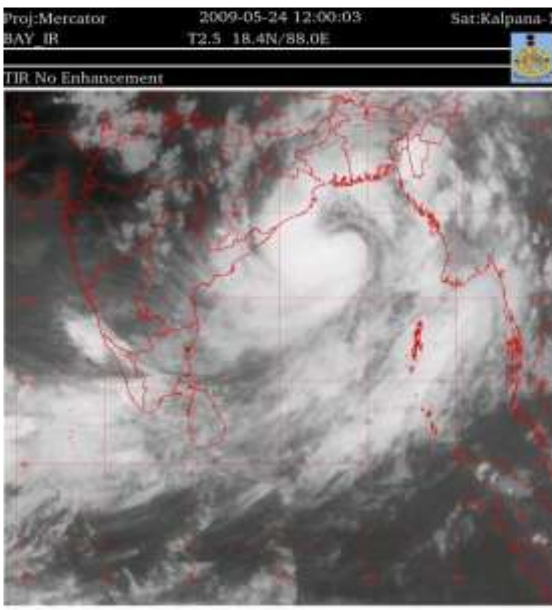
भारत मौसम विज्ञान विभाग

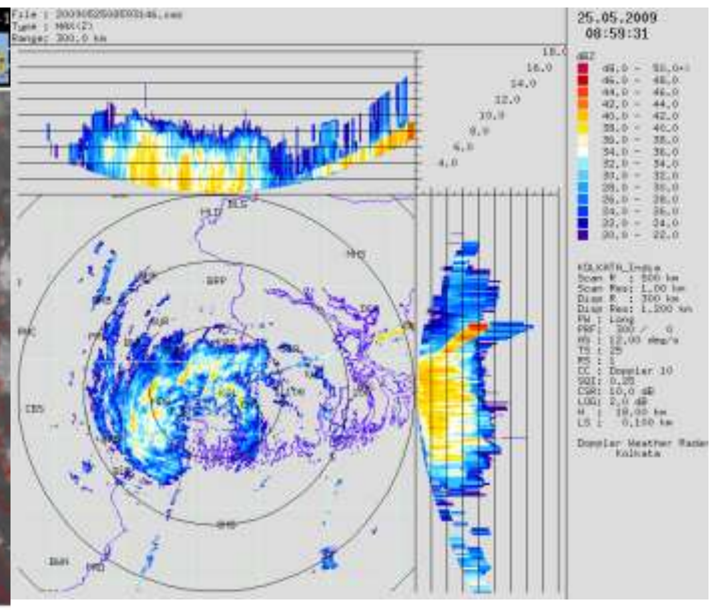
INDIA METEOROLOGICAL DEPARTMENT

Cyclone Warning No. 5/2010

CYCLONIC DISTURBANCES OVER NORTH INDIAN OCEAN DURING 2009: A REPORT



Kalpana-1 imagery of AILA: 24 May 2009



DWR imagery of AILA : 25 May 2009

CYCLONE WARNING DIVISION, NEW DELHI

JANUARY 2010

INDIA METEOROLOGICAL DEPARTMENT

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PREFACE

Tropical cyclones (TCs) which are accompanied with very heavy to extremely heavy rain, gales and storm surges are the most devastating phenomena among all natural disasters. The extensive coastal belts of India are exposed to TCs, which originate in the north Indian Ocean (NIO) including the Bay of Bengal and the Arabian Sea every year. Considering these, cyclone warning is one of the most important functions of the India Meteorological Department and it was the first service undertaken by the Department as early as in 1865. As per one of the recommendations of the Cyclone Review Committee (CRC), a Cyclone Warning Directorate was established in 1990 in the Office of the Director General of Meteorology, New Delhi to coordinate the cyclone warning work in the country in totality.

Cyclone Warning Division also acts as a Regional Specialised Meteorological Centre (RSMC), New Delhi and has the official responsibility to monitor and predict the cyclonic disturbances over the NIO and to issue warnings and advisories to different national and international disaster management agencies including National Disaster Management, Ministry of Home Affairs, Government of India and member countries of the World Meteorological Organisation (WMO)/ Economic and Social Co-operation for Asia and the Pacific (ESCAP) Panel, namely, Bangladesh, Pakistan, Maldives, Myanmar, 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 north Indian Ocean witnessed the formation of eight cyclonic disturbances during the year, 2009 including two deep depressions, three cyclonic storms **(BIJLI, PHYAN, WARD)** and one severe cyclonic storm **(AILA).** Cyclone Warning Division, New Delhi mobilized all its resources, both technical and human, to track these tropical disturbances and issued timely warnings and advisories.

This report on cyclonic disturbances over the NIO describes the current status of monitoring and prediction process for cyclonic disturbances, detailed characteristics of cyclonic disturbances during 2009, performance of various dynamical & statistical models used for prediction and the performance of the Cyclone Warning Division in monitoring and prediction of cyclonic disturbances.

I congratulate the Cyclone Warning Division for bringing out this report. I am sure the operational forecasters, researchers and other user community will find this publication very useful.

Ajit Tyagi

Director General of Meteorology
India Meteorological Department

INDIA METEOROLOGICAL DEPARTMENT
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17	Abstract	The activities of cyclone warning division along with the present state of art for monitoring and prediction of cyclonic disturbances over the north Indian Ocean is presented here. This report further describes the characteristics of cyclonic disturbances formed over the north Indian Ocean during 2009. 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 Cyclone Warning Division with respect to 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

As per the recommendations of the Cyclone Review Committee (CRC) set up by the Government of India, a Cyclone Warning Directorate, was established in 1990 in Northern Hemisphere Analysis Centre (NHAC) of India Meteorological Department (IMD), New Delhi to co-ordinate and supervise the cyclone warning in the country.

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, Pakistan, Maldives, Myanmar, 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 Cyclone Warning Division and 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 CYCLONE WARNING DIVISION AND REGIONAL SPECIALIZED METEOROLOGICAL CENTRE (RSMC) – TROPICAL CYCLONES, NEW DELHI

1.1 Area of Responsibility

The area of responsibility of Cyclone Warning Division and RSMC- New Delhi covers Sea areas of north Indian Ocean north of equator between $45^{\mathbf{0}}$ 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.

