. The initial echoes of the system were observed in the form of scattered clouds at about 200–300 kms south-southwest of Kolkata. Amount of convective clouds was increasing in the subsequent observations. Moderate type of clouds were observed with reflectivity about 40 dBz with vertical extension from 6 to 8 kms towards south-southwesterly and southerly direction of Kolkata at 1900 UTC of 7October. The maximum convection with reflectivity about 42 dBZ with vertical extension upto 12 kms was observed over Kolkata from 2200 UTC of 7 to 0000 UTC of 8 October. It was observed from subsequent DWR pictures from 0100 UTC of 8 October onwards that the system was moving toward Jessore (Bangladesh) at 0300 UTC of 8.

The maximum radial wind as observed from PPI (V) was in the range of 22 to 26 mps at a height of 0.5 km above ground level at 2100 UTC of 7 October at a distance of 140 kms south/southsouthwest from DWR.

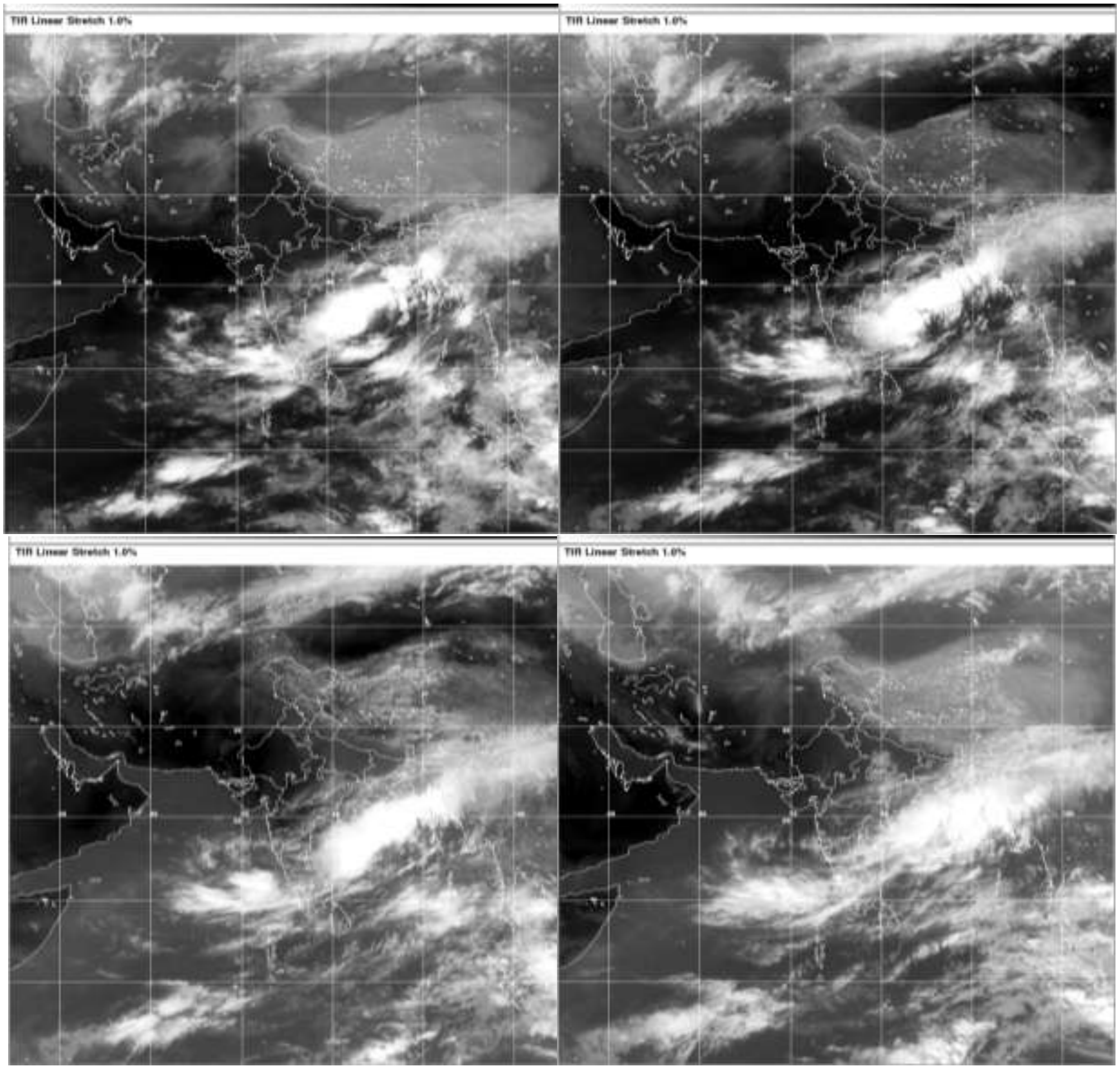


Fig.2.4.1. Kalpana-I imageries of depression over Bay of Bengal at 0000, 0300, 0600 and 1200 UTC of 7 October 2010.

2.4.4 Realized Weather

Heavy rainfall occurred at isolated places in interior Orissa on 6 and 7 and extremely heavy rain with heavy to very heavy falls at isolated places occurred in coastal Orissa on 8 October. The chief amounts of rainfall (≥ 7cm) are given below.

7.10.2010

Orissa: Kendrapada-9, Rajkanika-8, Soro & Chandbali-7 each

West Bengal: Nalhati-7, Sevoke-7

8.10.2010
Orissa: Paradip-25, Patamundai-15 each, Kendrapada, Bhadrak, Kakatpur & Chandbali-14 each, Rajkanika-11, Balasore & Puri-10 each, Athagarh & Soro-9 each, Mundali-8, Nimapada-7

Gangetic West Bengal: Canning -8, Diamond harbor and Durgachak-7 each

Nagaland Manipur Mizoram Tripura: Sonamura 15, Belonia 14, Sabroom and Udaipur 11 each.

Assam & Meghalaya : Barapani 46, Cherapunji 22

9.10.2010
Assam & Meghalaya: Cherapunji 30, Shillong & Silchar 14 each, Dholai, Walliamnagar 9, Lumding, Barapani, Gharmura & Amraghat 8 each, Khertunighat and Jorhat 7 each.

Nagaland Manipur Mizoram Tripura: Agartala 18, Kailashahar 12, Imphal 10.

2.4.5. Damage :

The system did not cause much damage in India. However, tidal waves wreaked havoc in east Midnapore district and 850 families were shifted to safer places.

2.5. Deep depression over the Bay of Bengal(13-16 Oct. 2010)

2.5.1. Introduction

A deep depression formed over the west central Bay of Bengal on 13 October,2010. It moved west-northwestwards and crossed Orissa coast near Gopalpur on 15 October. It caused heavy rainfall over south Orissa leading to flood.

2.5.2 Genesis:

Animated infrared Satellite imageries indicated that flaring deep convection associated with a broad low level circulation centre developed over the central Bay of Bengal on 12 October 2010. It concentrated into a low pressure area over eastcentral Bay of Bengal with T 1.0 at 0900 UTC of 12 October. The system lay equatorward of sub-tropical ridge along 22^0 N in an area of upper level of divergence and moderate vertical wind shear (10-20 knots). The sea surface temperature (SST) was about $28\text{-}32^0$ C over the central and north Bay of Bengal. The Ocean heat content was 80-100 KJ/cm^2 over the region which was favourable for intensification. Under this scenario, the low pressure area concentrated into a depression and lay centred at 0600 UTC of 13 October over eastcentral Bay of Bengal near lat. 17.5^0N and long. 90.0^0 E, about 550 km southeast of Gopalpur (43049).

2.5.3 Intensification and movement:

In association with above mentioned favorable conditions and further decrease in wind shear to 5-10 knots, the depression over eastcentral Bay of Bengal moved northwestwards, intensified into a deep depression and lay centred at 0300 UTC of 15 October over northwest Bay of Bengal near lat.19.0^0 N and long. 87.0^0 E. It then moved west-northwestwards and crossed Orissa coast near Gopalpur (43049) between 1500 and 1600 UTC of 15 October. After the landfall, it moved west-southwestwards and weakened into a depression and lay centred at 0000 UTC of 16 October over south Orissa near lat. 19.0^0 N and long. 84.0^0 E, about 100 km west-southwest of Gopalpur. It further weakened into a well marked low pressure area over south Orissa and adjoining Chhattisgarh and north Andhra Pradesh at 0300 UTC of the same day.

The track of the system is shown 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 Estimated lowest Central Pressure (ECP) was 995.0 hPa at 1200 UTC of 15 October. The estimated maximum wind speed was 30 kts during the period 0300 UTC to 2300 UTC of 15 October. As per the hourly observation from Orissa, Gopalpur recorded the lowest pressure of 994.6 hPa (wind 340°/10 kts) at 1000 UTC of 15 October, which is very close to the estimated central pressure. Puri reported maximum wind speed of 25 kts from 1600 UTC to 1800 UTC of 15 October.

The system was tracked initially with the help of satellite cloud imageries. As per satellite observations, the system crossed south Orissa coast around 1800 UTC of 15 and lay over land with centre near Lat. 19.0° N/Long. 84.7^0 E. From 0000 UTC of 13 October onwards, it was also tracked by DWR. Hourly coastal observations and AWS observations of Andhra Pradesh were also recorded after 0000 of 13.

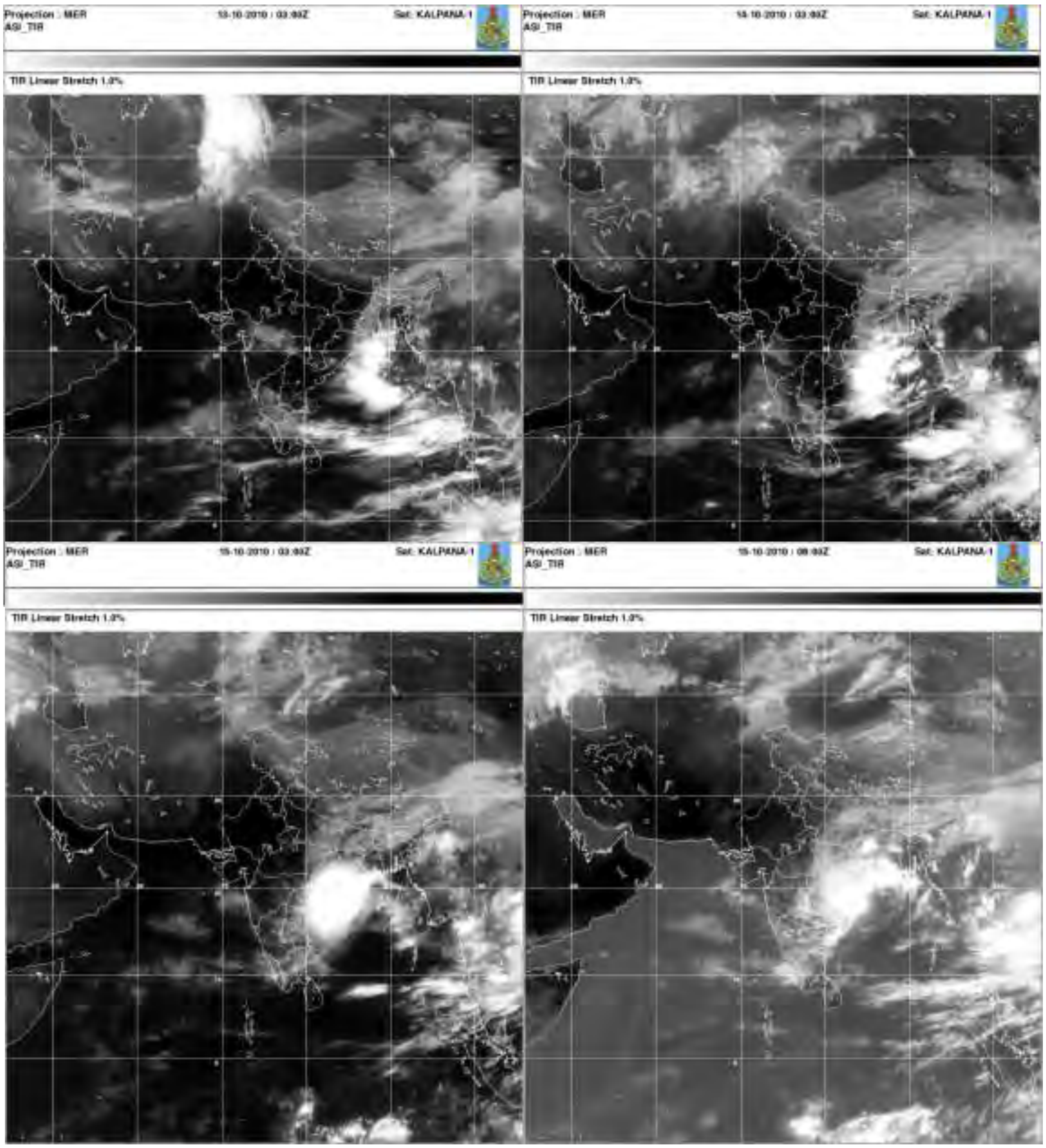


Fig.2.5.1. Kalpana imageries of deep depression over the Bay of Bengal at 0300UTC of 13, 14 and 15 October 2010 and 0900 UTC of 15 October 2010

Table 2.5.1. Best track Positions and other parameters for deep depression over Bay of Bengal during 13-16 October 2010

Date	Time (UTC)	Centre lat.^{0} N/ long. ^{0} E	C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
13.10.2010	0600	17.5/90.0	1.5	1002	25	4	D
	1200	17.5/89.0	1.5	998	25	4	D
	1800	18.0/88.5	1.5	998	25	4	D
14.10.2010	0000	18.0/88.5	1.5	998	25	4	D
	0300	18.0/88.5	1.5	998	25	4	D
	0600	18.0/88.5	1.5	998	25	4	D
	1200	18.0/88.0	1.5	996	25	4	D
	1800	18.0/88.0	1.5	996	25	4	D
15.10.2010	0000	18.5/87.5	1.5	996	25	4	D
	0300	19.0/87.0	2.0	996	30	5	DD
	0600	19.5/86.0	2.0	996	30	5	DD
	1200	19.5/85.5	2.0	995	30	5	DD
	The system crossed the Orissa coast near Gopalpur (43049) between 1500 &1600 UTC.						
	1800	19.0/84.5	--	996	30	5	DD
16.10.2010	0000	19.0/84.0	--	998	25	4	D
	0300	The system weakened into a well marked low pressure area over south Orissa and adjoining Chhattisgarh and north Andhra Pradesh at 0300 UTC.					

2.5.4. Realized Weather:

Under the influence of the system, widespread rainfall with isolated to scattered heavy to very heavy falls occurred over coastal and south Orissa and south Chhattisgarh. Fairly widespread rainfall also occurred over adjoining areas of north Andhra Pradesh. The chief amounts of rainfall (≥ 7 cm) are as follows:

15.10.2010

Andhra Pradesh: Palasa-8

Orissa: Paradip-14, Patamundai-9, Chandbali, Bhadarak, Khandapada, Pipili, Kendrapada & Rajkanika-8 each, Alipingal, Nimapada & Mahendragarh-7,

Gangetic West Bengal: Basirhat 11, Uluberia 8.

16.10.2010

Orissa: Kosagumda-24, Umarkote & Junagarh-15 each, Jaipatna-14, R. Udaygiri-13, Soro-12, Nawarangpur & Paralakhemundi-11, Kalinga & Jeypur-9, Daringibadi & Bhawanipatna-8, Raygada & Koraput-7

Chhattisgarh:_ Jagadalpur 11, Narayanpur & Kondagaon 8 ecah.

2.5.5. Damage: No damage was reported in Orissa and Andhra Pradesh.

2.6. Very severe cyclonic storm, GIRI over the Bay of Bengal (20-23 October 2010)

2.6.1. Introduction

A very severe cyclonic storm, 'GIRI' formed over the Arabian Sea on 20 October 2010 moving in a northeasterly direction, it crossed Myanmar coast between Sittwe and Kyakpyu around 1400 UTC of 22 October,2010 with estimated sustained maximum wind speed of about 190 kmph (105 knots). It caused damage to life and property of Myanmar. The salient features of this system are given below.

(i) Cyclone, Giri rapidly intensified from associated sustained maximum wind speed of 45 knots at 1200 UTC of 21 to 105 knots at 0900 UTC of 22 October, 2010.
(ii) No severe cyclone crossed Arakan coast prior to cyclone, GIRI during the month of October, as evident from the data of 1891-2009.
(iii) The genesis and intensification of the system could be predicted by ECMWF model to a large extent. It predicted lowest estimated central pressure of 970 hPa well in advance with landfall near lat.20^0N and long.93^0E between 1200 and 1800 UTC of 22^d October 2010 well in advance against the lowest estimated central pressure of 950 hPa and landfall near lat. 20^0N and long. 93.5^0E around 1400 UTC of 22 October 2010.

2.6.2. Genesis

A low pressure area formed over the east central Bay of Bengal on 19 October. It concentrated into a depression at 1200 UTC on 20 October over the same area near lat.17.5^0N and. lat. 91.5^0E. The dynamical parameters like upper level divergence, lower level relative vorticity and vertical wind shear at 0000 UTC of 20 October 2010 (Fig.2.6.1) were favourable for intensification of the system. The wind shear was low to moderate (10-15 knots). The sea surface temperature was $28\text{-}32^0$C were over the region. The ocean heat content over the central Bay of Bengal was also favourable for intensification. The system lay close to the upper tropospheric ridge, which roughly run along 17.5^0N (Fig.2.6.1) in association with anticyclonic circulation.

2.6.3. Intensification and movement

Remaining practically stationary, it intensified into a deep depression at 0300 UTC of 21 October and into a cyclonic storm, **GIRI** at 0600 UTC of the same day. It then moved slowly northeastwards and intensified into a severe cyclonic storm at 0000 UTC of 22 October and into a very severe cyclonic storm at 0300 UTC of the same day. It then moved relatively faster in the same direction and crossed Myanmar coast between Sittwe and Kyakpyu around 1400 UTC of 22 October 2010 with estimated sustained maximum wind speed of about

190 kmph (105 knots). After the landfall, it continued to move northeastwards and weakened gradually. The best track parameters of cyclone GIRI are shown in Table 2.6.1. The track of the system is shown in Fig.2.1. The typical satellite imageries of the system are shown in Fig.2.6.2. The lowest ECP was estimated as 950 hPa with pressure drop of 52 hPa. Kyakpyu reported lowest pressure of 990.7 hPa with surface wind southerly to southeasterly 35 knots and 24 hrs pressure fall of 11.9 hPa at 0900 UTC of 22 October 2010 when system was located 50 km west of Kyakpyu.

Table 2.6.1. Best track positions and other parameters of the severe cyclonic storm "GIRI" over the Bay of Bengal during 20-23 October, 2010

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
20-10-2010	1200	17.5/91.5	1.5	1002	25	4	D
	1800	17.5/91.5	1.5	1002	25	4	D
21-10-2010	0000	17.5/91.5	1.5	1002	25	4	D
	0300	17.5/91.5	2.0	1000	30	5	DD
	0600	17.5/91.5	2.5	998	35	6	CS
	0900	17.5/91.5	2.5	996	40	8	CS
	1200	18.0/92.0	3.0	990	45	10	CS
	1500	18.0/92.0	3.0	990	45	10	CS
	1800	18.0/92.0	3.0	988	50	12	CS
	2100	18.5/92.5	3.0	984	55	16	CS
22-10-2010	0000	18.5/92.5	3.5	980	60	20	SCS
	0300	19.0/93.0	4.5	974	80	30	VSCS
	0600	19.0/93.0	5.0	964	90	40	VSCS
	0900	19.5/93.5	5.5	950	105	52	VSCS
	1200	19.8/93.5	5.5	950	105	52	VSCS
	The system crossed Myanmar coast near lat. 20.0^0 N long. 93.5^0 E about 70 km east-southeast of Sittwe around 1400 UTC.						
	1500	20.0/93.5	--	966	80	36	VSCS
	1800	20.5/94.0	--	976	70	26	VSCS
	2100	20.5/94.0	--	986	55	16	SCS
23-10-2010	0000	21.0/94.5	--	992	45	10	CS
	0300	21.5/95.0	--	996	35	8	CS
	0600	22.0/95.5	--	998	25	4	D
	1200	The system weakened into a well marked low pressure area over central parts of Myanmar.					

Considering the environmental parameters, the low to moderate vertical wind shear continued throughout the life of the system (Fig.2.6.3 – 2.6.4). The warmer

SST continued however with Ocean heat content becoming less than 100 KJ/cm^2. It seems vertical wind shear played a major role than the Ocean heat content for rapid intensification of the system on 21-22 October 2010. As the system moved to the north of the ridge gradually, the system recurved north-northeastwards.

2.6.4. Structure and other parameters

The system was tracked with the help of satellite cloud imageries from 0600 UTC of 20 to 1400 UTC of 22 October. The maximum intensity of T. No. 5.5 was reported from 0900 of 20 October till it crossed Myanmar coast. The Estimated Lowest Central Pressure (ECP) was 950 hPa from 0900 UTC till the system crossed Myanmar coast. The estimated maximum wind speed was 105 kts.
At 0900 UTC of 22, the cloud pattern indicated sharp improvement in organization and convection around the vortex centre and also decrease in diameter of EYE, which is indicative of explosive intensification.

Continued development took place as convection consolidated around the system and banding features formed along the western side of the low. Situated in an area of weak wind shear, further development was anticipated over the following days. Cyclone ‘GIRI’ was seen clearly by the Tropical Rainfall Measuring Mission (TRMM) satellite twice on Oct. 21. The first good view was at 1534 UTC when TRMM data showed a very well organized storm with heavy rainfall south of Giri's partially formed eye. The heaviest rainfall was falling at about 2 inches per hour, south of Giri's eye. The second TRMM orbit at 2347 UTC captured Giri's rainfall. The wind speed increased to 80 knots at 0300 UTC of 22 October. The second TRMM image showed that Giri had developed a closed eye surrounded by powerful thunderstorms dropping heavy rainfall. Satellite imagery depicted a well-defined 46 km (29 mi) wide eye surrounded by deep convection. Accompanied by strong poleward outflow, additional strengthening took place despite Giri's proximity to land.

With the development of very intense convection, estimated lowest cloud top temperature was between -70 and -80 °C. Explosive intensification which took place with cyclone GIRI, is a more extreme case of rapid deepening that involves a tropical cyclone deepening at a rate of at least 2.5 hPa per hour for a minimum of 12 hours. Explosive intensification is rather rare, as conditions must be exceedingly favorable for cyclone intensification. Explosive intensification occurs regularly in the West Pacific basin, with the greatest frequency off the north coast of Australia; however, it has occurred numerous times in the Atlantic basin. It is rare in the North Indian Ocean, but Cyclone Giri is a good example of a storm going through explosive intensification in this basin.

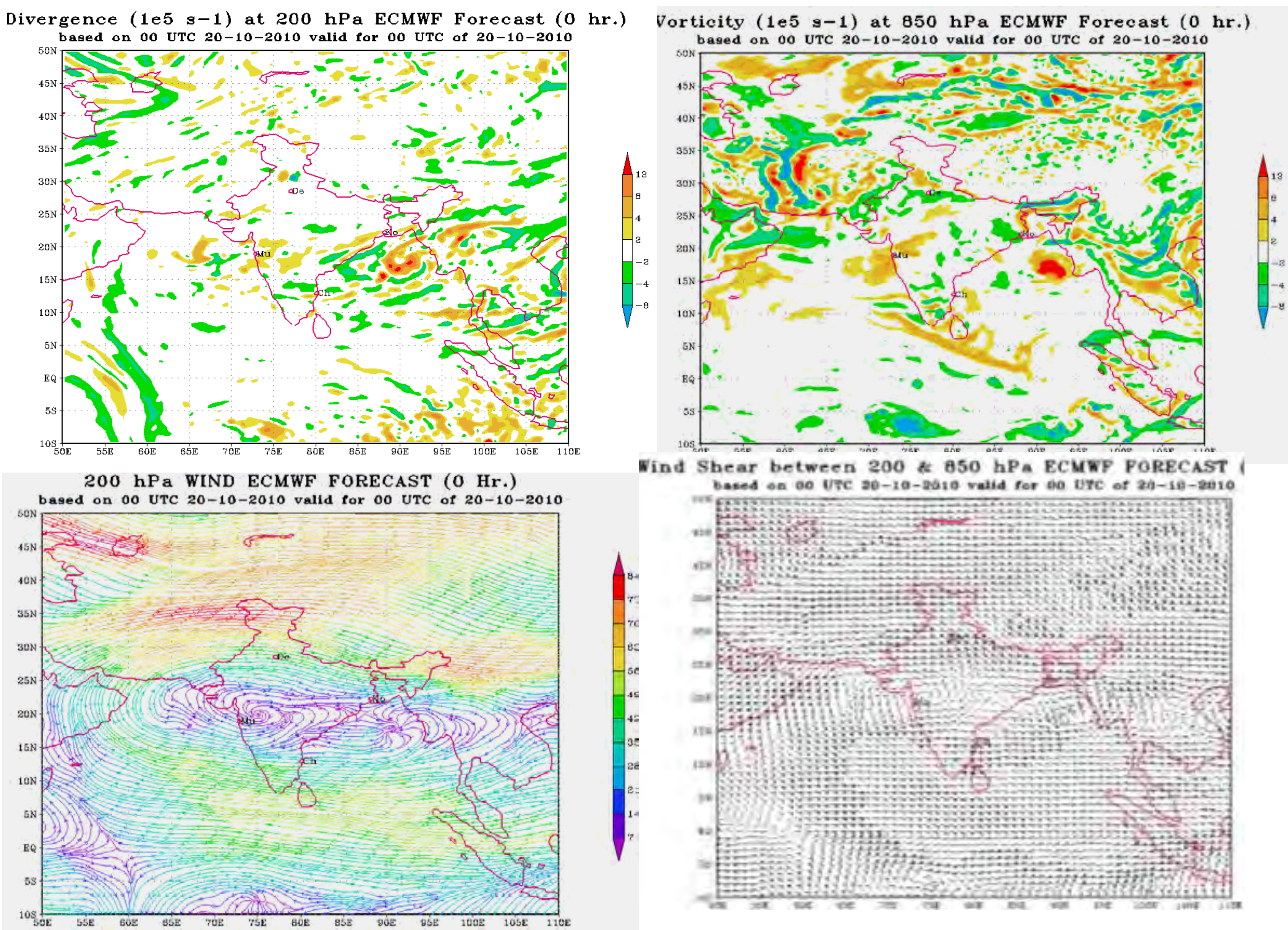


Fig.2.6.1 ECMWF analyses (a) Divergence at 200 hPa level, (b) Vorticity at 850 hPa level, (c) wind at 200 hPa level and (d) Vertical wind shear between 200 and 850 hPa level at 0000 UTC of 20 October 2010

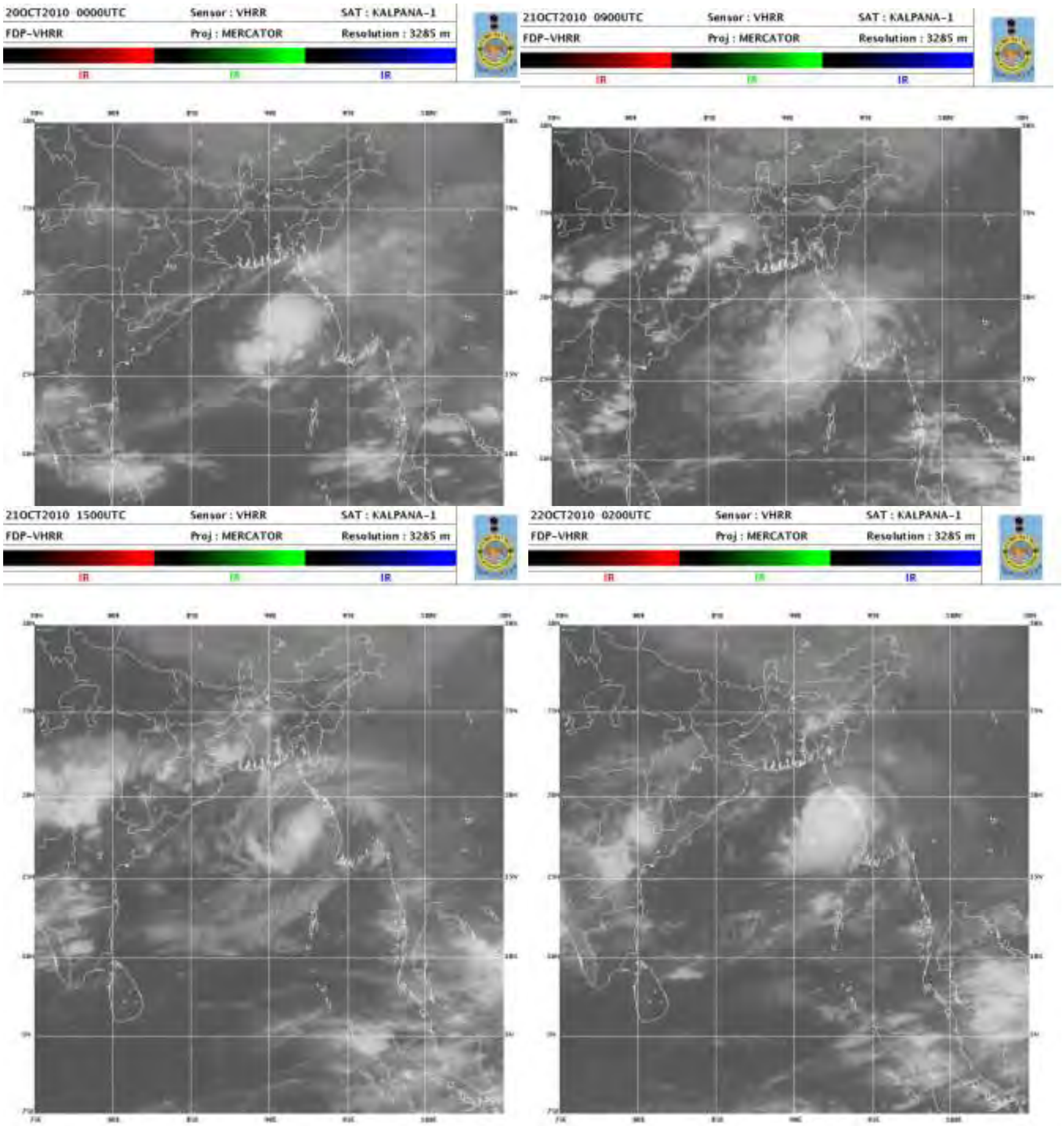


Fig.2.6.2 Kalpana imageries of cyclone GIRI over the Bay of Bengal 0000, 0900, 1500 and 0200 UTC of 20, 21 and 22 October 2010.

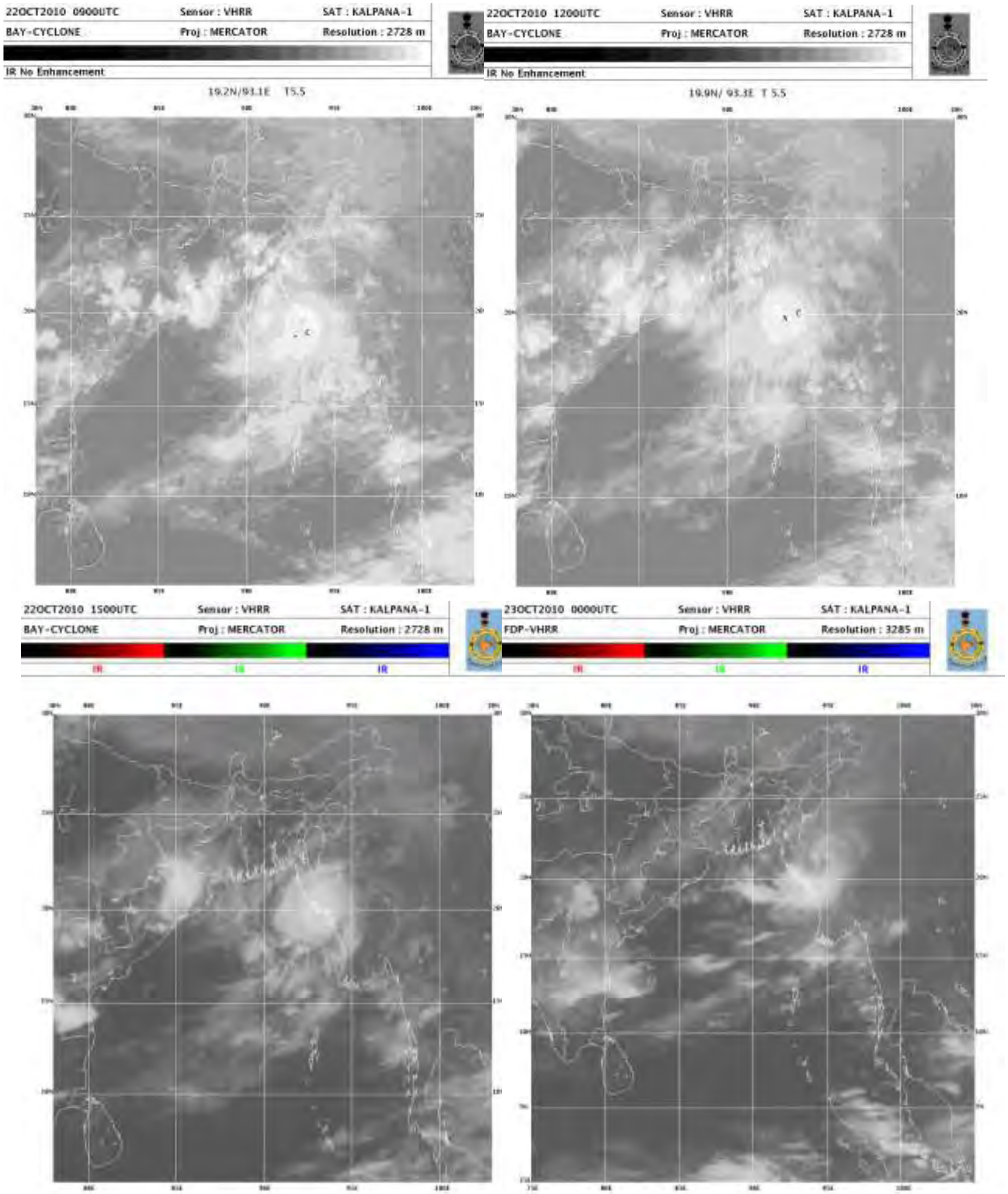


Fig.2.6.2(contd.) Kalpana imageries of cyclone „GIRI' over the Bay of Bengal 0900, 1200, 1500 UTC of 22 October 2010and 0000 UTC of 23 October 2010.

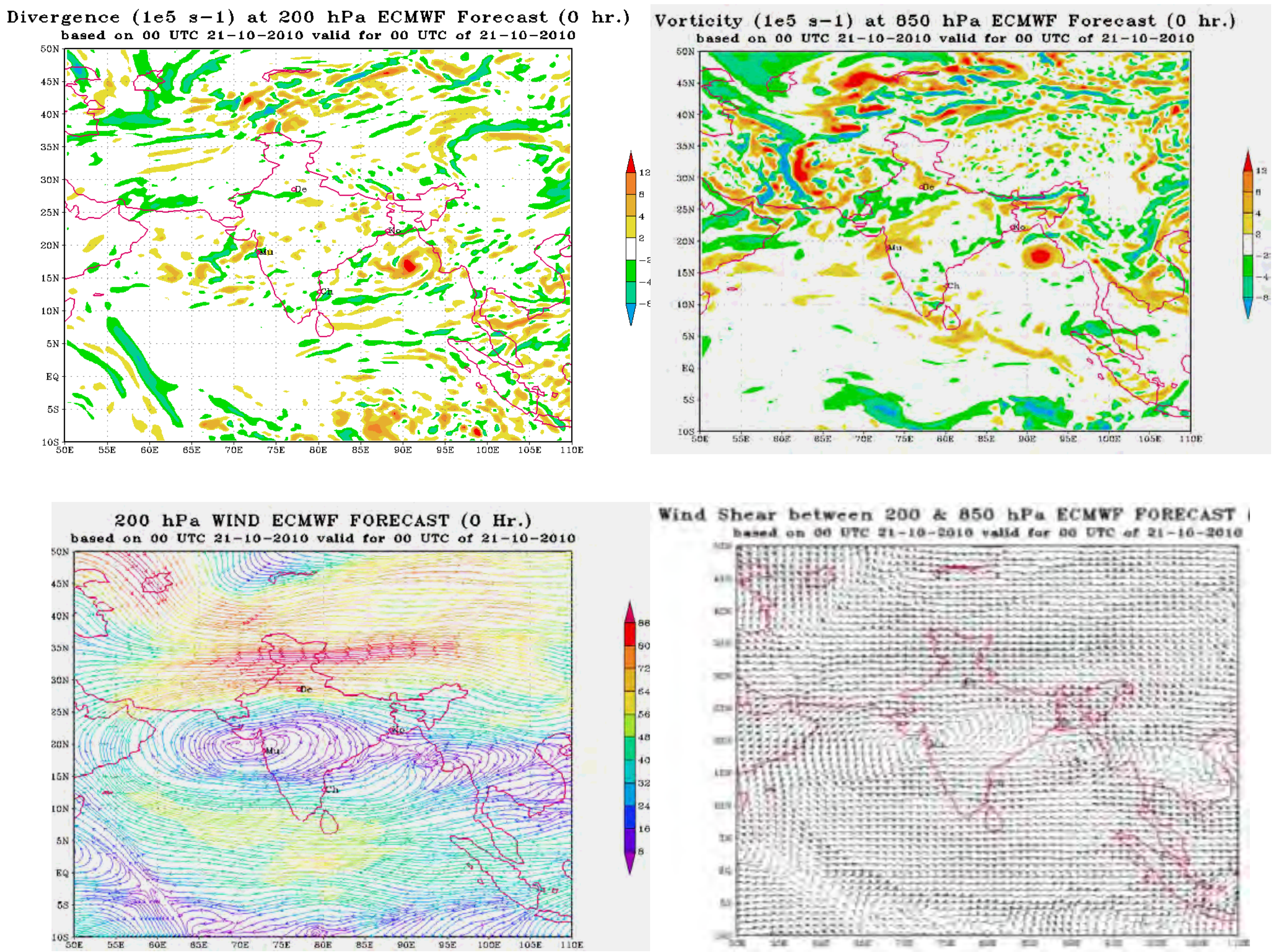


Fig.2.6.3. ECMWF analysis (a) Divergence at 200 hPa level, (b) Vorticity at 850 hPa level, (c) wind at 200 hPa level and (d) Vertical wind shear between 200 and 850 hPa level at 0000 UTC of 21 October 2010

2.6.4. Realised weather :

According to local media, Cyclone Giri brought a storm surge up to 3.7 m (12 ft), along with waves up to 8 m (26 ft). In Kyaukphyu, much of the city was left more than 1.2 m (3.9 ft) under water by the storm.

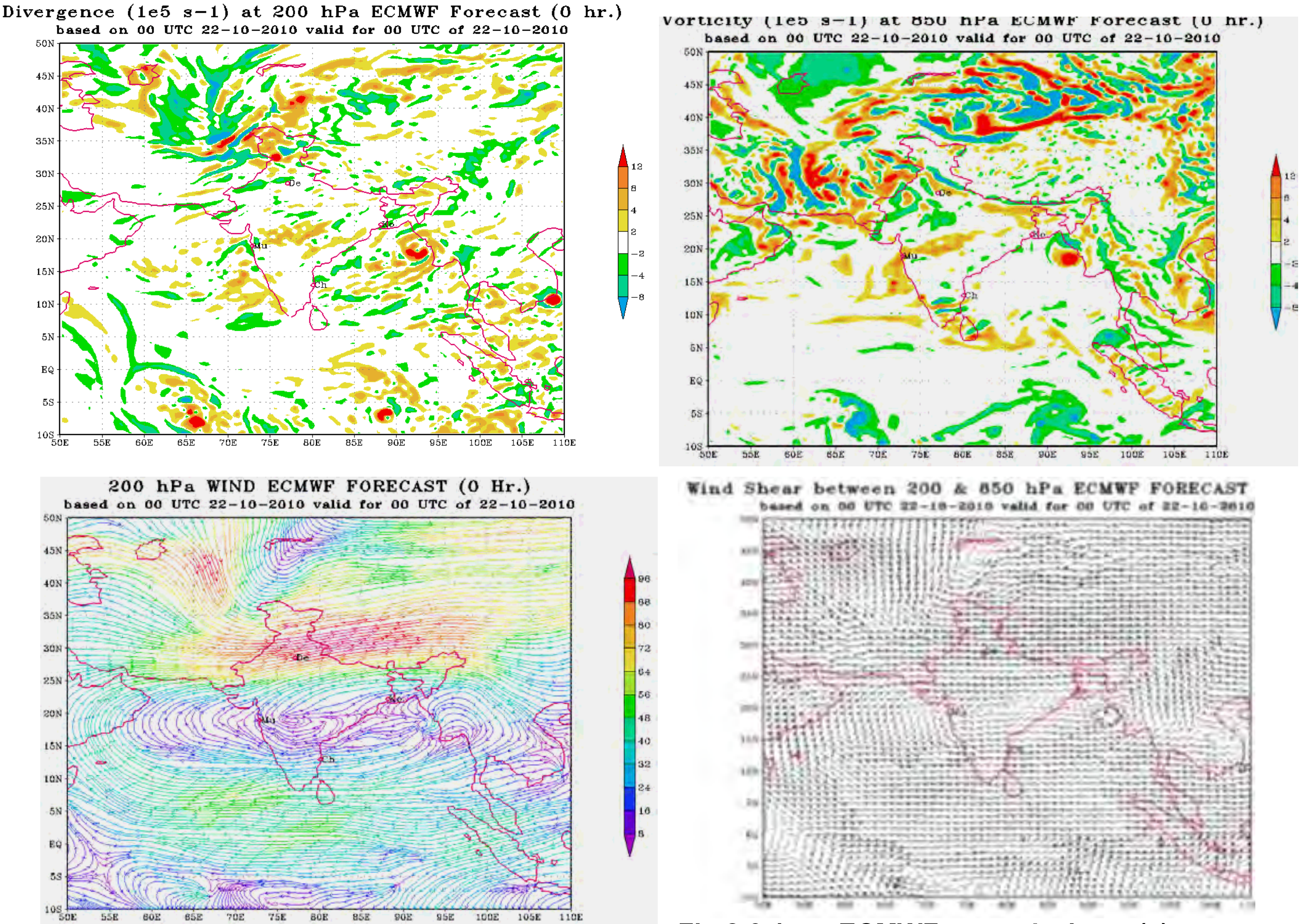


Fig.2.6.4. ECMWF analysis (a) Divergence at 200 hPa level, (b) Vorticity at 850 hPa level, (c) wind at 200 hPa level and (d) Vertical wind shear between 200 and 850 hPa level at 0000 UTC of 22 October 2010

2.6.5. Damage:

157 fatalities had been confirmed as a result of Cyclone Giri. Damage from the storm amounted to 2.34 billion kyat (US$359 million). Myebon Township was the hardest-hit area in the country. Several villages were completely destroyed by the storm and many others were severely damaged. According to the United Nations, roughly 15,000 homes were destroyed by the storm throughout Arakan State. According to the United Nations Food and Agriculture Organization, 16,187 hectares (40,000 acres) of rice paddies were destroyed and another 40,468 hectares (100,000 acres) were damaged.

2.7 Cyclone „JAL' over the Bay of Bengal (04-08 November 2010)

2.7.1. Introduction

A severe cyclonic storm, JAL developed over the Bay of Bengal from the remnant of a depression which moved from northwest Pacific Ocean to the Bay of Bengal across southern Thailand. It moved west-northwestwards and intensified upto severe cyclonic storm on 6 November, 2010. However due to lower ocean thermal energy and moderate to high vertical wind shear, the severe cyclonic storm, JAL weakened gradually into a deep depression and crossed north Tamilnadu – south Andhra Pradesh coast, close to the north of Chennai near 13.3^{0}N and 80.3^{0}E around 1600 UTC of 07 November 2010. Its salient features are as follows.

- The severe cyclonic storm, JAL weakened into a deep depression over the Sea before the landfall.
- The convective clouds were sheared to the west to a large extent on the date of landfall (7 November 2010). As a result, more rainfall occurred over the interior parts than over the coastal regions.

2.7.2 Genesis

A depression formed over the West Pacific Ocean on 31 October, 2010 in association with an active Inter-Tropical Convergence Zone (ITCZ). It moved west-northwestwards across southern Thailand and emerged as a low pressure area over the south Andaman Sea on 2 November. Animated imageries indicated merging of mesoscale convective clusters along with increase in deep convection from 3 to 4 October 2010. Further there was improvement in covecting band. As a result, the well marked low pressure area continued to move west-northwestwards and concentrated into a depression at 0000 UTC of 4 November 2010 over southeast Bay of Bengal near lat. 8.0^{0}N and 92.0^{0}E. The track of the system is shown below in Fig.2.1. The best track parameters of the system are shown in Table 2.7.1.

The environmental conditions were favourable with higher SST (30-32^{0}C), higher Ocean heat content (>100 KJ/cm^2), increased low level relative vorticity and upper level divergence and lo vertical wind shear (Fig.2.7.1)

2.7.3. Intensification and movement

The system intensified into a Deep Depression in the early morning of 5 November and into a Cyclonic Storm „JAL' at 0600 UTC of the same day with centre near lat. 9.0^{0}N and long. 87.5^{0}E, about 900 km east-southeast of Chennai. The cyclonic storm „JAL' over southeast Bay of Bengal continued to move west-northwestwards and intensified further into a severe cyclonic storm in the early hours of 6 November. However as the severe cyclonic storm, JAL moved to the southwest Bay of Bengal closer to India coast, it entered into a region of lower ocean thermal energy and moderate to high vertical wind shear in association with the strong easterlies in the upper tropospheric level. The high wind shear led to westward shearing of the convective clouds form the system centre and lower Ocean thermal energy led to unsustainability of convection over the region. Due to these two factors, the severe cyclonic storm, JAL weakened into a cyclonic storm at 0600 UTC of 7 November 2010 over southwest Bay of Bengal with centre near lat.12.5^{0}N and long. 82.5^{0}E, about 250 km east-southeast of Chennai. It weakened further into a deep depression and crossed north Tamilnadu – south Andhra Pradesh coast, close to the north of Chennai near 13.3^{0}N and 80.3^{0}E around 1600 UTC of 07 November 2010. It continued to move west-northwestwards, further weakened into a depression at 0300 UTC and into a well marked low pressure area over Rayalaseema and adjoining south interior Karnataka at 0600 UTC of today, the 8 November 2010. The environmental condition supporting the intensification, weakening and movement of the system are shown in Fig.2.7.2. The weakening of the system before landfall could be attributed to lower Ocean heat content, though the SST was higher than threshold

It emerged into the east central Arabian Sea on 9 November. It then moved initially northwestwards towards Saurashtra & Kutch and adjoining Pakistan coast during 9-11 November. It then moved northeastwards across Saurashtra & Kutch and adjoining Pakistan and became less marked on 12 November 2010. The typical satellite imageries of the system are shown in Fig.2.7.3

2.7.4. Structure and other parameters

The system was tracked by Satellite from 0600 UTC of 2 Nov. till the landfall. The maximum intensity of T 3.5 was reported from 2100 UTC of 5 to 0500 UTC of 7 November. The Estimated lowest Central Pressure (ECP) observed was 988 hPa. The estimated maximum wind speed was 60 kts. As per DWR Chennai and DWR SHAR reports, the system started weakening from 0300 UTC of 7 November, while continuing its northwesterly track and crossed the coast as deep depression north of Chennai, close to SHAR around 1800 UTC.

The cyclone ‘Jal’ formed in the south Bay of Bengal was well captured by the 3 data buoys viz. BD6, BD07_Omni & BD06_Omni, which are deployed in the Bay of Bengal; out of which 2 are equipped with sub-surface oceanographical instruments upto 500 meters depth which were deployed on 24 & 26 October 2010 and third buoy BD06 has an indigenize CPU. [The Buoys (i) BD06_OMNI (Lat. 9.9° N / Long. 88.4° E) Met Sub-Surface Ocean upto 500 meters depth (ii) BD07_OMNI (Lat. 8° N / Long. 88.5° E) Met. Sub-Surface Ocean upto 500 meters depth & Wave and (iii) BD6 (Lat. 17.989o N, Long. 88.089o E) Met and Sea Surface Current were recently deployed by NIOT.] The passage of the JAL was along these newly deployed Buoys. Among these Buoys, the BD07_OMNI buoy recorded maximum wind speed of 16 mps on 5 November around 2000 UTC.

DWR at Sriharikota recorded hourly observation from 0300 UTC of 6 November. It was observed that the Cyclonic Storm started moving towards the coast in a west-northwesterly direction. The structure/eye of the cyclone was not so well defined as the RADAR echoes did not have the required properties of a cyclone eye. A few typical DWR imageries of DWR, Sriharikota are shown in Fig.2.7.4.

Table 2.7.1. Best track positions and other parameters of the severe cyclonic storm " JAL' over the Bay of Bengal during 04-07 NOV, 2010

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
04.11.2010	0000	8.0/92.0	1.5	1002	25	3	D
	0300	8.5/91.0	1.5	1002	25	3	D
	0600	8.5/90.5	1.5	1002	25	3	D
	1200	8.5/90.0	1.5	1002	25	3	D
	1800	8.5/89.5	1.5	1002	25	4	D
05.11.2010	0000	9.0/88.5	2.0	1000	30	5	DD
	0300	9.0/88.0	2.0	1000	30	5	DD
	0600	9.0/87.5	2.5	998	35	6	CS
	0900	9.0/87.5	2.5	996	40	8	CS
	1200	9.5/87.0	2.5	994	45	10	CS
	1500	9.5/87.0	3.0	994	45	10	CS
	1800	10.0/86.5	3.0	992	50	12	CS
	2100	10.0/86.0	3.5	990	55	16	SCS
06.11.2010	0000	10.0/85.5	3.5	990	55	16	SCS
	0300	10.0/85.5	3.5	990	55	16	SCS
	0600	10.5/85.0	3.5	990	55	16	SCS
	0900	10.5/85.0	3.5	990	55	16	SCS
	1200	11.0/84.5	3.5	988	60	18	SCS
	1500	11.0/84.5	3.5	988	60	18	SCS
	1800	11.0/84.0	3.5	988	60	18	SCS
	2100	11.0/84.0	3.5	988	60	18	SCS
07.11.2010	0000	11.5/83.5	3.5	988	60	18	SCS
	0300	12.0/83.0	3.5	990	55	16	SCS
	0600	12.5/82.5	3.0	992	45	12	CS
	0900	12.5/81.5	2.5	994	40	8	CS
	1200	13.0/81.0	2.0	996	30	6	DD
	1500	13.0/80.5	2.0	998	30	5	DD
	The system crossed north Tamilnadu and south Andhra Pradesh coast close to north Chennai (43279) near 13.3^{0}N and 80.2^{0}E around 1600 UTC.						
	1800	13.5/80.0	--	1000	30	5	DD
08.11.2010	0000	14.0/79.0	--	1002	25	4	D
	0300	15.0/78.0	--	1004	25	3	D
	0600	The system weakened into a low pressure area over Rayalaseema and adjoining south interior Karnataka.					

The cloud heights were about 5 to 6 kms; the reflectivity in the wall cloud region was about 35-45 dBz maximum. General maximum velocities recorded are about 20-23 mps. The likely cloud center locations of the system are presented below along with related description. Arrangement of cloud, radial velocity diagrams are taken in to consideration while trying to fix the Cyclonic system center. DWR Chennai tracked from 0400 to 1800 UTC of 7 November. The vertical wind shear had detrimental effect on weakening the system at sea level. The centre of mass of dense convection area crossed north Cuddalore by about 0600 UTC of 7 November. Surface wind speed associated with the weak vortex was not more than 25 kts at any time.

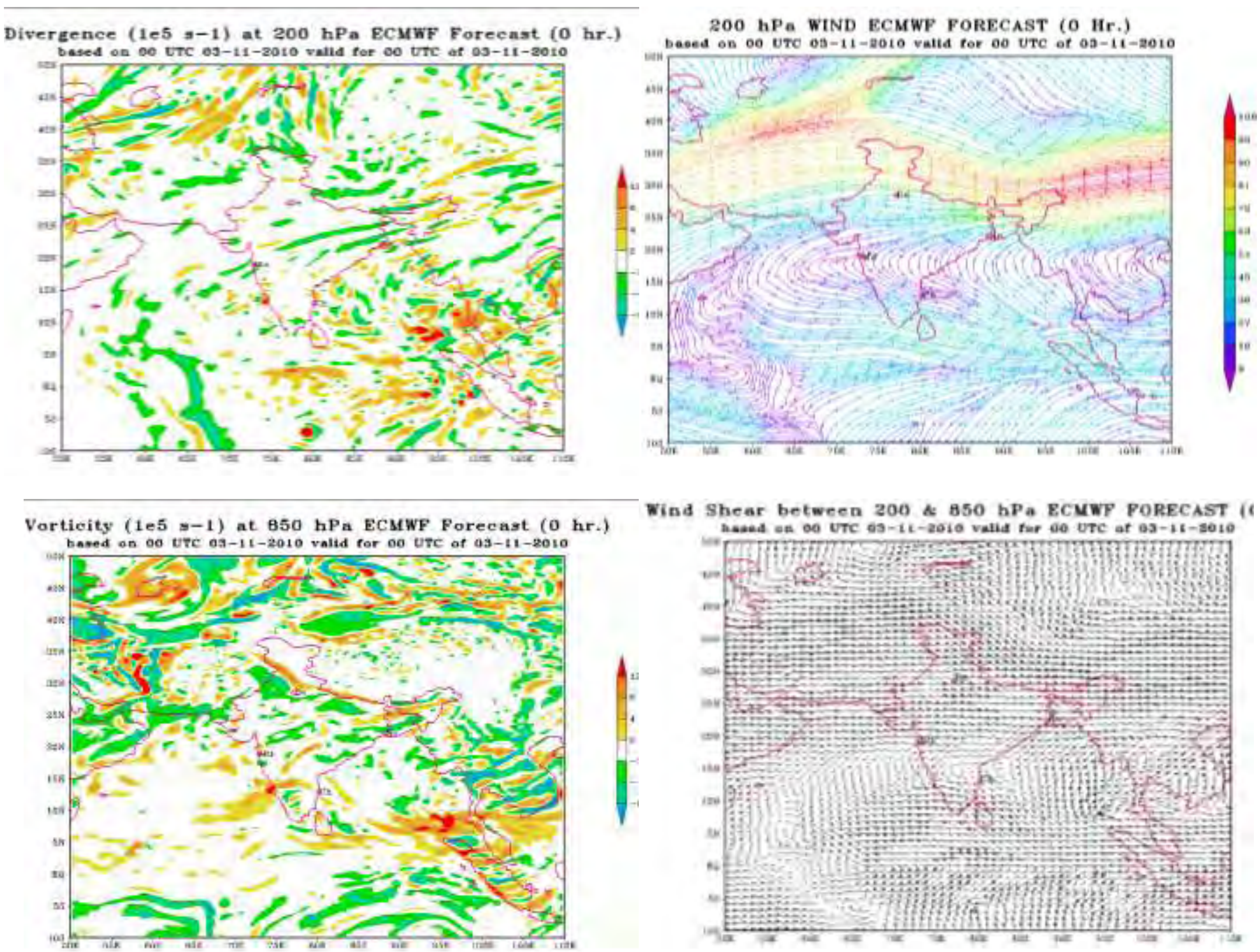


Fig.2.7.1. ECMWF analyses (a) Divergence at 200 hPa level, (b) Vorticity at 850 hPa level, (c) wind at 200 hPa level and (d) Vertical wind shear between 200 and 850 hPa level at 0000 UTC of 03 November 2010

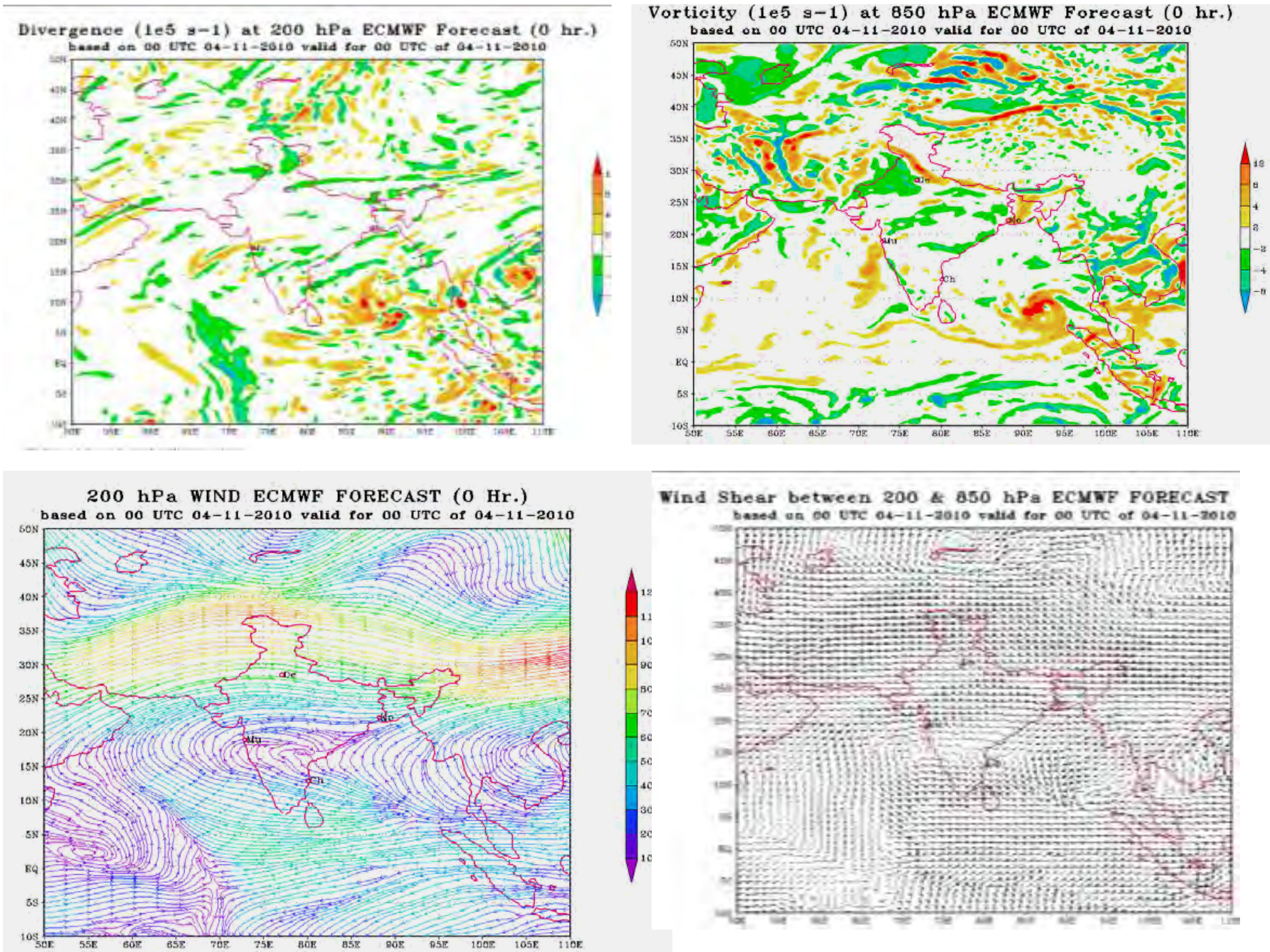


Fig.2.7.2(a). ECMWF analyses (a) Divergence at 200 hPa level, (b) Vorticity at 850 hPa level, (c) wind at 200 hPa level and (d) Vertical wind shear between 200 and 850 hPa level at 0000 UTC of 04 November 2010