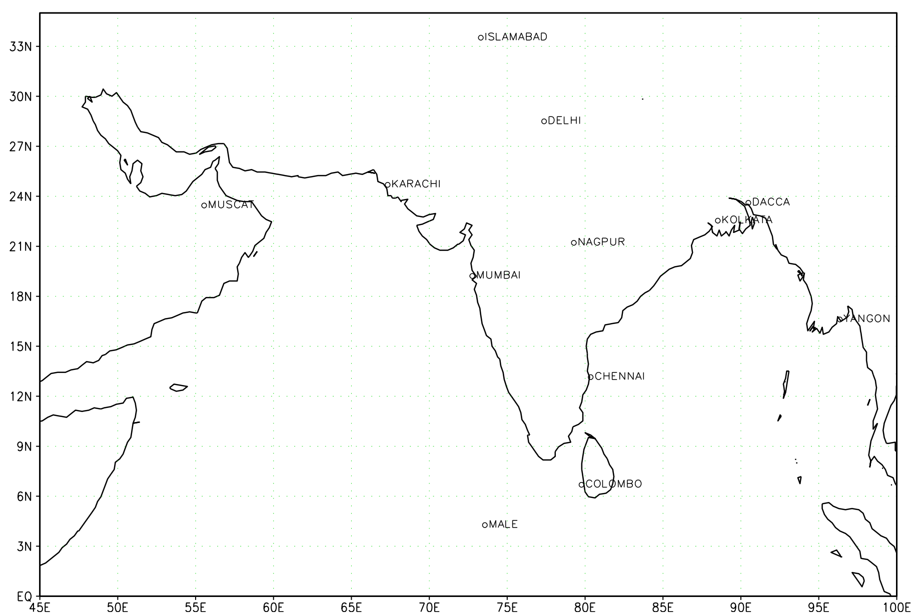


Fig. 1.1 Area of responsibility

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, 21 names have been utilized till the end of year 2009.

1.3 Observational System

A brief description of different types of observational network of 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 has been collected all over the country are used on real time basis for operational forecasting.

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

1.3.3. 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 developed by Indian Space Research Organization (ISRO) under IMD-ISRO collaboration has also been installed and made operational at SHAR Centre, Sriharikota (Andhra Pradesh) with effect from 9 April, 2004.Old conventional Radar at Kolkata was dismantled and was re-installed at Goa. As the radars at Goa, Mumbai, Paradip, Karaikal, Bhuj and Kochi have become old/obsolete, these radars are under the process of written off. In these places new radars procured from M/s Beijing Metstar, China will be installed. Rest of these radars are expected to be installed/commissioned by the end of December, 2010.

Doppler Weather Radars 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 Doppler Weather Radars have capability for correcting the values for clutters, partial beam filling, beam blockage and bright band. The Doppler Weather Radars 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 (DSD is different for different season, geographical location and type of precipitation).

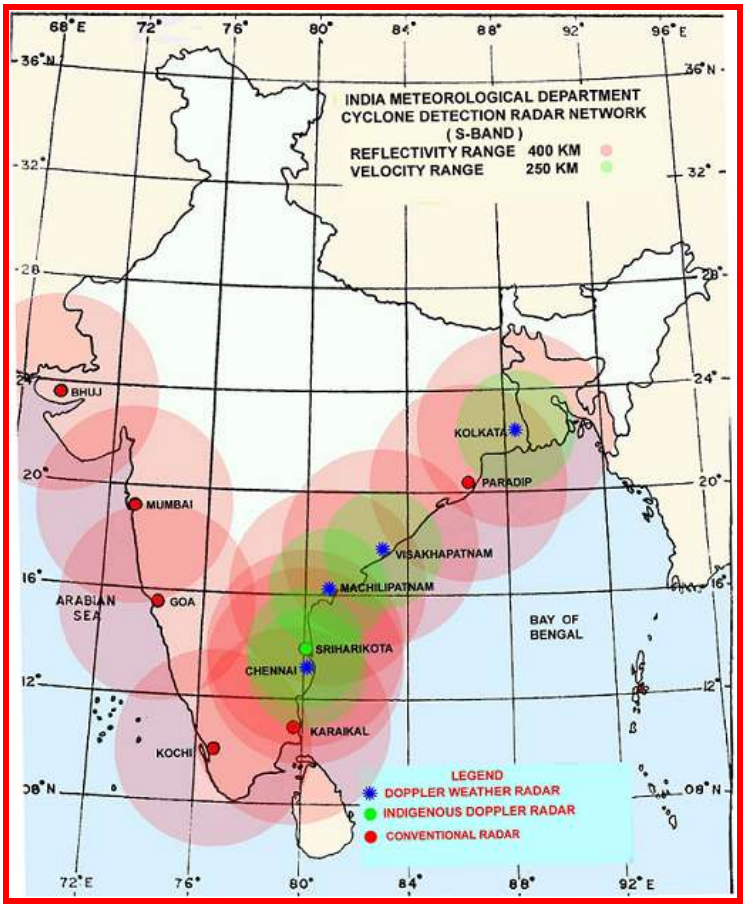


Fig. 1.2. S-band Cyclone Detection Radar Network

Future Plan

IMD is modernizing its observational network in the phased maner. In the first phase, Supply order for the supply of 12 DWRs has been placed on M/s Beijing Metstar, China. Four conventional radars located at Paradip,Karaikal, Goa and Mumbai will be replaced by the end of December,2010 with 4 S band Doppler weather radars. The other eight radars will replace X-band radars located at Delhi (Palam), Patiala, Lucknow, Nagpur, Hyderabad, Mohanbari, Agartala and Patna.

IMD is also procuring two S-band DWR's from M/s BEL, Bangalore which will replace Cyclone Detection Radars at CDR Bhuj and CDR Kochi. They are expected to be installed/commissioned by March,2010 and September,2010 respectively.

IMD plans to install 20 DWR's (7 C- band & 13 S-band) in 2nd Phase of modernisation scheme of IMD Weather Radar network by 2012.

1.3.4 Satellite Monitoring

1.3.4.1 Current status:

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

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

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

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

- Outgoing Longwave Radiation (OLR) are computed at $0.25^0 \times 0.25^0$ 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 in 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 will carry a ku band pencil beam scatterometer to provide ocean surface winds at 10 m ht for early detection of Tropical cyclones.

1.3.4.2. 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 no. 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.

1.3.4.3 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 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.

A new weather analysis and forecasting system has been installed at IMD, New Delhi, which has the capability to plot and analyse different weather parameters, INSAT & radar imagery and NWP products using a software known as synergie procured from Mateo France International (MFI). It has a tropical cyclone module, to deal with various aspects of cyclonic disturbance. The experimental run of the system commenced towards the end of 2009.

1.5. Prediction Models in operational use during the year 2009

1.5.1. 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 T254) 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.

1.5.2. Limited Area Model (LAM)

The operational forecasting system known as Limited Area Forecast System (LAFS) is a complete system consisting of data decoding and quality control procedures, 3-D multivariate optimum interpolation scheme for objective analysis and a semi-implicit semi-Lagrangian multi-layer primitive equation model. The model is run twice a day based on 00 UTC and 12 UTC observations. The horizontal resolution of the model is 0.75^0x0.75^0 lat. / long. With 16 sigma levels in the vertical. First guess and boundary conditions for running the LAFS are obtained online from global forecast model being operated by the NCMRWF. During cyclone situation, 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. 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.

1.5.4. Non-hydrostatic mesoscale model WRF

Weather Research and Forecast (WRF) model has been implemented based on 00 UTC initial and boundary conditions from NCEP model outputs for the forecast up to 72 hours. The model is run with a single forecast domain covering Indian subcontinent at the horizontal resolution of 27 km. The performance of the model is found to be reasonably skilful for cyclone genesis and track prediction.