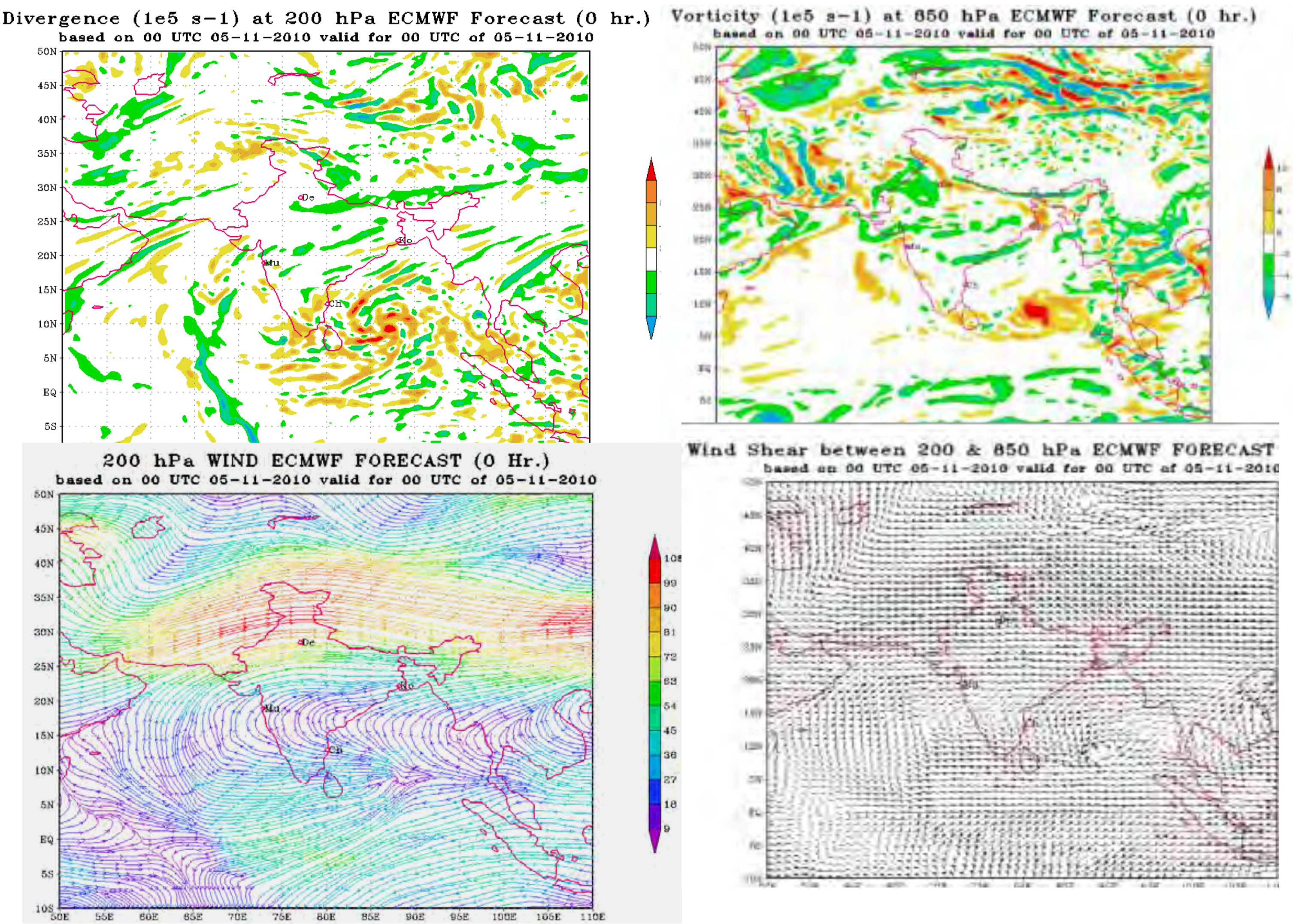


Fig.2.7.2(b). ECMWF analysis (a) Divergence at 200 hPa level, (b) Vorticity at 850 hPa level, (c) wind at 200 hPa level and (d) Vertical wind shear between 200 and 850 hPa level at 0000 UTC of 05 November 2010

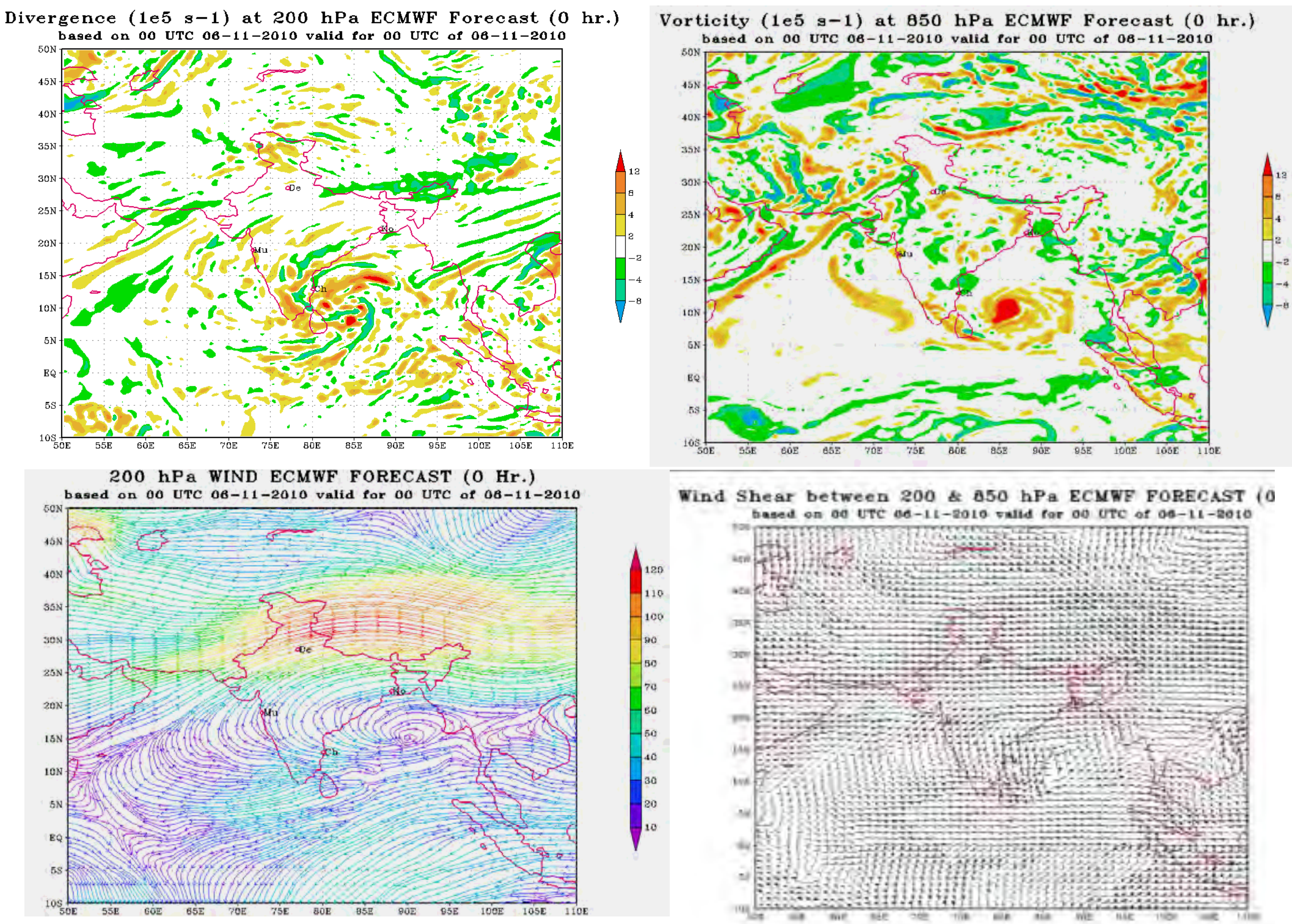


Fig.2.7.2(c). ECMWF analysis (a) Divergence at 200 hPa level, (b) Vorticity at 850 hPa level, (c) wind at 200 hPa level and (d) Vertical wind shear between 200 and 850 hPa level at 0000 UTC of 06 November 2010

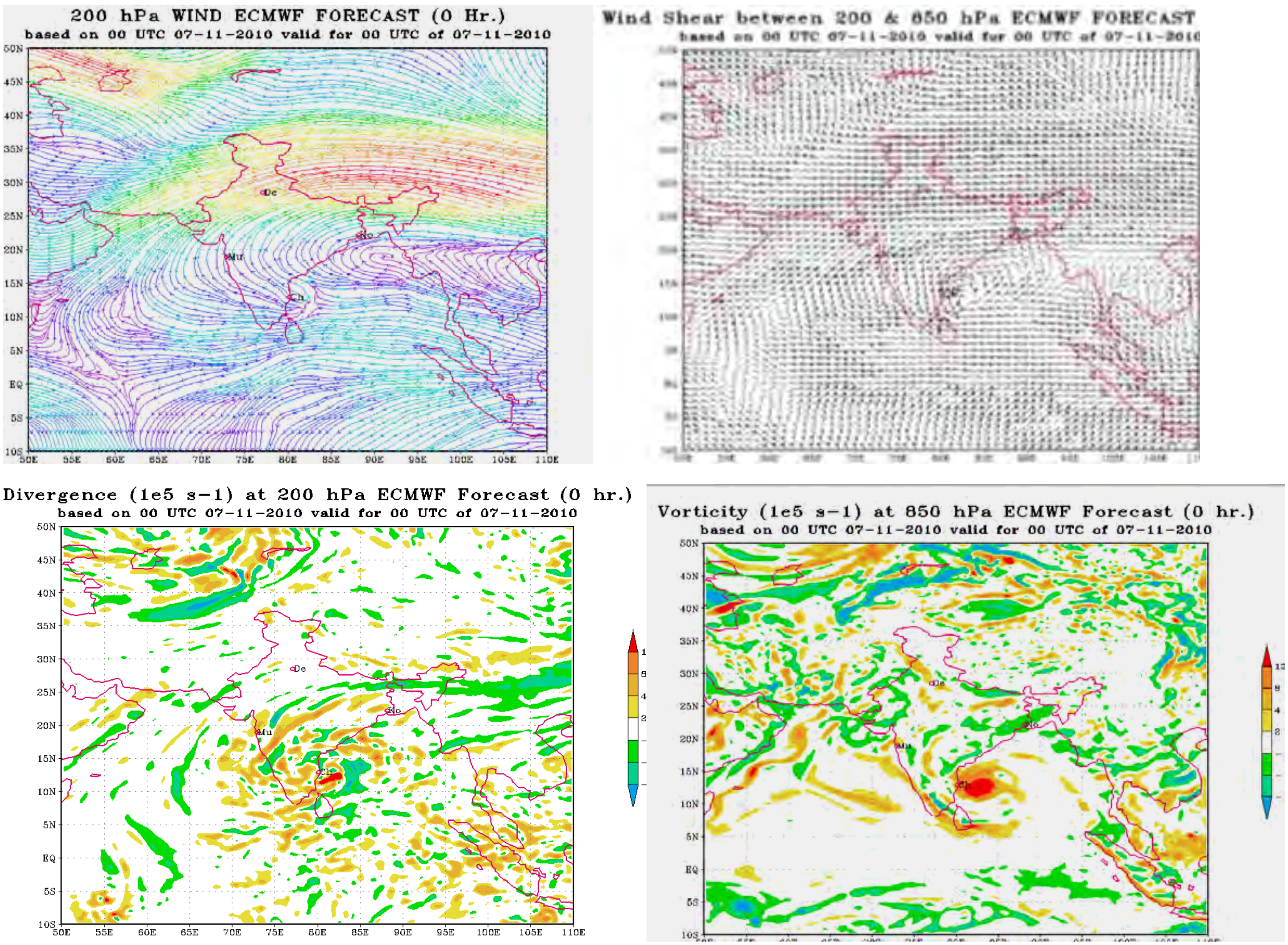


Fig.2.7.2(d). ECMWF analysis (a) Divergence at 200 hPa level, (b) Vorticity at 850 hPa level, (c) wind at 200 hPa level and (d) Vertical wind shear between 200 and 850 hPa level at 0000 UTC of 07 November 2010

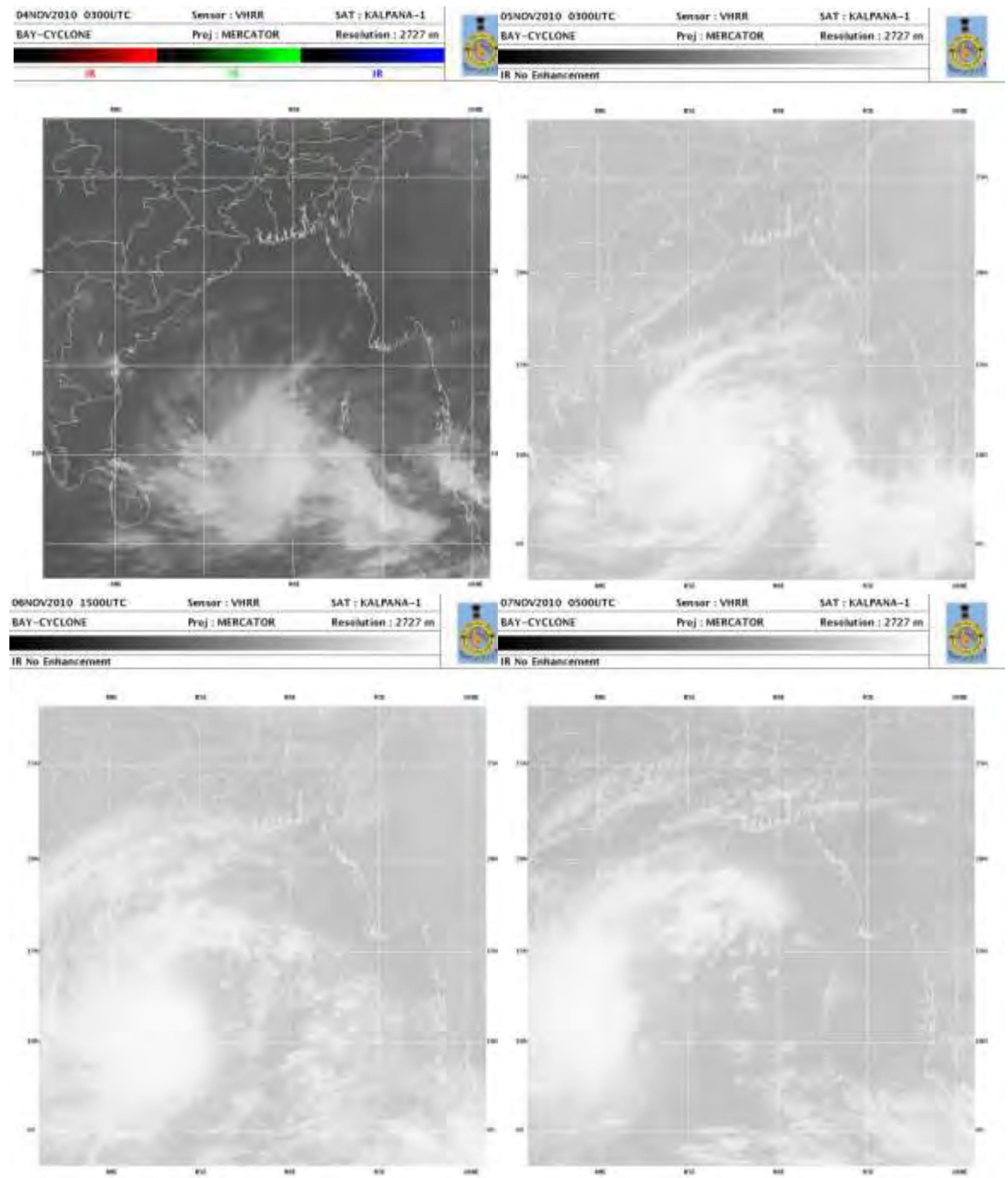


Fig.2.7.3. Kalpana imageries of the cyclone, JAL at different stages on intensity

2.7.5 Realised Weather

(a) Rainfall

Rainfall occurred at most places with heavy to very heavy fall at a few places over north Tamil Nadu, Puducherry, coastal Andhra Pradesh, Rayalaseema, south Interior Karnataka and coastal Karnataka. Chief amount of 24 hrs accumulated rainfall (≥7 cm) as recorded at 0300 UTC of 8 and 9 November 2010 are as follows.

08.11.2010

Andhra Pradesh

Palasa-27, Sompeta-14, Itchhapuram-12, Puttur-11, Kalingapatnam, Rayacholi and Kuppam-10 each, Tekkali-9, Vempalli & Bhimunipatnam-8 each, Thambalapalli, Madakasira,Kadiri, Hindupur, Nellore, Anakapalli, Mandasa and Kandukur - 7 each.

Tamil Nadu and Puducherry

Gingee - 16, Panruti -15, Ambur- 13, Vaniyambadi- 12, Tiruvannamalai and Alangayam - 11 each, Tindivanam , Villupuram, Puducherry Airport 10 each, Cuddalore , Vanur and Thali- 9 each, Chengalpattu , Polur and Krishnagiri -8 each, Dharmapuri, Palacode , Tirukoilur , Vandavasi , Arakonam, Gudiyatham, Sholingur, Tirupattur and Vellore 7 each.

South Interior Karnataka

Lakkavalli 11; Chitradurga 10; Hesaraghatta, B Durga, YN Hoskote 8 each; Bangalore HAL AP, Hoskote, Holalkere, Bargur, Pavagada, Thondebhavi, Gowribidanur, Ramanagara 7 each

09.11.2010:

Coastal Karnataka:

Karwar 21; Ankola 11; Kota 10; Kumta 9; Honavar 8;

North Interior Karnataka:

Ramdurga, Ron 7 each;

(b) Wind

Squally winds with maximum speed reaching upto 60 kmph has been reported from the observatory stations of IMD along north Tamil Nadu – south Andhra Pradesh coast. Ennore Port in Tamil Nadu reported 33 knots (61 kmph) in the forenoon of 7 October 2010. The wind speed decreased at the time of landfall, as the system weakened gradually and crossed as a deep depression.

2.7.6. Damage:

Andhra Pradesh:

Eleven people died in Andhra Pradesh, Hundreds of houses were damaged and crops over about 15000 hectares were destroyed. A loss of about 83 crores was estimated.

Tamil Nadu:

Five persons lost their lives. About 100 pucca/kutcha houses were either fully or partially damaged. May boast were damaged and some were also missing due to floods. Rail, road and air transports were affected due to heavy rain. Sea water inundated low lying areas.

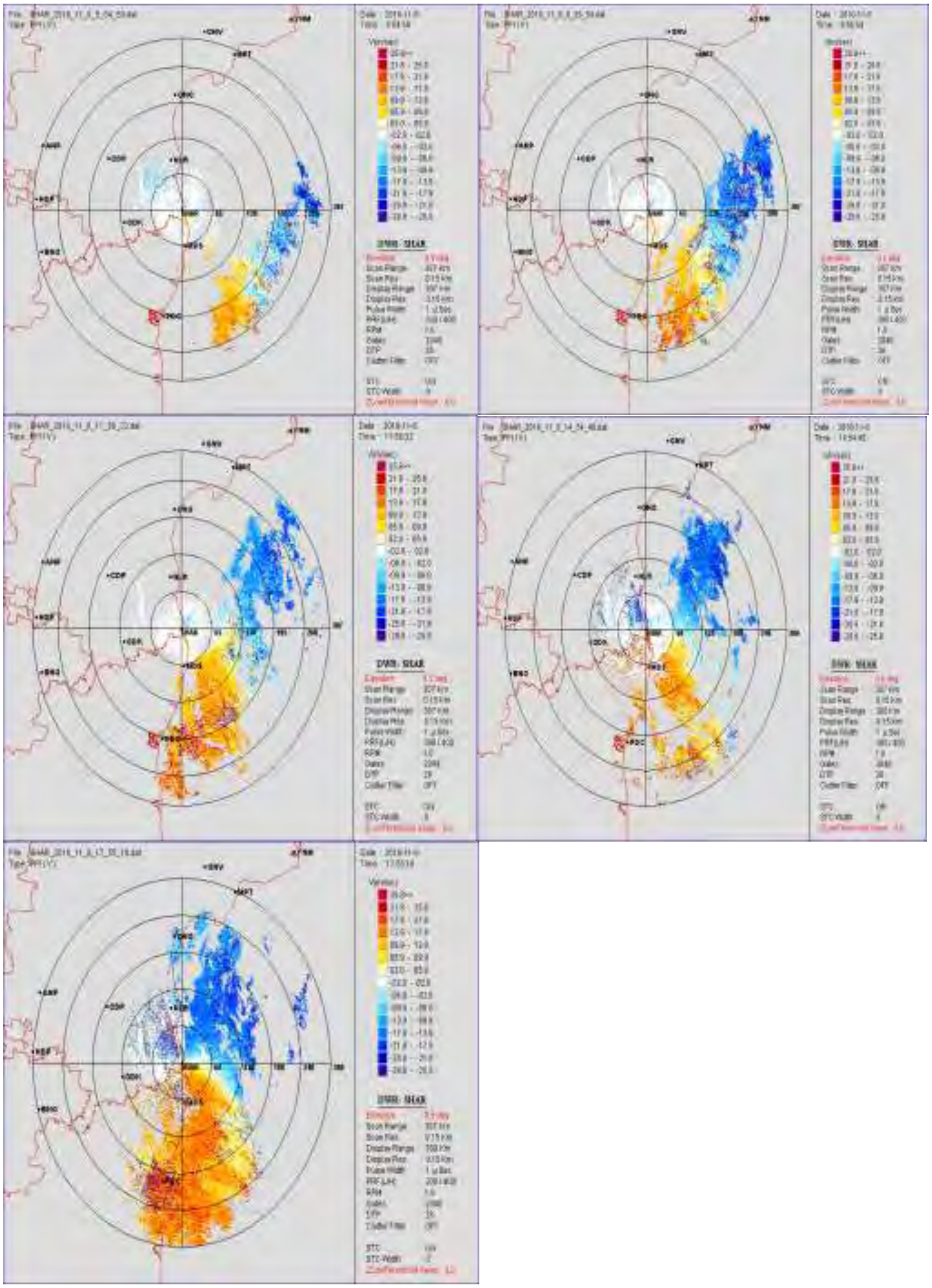


Fig.2.7.4 (a). DWR images of cyclone JAL for 0600,0900,1200,1500,1800 UTC of 06 November 2010.

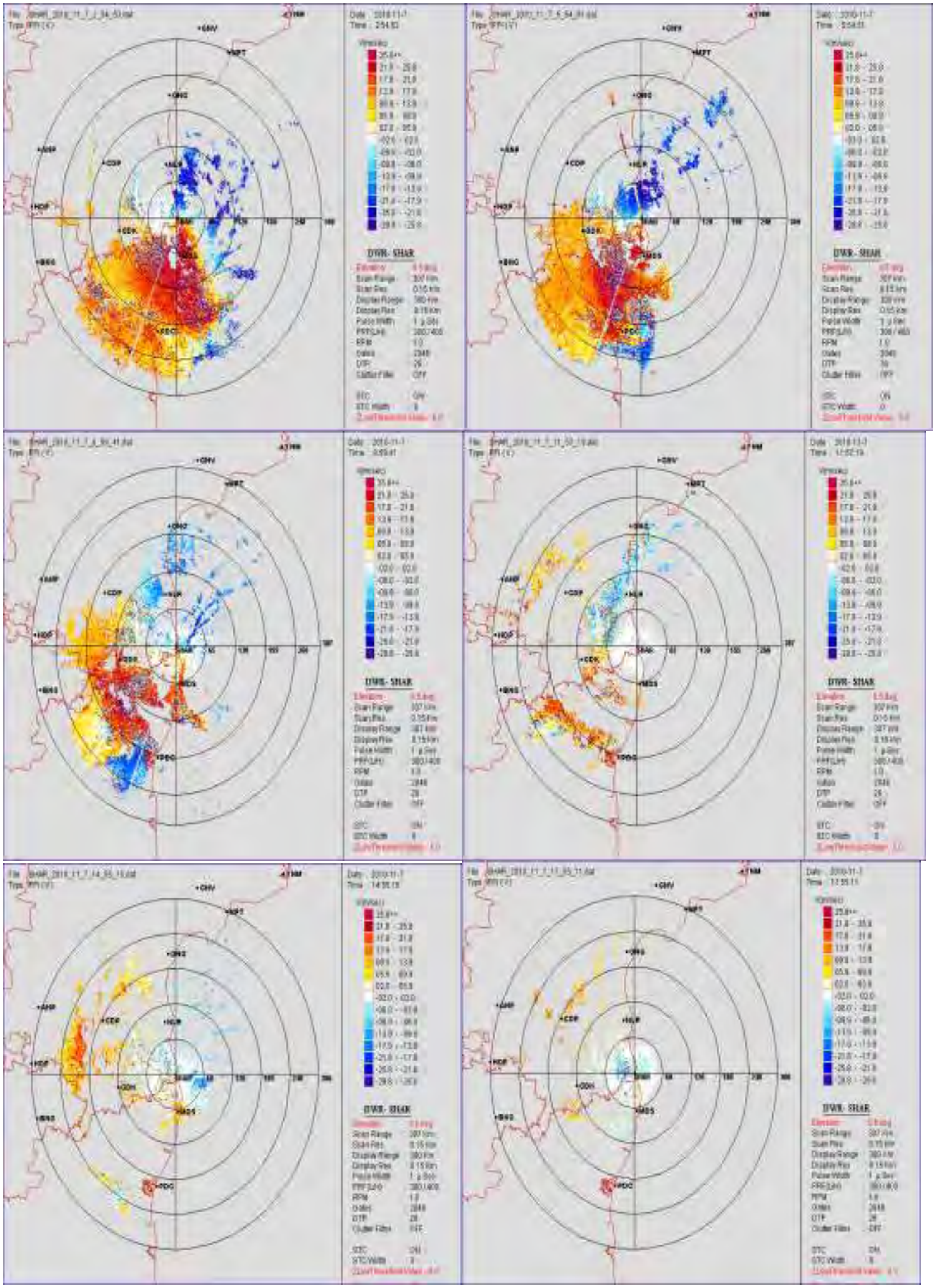


Fig.2.7.4(b). DWR images of cyclone JAL for 0300,0600,0900,1200,1500,1800 UTC of 07-11-10

2.8 Depression over the Bay of Bengal during 7-8 December, 2010

2.8.1. Genesis

Under the influence of an active inter-tropical convergence zone, a low pressure area formed over southwest Bay of Bengal on 4 December 2010. It persisted over the same region on 5 and became well marked on 6. It concentrated into a depression and lay centred at 0300 UTC of 7 December 2010 over westcentral Bay of Bengal near lat. 14.0^{0}N and long. 82.0^{0}E, about 230 km southeast of Kavali (Andhra Pradesh).

2.8.2. Intensification and movement

Considering the environmental features, the sea surface temperature was about 27-29^{0}C over westcentral Bay of Bengal during and prior to genesis. However, The Ocean heat content was very less (40-50 KJ/cm^2) over the westcentral Bay of Bengal which was unfavourable for further intensification of the system. The vertical wind shear of horizontal wind was moderate to high (15-25 knots) through the life period of the system. The system lay to the south of the upper tropospheric ridge through out its life period also. Considering all these, the depression moved initially north-northwestward, then northwestward and crossed south Andhra Pradesh coast near Baptla around 2000 of 7 Dec. 2010 without further intensification. After the landfall, the system continued to move northwestwards and weakened into a well marked low pressure area over central parts Andhra Pradesh at 0300 UTC of 8 Dec. 2010.

The typical satellite imageries of the system are shown in Fig.2.8.1. The best track parameters of the system are given in Table 2.8.1. The track of the system is shown in Fig.2.1.

Table 2.8.1. Best track Positions and other parameters for depression over the Bay of Bengal during 7-8 December 2010

Date	Time (UTC)	Centre lat.^{0}N/ long. ^{0} E	C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
07-12-2010	0300	14.0/82.0	1.5	1000	25	4	D
	0600	14.5/82.0	1.5	1000	25	4	D
	1200	15.0/81.5	1.5	1000	25	4	D
	1800	15.5/81.0	1.5	1000	25	4	D
	Depression crossed south Andhra Pradesh coast near Baptla (43220) around 2000 UTC						
08-12-2010	0000	16.0/80.0	1.5	1000	20	3	D
	0300	Well marked low pressure area over central Andhra Pradesh					

2.8.3. Structure

The estimated central pressure (ECP) of the system was 1000 hPa with estimated sustained maximum wind of 25 knots at the time of landfall. The lowest MSLP of 1000.7 hPa was reported by Baptla during 1900-2000 UTC of 7 December. The satellite imagery indicated shear pattern of the system of the system through out its life period. The intense convection was sheared to the northwest of the system centre. The lowest cloud top temperature in association with system was about -70^{0}C.

2.8.4 Realized weather

Under the influence of the depression, widespread rainfall with isolated heavy to very heavy falls occurred over coastal Andhra Pradesh on 7 and 8 December 2010. Heavy to very heavy rainfall also occurred over Tamil Nadu from 6 to 8 December. Fairly widespread rainfall with isolated heavy rainfall occurred over Orissa during the same Period. Northeast monsoon was vigorous in Andhra Pradesh from 6 to 8 December. The chief amount of rainfall (≥ 7 cm) recorded over these regions are given below.

7.12.2010
Andhra Pradesh: Bapatla & Narsapur -10 each, Repalle & Sullurpet-9 each, Tada-8, Sattenapalli, Kaikalur), Machilipatnam, Nuzvid , Gudur, Bhimavaram-7 each.

8.12.2010
Andhra Pradesh: Ranasthalam-14, Tekkali & Cheepurupalli-13 each, Kakinada, Kalingapatnam & Araku Valley -12 each, Macherla, Udayagiri, Vinjamur, Cumbum, Visakhapatnam & Salur-11 each, Amalapuram, Peddapuram, Patapatnam, Elamanchili, Srungavarapukota, Terlam & Vizianagaram-10 each, Veeraghattam, Bheemunipatnam, Paderu & Koderu-9 each, Atmakur(N), Addanki, Palakonda , Palasa , Chodavaram, Visakhapatnam (AP) & Bobbili-8 each, Badvel, Porumamilla, Piduguralla, Suryapet, Mandasa, Anakapalle, Narsipatnam & Parvathipuram -7 each.

9.12.2010
Andhra Pradesh: Elamanchili-11

2.8.5. Damage:

Heavy rains claimed 2 lives in Andhra Pradesh. As the Depression did not cross Tamil Nadu coast, there was no serious loss of life and property. However, when it was located over west central Bay of Bengal off south Andhra Pradesh coast; Tamil Nadu received bountiful rainfall almost in all the districts of Tamil Nadu with heavy rainfall over Kanyakumari district in which 4500 huts were damaged and about thousand acres of Paddy field were submerged.