1.5.5. 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 by multiple linear regressions technique is defined as:

$$\left.\begin{aligned} LAT^f_t &= a_0 + a_1 ECMWF_t^{lat} + a_2 NCEP_t^{lat} + a_3 JMA_t^{lat} + a_4 MM5_t^{lat} + a_5 QLM_t^{lat} \\ LON^f_t &= a'_0 + a'_1 ECMWF_t^{lon} + a'_2 NCEP_t^{lon} + a'_3 JMA_t^{lon} + a'_4 MM5_t^{lon} + a'_5 QLM_t^{lon} \end{aligned}\right\}$$

for t = forecast hour 12, 24, 36, 48, 60 and 72

The constant term a_0 and coefficients a_1, a_2, ….., a_5 for 12 hourly forecast intervals for latitude and a'_0 and coefficients a'_1, a'_2, ….., a'_5 for longitude are given in Table 1.2 and Table 1.3 respectively. In the updated version, IMD WRF model is also included as an ensemble member.

Table 1.1: Model Parameters

S.No.	Member models	Symbol of Predictors	
		Latitude position	Longitude position
1.	European Centre for Medium-Range Weather Forecasts (ECMWF),	$ECMWF^{lat}$	$ECMWF^{lon}$
2.	GFS of National Centers for Environmental Prediction (NCEP)	$NCEP^{lat}$	$NCEP^{lon}$
3.	Japan Meteorological Agency (JMA)	JMA^{lat}	JMA^{lon}
4.	MM5 Model	$MM5^{lat}$	$MM5^{lon}$
5.	Quasi-Langrangian model (QLM)	QLM^{lat}	QLM^{lon}

Table 1.2: Regression coefficients for latitude position for different forecast hours

Forecast hours	a_0	a_1	a_2	a_3	a_4	a_5
12 hr	1.46633	0.4837	0.08762	0.0474	-0.06954	0.34208
24 hr	0.75662	0.7622	-.08543	-.17727	-0.02354	0.45521
36 hr	1.28923	0.6177	-.05394	0.0407	0.12614	0.17496
48 hr	0.60173	1.3521	0.30361	-0.3094	-0.00463	-0.27553
60 hr	0.36611	1.1298	-.15616	0.1433	-0.11323	0.03574
72 hr	2.49751	0.3766	-.37158	0.9005	-0.21182	0.14239

Table 1.3: Regression coefficients for longitude position for different forecasts hour

Forecast hours	a'_0	a'_1	a'_2	a'_3	a'_4	a'_5
12 hr	2.1269	0.3363	0.07031	0.1089	-0.04351	0.4990
24 hr	1.04316	0.85076	-0.14555	-.07929	0.16159	0.19624
36 hr	5.82346	0.32571	-0.10423	0.34342	-0.05668	0.42152
48 hr	0.29452	0.36666	-0.04239	0.08226	0.18461	0.40281
60 hr	1.63954	0.24631	0.03642	0.23184	-0.12901	0.59908
72 hr	6.21043	0.28419	0.04475	0.48297	-0.01591	0.13165

The MME technique has been implemented from 2009 for real time forecasting of tropical cyclones.

1.5.6. 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.

1.5.7. 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 Cyclone Warning Division and RSMC, New Delhi

Cyclone Warning Division and 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 one 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+ 3 hours.

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 India Ocean.

1.6.2. Tropical Cyclone Advisories

Tropical cyclone advisory bulletin is issued when a deep depression intensified 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 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 likely in special tropical weather outlook expected point and time of landfall. Forecast of winds, squally weather and state of the Sea in and around the system are also mentioned. Storm surge guidance is also provided in the bulletin as when required. Tropical cyclone advisories 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 India 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 contains 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 Indian coasts

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

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

1.7. 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 almost 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.

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

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

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

During pre-pilot phase **(15 Oct- 30 Nov. 2009),** several national institutions participated for joint observational, communicational & NWP activities, like during 2008. However, there was no intense observation period during the pre-pilot phase 2009, as there was no cyclonic disturbance over the Bay of Bengal during this period. The daily reports prepared during this period will be helpful to find out the reasons for suppressed cyclogenesis over the Bay of Bengal during 15^{th} Oct. to 30^{th} November 2009.

1.9. Modernization Programme of IMD

During the past 133 years, IMD has undergone several instances of modernization helping it to harmonize with emerging technologies and societal demands. Present phase of modernization is driven by:-

- Demand for high resolution data and forecasts in all time scales with higher accuracies
- 24x7 weather surveillance and dedicated telecom systems for issuing early warnings of disastrous weather
- District specific data, forecasts and Agro advisories
- Specialized Met information to various sectors
- Delivery of Weather Information to Public

Modernization refers to adoption of technologies enabling

- Observational Upgradation
  - Insat-3D, Megha-Tropique, Ocean Sat 2
  - Ocean Sat 2 (already launched)
  - Doppler Weather Radars
  - Automatic Rain Gauges
  - Automatic Weather Stations
  - Upper Air Systems
  - Environment Monitoring
  - Seismic Network
- Advanced data communication and processing Technology
- Advanced Computing Systems
- Installation of following specific purpose Numerical Prediction Models
  - Cyclone Warning
  - Now casting

General Weather Prediction
Climate Simulation
Environmental Predictions

- Human Resource Development

Agro Met Services
Aviation Met Services
Web Enabled Services

- Weather Channel

The ongoing modernization programme aims at the following:

1. Establishing connectivity (network) for various kinds of instruments across the country to Atmospheric Data Centre at Delhi.
2. The data management software for managing huge quantity (25 Terabytes) of data on continuous basis for 20000 odd sensors including Doppler Weather Radar. This software will enable the scientists of IMD to access relevant data from the data repository;
3. Software tools for various meteorology, climatology and public weather service applications relating to forecasting like nowcasting using DWR and other sensor data, short range forecasting using numerical models and synoptic observation, medium and long range forecasts, specialized services like agro-met advisories and aviation service, climatological software for managing 130 years of observational data of IMD and automatic public weather warning (TV, radio, newspaper, mobile, Phone) preparation and dissemination software;
4. Setting up a forecasting environment as an integrated fully automated facility in which manual synoptic weather forecasting will be replaced by hybrid systems in which synoptic method is overlaid on numerical models supported by modern graphical and GIS applications to produce (i) high quality analyses (ii) Ensemble of forecasts from numerical models at different scales - global, regional and mesoscale (iii) nowcasting with radar mosaics for severe thunderstorms and tornadoes (iv) Prediction of intensity and track of tropical cyclone and storm surge (v) Aviation forecasts (vi) Forecasts and warning for shipping (vii) High quality Agro-met Advisory Services (viii) High quality extension of the forecast upto district and village levels. The proposed forecasting network to be established during phase 1 of modernization programme is shown in Fig.1.3

The expected outcomes of the modernization programme are as follows.

- Improved Weather and Climate Monitoring
- Real time data availability with rapid updation of data, quicker response time for management, easy accessibility, opportunities for value addition.
- Improved Weather Forecasting for Nowcasting, Short, Medium and Long-range scales (months to Seasons),
- Reduction in loss of life and property from weather hazards

- ❖ Understanding, assessment and prediction of climate variability and change for mitigation and adaptation measures,
- ❖ Support sustainable agriculture and horticulture and provide inputs for managing rising agricultural risks,
- ❖ Meet increasing requirements of civil aviation,
- ❖ Understand the effect of environmental factors on human well being, human health and ecology to make more informed decisions
- ❖ Monitor and manage Water and Energy Resources of the country.

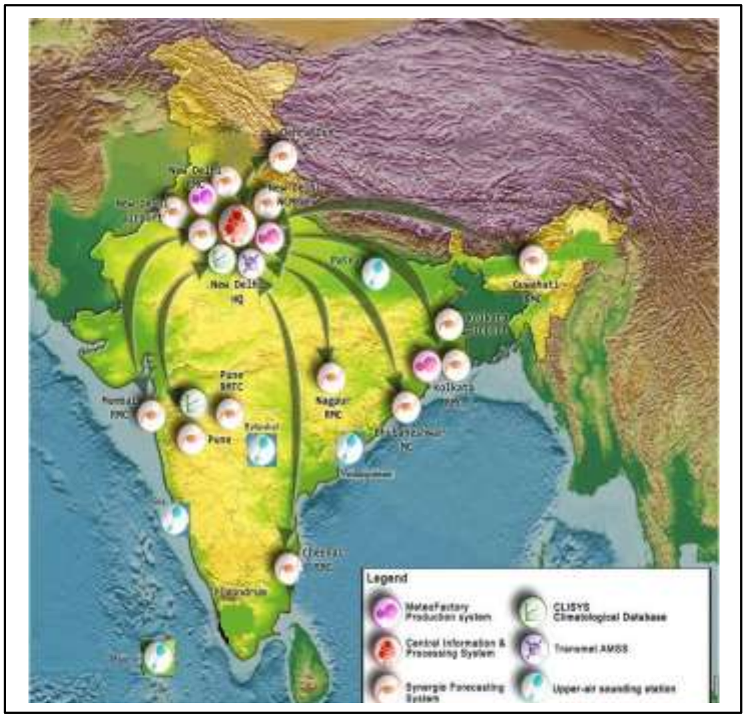


Fig.1.3. Proposed network of forecasting system during phase I of modernization programme

The scientists and forecasters have been trained and the synergie forecasting system has been installed at IMD, New Delhi. The system is running on experimental basis and will be made fully operational during 2010. This system would be helped for better monitoring & prediction of cyclonic disturbances and issue of warning and advisory to users.

CHAPTER –II

CYCLONIC ACTIVITIES OVER NORTH INDIAN OCEAN DURING 2009

The north Indian Ocean witnessed the formation of eight cyclonic disturbances (Table 2.1) during the year, 2009 against a normal of fifteen. Out of eight disturbances two intensified upto deep depression, three upto the stage of cyclonic storms and one upto severe cyclonic storm. Tracks of the cyclonic disturbances formed over the north Indian Ocean during 2009 are shown in Fig. 2.1. Comparing Bay of Bengal and Arabian Sea, two depressions and one cyclone "PHYAN" formed over the Arabian Sea, while the Bay of Bengal witnessed the formation of five disturbances including one severe cyclonic storm, '**AILA'**, two cyclonic storm, '**BIJLI'** & **'WARD**' and two deep depressions during the year.

Some characteristic features of cyclonic disturbances formed over the north Indian Ocean during 2009 are given in Table 2.2. The statistical characteristics including frequency, intensity and total life time of cyclonic disturbances formed over the north India Ocean and land areas of India are given in Table 2.3 and 2.4.

Salient features of cyclonic disturbances during 2009

- The north Indian Ocean witnessed formation of eight cyclonic disturbances including four cyclones during 2009, compared to ten disturbances including four cyclones during 2008. Out of the four cyclones, one intensified into severe cyclonic storm during 2009.
- The Bay of Bengal was active during pre-monsoon storm season (April-May) with the formation of one cyclonic storm (BIJLI) and another severe cyclonic storm (AILA).
- There was no cyclogenesis over the Bay of Bengal during October-November, 2009.
- Out of four cyclones, two (BIJLI and PHYAN) recurved northeastwards, one (WARD) recurved southwestwards and the other (AILA) moved almost northward throughout its life period.

The brief synopses of the cyclones during 2009 are given below:

(a) Cyclonic Storm, "BIJLI" over the Bay of Bengal during 14-17 April, 2009.

A low pressure area developed over the southeast Bay of Bengal on 13 April, 2009. It concentrated into a depression at 0900 UTC of 14 April over the southeast and adjoining eastcentral Bay of Bengal. It moved in a north-northeasterly direction and intensified into a cyclonic storm **'BIJLI'** at 1200 UTC of 15 April over the eastcentral Bay of Bengal. It thereafter moved in a northerly direction and finally recurved northeastwards towards Bangladesh coast. It also gradually weakened prior to landfall and crossed Bangladesh coast close to south Chittagaon around 1600 UTC of 17 April, 2009. It caused moderate damage over Bangladesh with death of three persons. The special features of the storm are as follows.

(i) The system developed as a depression during first fortnight of April. Climatologically, cyclogenesis during first fortnight of April is rare. Only a few cyclones have developed over the Bay of Bengal during first fortnight of April over the period of 1891-2008.

(ii) The track of the system was climatological in nature as most of the storms developing in the month of April during 1891-2008 have recurved northeastwards.

(iii) The system weakened into a depression prior to landfall.

(b) Severe cyclonic storm, "AILA" over the Bay of Bengal during 23-26 May, 2009

A depression formed over the southeast Bay of Bengal at 0600 UTC of 23 May, 2009. Under favourable conditions like warmer Sea surface temperature, low to moderate vertical wind shear and upper level divergence, it intensified into a cyclonic storm **"AILA"** at 1200 UTC of 24 May and into a severe cyclonic storm at 0600 UTC of 25 May. The system moved in a northerly direction and crossed West Bengal coast close to Sagar Island between 0800 & 0900 UTC of 25 May. It caused loss of about 100 lives and left several injured in West Bengal. It also caused about 175 human deaths and several injured in adjoining Bangladesh. The special features of the severe cyclonic storm **"AILA"** are given below:

(I) The system moved in a near northerly direction throughout its life span.

(II) It intensified into severe cyclonic storm only a few hours before landfall.

(III) The system maintained the intensity of the cyclone (T2.5) even upto 15 hours after the landfall.

(c) Cyclonic Storm 'PHYAN' over the Arabian Sea during 09-12 November 2009

A low pressure area formed over Comorin area on 7 November, 2009. It intensified into a depression at 0900 UTC of 9 November over the southeast Arabian Sea. It moved north-northwestwards till 10 morning. It then recurved north-northeastwards, intensified into a deep depression at 0300 UTC and into a cyclonic storm, **'PHYAN'** at 1800 UTC of 10 November. Continuing to move in a north-northeasterly direction, it crossed Maharashtra coast between Alibag and

Mumbai between 1000 & 1100 UTC of 11 November 2009. The special features of ‘PHYAN’ are given below.