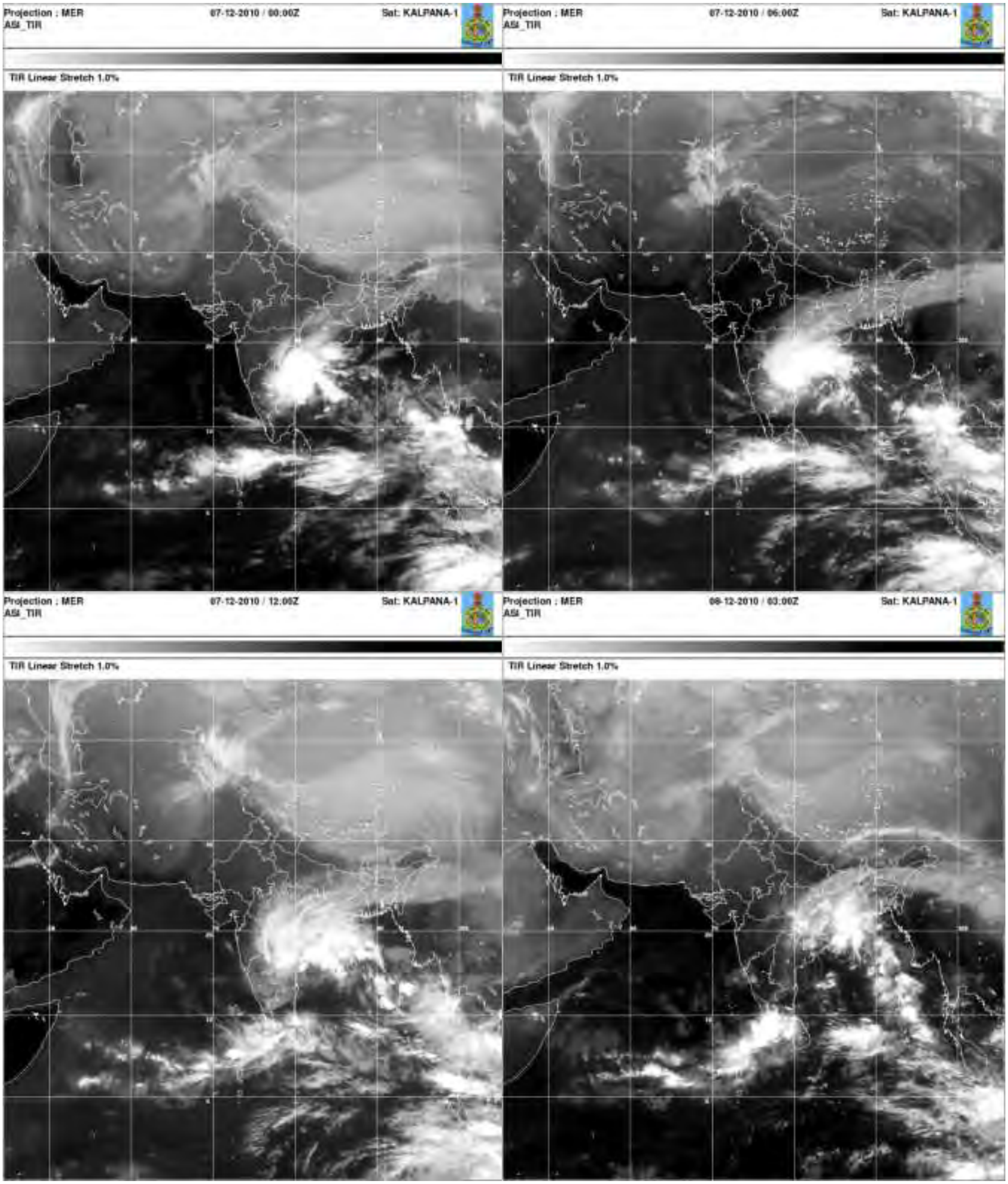


Fig2.8.1. Kalpana imageries of the depression at different stages on intensity

CHAPTER – III

Performance of operational NWP models during the year 2010

3.1 Introduction:

India Meteorological Department (IMD) operationally runs three regional models WRF, MM5 and Quasi-Lagrangian Model (QLM) for short-range prediction and one Global model (T382L64) for medium range prediction (7 days). 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 35km. The boundary conditions are updated at every six hours interval. MM5 model is run at the horizontal resolution of 45 km with 23 sigma levels in the vertical and the integration is carried up to 72 hours over a single domain covering the area between lat. 30^{o} S to 45^{o} N, long. 25^{o} E to 125^{o} E. 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 in India like Indian institute of Technology (IIT)Delhi, NCMRWF, Indian Airforce etc. and international centres like European Centre for Medium Range Weather Forecasting (ECMWF), GFS, National Centre for Environmental Prediction (NCEP), Japan Meteorological Agency (JMA), UK Meteorological Office (UKMO), Meteo France ARPS model 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 MM5, QLM, GFS (NCEP), ECMWF and JMA. In this report performance of these individual models and MME forecasts for cyclones during 2010 are presented and discussed.

3.2 Cyclonic storm "LAILA " (17-21 May, 2010)

3.2.1 Genesis

Analysis of Genesis Potential Parameter (GPP) values computed (Kotal et al, 2009) for cyclone „LAILA' on the basis of real time model analysis fields along with the GPP values for developing systems and non-developing systems are shown in Table 3.2.1 The higher GPP values (> 8.0, the threshold value) at early stages of development (T.No. 1.0, 2.0) have clearly indicated that the cyclone "LAILA" had enough potential to intensify into a cyclone (>35 knots).

Table 3.2.1 GPP ($x10^{-5}$) for developing system , non-developing system and Cyclone “LAILA”

Date/Time	16.05.2010 1200 UTC	17.05.2010 0000 UTC	17.05.2010 1200 UTC
T.No. →	**1.0**	**1.0**	**2.0**
Developing	11.1	11.1	13.3
Non-Developing	3.4	3.4	4.6
LAILA	**17.4**	**13.5**	**16.5**

3.2.2 Track and Landfall:

Fig. 3.2.1(a-d) display the forecast tracks of the cyclone, “LAILA” by various NWP models (ECMWF, IMD-GFS, NCEP-GFS, JMA, MM5, QLM, WRF, UKMO and MME) with the initial conditions of 0000 UTC of 17, 18, 19 and 20 May 2010 respectively. All the NWP models indicated that the cyclonic storm “LAILA” would cross the Andhra Pradesh coast, although there is variation of landfall from extreme north to extreme south Andhra Pradesh coast by different models. But the MME could predict landfall near middle of Andhra Pradesh coast around latitude 16^o N.

The forecast errors of member models based on different initial conditions and the corresponding MME forecast are summarized in Table 3.2.2 (a-e). The MME forecasts could provide useful guidance under the circumstances of wide variations of individual model forecasts.

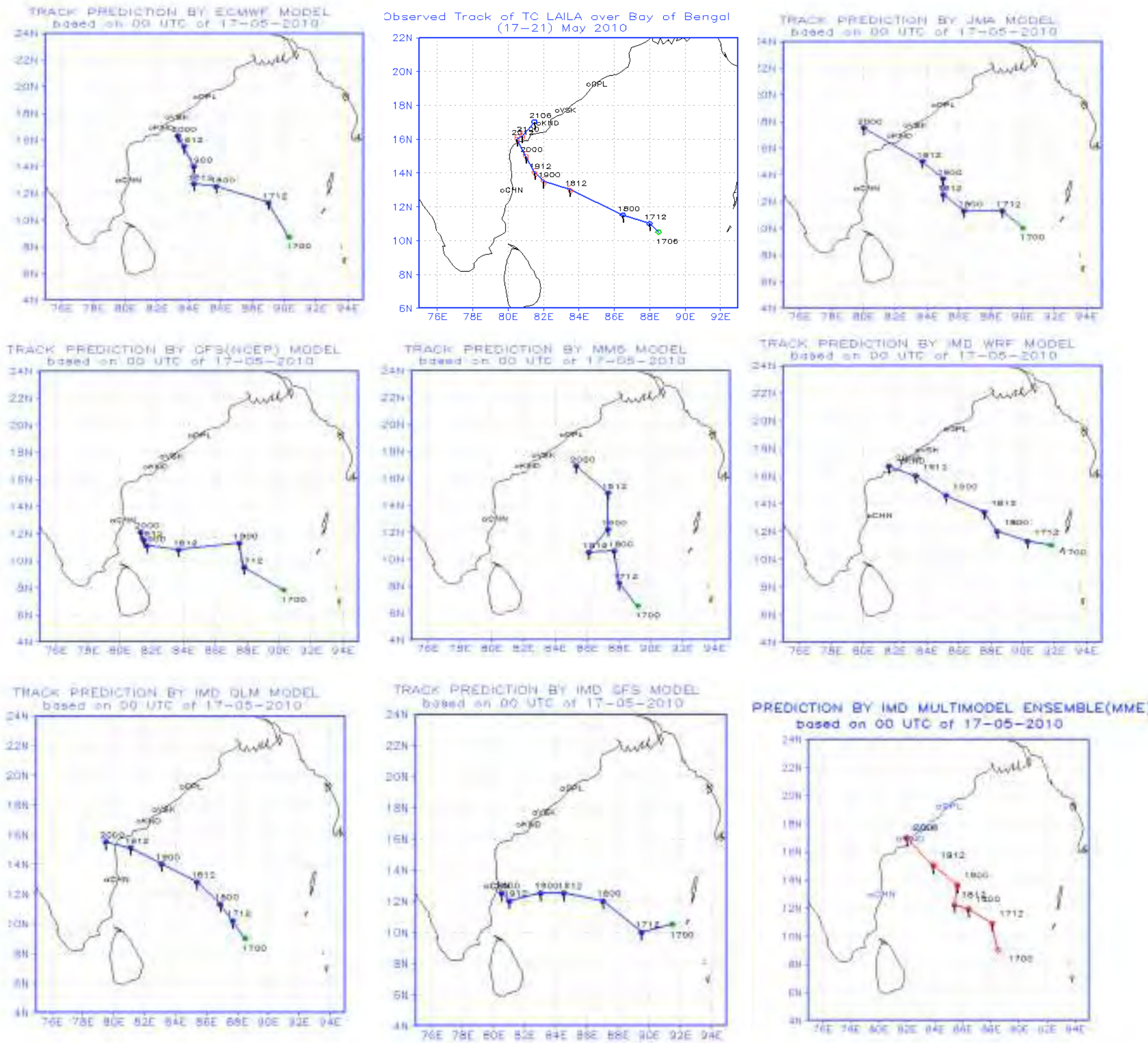


Fig.3.2.1 (a) Track forecasts of multimodel ensemble and its member models based on 0000 UTC of 17.5.2010

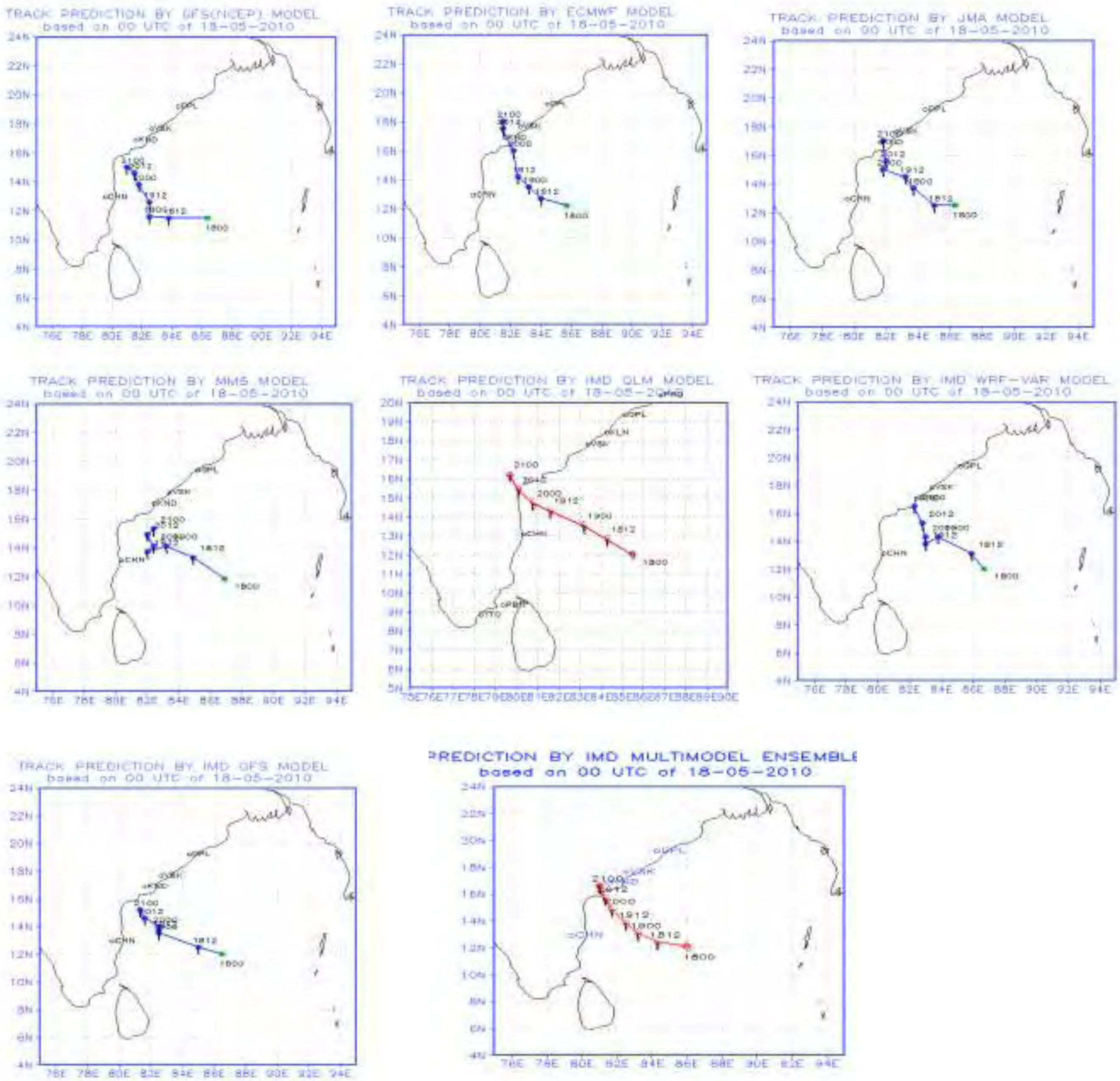


Fig. 3.2.1(b) Track forecasts of multimodel ensemble and its member models based on 0000 UTC of 18.5.2010

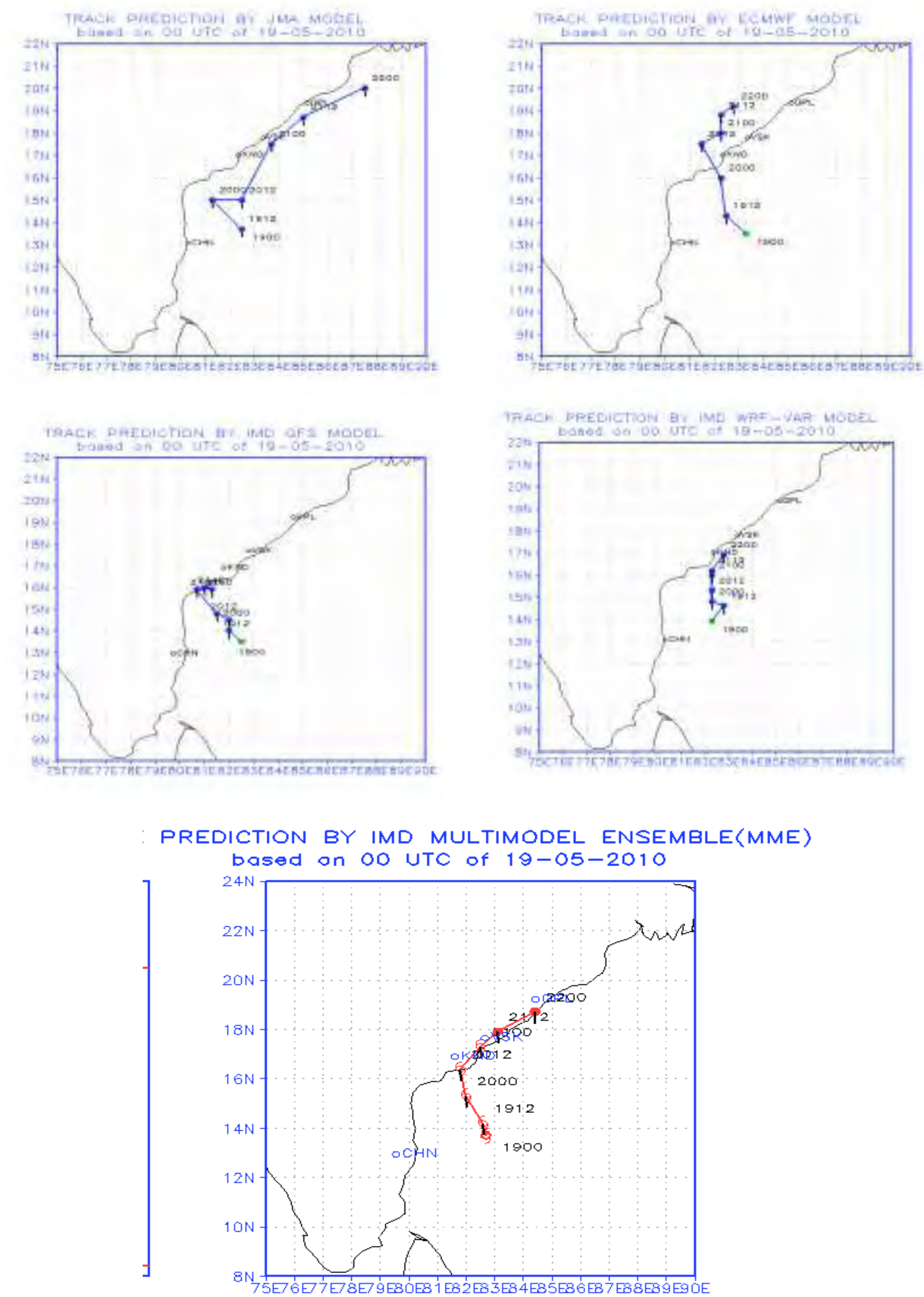


Fig.3.2.1(c) Track forecasts of multimodel ensemble and its member models based on 0000 UTC of 19.5.2010

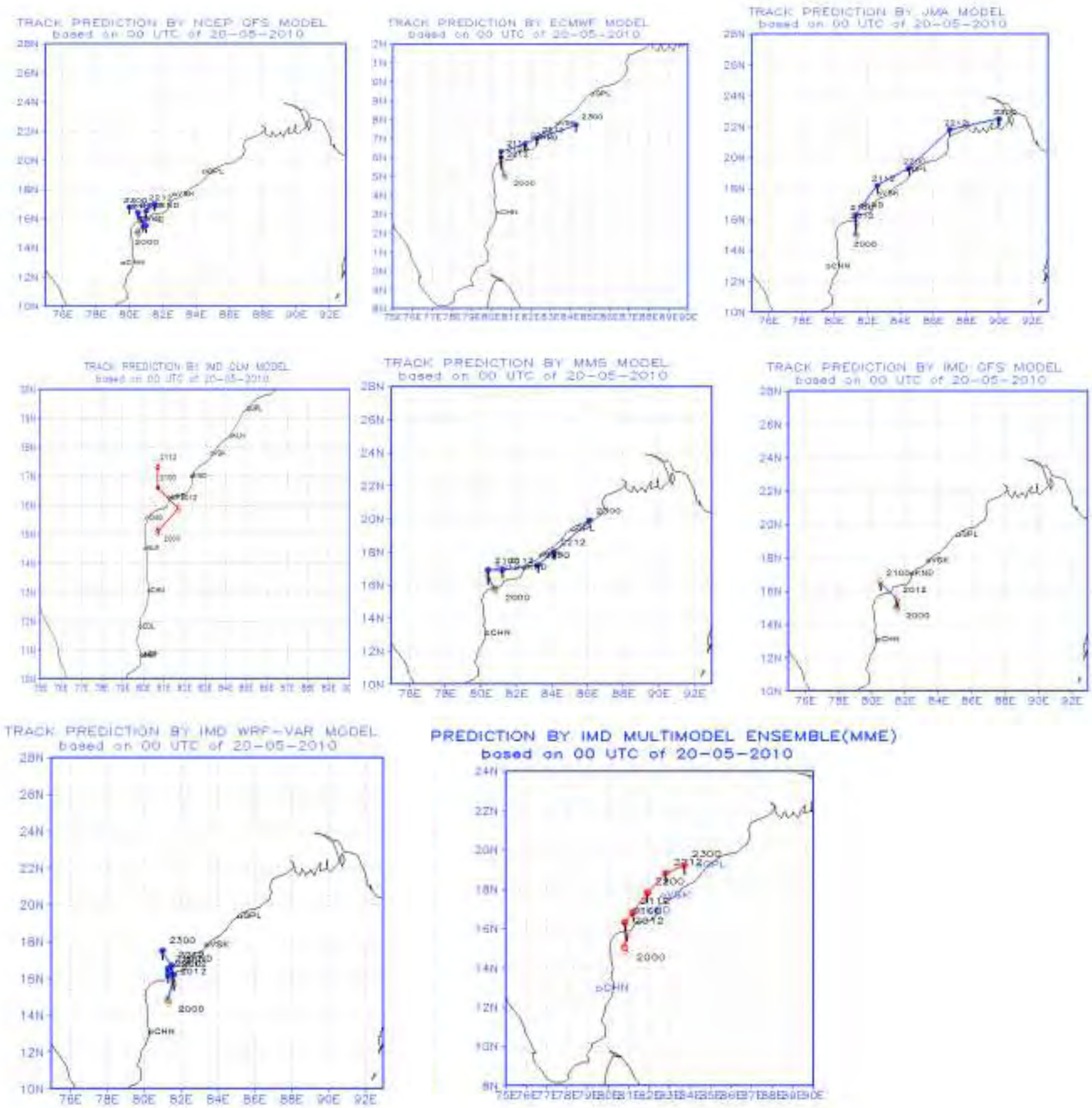


Fig.3.2.1(d) Track forecasts of multimodel ensemble and its member models based on 0000 UTC of 20.5.2010

The cyclone track forecast errors in case of cyclone, Laila by Indian Air Force (IAF) WRF (ARW) model, IIT, Delhi WRF (ARW) model, IMD WRF (NMM) model and NCMRWF(T254, L64), India model are shown in Fig. 3.2.2, Fig.3.2.3, Fig.3.2.4 and Fig.3.2.5 respectively.