(i) Cyclone, ‘Phyan’ moved very fast prior to landfall. It moved about 450 km during 0000 to 1200 UTC of 11 November 2009.
(ii) Though it crossed as a cyclonic storm, it slightly weakened before the landfall.

(d) Cyclonic storm ‘WARD’ over the Bay of Bengal during 10-15 December, 2009

A cyclonic storm, ‘WARD’ (10-15 December) developed over the south Bay of Bengal and crossed northeast Sri Lanka coast, close to south of Trincomalee as a deep depression between 0800 and 0900 UTC of 14 December 2009. It weakened into a well marked low pressure area over north Sri Lanka at 0300 UTC of 15 December. It then emerged into Gulf of Mannar and became insignificant on 16 December. The main features of this cyclone are as follows.
(i) Cyclone, ‘WARD’ followed a rare track, as it moved initially in a northerly direction and then moved west-southwestwards across Sri Lanka.
(ii) It was a slow moving system, as it travelled at the average rate of 200 km per day (8 km per hour).
(iii) It weakened into deep depression over the Sea before the landfall over Sri Lanka.

Cyclonic disturbances during monsoon Season (June-September), 2009

Four cyclonic disturbances developed during the monsoon Season (June-September), 2009. These included two depressions over the Arabian Sea in the month of June and two deep depressions over the Bay of Bengal, one each in the month of July and September. The tracks of these systems are shown in Fig. 2.1. Frequency of disturbances over the Indian region was significantly less compared to long period average of about 7 disturbances. However, it was comparable considering recent years, as the average frequency of the disturbances during monsoon Season was about 3.5 based on data of 1991-2008. The month of August was devoid of any monsoon depression like the previous August of 1992, 1993, 1995, 1996, 1998, 2001, 2002, 2004 and 2005. The movement of the systems was climatological, as the depressions developing over the Bay of Bengal moved west-northwestwards/ northwestwards. However, the systems were short lived. No system developing over the Bay of Bengal moved to the west of the longitude 80^0E.

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 2009

1.	Cyclonic Storm, ' BIJLI' over the Bay of Bengal 14-17 April, 2009.
2.	Severe Cyclonic Storm, 'AILA" over the Bay of Bengal 23-26 May, 2009
3.	Depression over the Arabian Sea 23-24 June, 2009
4.	Depression over the Arabian Sea 25-26 June, 2009
5.	Deep depression over the Bay of Bengal 20-21 July, 2009
6.	Deep depression over the Bay of Bengal 05-07 September, 2009
7.	Cyclonic Storm, 'PHYAN' over the Arabian Sea 09-12 November, 2009
8.	Cyclonic Storm, 'WARD' over the Bay of Bengal 10-15 December, 2009

Table 2.2: Some Characteristic features of cyclonic disturbances formed over north Indian Ocean and adjoining region during 2009

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
Cyclonic Storm, "BIJLI" over the Bay of Bengal during 14-17 April, 2009.	14 April 0600 UTC near 12.5/88.0	Crossed Bangladesh Coast near 22.2/91.8 around 1600 UTC of 17 April	996 hPa at 1500 UTC of 15 April near 15.5/86.5	40 kt at 1500 UTC of 15 April	T 2.5
Severe Cyclonic Storm, "AILA" over the Bay of Bengal during 23-26 May, 2009	23 May, 0600 UTC near 16.5/88.0	Crossed west Bengal Coast close to Sagar Island near 21.8/88.0 between 0800 & 0900 UTC of 25 May	968 hPa at 0900 UTC of 25 May near 22.0/88.0	60 kt at 0900 UTC of 25 May near 22.0/88.0	T 3.5
Depression over the Arabian Sea during 23-24 June, 2009	23 June, 0000 UTC near 18.0/71.5	Crossed Gujarat coast near 20.8/71.0 between 1300-1400 UTC of 23 June	998 hPa at 0000 UTC of 23 June near 18.0/71.5	25 kt at 0000 UTC of 23 June	T 1.5
Depression over the Arabian Sea during 25-26 June, 2009	25 June, 0900 UTC near 22.5/68.5	Weakened into a well marked low pressure area over Kutch and neighbourhood	996hPa at 0900 UTC of 25 June near 22.5/68.5	25 kt at 0900 UTC of 25 June	T1.5

Deep Depression over the Bay of Bengal during 20-21 July, 2009.	20 July 0300 UTC near 21.0/88.5	Crossed north Orissa coast between Balasore and Digha near 21.4/87.4 between 1600 and 1700 UTC of 20 July.	988 hPa at 1200 UTC of 20 July near 21.0/88.0	30 kt at 1200 UTC of 20 July	T 2.0
Deep Depression over the Bay of Bengal during 05-07 September, 2009	05 September, 0000 UTC near 20.5/88.0	Crossed West Bengal Coast close to Digha near 21.7/87.5 between 0700 & 0800 UTC of 05 September.	988 hPa at 0300 UTC of 05 September, near 21.0/87.5	30 kt at 0300 UTC of 5 September.	T 2.0
Cyclonic Storm "PHYAN" over the Arabian Sea during 09-12 November	09 November 0900 UTC near 11.0/72.0	Crossed Maharashtra coast between Mumbai & Alibag near 18.7/73.0 between 1000 & 1100 UTC of 11 November near 18.8N/73.0 E	988 hPa at 0600 UTC of 11 November near 17.5/72.5	45 kt at 0600 UTC of 11 November.	T 3.0
Cyclonic Storm "WARD" over the Bay of Bengal during 10-15 December	10 December 0900 UTC near 6.5N/85.0E	Crossed north Sri Lanka near 8.8/81.3 between 0800 & 0900 UTC of 14 December near 8.5N/81.4 E	996 hPa at 2100 UTC 11 December near 9.5N/84.5E	45 kt at 2100 UTC 11 December	T3.0

Table 2.3: Statistical data relating to cyclonic disturbances over the north Indian Ocean during 2009

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 2009 at different stages of intensity

S.No	Type	Life Time in (Days)
1.	D	6.50
2.	DD	6.75
3.	CS	5.25
4.	SCS	0.37
5.	VSCS	--
6.	SuCS	--
Total Life Time in (Days)		18.87

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	4	3	1	-	-	-

D) Basin-wise distribution of cyclonic disturbances

Basin	Number of cyclonic disturbances
Bay of Bengal	5
Arabian Sea	3
Land depression	-

Table 2.4
Cyclonic disturbances formed over the north Indian Ocean and land areas of India during 1997-2009

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**

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

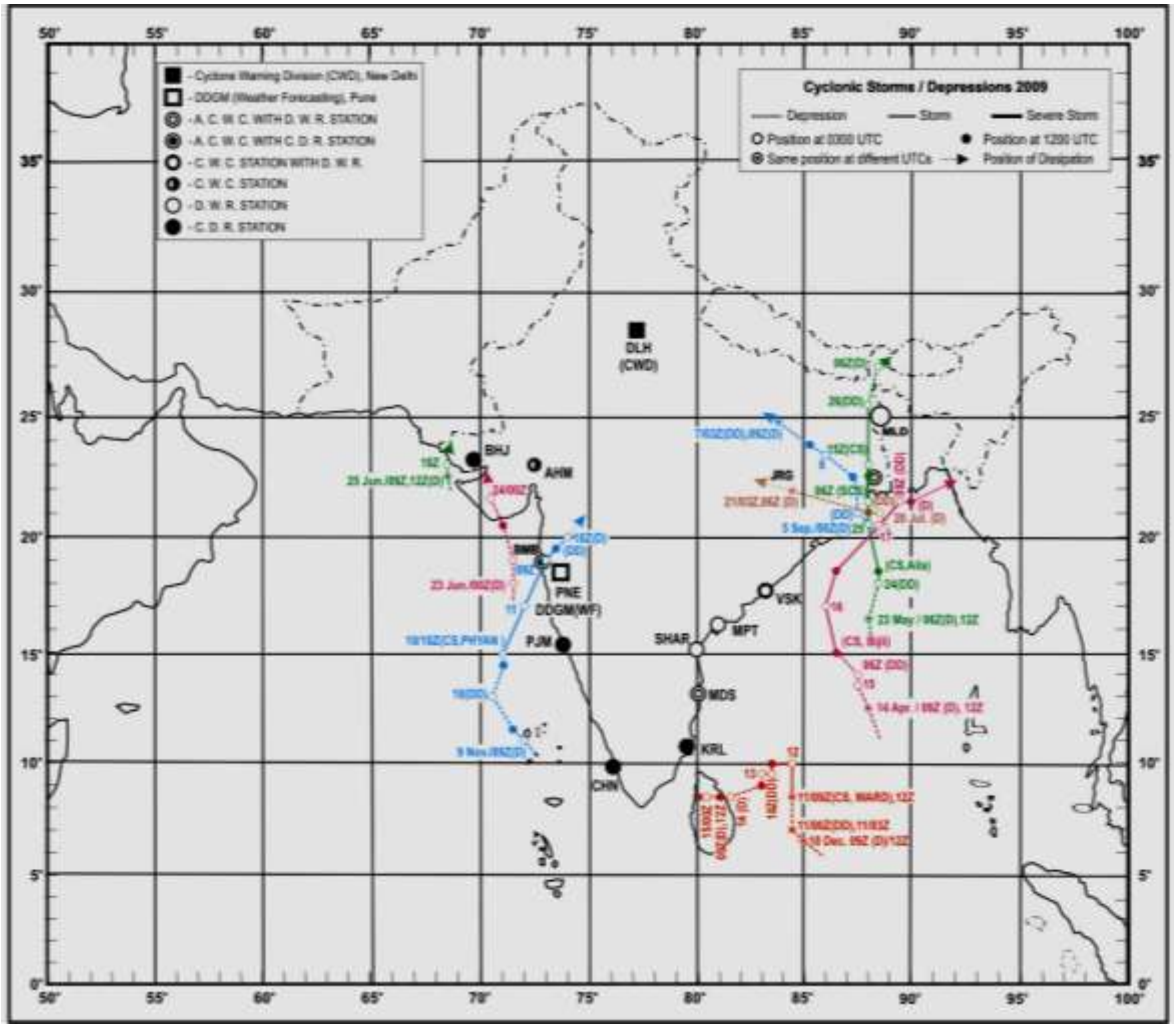


Fig. 2.1 Tracks of the cyclonic disturbances formed over the north Indian Ocean during the year, 2009

2.1 Cyclonic Storm' BIJLI' over the Bay of Bengal (14-17 April, 2009)

2.1. Introduction:

A cyclonic storm "BIJLI " (14-17 April) developed over the westcentral Bay of Bengal. It moved initially in north-northwesterly direction and then recurved northeastwards towards Bangladesh coast. However, it gradually weakened and crossed Bangladesh coast close to south of Chittagaon around 1600 UTC of 17 April 2009 as a depression. It caused moderate damage over Bangladesh with death of 3 persons. The special features of the system are as follows:

(i) The system developed as a depression during first fortnight of April. Climatologically, cyclogenesis during first fortnight of April is rare. Only ten cyclones have developed over the Bay of Bengal during 1891-2008.

(ii) The track of the system was climatological in nature as most of the storms developing in the month of April during 1891-2008 have recurved northeastwards.

(iii) The system weakened into a depression prior to landfall.

The genesis, intensification and movement, 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:

A convective cloud cluster developed over southeast Bay of Bengal and adjoining Andaman Sea on 10 April. It persisted over the same region till 13 April. Under its influence, a low pressure area formed over southeast Bay of Bengal on 13 April. It become a well marked low pressure area over the southeast and adjoining central Bay of Bengal at 0300 UTC of 14 April with associated cyclonic circulation extending upto mid-tropospheric level. The well marked low pressure area concentrated into a depression and lay centred at 0900 UTC of 14 April over southeast and adjoining central Bay of Bengal near lat. 12.5^0N and long. 88.5^0E, about 550 KM west-northwest of Port Blair (43333).

The satellite imageries of the system at 0900 UTC of 12, 13 and 14 April are shown in fig. 2.1.1. It clearly shows gradually organization of the convection in association with the system. The intensity of the system at 0900 UTC of 14 was estimated as T1.5. Associated broken intense to very intense convection observed over the area between lat. 7.0^0N and 16.0^0N and long. 83.0^0E and 91.0^0E. The lowest cloud top temperature (CTT) was about -60^0C.

The sustained maximum wind speed was about 25 knots around the system centre. The estimated central pressure was about 1000 hPa with a pressure drop about 4 hPa. The size of the system was about 4^0X6^0 lat. /long. and the shape of the closed isobars was elliptical.