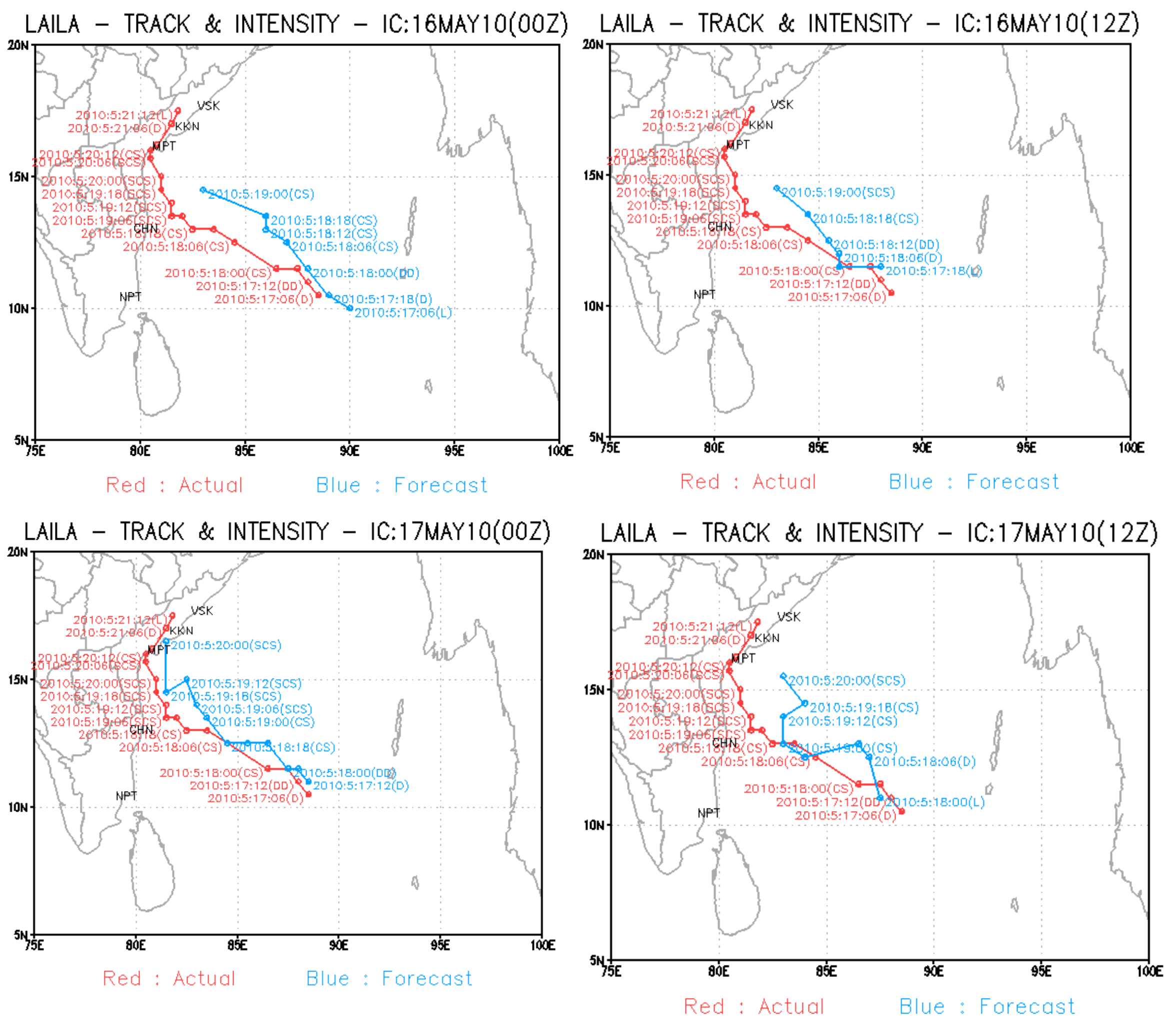


Fig.3.2.2. Track forecasts of IAF model during cyclone, LAILA

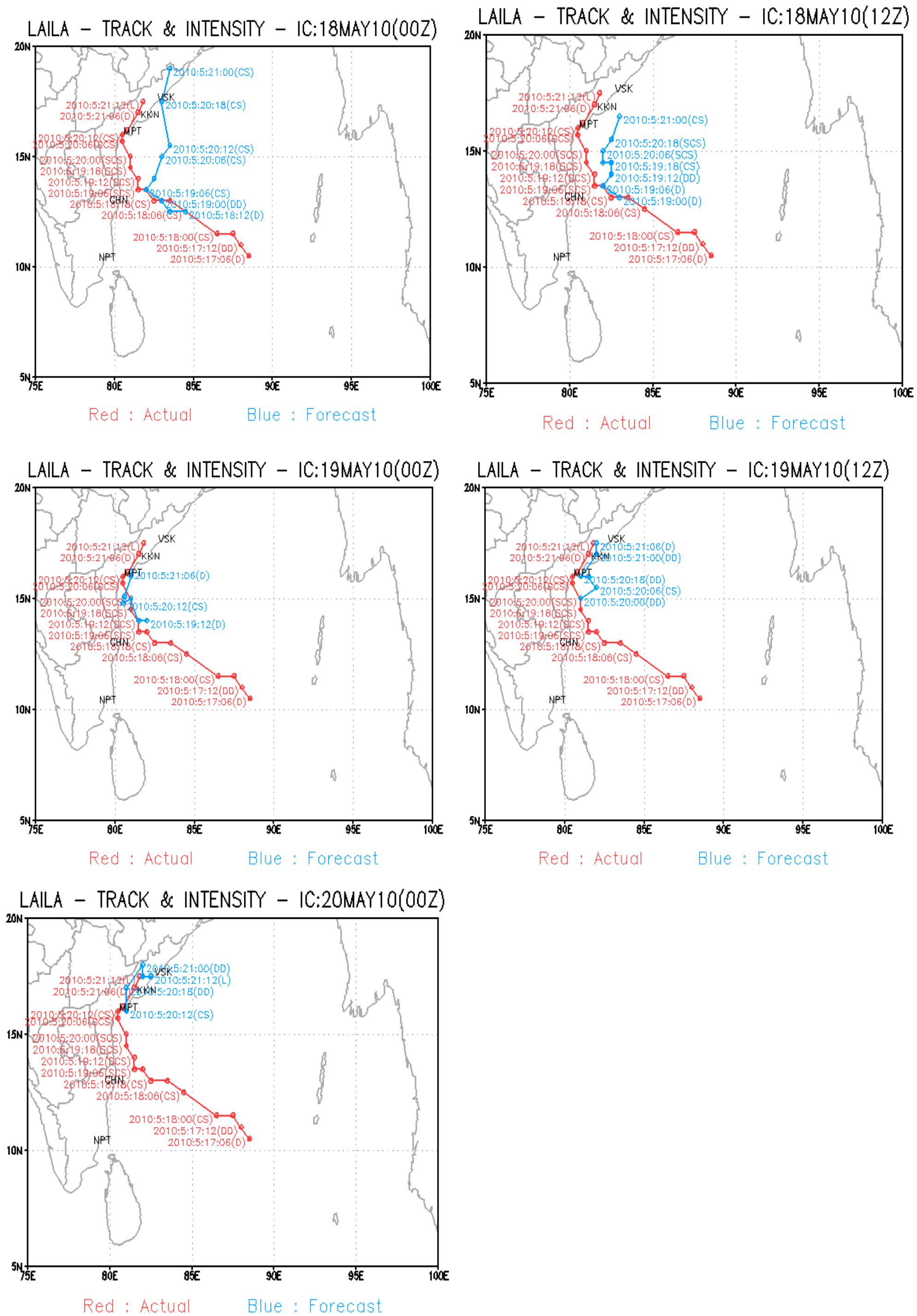


Fig.3.2.2(Contd) Track forecasts of IAF model during cyclone, LAILA

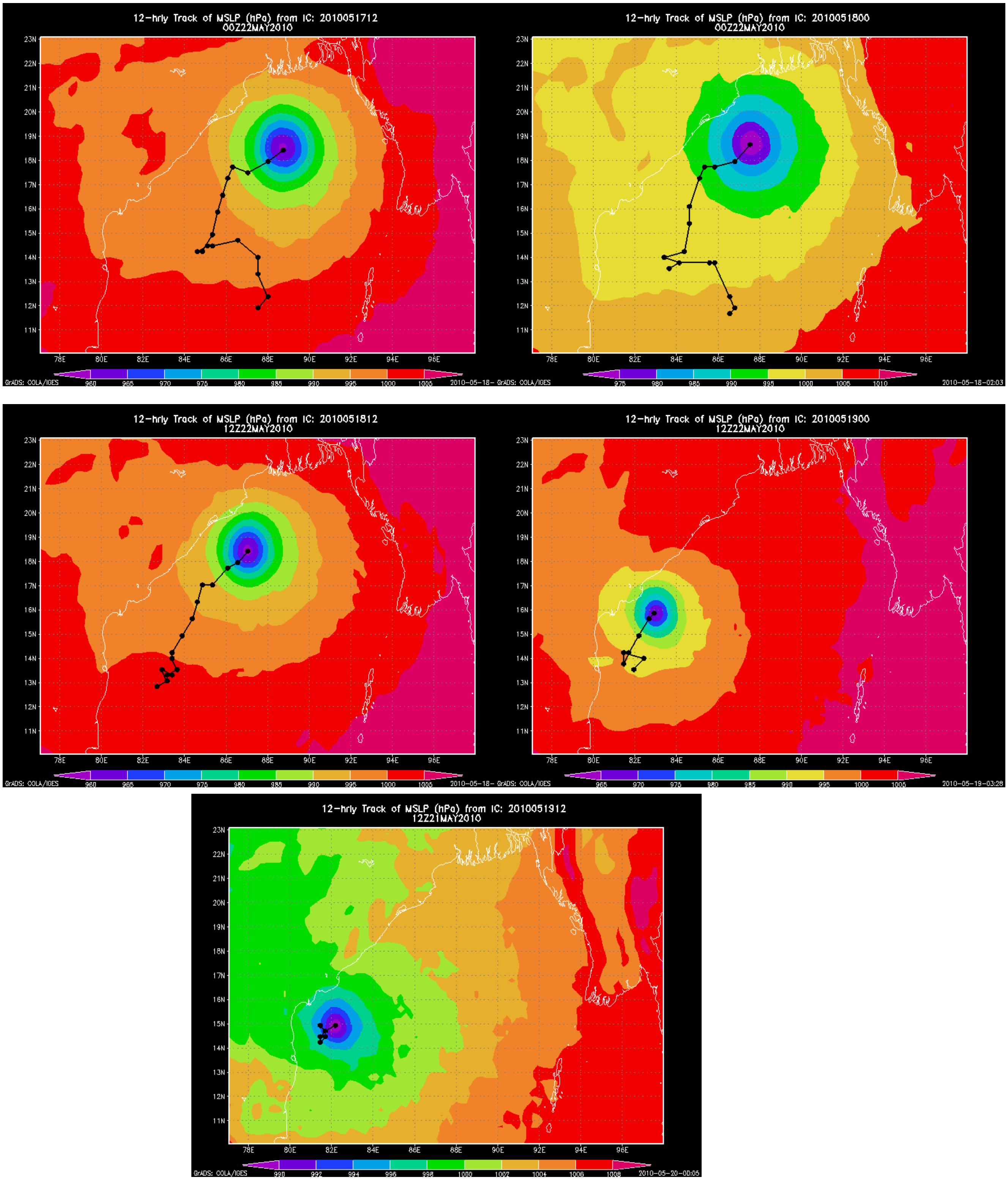


Fig.3.2.3(a).Track forecasts of IIT Delhi WRF (ARW) model during cyclone, LAILA

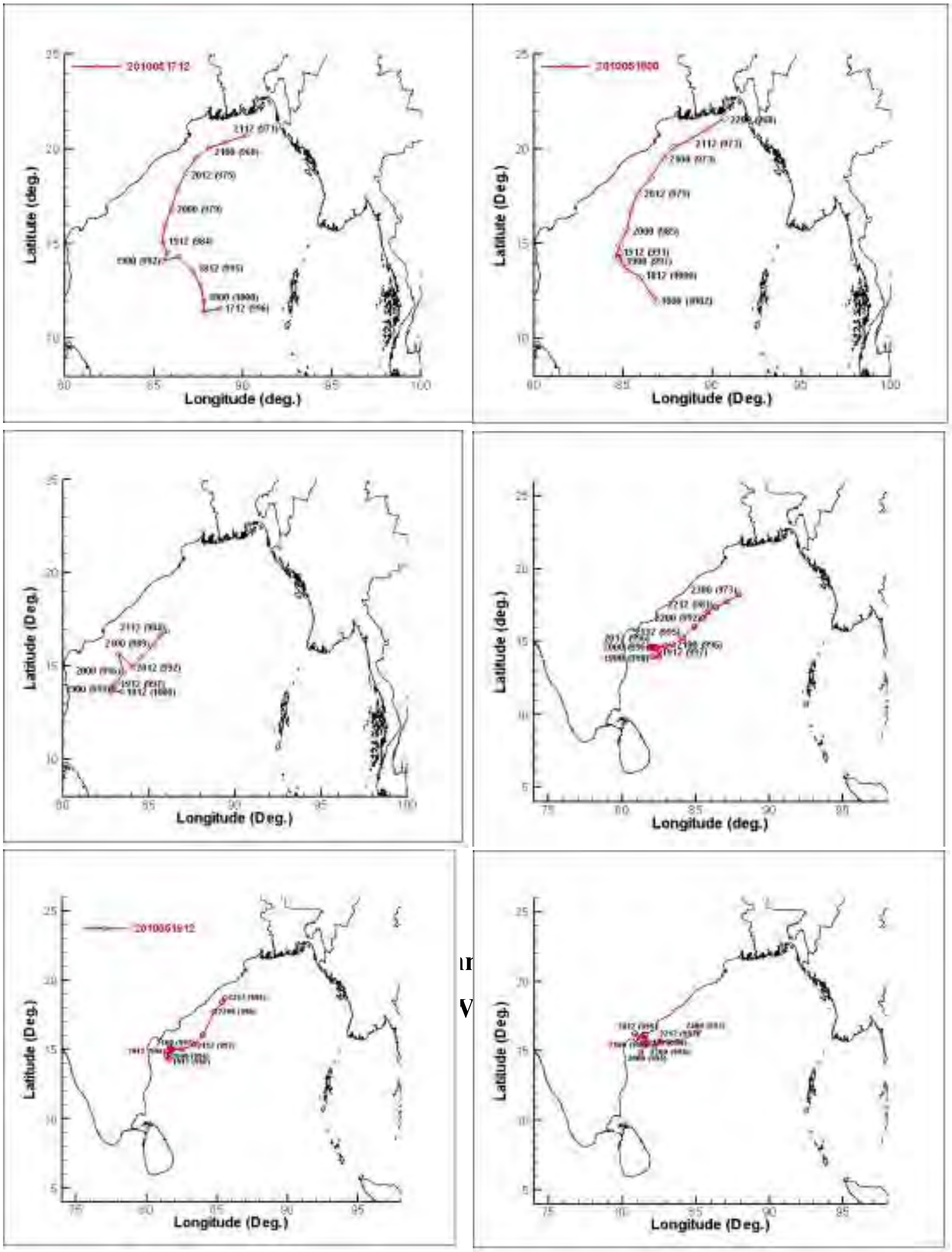


Fig.3.2.3(b).Track forecasts of IIT Delhi WRF (NMM) model during cyclone, LAILA

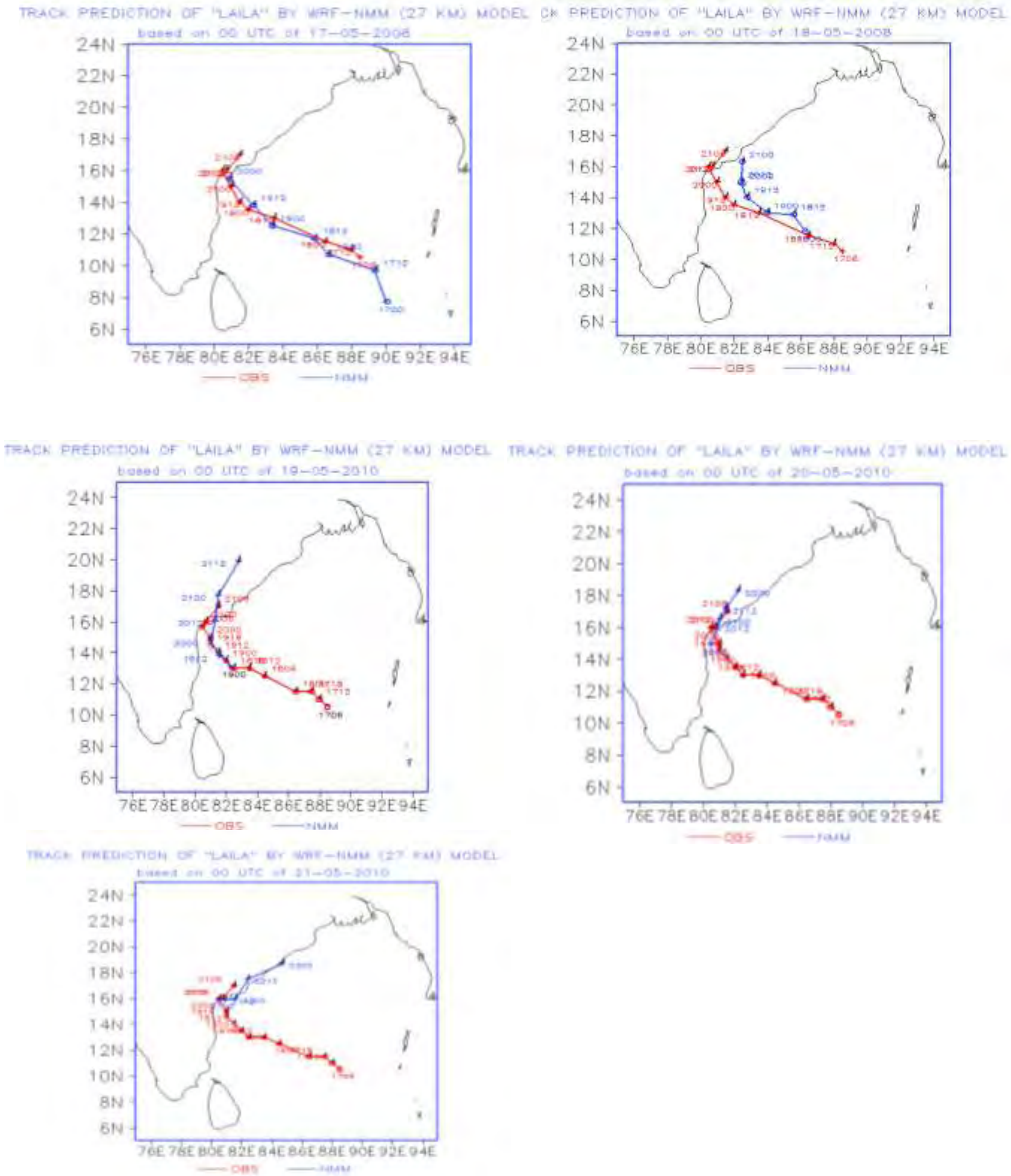
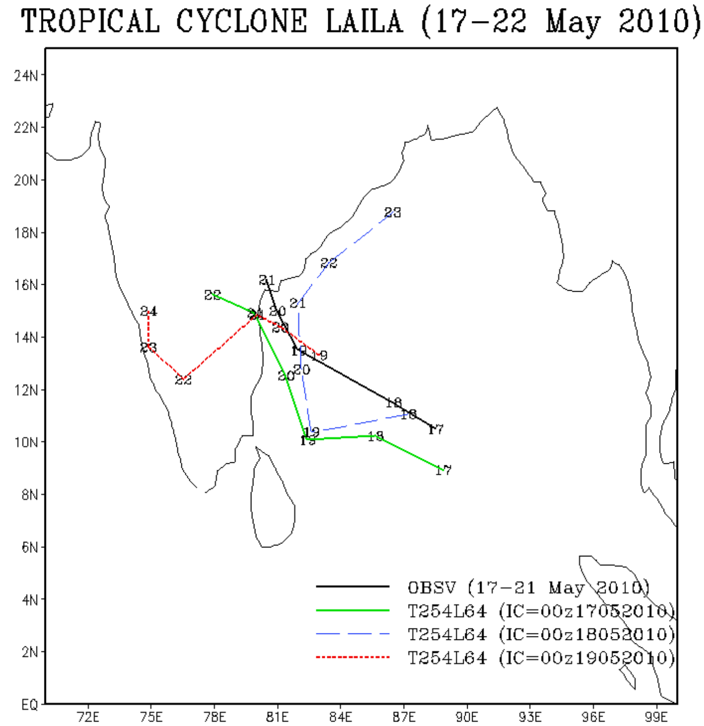


Fig.3.2.4.Track forecasts of IMD WRF (NMM) model during cyclone, LAILA



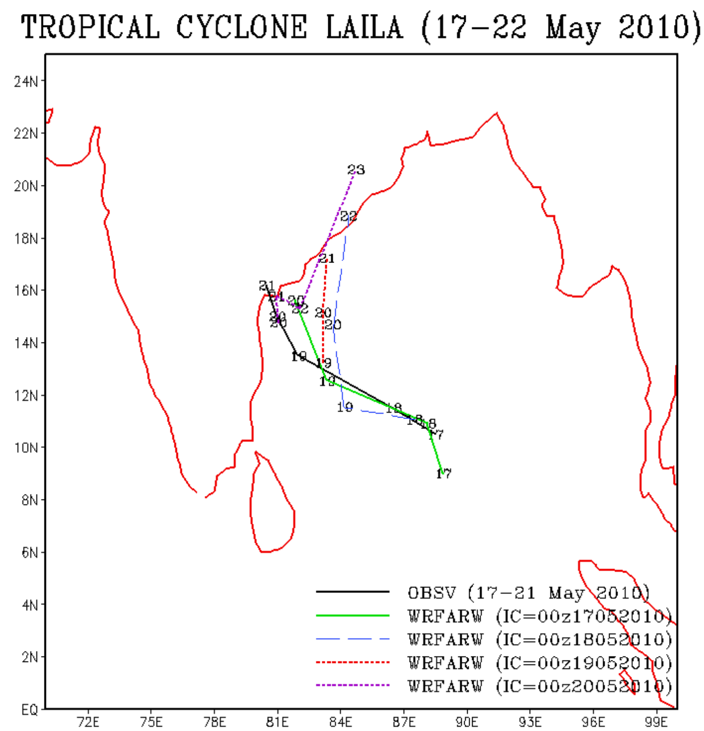


Fig.3.2.5.Track forecasts of NCMRWF, India global model during cyclone, LAILA

Table 3.2.2 (a) Initial position error (km) with respect to landfall time

Lead time (hrs)	ECMWF	GFS NCEP	JMA	IMD-MM5	IMD-QLM	IMD-MME	IMD-T382	IMD-ARW-WRF
12	32	54	32	81	34	21	54	39
36	140	No data	58	No data	No data	79	54	55
60	117	11	113	55	122	86	56	60
Lead time (hrs)	WRF-NMM (IMD)	NCMRWF	NCMRWFWRF-ARW	IAF	IITD			
12	56	-	27	-	-			
24	70	-	-	-	-			
36	55	107	51308	-	-			
48	56	-	-	-	-			
60	137	90	119	-	-			
72	59	180	171	-	-			

Table 3.2.2 (b) Average Track forecast errors (Direct position error in Km)

Models	**Lead time**					
	12 hours	24 hours	36 hours	48 hours	60 hours	72 hours
ECMWF	80	123	132	241	246	261
NCEP-GFS	131	123	217	214	234	241
JMA	114	92	201	237	213	245
IMD-MM5	141	131	229	387	416	378
IMD-QLM	83	83	121	85	105	115
IMD-MME	68	89	169	246	185	171
IMD-T382	136	75	135	138	209	137
IMD-ARW-WRF	197	173	272	273	276	213
IMD-NMM-WRF	107	141	204	250	189	158
NCMRWF	-	197	-	328	-	218
NCMRWF (WRF-ARW)	-	320	-	253	-	297
IAF	77	151	142	204	232	253
IITD (WRF-ARW)	157	220	290	310	398	438

Table 3.2.2 (c) Genesis : (formation of Depression) Forecast errors (km)

	Lead time					
Models	24 hours	48 hours	72 hours	-	-	-
ECMWF	156	283	323	-	-	-
NCEP-GFS	337	No data	No vortex indicated	-	-	-
JMA	167	No data	612	-	-	-
IMD-MM5	No vortex indicated	No data	279	-	-	-
IMD-GFS	518	547	No vortex indicated	-	-	-
IMD- WRF	629	-	572	-	-	-

Table 3.2.2 (d): Landfall forecast error (km); F/C-Forecast

Model	12 (11:30) based on 20.05.2010	36 (35:30) based on 19.5.2010	60 (59:30) based on 18.05.2010	84 (83:30) based on 17.05.2010
	F/C	F/C	F/C	F/C
ECMWF	33	176	169	No Landfall
GFS	31	No data	No Landfall	No Landfall
JMA	86	No Landfall	159	116
IMD-MM5	31	No data	No Landfall	No Landfall
IMD-QLM	111	No data	89	79
IMD-MME	31	176	64	203
IMD-T382	52	31	No Landfall	No Landfall
IMD-ARW-WRF	88	No Landfall	200	200
IMD-NMM-WRF	46	56	435	-
NCMRWF		139	483	
IAF	55	55	335	

Table 3.2.2 (e): Landfall time error. (E- Early; D- Delay; F/C-Forecast)

Model	12 hrs based on 20.05.2010	36 hrs based on 19.5.2010	60 hrs based on 18.05.2010	84 hrs based on 17.05.2010
	F/C	F/C	F/C	F/C
ECMWF	03hr 30min D	07hr 30min E	07hr 30min E	No Landfall
NCEP-GFS	02hr 30min D	No data	No Landfall	No Landfall
JMA	02hr 30min D	No Landfall predicted	06hr 30min D	16hr 30min E
IMD-MM5	08hr 30min E	No data	No Landfall	No Landfall
IMD-QLM	06hr 30min D	No data	Close to Landfall time	16hr 30min E
IMD-MME	03hr 30min D	00hr 30min D	03hr 30min D	13hr 30min E
IMD-T382	06hr 30 min D	10hr 30min D	No Landfall predicted	No Landfall predicted
IMD-ARW-WRF	04hr 30min D	No Landfall	12hr 30min D	15hr 30min E
IMD-NMM-WRF	00	00	12 hr D	-
NCMRWF	-	12.5 hr E	10.5 hr E	-
IAF	0.5 hr D	12 hr D	0.5 hr D	-

3.3 Very Severe Cyclonic Storm "PHET" over the Arabian Sea (31 May – 7 June, 2010)

3.3.1. Genesis

Analysis of GPP values computed for this cyclone (PHET) on the basis of real time model analysis fields along with the GPP values for developing systems and non-developing systems are shown in Table 3.3.1. The higher GPP values (> 8.0, the threshold value) at early stages of development (T.No. 1.0, 1.5, 2.0) have clearly indicated that the cyclone "PHET" had enough potential to intensify into a developing system (>35 knots). The performance of NWP models on prediction of genesis (formation of depression) is shown in Table 3.3.1(b).

Table 3.3.1(a). GPP($x10^{-5}$) for Developing System, Non-Developing System and cyclone "PHET"

Date/Time	31.05.2010 0000 UTC	31.05.2010 1200 UTC	01.06.2010 0000 UTC
T.No. →	**1.0**	**1.5**	**2.0**
Developing	11.1	11.1	13.3
Non-Developing	3.4	3.4	4.6
Cyclone PHET	**9.7**	**14.2**	**17.3**

Table 3.3.1(b) Genesis: (formation of Depression) Forecast errors (km)

	Lead time →		
Models	**24 hours**	**48 hours**	**72 hours**
ECMWF	237	456	508
GFS (NCEP)	301	684	1144
JMA	376	1048	No genesis picked up
MM5 (IMD)	469	801	-
GFS (IMD)	412	700	1001
WRF (IMD)	322	709	732

3.3.2 Track and Landfall:

Fig. 3.3.1(a-g) display the forecast tracks of the cyclone, "LAILA" by various NWP models with the initial conditions of 0000 UTC of 31 May, and (1-6) June 2010 respectively. Initially NWP models indicated the northward movement of the cyclonic storm "PHET" except QLM and UKMO while QLM predicted northeastwards track, UKMO predicted northwestwards track. Subsequent updated forecasts by a few models (NWP, GPS, IMD GFS) based on intial conditions of 0000 UTC of 3 June many models predicted landfall over Oman. The landfall over Pakistan could be predicted by models though with large variation in landfall point & time based on 0000 UTC of 4 June. The forecast errors of member models based on different initial conditions and the corresponding consensus forecasts (MME) are summarized in Table 3.3.2(a-h).

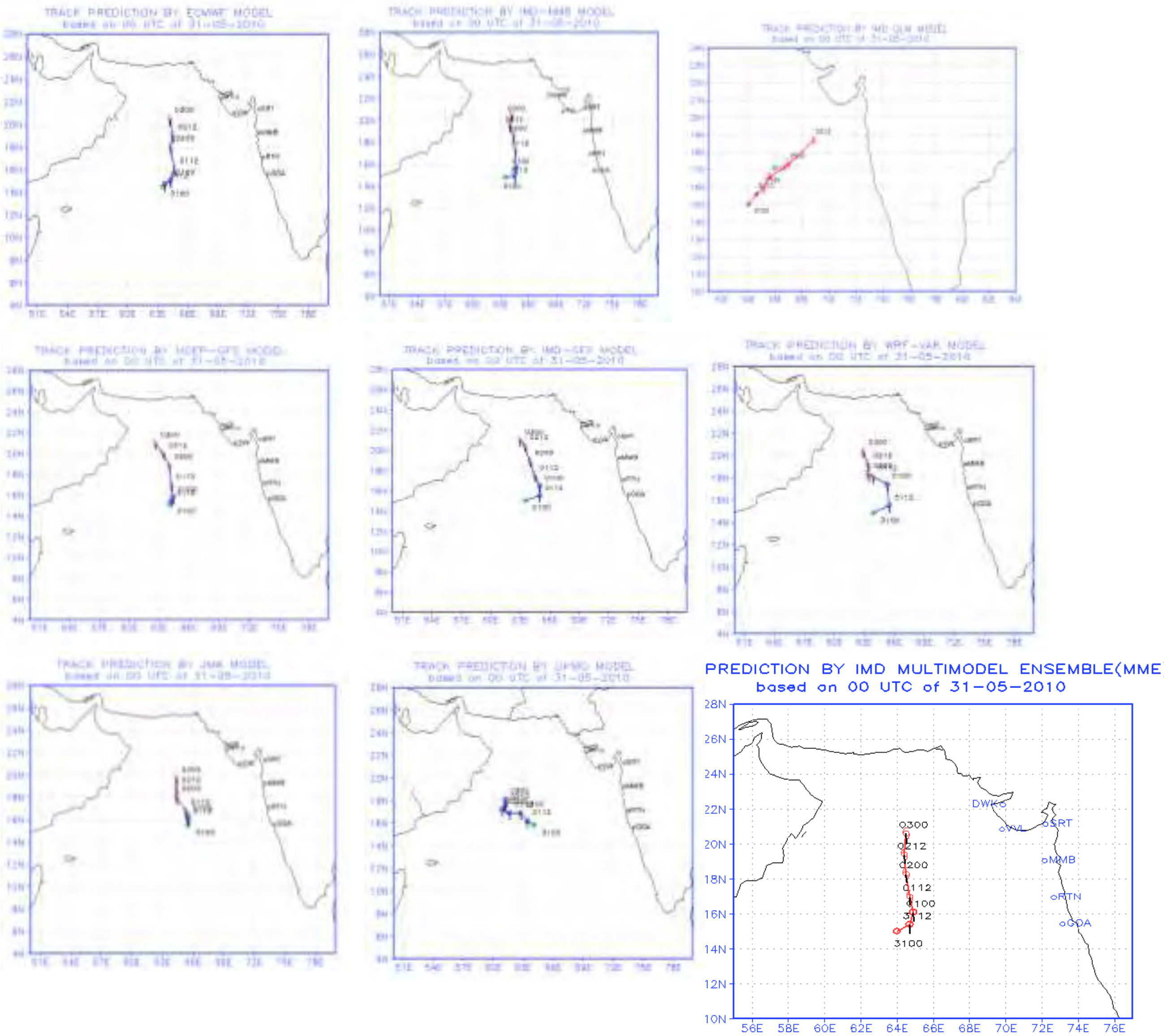


Fig.3.3.1(a) Track forecasts of multimodel ensemble and its member models based on 0000 UTC of 31.5.2010

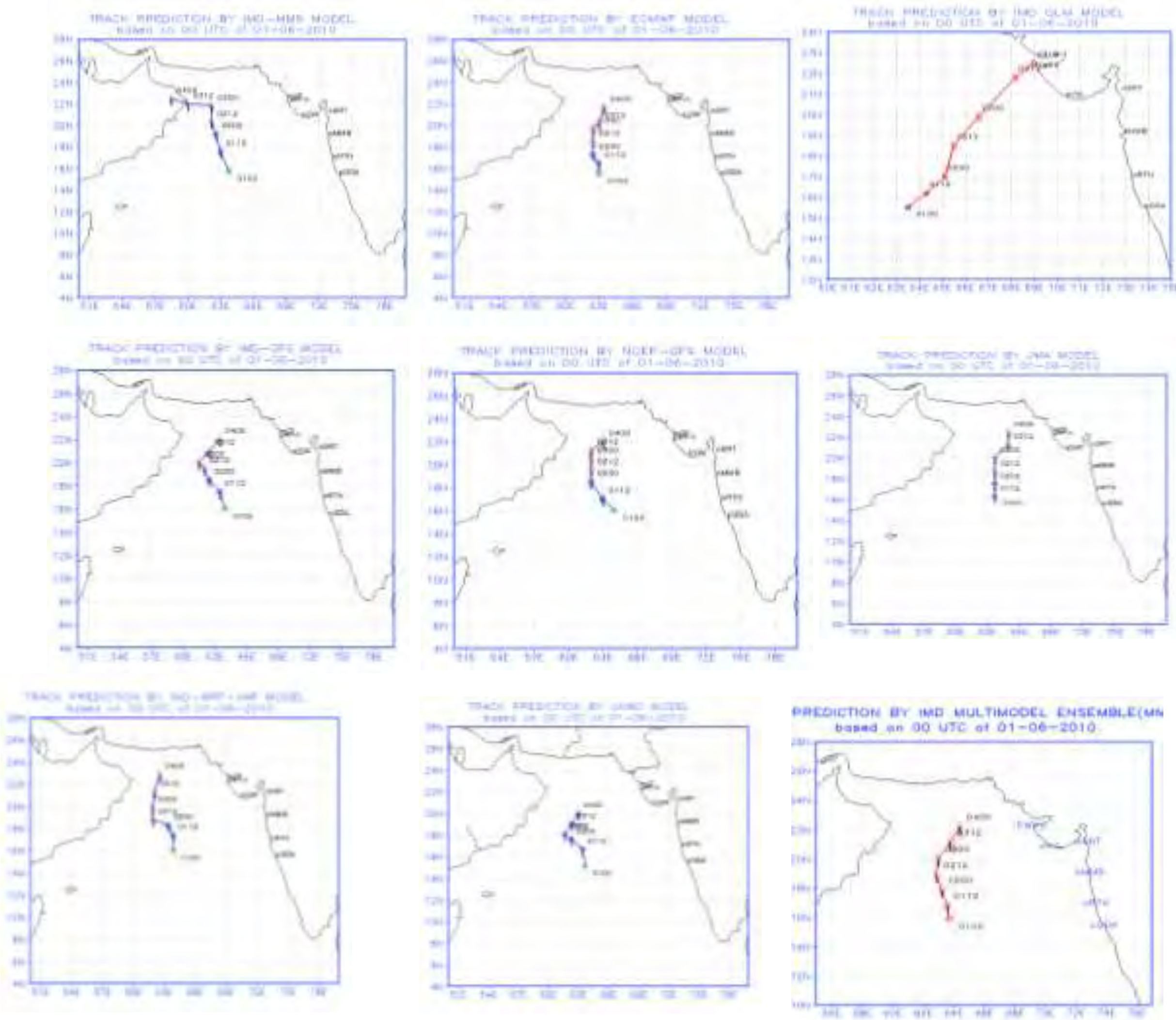


Fig.3.3.1(b) Track forecasts of multimodel ensemble and its member models based on 0000 UTC of 01.06.2010

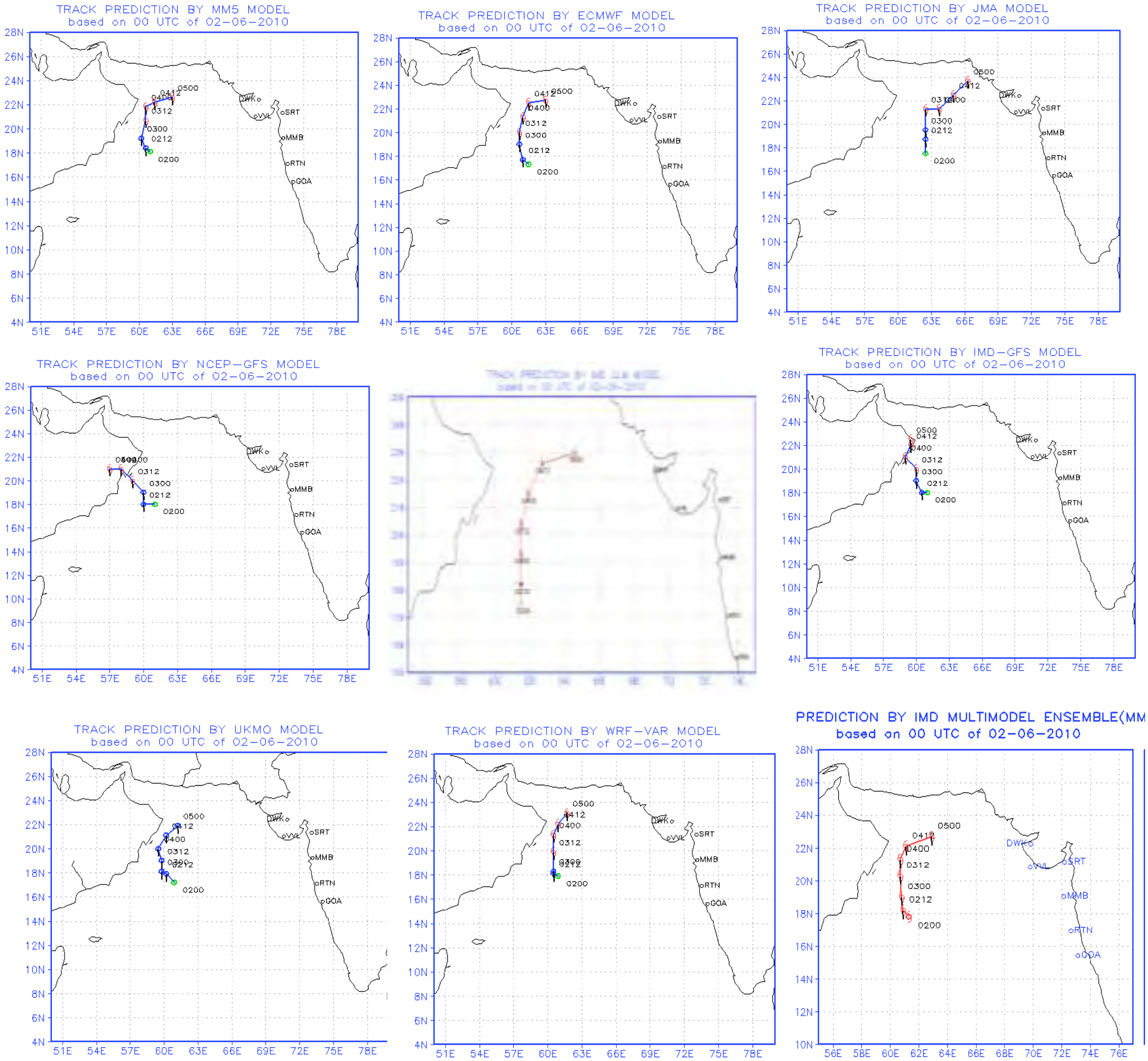


Fig.3.3.1(c) Track forecasts of multimodel ensemble and its member models based on 0000 UTC of 02.06.2010

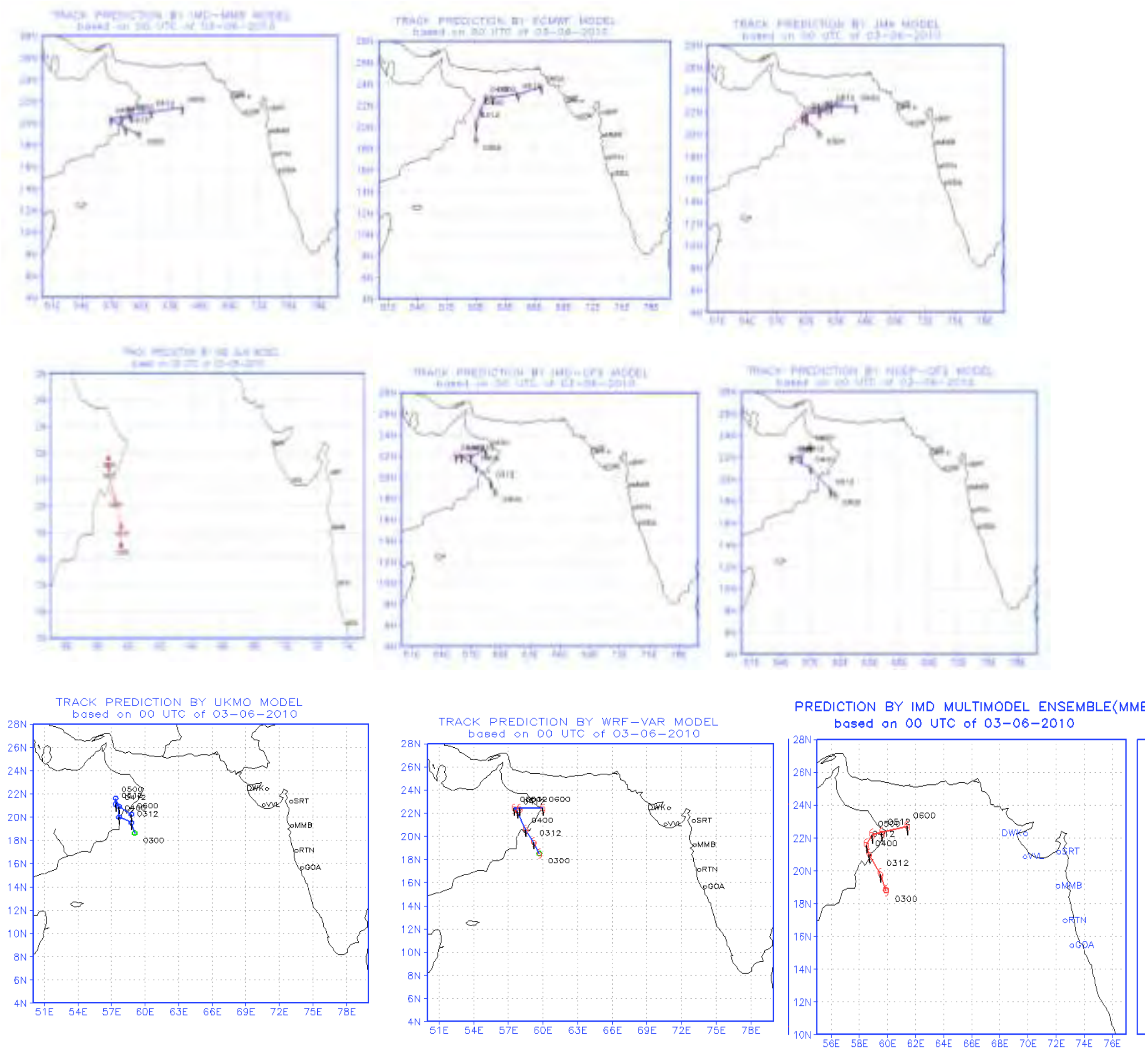


Fig.3.3.1(d) Track forecasts of multimodel ensemble and its member models based on 0000 UTC of 03.06.2010

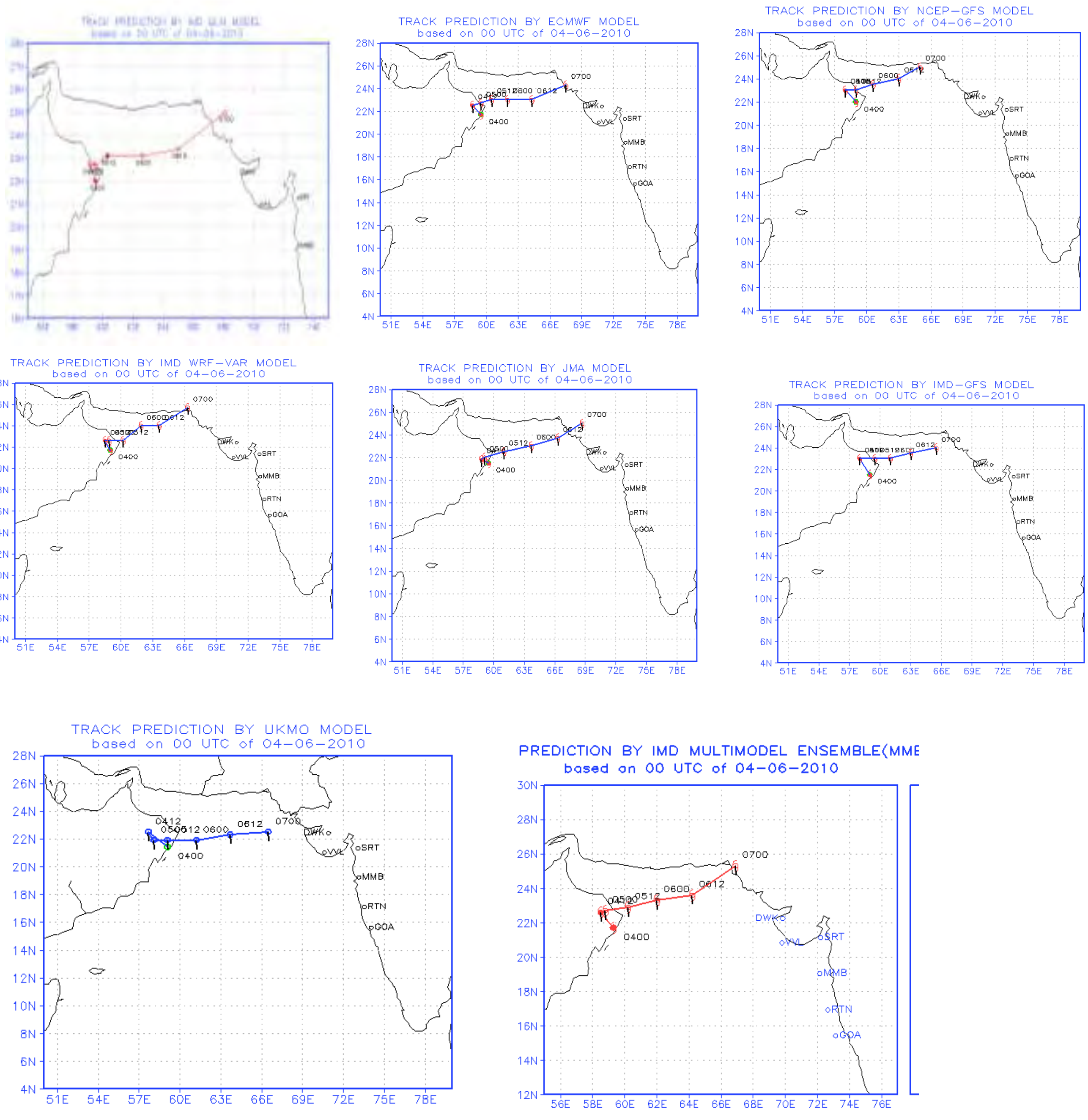


Fig.3.3.1(e) Track forecasts of multimodel ensemble (MME) and its member models based on 0000 UTC of 04.06.2010

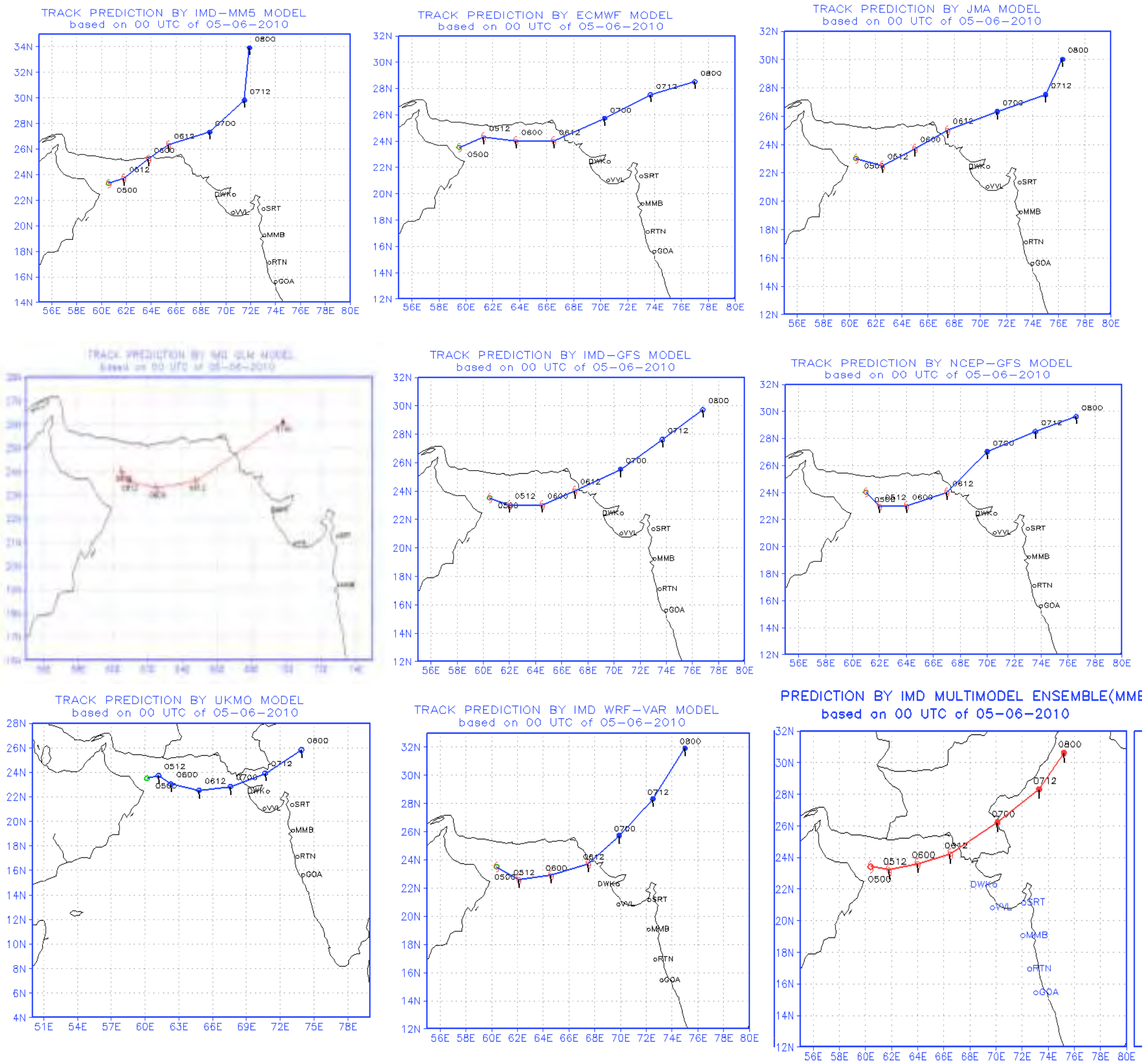


Fig.3.3.1(f). Track forecasts of multimodel ensemble and its member models based on 0000 UTC of 05.06.2010

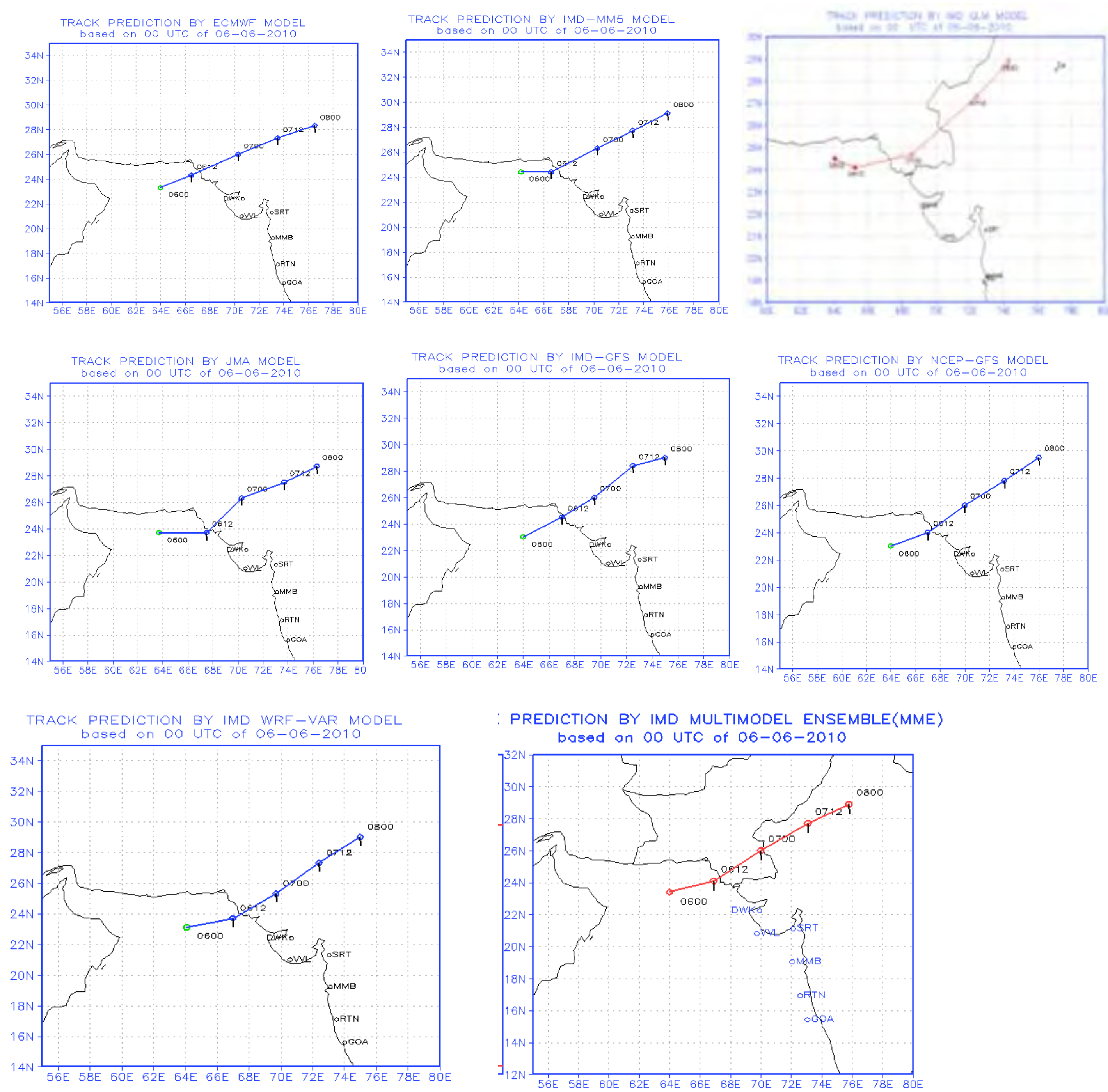


Fig.3.3.1(g). Track forecasts of multimodel ensemble and its member models based on 0000 UTC of 06.06.2010

Table 3.3.2(a). Initial position error (km) in respect of landfall time at OMAN Coast:

Lead time (hrs)	ECMWF	GFS (NCEP)	JMA	MM5 (IMD)	QLM (IMD)	MME (IMD)	GFS (IMD)	WRF (IMD)	UKMO
24 (25hrs)	57	00	252	55	00	52	00	21	43
48 (49 hrs)	22	77	106	85	00	39	77	77	72
72 (73hrs)	53	77	91	39	00	49	77	70	49

Table 3.3.2(b). Initial position error (km) in respect of landfall time at KARACHI Coast:

Lead time (hrs)	ECMWF	GFS (NCEP)	JMA	MM5 (IMD)	QLM (IMD)	MME (IMD)	GFS (IMD)	WRF (IMD)	UKMO
12 (13hrs)	133	167	94	23	00	122	167	156	-
36 (37hrs)	116	51	111	79	00	67	56	57	63
60 (61hrs)	22	76	00	-	00	30	52	56	43

Table 3.3.2(c). Average Track forecast errors (Direct position error in Km)

	Lead time ⟶					
Models	**12 hr**	**24 hr**	**36 hr**	**48 hr**	**60 hr**	**72 hr**
ECMWF	65	111	169	228	333	393
GFS (NCEP)	102	161	218	316	409	527
JMA	175	183	239	277	387	445
MM5 (IMD)	95	151	253	312	310	334
QLM (IMD)	122	230	279	375	545	582
MME (IMD)	90	151	185	243	342	426
GFS (IMD)	103	179	203	281	364	459
WRF(IMD)	127	194	176	223	317	375
UKMO	98	191	222	304	321	436
IITD (WRF-ARW)	121	147	182	222	283	413
IMD (WRF-NMM)	90	152	172	214	249	393

Table 3.3.2(d). Landfall forecast error (km) in respect of OMAN Coast (21.5°N/59.5°E at 0100 UTC of 04.06.2010):

Lead Time (hr) →	**24 (25:00) Hr based on 03.06.2010**	**48 (49:00) Hr based on 02.06.2010**	**72 (73:00) Hr based on 01.06.2010**
Model	F/C	F/C	F/C
ECMWF	No L/F	No L/F	No L/F
GFS (NCEP)	220	138	No L/F
JMA	No L/F	No L/F	No L/F
MM5(IMD)	243	No L/F	73
QLM(IMD)	100	No L/F	No L/F
MME(IMD)	100	No L/F	No L/F
GFS (IMD)	175	68	No L/F
WRF-VAR(IMD)	144	No L/F	No L/F
UKMO	251	No L/F	No L/F

F/C - Forecast L/F- Landfall

Table 3.3.1 (e): Landfall time error (in Hr) at Oman; (E: Early; D: Delayed)

Lead time (hr) →	**24 (25:00) Hr based on 03.06.2010**	**48 (49:00) Hr based on 02.06.2010**	**72 (73:00) Hr based on 01.06.2010**
Model	F/C	F/C	F/C
ECMWF	No L/F	No L/F	No L/F
GFS (NCEP)	06 hr E	07 hr E	No L/F
JMA	No L/F	No L/F	No L/F
MM5(IMD)	07 hr E	No L/F	10 hr E
QLM(IMD)	08 hr D	No L/F	No L/F
MME	01 hr E	No L/F	No L/F
GFS (IMD)	05 hr E	03 hr D	No L/F
WRF(IMD)	01 hr E	No L/F	No L/F
UKMO	01 hr E	No L/F	No L/F

Table 3.3.1 (f): Landfall forecast error (km) in respect of Karachi, Pakistan Coast (24.7°N/67.2°E at 1300 UTC of 04.06.2010):

Lead time (hr) →	12 (13:00) based on 06.06.2010	36 (37:00) based on 05.06.2010	60 (61:00) based on 04.06.2010
Model	F/C	F/C	F/C
ECMWF	23	11	54
GFS (NCEP)	55	22	No L/F
JMA	83	23	49
MM5(IMD)	20	319	-
QLM(IMD)	33	20	22
MME(IMD)	44	15	67
GFS (IMD)	20	55	No L/F
WRF(IMD)	80	99	161
UKMO	196	No L/F	No L/F

F/C - Forecast, A/C-Actual

Table 3.3.2 (g): Landfall time error (in Hr) for Pakistan coast; (E: Early; D: Delayed)

Lead time (hr) →	12 (13:00) Hr based on 06.06.2010	36 (37:00) Hr based on 05.06.2010	60 (61:00) Hr based on 04.06.2010
Model	F/C	F/C	F/C
ECMWF	02 hr D	02 hr D	11 hr D
GFS (NCEP)	01 hr D	01 hr D	No L/F
JMA	Close to actual	03 hr E	07 hr E
MM5(IMD)	01 hr D	11 hr E	No data
QLM(IMD)	07 hr D	04 hr D	07 hr D
MME(IMD)	01 hr D	02 hr D	10 hr D
GFS (IMD)	Close to actual	Close to actual	No L/F
WRF(IMD)	01 hr D	Close to actual	09 hr D
UKMO	16 hr D	No L/F	No L/F

F/C - Forecast

3.3.3. Intensity

The 12 hourly intensity forecasts by Statistical intensity Prediction (SCIP) model valid up to 72 hours (Table 3.3.3(a-f)) show that mean model forecast errors for this cyclone variesd between 8 knots to 26 knots.

Table 3.3.3(a). Model (SCIP) performance based on 0000 UTC of 01.06.2010

Forecasts hours	00 hr	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
Observed (knots)	30	35	55	85	75	70	65
Forecasts (knots)	30	32	34	36	41	50	67
Error (knots)	-	-3	-21	-49	-34	-20	+2

Table 3.3.3(b). Model (SCIP) performance based on 0000 UTC of 02.06.2010

Forecasts hours	00 hr	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
Observed (knots)	55	85	75	70	65	60	45
Forecasts (knots)	55	61	65	72	79	89	97
Error (knots)	-	-24	-10	+2	+14	+29	+52

Table 3.3.3(c). Model (SCIP) performance based on 0000 UTC of 03.06.2010

Forecasts hours	00 hr	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
Observed (knots)	75	70	65	60	45	40	30
Forecasts (knots)	75	75	80	71	63	55	54
Error (knots)	-	+5	+15	+11	+18	+15	+24

Table 3.3.3(d). Model (SCIP) performance based on 0000 UTC of 04.06.2010

Forecasts hours	00 hr	12 hr	24 hr	36 hr	48 hr	60 hr
Observed (knots)	65	60	45	40	30	25
Forecasts (knots)	65	56	50	46	45	47
Error (knots)	-	-4	+5	+6	+15	+22

Table 3.3.3(f). Model (SCIP) performance based on 0000 UTC of 05.06.2010

Forecasts hours	00 hr	12 hr	24 hr	36 hr
Observed (knots)	45	40	30	25
Forecasts (knots)	45	45	41	38
Error (knots)	-	+5	+11	+13

Table 3.3.3(g). Mean intensity forecast error (PHET)

Forecasts hours	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
Average Absolute Error(AAE)	**8.2**	**12.4**	**16.2**	**15**	**21.5**	**26**

3.4 Very Severe Cyclonic Storm "GIRI" (20 – 23 October 2010)

3.4.1. Genesis

Analysis of GPP values computed for this cyclone on the basis of real time model analysis fields along with the GPP values for Developing Systems and Non-Developing Systems are shown in Table 3.4.1. The higher GPP values (> 8.0, the threshold value) at early stages of development (T.No. 1.5) have clearly indicated that the cyclone “GIRI” had enough potential to intensify into a developing system (>35 knots).

Table 3.4.1. GPP($x10^{-5}$) for Developing System, Non-Developing System and Cyclone “GIRI”

Date/Time	21.10.2010 **0000 UTC**
T.No.	**1.5**
Developing	11.1
Non-Developing	3.4
Cyclone GIRI	**15.89**

No NWP model except ECMWRF could predict genesis and intensification of cyclone Giri. It was observed a low or cyclonic circulation by these models . Moreover ECMWRF model could predict genesis , intensity and movement with reasonable accuracy.

3.4.2 Track and Landfall:

Fig. 3.4.1(a-b) display the forecast tracks of the cyclone, “GIRI” by various NWP models (ECMWF, IMD-GFS, NCEP-GFS, JMA, WRF, and MME) with the initial conditions of 0000 UTC of 21 and 22 October 2010 respectively. It is noted that all models showed northeastward movement of cyclonic storm “GIRI” towards Myanmar coast with of course large variations except JMA, NCEP-GFS and WRF models which showed northwestward movement towards Bangladesh coast, but MME could predict landfall near north Myanmar coast to the north of actual landfall point.

The forecast errors of member models based on different initial conditions and the corresponding MME are summarized in Table 3.4.2 (a-e). The tables show that MME forecasts could provide useful guidance under the circumstances of wide variations of individual model forecasts.