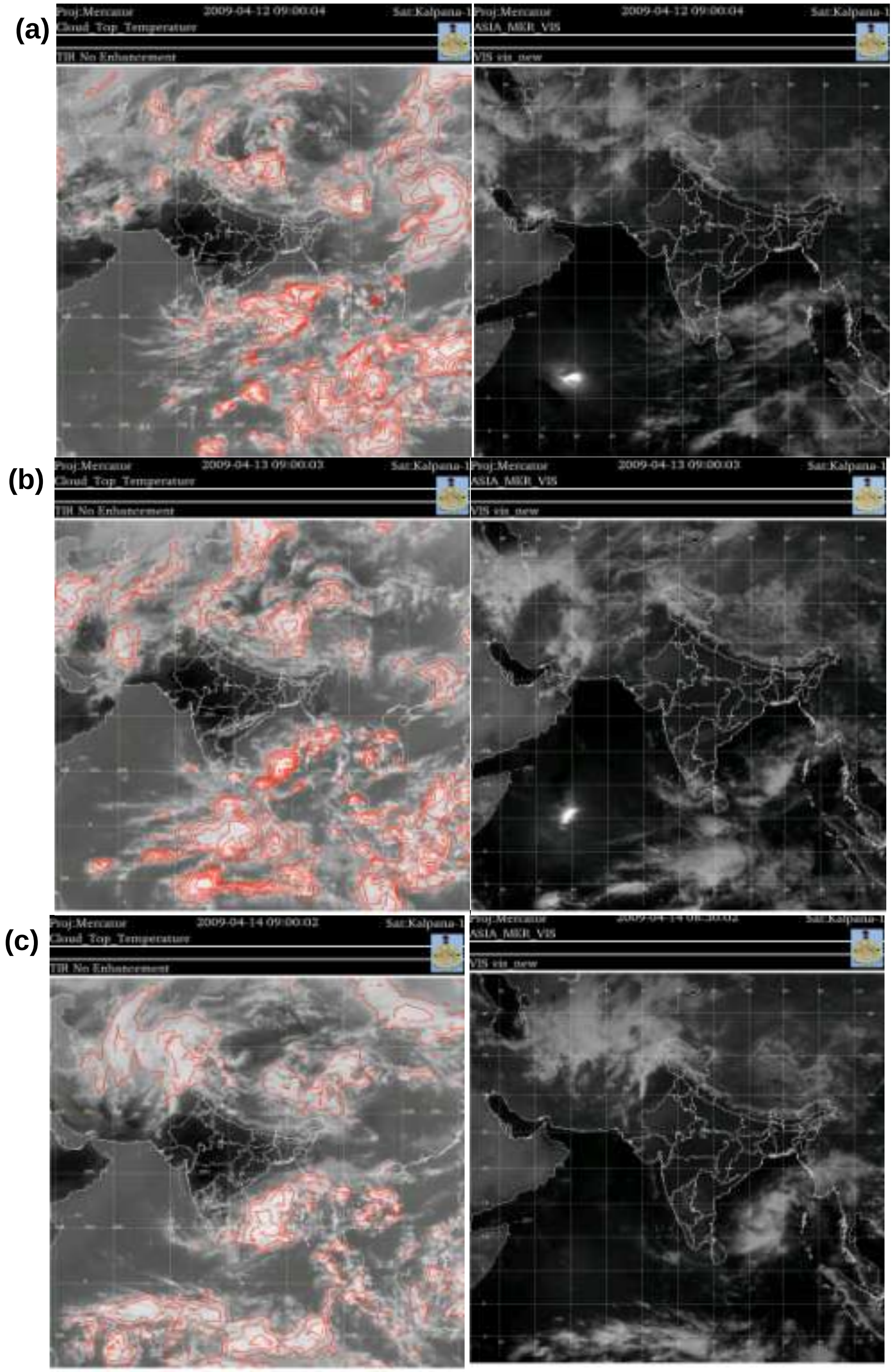


Fig.2.1.1. INSAT IR with cloud top temperature (CTT) and visible imageries of the system at 0900 UTC of 14 April 2009.

The vertical wind shear of horizontal wind over the region remained about 5-10 kmph during the pre-genesis period. The wind shear gradually decreased from 13 to 14 April and divergence was maximum to the west and northwest of the system centre. The sea surface temperature (SST) was about 27^0C over south and central Bay of Bengal, which was about 0.5 to 1.0^0 C above the normal. The wind shear of 14 April based on IMD limited area model (LAM) analysis is shown in fig. 2(a). There was higher mid-tropospheric humidity as observed from the LAM analysis. Hence the Gray Parameters were satisfied during the period of cyclone genesis. Also there was gradual increase in low-level vorticity, upper air divergence over the region from 11 to 14 April 2009.

It may be further mentioned that another low pressure area formed over southwest Bay of Bengal on 11 April. It persisted over the same region on 12 and became less marked on 13 April.

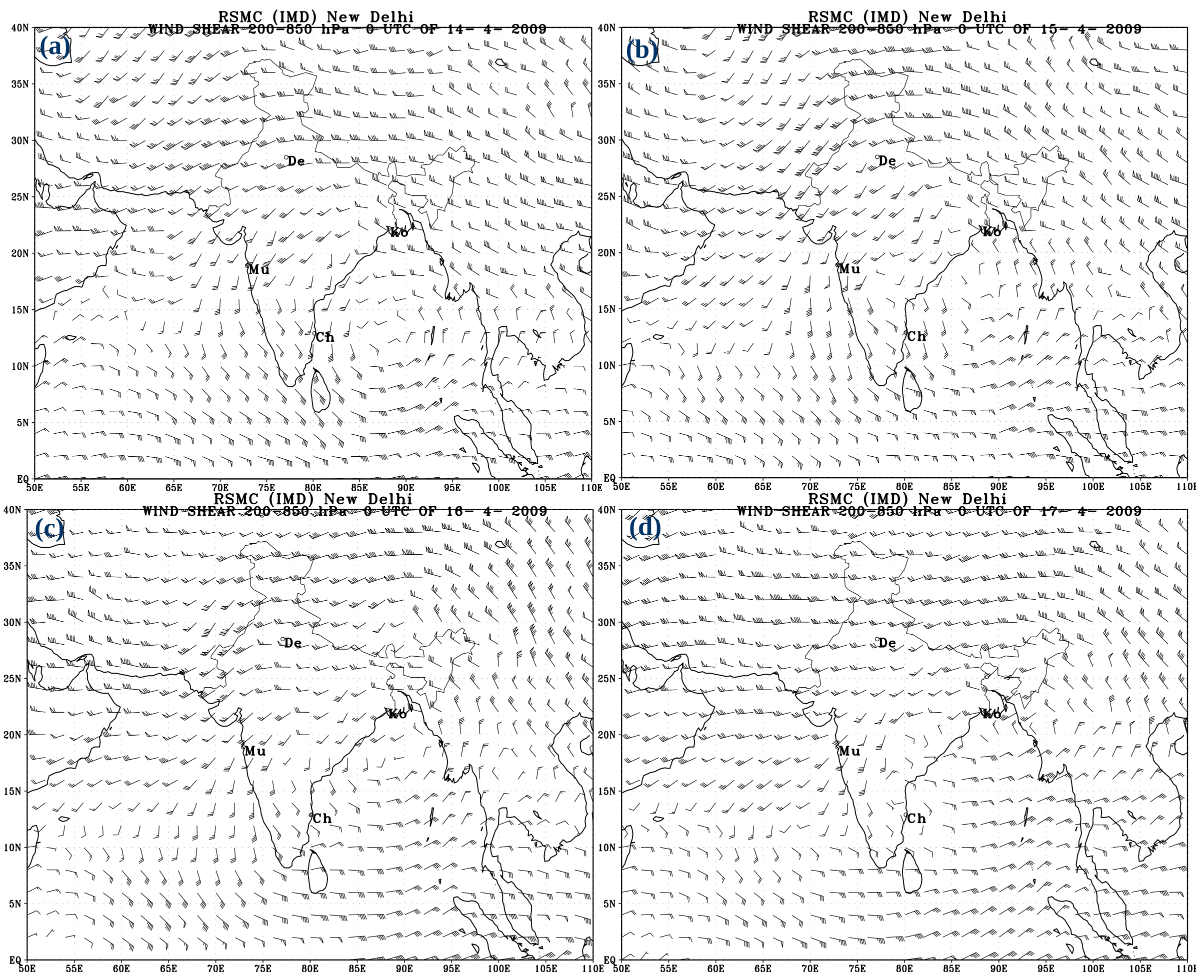


Fig.2.1.2. Vertical wind shear of the system at 0000 UTC of 17 April 2009.