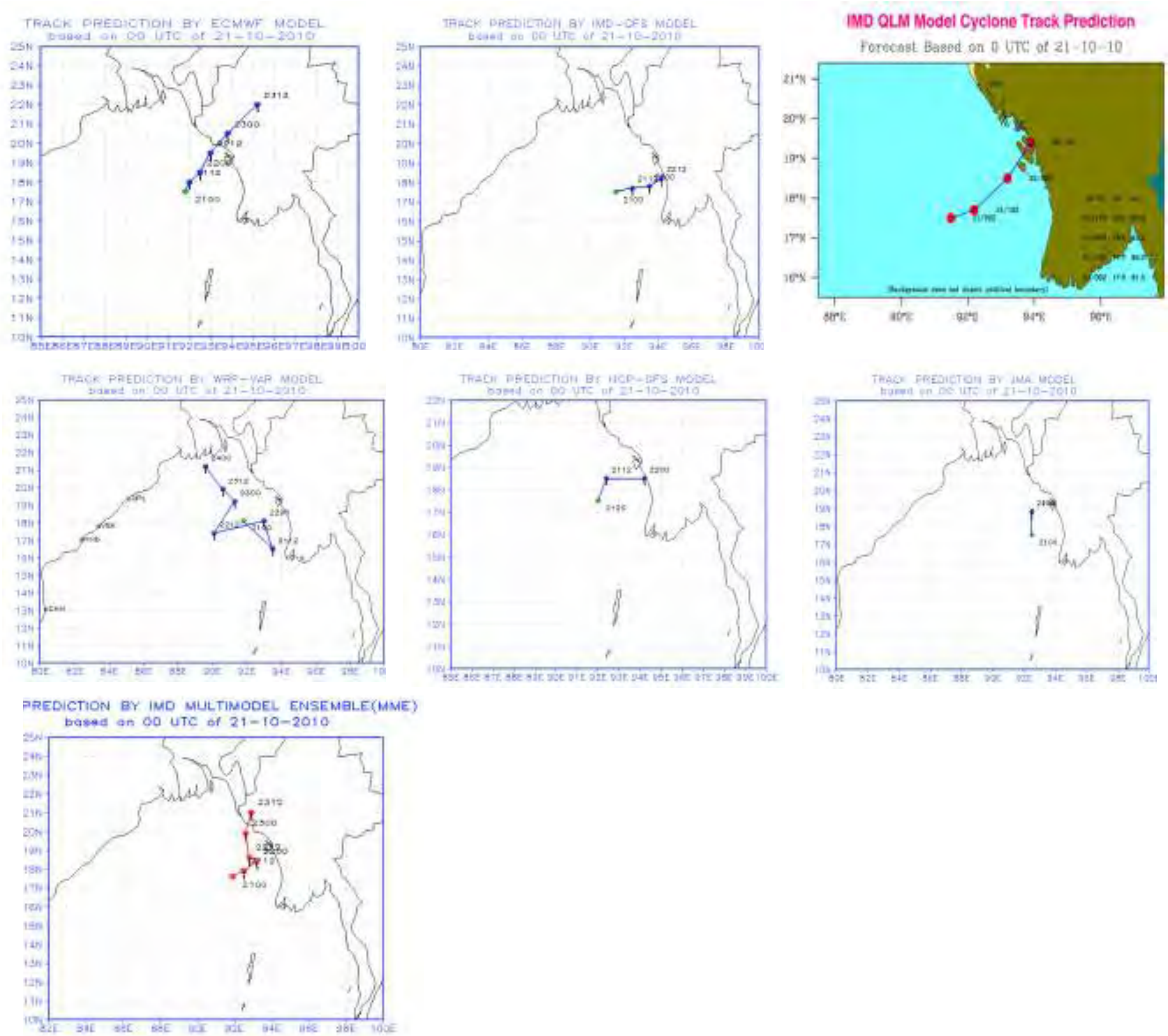


Fig.3.4.1(a) Track forecasts of multi-model ensemble and its member models based on 0000 UTC of 21.10.2010

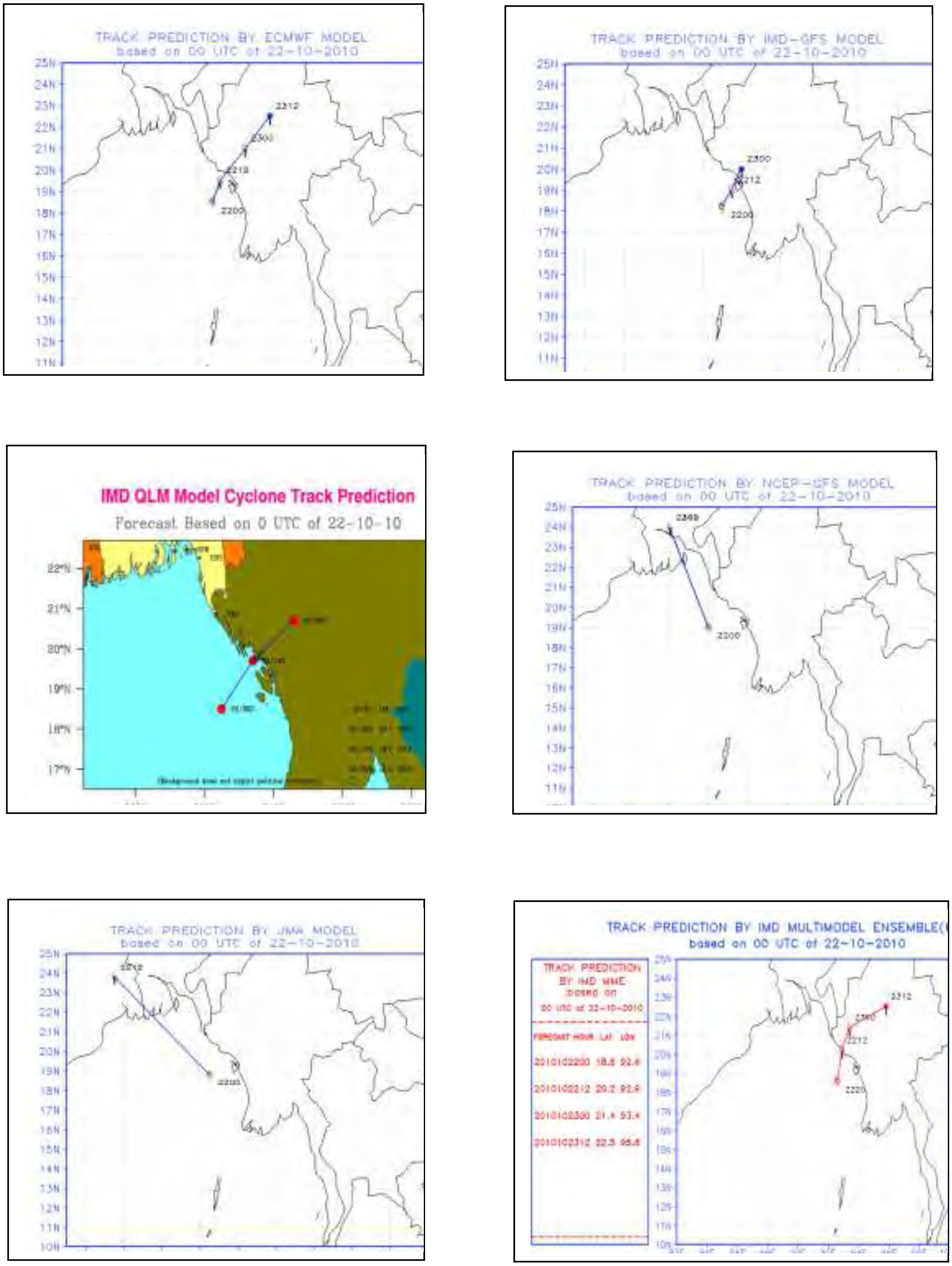


Fig.3.4.1(b). Track forecasts of multi-model ensemble and its member models based on 0000 UTC of 22.10.2010

Table 3.4.2 (a) Initial position error (km) with respect to landfall time

Lead time (hrs)	ECMWF	GFS (NCEP)	JMA	QLM (IMD)	GFS (IMD)	WRF (IMD)	MME (IMD)
12 (14hrs)	32	77	33	**	62	-	15
36 (38 hrs)	32	53	106	**	01	74	44

**** Initial position taken from observed field.**

Table 3.4.2 (b) Average track forecast errors (Direct position error in Km)

	Lead time →					
Models	**12 hr**	**24 hr**	**36 hr**	**48 hr**	**-**	**-**
ECMWF	23	01	62	92	-	-
GFS (NCEP)	330	285	-	-	-	-
JMA	433	33	-	-	-	-
QLM(IMD)	27	54	61	-	-	-
GFS (IMD)	76	121	192	-	-	-
WRF(IMD)	230	69	446	389	-	-
MME(IMD)	65	98	152	233	-	-
IMD (WRF-NMM)	-	-	-	-	-	-
IITD (WRF-ARW)	135	195	250	366	-	-

Table 3.4.2 (c) Genesis : (formation of Depression) Forecast errors (km)

	Lead time →		
Models	**24 hours**	**48 hours**	**72 hours**
ECMWF	53	119	127
GFS (NCEP)	169	77	271
JMA	106	238	27
GFS (IMD)	No Detection	53	No Detection
WRF(IMD)	63	423	437

Table 3.4.2 (d) Landfall forecast error (km) in respect of MYANMAR Coast

Lead Time (hr) →	**12 (14:00) Hr based on 22.10.2010**	**36 (38:00) Hr based on 21.10.2010**
Model	F/C	F/C
ECMWF	15	10
GFS (NCEP)	372	No L/F
JMA	480	No L/F
QLM(IMD)	35	100
GFS (IMD)	46	No L/F
WRF(IMD)	No Plot	No L/F
MME(IMD)	25	85

F/C - Forecast; L/F-Landfall

Table 3.4.2 (e) Landfall time error (in Hr) at Myanmar; (E: Early; D: Delayed)

Lead Time (hr) →	**12 (14:00) based on 22.10.2010**	**36 (38:00) based on 21.10.2010**
Model	F/C	F/C
ECMWF	01:00 D	03:00 D
GFS (NCEP)	06:00 E	No L/F
JMA	06:00 E	No L/F
QLM(IMD)	02:00 E	06:00 E
GFS (IMD)	05:00 E	No L/F
WRF(IMD)	No Plot	No L/F
MME	02:00 E	15:00 D

3.5 Cyclonic Storm "JAL" (4-7 November 2010)

3.5.1. Genesis

Analysis of GPP values computed for this cyclone on the basis of real time model analysis fields along with the GPP values for Developing Systems and Non-Developing Systems are shown in Table 3.5.1. The higher GPP values (> 8.0, the threshold value) at early stages of development (T.No. 1.5, 2.0) have clearly indicated that the cyclone "JAL" had enough potential to intensify into a developing system (>35 knots).

Table 3.5.1. GPP ($x10^{-5}$) for Developing System, Non-Developing System and Cyclone "JAL"

Date/Time	04.11.2010 **0000 UTC**	05.11.2010 **0000 UTC**
T.No. □	**1.5**	**2.0**
Developing	11.1	13.3
Non-Developing	3.4	4.6
Cyclone JAL	**13.5**	**17.4**

Genesis and intensification of the system was picked up by many models especially ECMWF. However the weakening of the system before landfall to a depression could not be predicted by many models. Similarly many models predicted further intensification of the system in emergence over the Arabian sea which did not occur.

3.5.2 Track and Landfall:

Fig. 3.5.1(a-d) display the forecast tracks of the cyclone, "JAL" by various NWP models with the initial conditions of 0000 UTC of 4, 5, 6 and 7 November 2010 respectively. It is encouraging to note that all models showed northwestward movement of cyclonic storm "JAL" towards north Tamilnadu and south Andhra Pradesh coast.

The forecast errors of member models based on different initial conditions and the corresponding consensus forecasts (MME) are summarized in Table 3.5.2 (a-e).

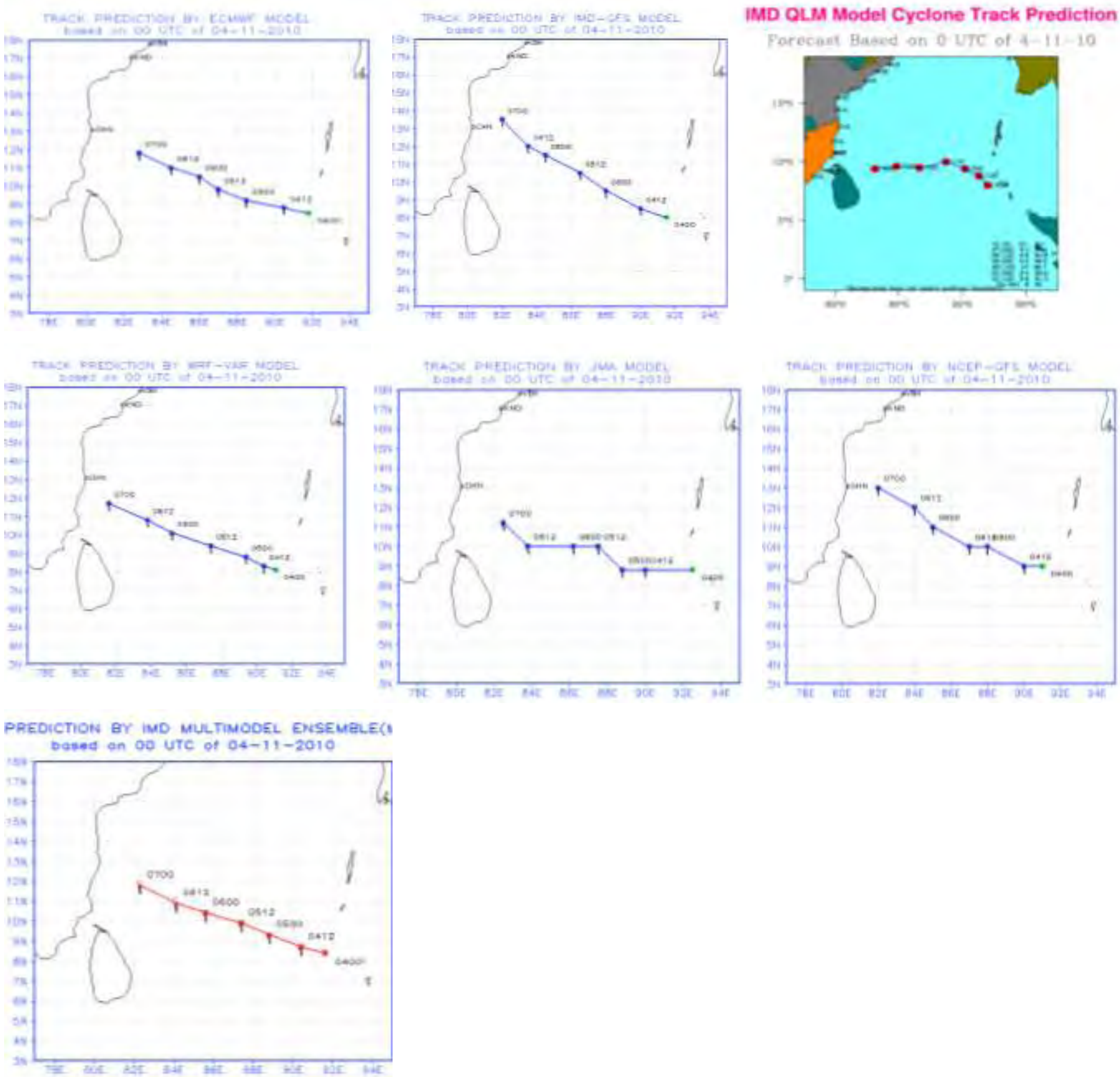


Fig.3.5.1(a). Track forecasts of multi-model ensemble and its member models based on 0000 UTC of 04.11.2010

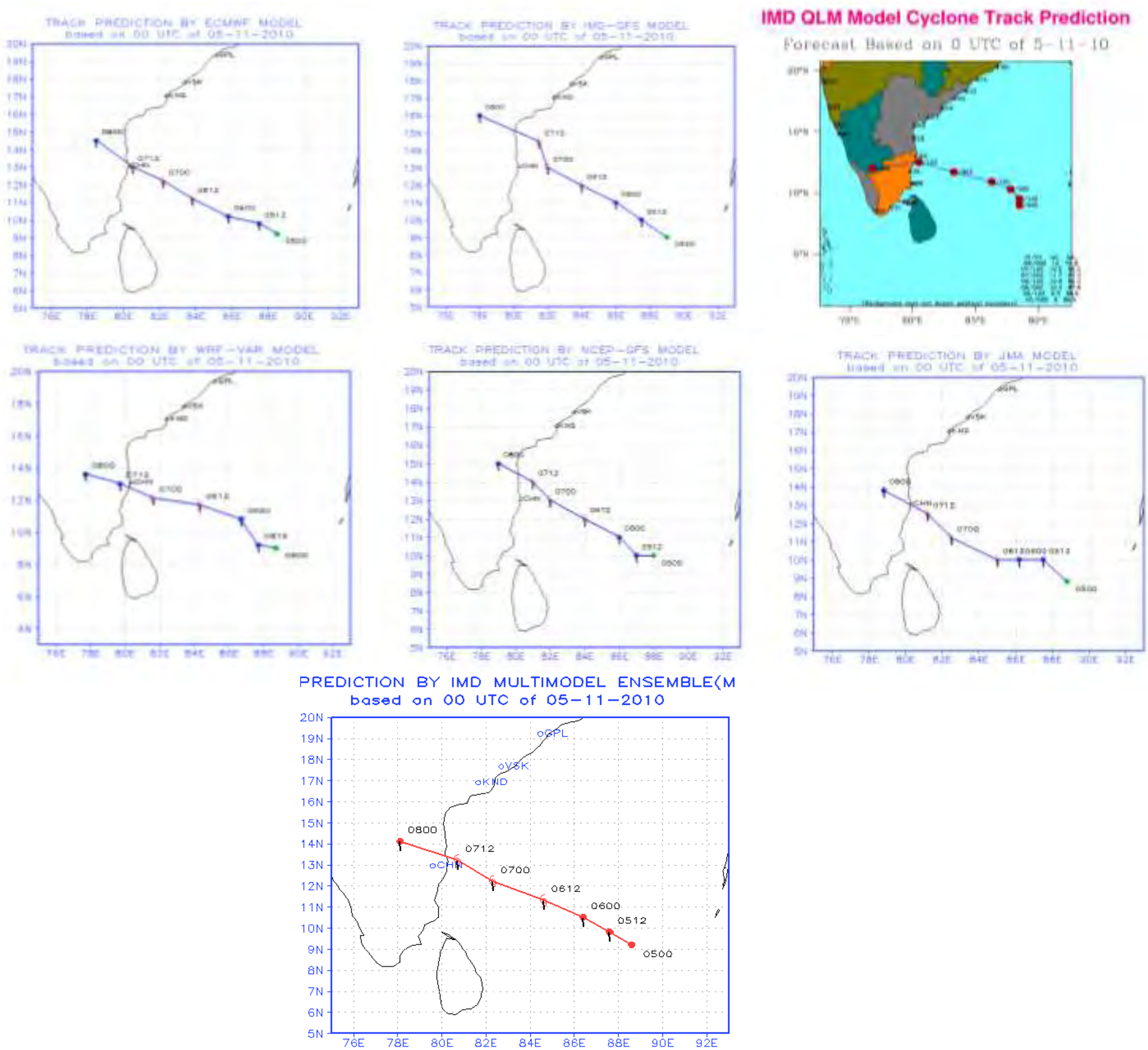


Fig. 3.5.1(b). Track forecasts of multi-model ensemble and its member models based on 0000 UTC of 05.11.2010

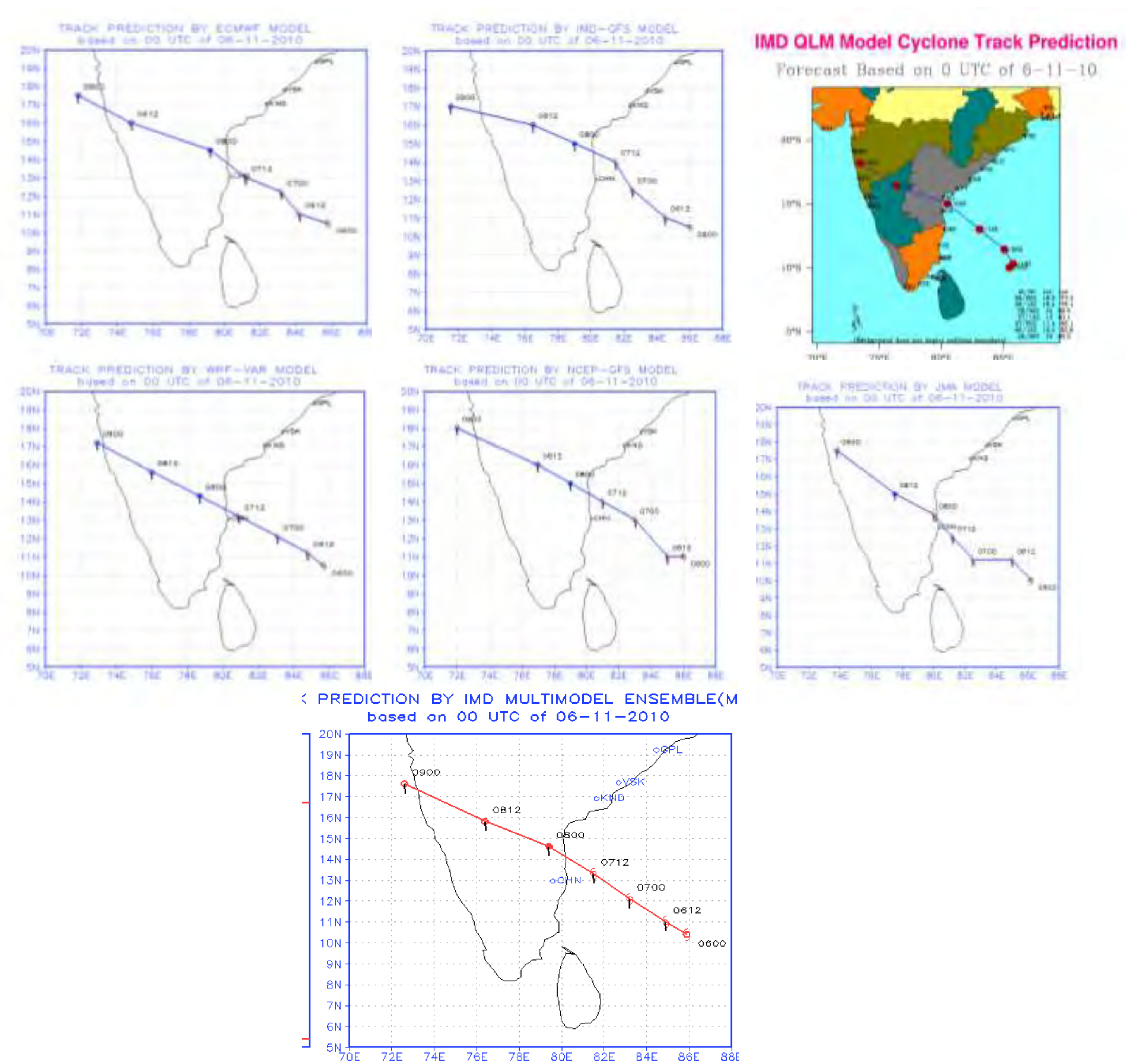


Fig. 3.5.1(c). Track forecasts of multi-model ensemble and its member models based on 0000 UTC of 06.11.2010

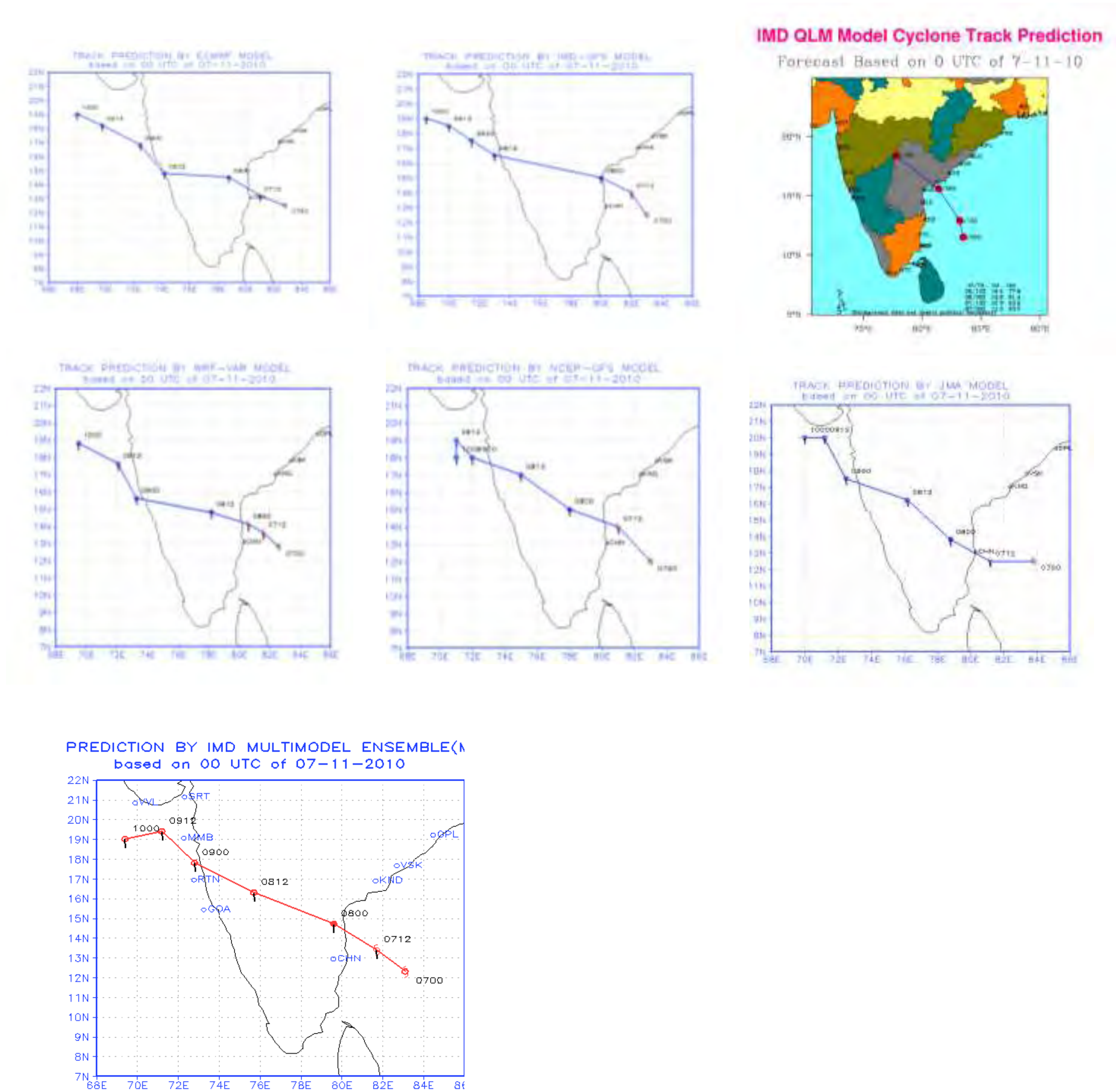


Fig. 3.5.1(d). Track forecasts of multi-model ensemble and its member models based on 0000 UTC of 07.11.2010

Table 3.5.2(a) Initial position error (km) in respect of landfall time at Tamil nadu-Andhra Coast:

Lead time (hrs)	ECMWF	GFS (NCEP)	JMA	QLM (IMD)	GFS (IMD)	WRF (IMD)	MME (IMD)
12 (16hrs)	135	78	116	**	124	174	99
36 (40 hrs)	65	124	77	**	78	60	62
60 (64hrs)	22	124	40	**	55	22	25

**** Initial position taken from observed field.**

Table 3.5.2(b) Average track forecast errors (Direct position error in Km)

Models	Lead time ⟶					
	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
ECMWF	46	49	45	120	27	83
GFS (NCEP)	69	141	97	178	117	233
JMA	57	77	87	95	97	114
QLM(IMD)	178	207	206	82	118	237
GFS (IMD)	59	119	124	216	165	275
WRF(IMD)	66	113	50	126	110	208
MME(IMD)	64	78	54	99	42	135
WRF-NMM(IMD)	63	68	105	156	213	304
WRF-ARD(IITD)	53	72	66	99	159	179

Table 3.5.2(c) Genesis : (formation of Depression) Forecast errors (km)

Models	Lead time ⟶		
	24 hours	48 hours	72 hours
ECMWF	92	104	111
GFS (NCEP)	156	156	312
JMA	105	335	217
GFS (IMD)	156	246	431
WRF(IMD)	45	197	70

Table 3.5.2(d): Landfall forecast error (km)

Lead Time (hr)/Model	12 (16:00) Hr based on 07.11.2010	36 (40:00) Hr based on 06.11.2010	60 (64:00) Hr based on 05.11.2010
ECMWF	46	56	22
GFS (NCEP)	111	133	133
JMA	33	45	35
QLM(IMD)	291	189	90
GFS (IMD)	189	144	200
WRF (IMD)	111	33	57
MME (IMD)	123	90	11

Table 3.5.2(e): Landfall time error (in hour)

Lead Time (hr)/Model	12 (16:00) hr based on 07.11.2010	36 (40:00) hr based on 06.11.2010	60 (64:00) hr based on 05.11.2010
ECMWF	02:30 E	04:00 D	01:00 D
GFS (NCEP	00	04:00 D	04:00 D
JMA	01:30 D	07:00 D	01:30 D
QLM(IMD)	09:00 D	09:30 D	02:30 E
GFS (IMD)	07:30 D	02:00 D	01:30 D
WRF(IMD)	11:00 D	01:00 D	07:00 E
MME (IMD)	05:00 D	04:00 D	01:00 E

3.5.3 Intensity

The 12 hourly intensity forecasts by SCIP model valid up to 72 hours (Table 3.3.3(a-e)) show that mean model forecast errors for this cyclone varies between 5 knots to 18 knots.

Table 3.5.3(a). Model (SCIP) performance based on 0000 UTC of 04.11.2010

Forecasts hours	00 hr	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
Observed (knots)	25	25	30	45	55	60	60
Forecasts (knots)	25	29	31	34	32	36	51
Error (knots)	0	4	1	-11	-23	-24	-9

Table 3.5.3(b) Model (SCIP) performance based on 0000 UTC of 05.11.2010

Forecasts hours	00 hr	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
Observed (knots)	30	45	55	60	60	35	-
Forecasts (knots)	30	35	40	42	48	37	-
Error (knots)	0	-10	-15	-18	-12	2	-

Table 3.5.3(c) Model (SCIP) performance based on 0000 UTC of 06.11.2010

Forecasts hours	00 hr	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
Observed (knots)	55	60	60	35	-	-	-
Forecasts (knots)	55	57	55	55	-	-	-
Error (knots)	0	-3	-5	20	-	-	-

Table 3.5.3(d). Model (SCIP) performance based on 0000 UTC of 07.11.2010

Forecasts hours	00 hr	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
Observed (knots)	60	35	-	-	-	-	-
Forecasts (knots)	55	55	-	-	-	-	-
Error (knots)	-5	20	-	-	-	-	-

Table 3.5.3(e). Mean intensity forecast error (JAL)

Forecasts hours	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
AAE (KNOTS)	**5**	**10**	**16**	**18**	**13**	**9**

3.6 Mean Track forecast errors of NWP models for cyclones during 2010

The average NWP model forecasterrors duting 2010 are shoen in Table 3.6.1. It is evident that the performance of ECMWF model was the best among various NWP models for all time scales upto 48 hrs. In 60 and 72 hr forecast time scale, the IMD MME is slightly better than ECMWF model.

Table 3.6.1. Mean Track forecast errors of NWP models for cyclones during 2010

AVERAGE	12 hours	24 hours	36 hours	48 hours	60 hours	72 hours
ECMWF	54	71	102	170	202	246
NCEP-GFS	158	178	177	236	253	334
JMA	195	96	176	203	232	268
IMD-MM5	118	141	241	350	363	356
IMD-QLM	103	144	167	181	256	311
IMD-MME	72	104	140	205	190	244
IMD-T382	94	124	164	212	246	290
IMD-WRF-VAR	155	137	236	253	234	265

CHAPTER-IV

PERFORMANCE OF RSMC, NEW DELHI IN TRACK AND INTENSITY PREDICTION OF CYCLONES DURING 2010

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 2010. 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.

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 2010 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 2010.

Bulletins issued during 'LAILA'

Bulletins for Indian coast : 31
RSMC bulletin for WMO/ESCAP Panel member countries
(Special Tropical Weather Outlook and Tropical Cyclone Advisory) : 23
TCAC bulletin for international civil aviation : 10

Bulletins issued during 'BANDU'

Bulletins for Indian coast : 00
RSMC bulletin for WMO/ESCAP Panel member countries:
(Special Tropical Weather Outlook and Tropical Cyclone Advisory) :22
TCAC bulletin for international civil aviation :05

Bulletins issued during 'PHET'

Bulletins for Indian coast : 52
RSMC bulletin for WMO/ESCAP Panel member countries:
(Special Tropical Weather Outlook and Tropical Cyclone Advisory) :45
TCAC bulletin for international civil aviation : 19

Bulletins issued during `GIRI'

Bulletins for Indian coast : 15
RSMC bulletin for WMO/ESCAP Panel member countries:
(Special Tropical Weather Outlook and Tropical Cyclone Advisory) : 22
TCAC bulletin for international civil aviation : 09

Bulletins issued during `JAL'

Bulletins for Indian coast :31
RSMC bulletin for WMO/ESCAP Panel member countries:
(Special Tropical Weather Outlook and Tropical Cyclone Advisory) :27
TCAC bulletin for international civil aviation :11

Bulletins issued for all cyclones during 2010

Bulletins for Indian coast : 129
RSMC bulletin for WMO/ESCAP Panel member countries : 139
(Special Tropical Weather Outlook and Tropical Cyclone Advisory)
TCAC bulletin for international civil aviation : 54

Bulletins issued for all cyclonic disturbances (depression and above) during 2010

Bulletins for Indian coast :154
RSMC bulletin for WMO/ESCAP Panel member countries :
(Special Tropical Weather Outlook and Tropical Cyclone Advisory) :150
TCAC bulletin for international civil aviation : 54

4.3. Performance of Operational Track and landfall forecast

The performance of operational genesis, track and intensity forecasts issued by IMD, New Delhi for five cyclones during 2010 are described below.

4.3.1. Cyclone, `LAILA' (17-21 May 2010)

4.3.1.1. Intensity:

The average intensity forecast errors ranged from 5 to 11 km for various lead time periods as shown in Table 4.1.

Table 4.1. Average Intensity forecast error

Lead Period of forecast	Intensity Error (knots)			No. of observations verified
	Average	Absolute Average	RMS	
12	2.7	5.8	6.9	13
24	7.7	8.5	10.4	13
36	09.0	10.0	14.8	10
48	8.7	11.2	14.1	08
60	10.0	10.0	13.2	06
72	16.3	16.3	19.5	04

4.3.1.2. Track and landfall:

Table 4.2. Average track forecast errors (Direct position error in Km)

Lead time (hours)	Direct position error (Km)	Number of forecasts verified
12	76	14
24	165	12
36	228	10
48	277	08
60	281	06
72	160	03

Table 4.3. 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	15.9/81.0	16.0/80.5	55	201300	201130	1.5E
24	15.9/81.0	16.0/80.5	55	201300	201130	1.5 E
36	16.4/81.5	16.0/80.5	115	200800	201130	3.5 D
48	16.4/81.5	16.0/80.5	115	200800	201130	3.5 D
60	16.4/81.5	16.0/80.5	122	200900	201130	2.5 D
72	16.7/82.3	16.0/80.5	207	200800	201130	3.5D

D: landfall occur after forecast time. E: landfall occur before forecast time

4.3.1.3. Heavy rainfall

The adverse weather like heavy rain and gale wind warnings issued by IMD have been verified based on the recorded actual weather by the observatory network of IMD. The storm surge warning has been verified with the survey report prepared by IMD based on post-cyclone survey. The results are shown in Table 4.4 to 4.6 for heavy rain, gale wind and storm surge respectively.

Table 4.4. Verification of heavy rainfall warning issued by IMD

Base Chart (Date and time in UTC)	Forecast issue date and time in UTC	Hours in advance of landfall	Heavy rainfall warning	Observed heavy rainfall
17/0600	17/0900	78 hrs	Isolated heavy to very heavy rainfall over coastal Andhra Pradesh from 19th May	**19.05.2010** **North coastal Tamil Nadu and Puducherry** Isolated heavy rainfall **20-05-2010** **Northcoastal Tamil Nadu & Puducherry:** Scattered heavy to very heavy rainfall. **Coastal**
18/0000	18/0300	60 hrs	Scattered heavy to very heavy rainfall over north Tamil Nadu & coastal Andhra Pradesh from 18th May night	
18/0600	18/0900	54 hrs	Scattered heavy to very heavy and isolated Extremely heavy rainfall over coastal Tamil Nadu & Andhra Pradesh from 18 May evening/ night	
18/0900	18/1200	51 hrs	Scattered heavy to very heavy and isolated Extremely heavy rainfall over coastal Tamil Nadu & Andhra	

			Pradesh next 48 hours.	**Andhra Pradesh:** Scattered heavy to very heavy with isolated extremely heavy rainfall **Rayalaseema:** Isolated heavy rainfall **21-05-2010** **Coastal Andhra Pradesh:** Scattered heavy to very heavy with isolated extremely heavy rainfall **Rayalaseema: & Orissa:** Isolated heavy rainfall **22-05-2010** **Coastal Andhra Pradesh:** Scattered heavy to very heavy with isolated extremely heavy rainfall **Telngana & Orissa:** Isolated heavy rainfall **23-05-2010** **Orissa:** Isolated heavy to very heavy rainfall **24-05-2010.** **Orissa** : Isolated heavy rainfall
19/0300	19/0600	33 hrs	Scattered heavy to very heavy and isolated Extremely heavy rainfall over coastal Tamil Nadu & Andhra Pradesh next 36 hours.	
19/1800	19/2100	18 hrs	Scattered heavy to very heavy and isolated Extremely heavy rainfall over coastal next 36 hours Tamil Nadu & Andhra Pradesh next 24hours.	
20/0300	20/0600	9 hrs	Scattered heavy to very heavy and isolated Extremely heavy rainfall over coastal Andhra Pradesh and Telangananext 36 hours	
20/0900	20/1200	3 hrs	Scattered heavy to very heavy and isolated Extremely heavy rainfall over coastal Andhra Pradesh and Telangananext 24hours	
20/1800	20/2100	-	Scattered heavy to very heavy and isolated Extremely heavy rainfall over north coastal Andhra Pradesh and Telangana next 24 hours isolated heavy to very heavy south coastal Andhra Pradesh next 24	
21/0300	21/0600	-	Scattered heavy to very heavy over north coastal Andhra Pradesh and Telangana next 12 hours and isolated heavy to very heavy south coastal Andhra Pradesh next 24	
21/0600	21/0900	-	Scattered heavy to very heavy over north coastal Andhra Pradesh and Telangana and isolated heavy to very heavy over Orissa next 36 hrs isolated heavy rainfall over GWB next 48 hrs	
21/1200	21/1500	-	Isolated heavy to very heavy over north coastal Andhra Pradesh & adjoining Telangana next 24 hrs and isolated heavy to very heavy over Orissa next 36 hrs and isolated heavy over GWB next 48 hrs.	

Table 4.5. Verification of surface wind forecast issued by IMD

Base Chart (Date and time)	Forecast issue date and time in UTC	Hours in advance of landfall	Forecast issue date and time	Actual wind (kmph)
17/0600	17/0900	78 hrs	Squally wind 45-55 kmph along and off Andhra Pradesh coast from 19th May	Suryalanka IAF station :53 knots (98 Kmph) Machilipatnam: 34 kts (63 kmph) Maximum wind based on damage Beaufort scale : 10 (89-102 kmph).
17/1200	17/1500	72 hrs	Squally wind 55-65 kmph along and off Andhra Pradesh coast from 19th May	
17/1800	17/2100	66 hrs	Gale wind 65-75 kmph along and off Andhra Pradesh coast from 18th May evening	
18/0000	18/0300	60 hrs	Gale wind 65-75 kmph along and off Andhra Pradesh coast from 18th May night	
18/0300	18/0600	57 hrs	Gale wind 65-75 kmph along and off Andhra Pradesh coast and squally wind 50-60 kmph north Tamil Nadu coast from 18th May night	
19/0300	19/0600	33 hrs	Gale wind 115-125 kmph at time of landfall along and off Andhra Pradesh coast and squally wind 50-60 kmph north Tamil Nadu coast next 24 hours	
19/2100	20/0000	15hrs	Gale wind 100-110 kmph at time of landfall along and off Andhra Pradesh coast and squally wind 50-60 kmph north Tamil Nadu coast next 24 hours	
20/0300	20/0600	9hrs	Gale wind 100-110 kmph likely along and off Andhra Pradesh coast	

20/0900	20/1200	3 hrs	Gale wind 100-110 kmph likely along and off Andhra Pradesh coast next 12 hours	
20/1200	20/1500	-	Gale wind 75-85 kmph likely along and off Andhra Pradesh coast next 12 hours	
21/0300	21/0600	-	Squally wind 45-55 kmph along and off north coastal Andhra Pradesh next 12 hrs	

Table 4.6. Verification of storm surge warning issued by IMD

Base Chart (Date and time)	Forecast issue date and time	Hours in advance of landfall	Forecast storm surge(m) at time of landfall	Actual storm surge (m)
19/0300	1.5 to 2 m	33 hrs	1.5 to 2.0 m over low lying areas of Guntur Krishna East and West Gidavari Districts	2.0 to 3.0 m near Surya Lanka (near Baptla) as estimated by survey team. Storm surge inundated the low lying areas upto 0.5 to 1.0 km in land from the sea shore.

4.3.2. Cyclonic storm, 'BANDU' (19-23 May 2010)

4.3.2.1. Intensity

The intensity forecast error of cyclone „BANDU' is shown in Table 4.7.

Table 4.7. Average Intensity forecast error

Lead Period of forecast	Intensity Error (knots)			No. of observation verified
	Average	Absolute Average	RMS	
12	6.3	6.3	6.6	04
24	10.0	10.0	10.0	02

4.3.2.2. Track and landfall

The track forecast errors of cyclone, BANDU are given in Table 4.8 There was no landfall, as the system dissipated over the Sea.

Table 4.8. Average track forecast errors of cyclonic storm, BANDU

Lead time (hours)	Direct position error (Km)	Number of forecasts verified
12	39	04
24	78	02
36	78	01

4.3.3. Very Severe Cyclonic Storm, `PHET' (31 May-07 June 2010)

4.3.3.1. Intensity

The intensity forecast error of cyclone PHET are shown in table 4.9

Table 4.9. Intensity forecast error of cyclone, PHET

Lead Period of forecast	Intensity Error (knots)			No. of observation verified
	Average	Absolute Average	RMS	
12	-1.3	7.3	10.7	20
24	1.3	11.7	16.8	20
36	7.5	18.4	25.4	16
48	15.3	20.0	27.9	15
60	23.2	25.4	33.6	14
72	22.1	22.1	31.1	14

Table 4.10. (a)Landfall forecast error of cyclone, „PHET' for Oman coast

Lead time (hours)	Landfall point error (km)	Landfall time error
12	25	05 hrs delay*
24	150	hr early**

Table 4.10. (b) Landfall forecast error of cyclone, „PHET' for Pakistan coast

Lead time (hrs)	Landfall point error (km)	Landfall time error
12	15	02hrs delay
24	115	02 hr delay
36	275	15 hrs early
48	100	01 hrs early
60	90	02 hrs delay
72	90	1. hrs delay

Early : Forecast landfall was early compared to actual
Delay : Forecast landfall was delayed compared to actual

4.3.3.2. Track and landfall

The landfall forecast errors of cyclone PHET near Oman coast and Pakistan coast given in table4.10 (a) and 4.10 (b) respectively. The track forecast error of the cyclone are shown in table 4.11.

Table 4.11. Track Forecast Error (km) of cyclone, „PHET'

Lead Time (hrs)	Direct Position Error (km)	Number of forecasts verified
12	82	20
24	162	20
36	215	16
48	311	15
60	410	14
72	549	14

The relatively higher error in 24 hr landfall forecast may be attributed to recurving track of the system.

4.3.4. Very Severe Cyclonic Storm, `GIRI' (20-23 October 2010)

4.3.4.1.Intensity

The intensity forecast of cyclone „GIRI' is shown in table 4.12.

Table 4.12. Intensity forecast error of cyclone, GIRI

Lead Period of forecast	Intensity Error (knots)			No. of observation verified
	Average	Absolute Average	RMS	
12	-7.8	17.9	24.6	07
24	-12.0	20.0	25.1	05
36	-8.3	11.7	12.6	03
48	05.0	05.0	05.0	01

4.3.4.2.Track and landfall

On the first bulletin issued at 2030 hrs IST based on 1730 hrs IST observation of 20th October (48 hrs in advance), it was predicted that the system will move towards north Myanmar and adjoining south Bangladesh coast during next 48 hrs. Subsequently, based on 0830 hrs IST observation, it was predicted that the cyclone would cross Myanmar and adjoining Bangladesh coast between Teknaf (Bangladesh) and Kyakpyu (Myanmar), closed to Sittwe.

The operational landfall forecast error of RSMC, New Delhi for this system has been 55 km for both 24 and 36 hrs forecasts. The landfall forecast could not be given for longer period due to short life period of the system.

Considering the operational track forecast errors, The average errors was about 124 and 221 km for 12hr and 24 hr forecast (Table 4.14). The relatively higher error may be attributed to unusual track and slow movement of the system. Further the relatively higher error is mainly due to similar error in the time component of the forecast. The forecast position was ahead of the actual realized position throughout the life period of this system.

Table 4.13. Landfall forecast error of cyclone, GIRI

Lead Time	Landfall point error (km)			Landfall Time error(hrs)		
(hours)	Forecast	Actual	Error (km)	Forecast Time	Actual Time	Error (hrs)
12	20.0^0N /94.0^0E	20.0^0 N /93.5^0 E	55	22/1800 UTC	22/1400 UTC	4 (Delay)
24	20.0^0 N /94.0^0 E	20.0^0 N /93.5^0 E	55	22/1200 UTC	22/1400 UTC	2 (Early)
36	20.0^0 N /93.0^0 E	20.0^0 N /93.5^0 E	55	22/1200 UTC	22/1400 UTC	2(Early)

Early : Forecast landfall was early compared to actual
Delay : Forecast landfall was delayed compared to actual

Table 4.14. Average track forecast error of cyclone, GIRI

Lead Time (hrs)	Direct Position Error (km)	No. of Forecasts verified
12	45	7
24	73	5
36	68	3
48	117	1

4.3.5. Severe Cyclonic Storm, `JAL' (04-08 November 2010)
4.3.5.1.Intensity

The intensity forecast error of cyclone JAL is shown in Table 4.15

Table 4.15. Intensity forecast error of cyclone, JAL

Lead Period of forecast	Intensity Error (knots)			No. of observation verified
	Average	Absolute Average	RMS	
12	6.8	6.8	10.6	11
24	15.0	15	20.6	09
36	19.3	19.3	23.4	07
48	17.0	17.0	19.9	05
60	21.7	21.7	22.5	03
72	25.0	25.0	25.0	01

4.3.5.1. Track and landfall

Based on 0300 UTC observation when the system was a depression, it was predicted that the system would intensify into a cylone and would cross north Tamil Nadu-south Andhra Pradesh coast between Chennai and Ongole by 7 November 2010 evening/night.

Table 4.16. Landfall forecast error of cyclone, „JAL'

Lead Time (hours)	Landfall point error (km)			Landfall Time error(hrs)		
	Forecast	Actual	Error (km)	Forecast	Actual	Error (hrs)
12	13.6^0 N /80.2^0 E	13.3^0 N /80.3^0 E	35	07/1630 UTC	07/1600 UTC	0.5 (Delay)
24	13.1^0 N /80.2^0 E	13.3^0 N /80.3^0 E	25	07/1630 UTC	07/1600 UTC	0.5 (Delay)
36	13.0^0 N /80.3^0 E	13.3^0 N /80.3^0 E	33	07/1630 UTC	07/1600 UTC	0.5 (Delay)
48	12.9^0 N /80.3^0 E	13.3^0 N /80.3^0 E	44	07/1430 UTC	07/1600 UTC	1.5 (Early)
60	13.1^0 N /80.3^0 E	13.3^0 N /80.3^0 E	22	07/1430 UTC	07/1600 UTC	1.5 (Early)
72	14.2^0 N /80.2^0 E	13.3^0 N /80.3^0 E	101	07/1430 UTC	07/1600 UTC	1.5 (Early)

Early : Forecast landfall was early compared to actual
Delay : Forecast landfall was delayed compared to actual

The landfall and track forecast errors of RSMC, New Delhi for the cyclone „JAL' are shown in table 4.16 and 4.17 respectively.

Table 4.17. Track Forecast Error (km) of cyclone, „JAL'

Lead Time (hrs)	Direct Position Error (km)	Number of forecasts verified
12	41	11
24	78	09
36	56	07
48	83	05
60	54	03
72	54	01

4.3.5.3. Heavy Rainfall

The forecast issued and realized heavy rainfall due to cyclone Jal is given in Table 4.18.

Table 4.18. Verification of heavy rainfall warning issued by IMD

<table>
<tr><th>Observation Time (UTC)</th><th>Forecast issue time (UTC)</th><th>Heavy rainfall warning</th><th>Observed heavy rainfall</th></tr>
<tr><td>040000</td><td>040300</td><td>Isolated heavy to very heavy falls would commence over north coastal Tamil Nadu and south coastal Andhra Pradesh from 6th November morning. Intensity would increase with heavy to very heavy falls at a few places and isolated extremely heavy falls (≥ 25 cm) over the same region from 7th November morning</td><td rowspan="3">Heavy to very heavy rainfall at a few places occurred over north Tamil Nadu, coastal Andhra Pradesh and Rayalaseema. Isolated heavy to very heavy falls also occurred over south interior and coastal Karnataka.</td></tr>
<tr><td>05000</td><td>050300</td><td>Isolated heavy to very heavy falls would commence over north coastal Tamil Nadu, Puducherry and south coastal Andhra Pradesh from 6th November morning. Intensity would increase with heavy to very heavy falls at a few places and isolated extremely heavy falls (≥ 25 cm) over the north Tamil Nadu, Puducherry, south coastal Andhra Pradesh and Rayalaseema from 7th November morning.</td></tr>
<tr><td>070000</td><td>070300</td><td>Heavy to very heavy falls at a few places and isolated extremely heavy falls (≥ 25 cm) over the north Tamil Nadu, Puducherry, south coastal Andhra Pradesh and Rayalaseema during next 48 hrs. Isolated heavy to very heavy rainfall would occur over south Interior Karnataka during next 48 hrs</td></tr>
</table>

4.3.5.4.Strong wind

Considering the prediction of maximum sustained wind at the surface level, the maximum predicted wind speed and the time of prediction along with the observed wind speed are shown in the Table 4.18.

Table 4.19. Verification of maximum wind forecast issued by IMD

Observation Time (UTC)	Forecast issue time (UTC)	Hours in advance of landfall	Forecast maximum wind (kmph) at time of landfall (North Tamil Nadu- south Andhra Pradesh coast	Actual wind (kmph)
050000	050300	61	55-65	Maximum wind speed: Ennore Port in Tamil Nadu : 33 knots (61 kmph) in the forenoon of 7th October 2010.
051200	051400	50	120-130	
070000	070300	13	110-120	
070600	070830	7.5	80-90	

4.3.5.5.Storm surge

The storm surge predicted by IMD and the realised surge are given in Table 4.20.

Table 4.20. Verification of storm surge predicted by IMD

Observation Time (UTC)	Forecast issue time (UTC)	Hours in advance of landfall	Forecast storm surge(m) at time of landfall	Actual storm surge (m)
051200	051400	52	Storm surge of about 1-2 meters above astronomical tide may inundate low lying areas of Nellore, Prakasham districts of Andhra Pradesh and Tiruvallur, Chennai and Kanchipuram districts of Tamil Nadu at the time of landfall.	Inundation of low lying areas have been reported. However, the storm surge was negligible as the system crossed coast as a deep depression.

4.3.6. Average forecast error of 2010

The average landfall and track forecast error of cyclonic storms during 2010 based on the forecast issued by RSMC, New Delhi are given in Table 4.21-4.22. The landfall point and time forecast errors as well as track forecast errors have improved during 2010. There is also improvement in the skill score of the track forecast (Table 4.23). For comparison, the 12 and 24 hr track forecast errors and the skill scores during 2003 and 2010 are shown in Fig.4.1 and 4.2 respectively. 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. Considering, the intensity forecast, the average 24 hrs wind forecast error has been about 10 knots for these cyclones.

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;

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

Table 4.21(a). Landfall Point Forecast error (km)

System	Lead Time (hours)					
	12	**24**	**36**	**48**	**60**	**72**
LAILA	55	55	115	115	122	207
BANDU	--	--	--	--	--	--
PHET	15/25	115/150	275/--	100/--	90/-	90/-
GIRI	55	55	55	--	--	--
JAL	35	25	33	44	22	101
MEAN	37	80	120	86	78	133

-- : No landfall as the system dissipated over the Sea

Table 4.21(b). Landfall time forecast error (hrs)

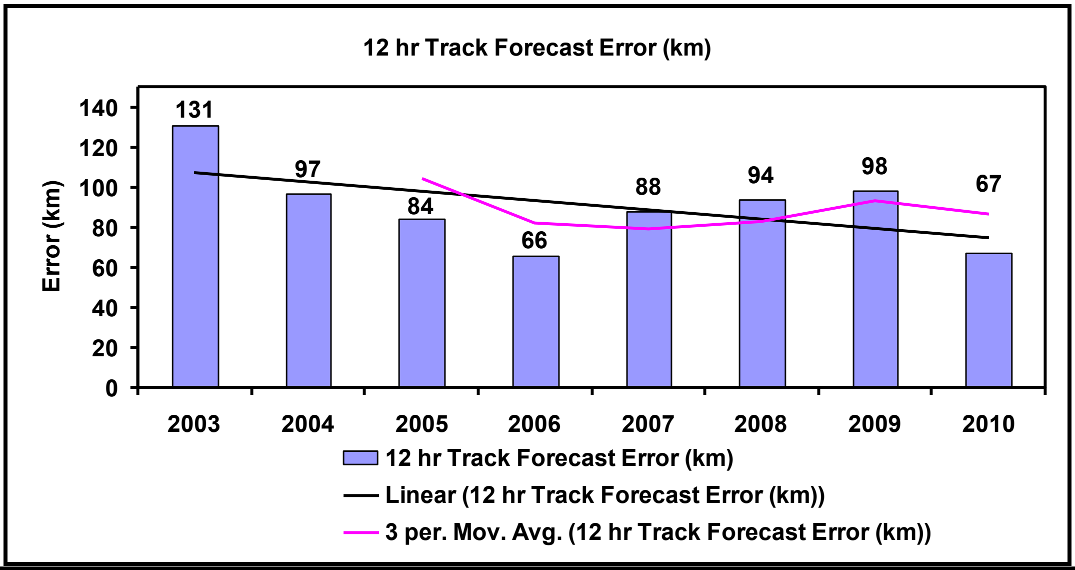
System	Lead Time (Hrs)					
	12	**24**	**36**	**48**	**60**	**72**
LAILA	1.5 D	1.5 D	3.5E	3.5E	2.5E	1.0E
BANDU	--	--	--	--	--	--
PHET	02E/0.5E	02E/2D	15D/-	01D/-	02E/-	1E/-
GIRI	4D	2E	2E	--	--	--
JAL	0.5 D	0.5D	0.5D	1.5E	1.5E	1.5E
MEAN						

-- : No landfall as the system dissipated over the Sea

Table 4.22. Average cyclone track forecast error (km)

System	Lead Time (Hrs)					
	12	**24**	**36**	**48**	**60**	**72**
LAILA	84(12)	153(11)	228(9)	254(7)	372(5)	210(3)
BANDU	39(4)	78(2)	78(1)	-	-	-
PHET	82(20)	162(20)	215(16)	311(15)	410(14)	545(14)
GIRI	45(7)	73(5)	68(3)	117(1)	-	-
JAL	41(11)	78(9)	56(7)	83(5)	54(3)	54(01)
MEAN	66(54)	131(47)	167(36)	249(28)	330(22)	465(18)

Figures inside the brackets indicate number of forecasts verified based on 00, 06, 12 and 18 UTC.



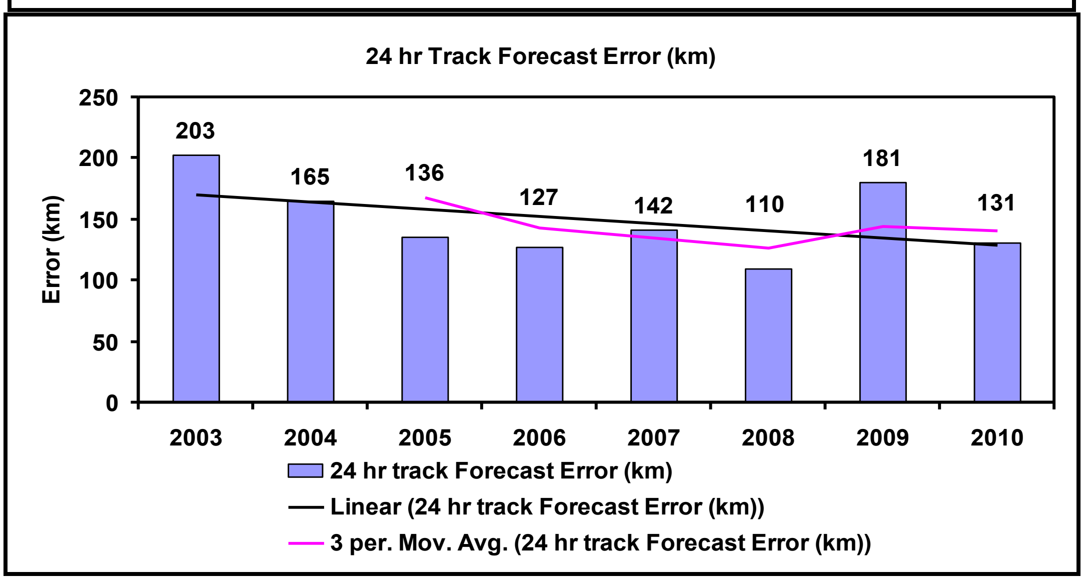


Fig.4.1. 12 hr and 24 hr cyclone track forecast errors of IMD during 2003-2010.

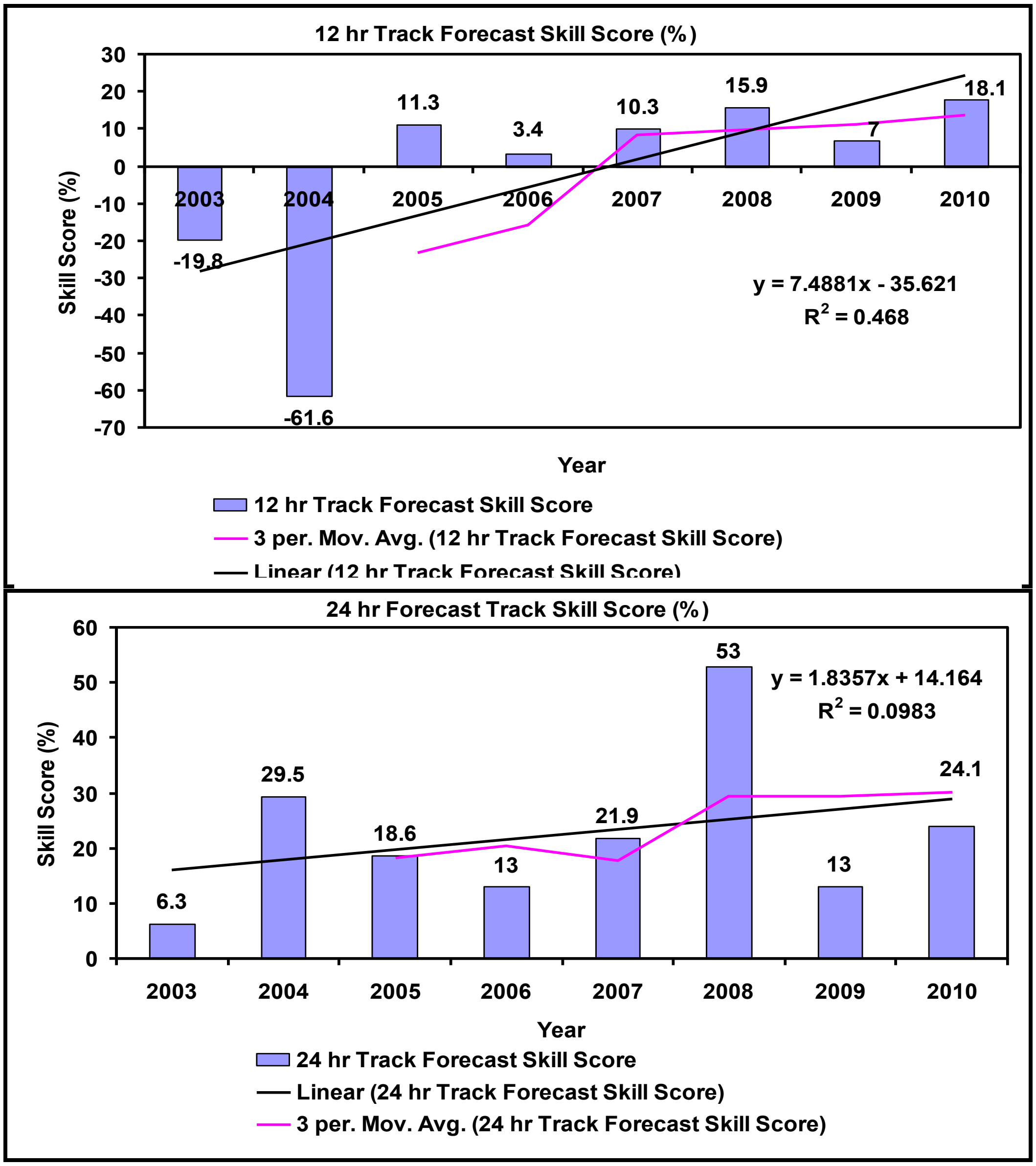


Fig.4.2. 12 hr and 24 hr cyclone track forecast skill scores of IMD during 2003-2010.

Table 4.23. Skill score (%) of cyclone track forecast issued by IMD during 2010

System	Lead Time (hrs)					
	12 hr	24hr	36hr	48hr	60hr	72hr
LAILA	17.9	17.9	25.4	51.2	68.0	68.0
BANDU	52.0	52.0	52.0	-	-	-
PHET	2.4	1.5	27.0	27.0	30.0	33.0
GIRI	15.1	57.1	78.8	82.1	-	-
JAL	43.0	32.0	45.0	43.0	69.0	77.0
MEAN	18.1	24.1	33.9	38.7	43.8	40.4

The average intensity forecast error of RSMC, New Delhi for five cyclones during 2010 are shown in Table 4.24. The average intensity error is about 16 kt, 22 kt and 28 kt for 24, 48 and 72 hr forecast period.

Table 4.24. Average annual intensity error 2010

Lead Period of forecast	Intensity Error (knots)			No. of observation verified
	Average	Absolute Average	RMS	
12	1.0	8.1	11.3	55
24	4.5	12.2	16.4	49
36	8.7	15.3	20.4	37
48	13.4	16.5	21.9	29
60	19.6	20.9	26.8	23
72	21.0	21.0	28.3	19