2.1.3 Intensification and movement:

As discussed in the previous sections, different parameters like vertical wind shear, mid-tropospheric humidity, upper level divergence, SST etc. were favourable for further intensification of the system.

The vertical wind shear of 15, 16 and 17 April are shown in figure 2.1.2 In addition, the system lay to south of the upper tropospheric ridge, which roughly ran along 15^0N at 0900 UTC of 14 April. An anticyclonic circulation lay over Myanmar and adjoining Bangladesh according to METEOSAT based water vapour derived wind. This anticyclonic circulation provided the required upper level divergence to the system for further intensification. However, as the system lay on the southwest periphery of this anticyclonic circulation, it moved north-northwestwards initially and further intensified into a deep depression and lay centred at 0600 UTC of 15 April over central & adjoining southeast Bay of Bengal near lat. 14.0^0N and long. 87.5^0E, about 600 KM west-northwest of Port Blair. Wind analysis at 850 hPa and 200 hPa of the system at 0000 UTC of 17 April are shown in figure 2.1.3.

The convection according to satellite imagery further organized and curved band pattern of the system with T 2.5 was seen at 0600 UTC of 15 April. The lowest CTT due to convection was about -60^0C at 1200 UTC of 15 April. The vertical wind shear of horizontal wind continued to be 05-10 knots. The wind shear tendency was negative to the northwest of the system. The system continued to be close to the upper tropospheric ridge and the system lay on the southwest periphery of this anticyclonic circulation. With the these favourable environment conditions, the system moved in a northwesterly direction, intensified into a cyclonic storm 'BIJLI' and lay centred at 1200 UTC of 15 April over central & adjoining southeast Bay of Bengal near lat. 15.0^0N and long. 86.5^0E, about 470 km southeast of Visakhapatnam (43150). There was no upper tropospheric westerly trough to the west of the system. As a result, system could not get required upper level divergence for further intensification. The system moved in a north-northwesterly direction till 0900 UTC of 16 April and recurved thereafter towards north-northeast. The METEOSAT based middle and upper level winds supported the above movement of the system. As the system moved northeastwards skriting the coast (it was lying around 100 km from Orissa coast at 00 UTC of 17 April) from 17 April morning onwards, the system interacted with land surface also. As a result the system gradually weakened into a deep depression at 0900 UTC and into a depression at 1200 UTC of 17 April near at Bangladesh coast. INSAT CTT and visible imageries of the system at 0600 UTC at 16 and 17 April are shown in figure 2.1.4. After the landfall, system rapidly weakened into a well marked low pressure area due to increase in interaction with orography and cut off moisture supply. The best track parameters of the system is shown are Table 2.1.1. The track of the system is shown in fig 2.1.

(a) (b) (c)

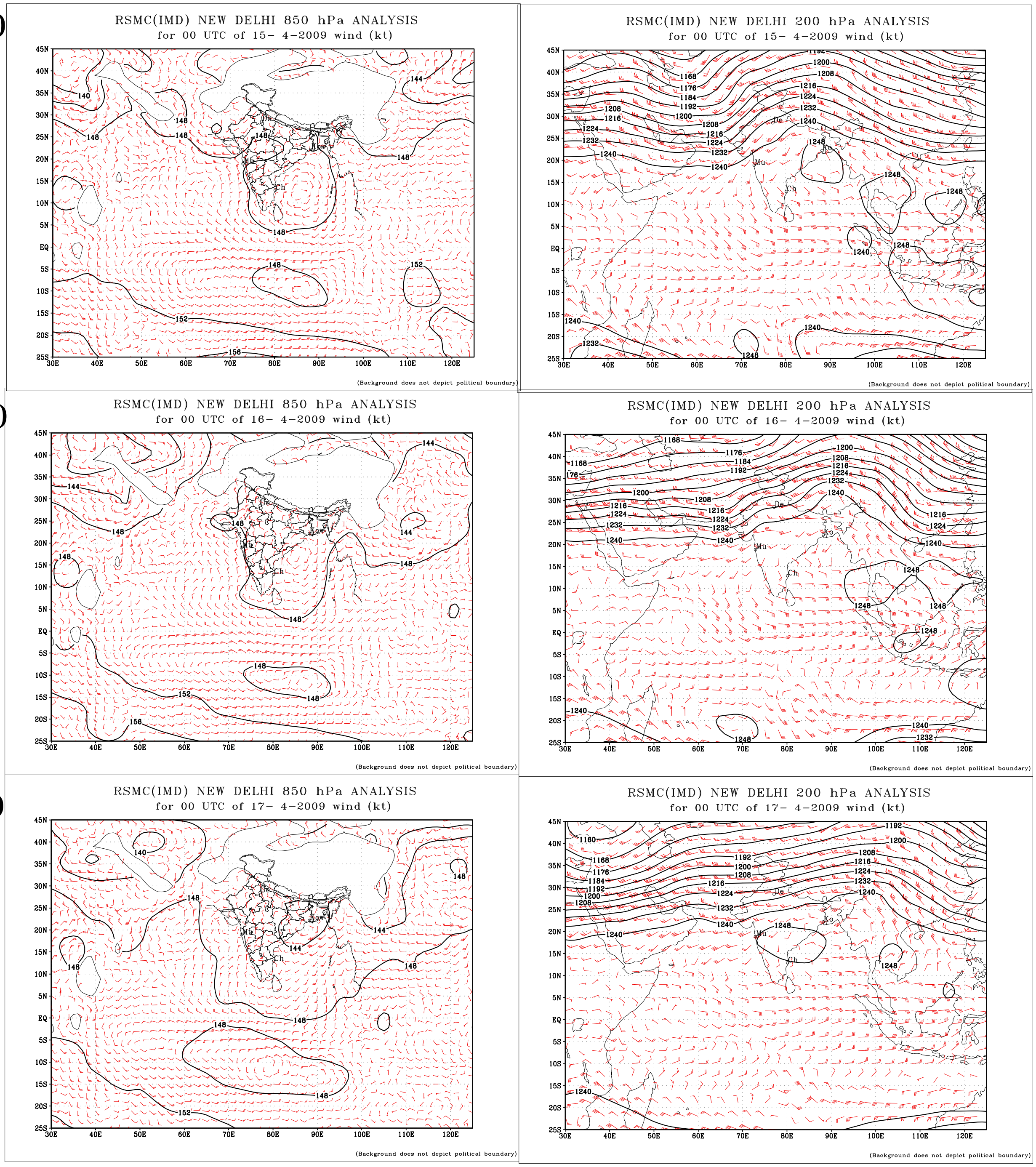


Fig.2.1.3 Wind analysis of 850 hPa and 200 hPa levels at 0000 UTC of 17 April.

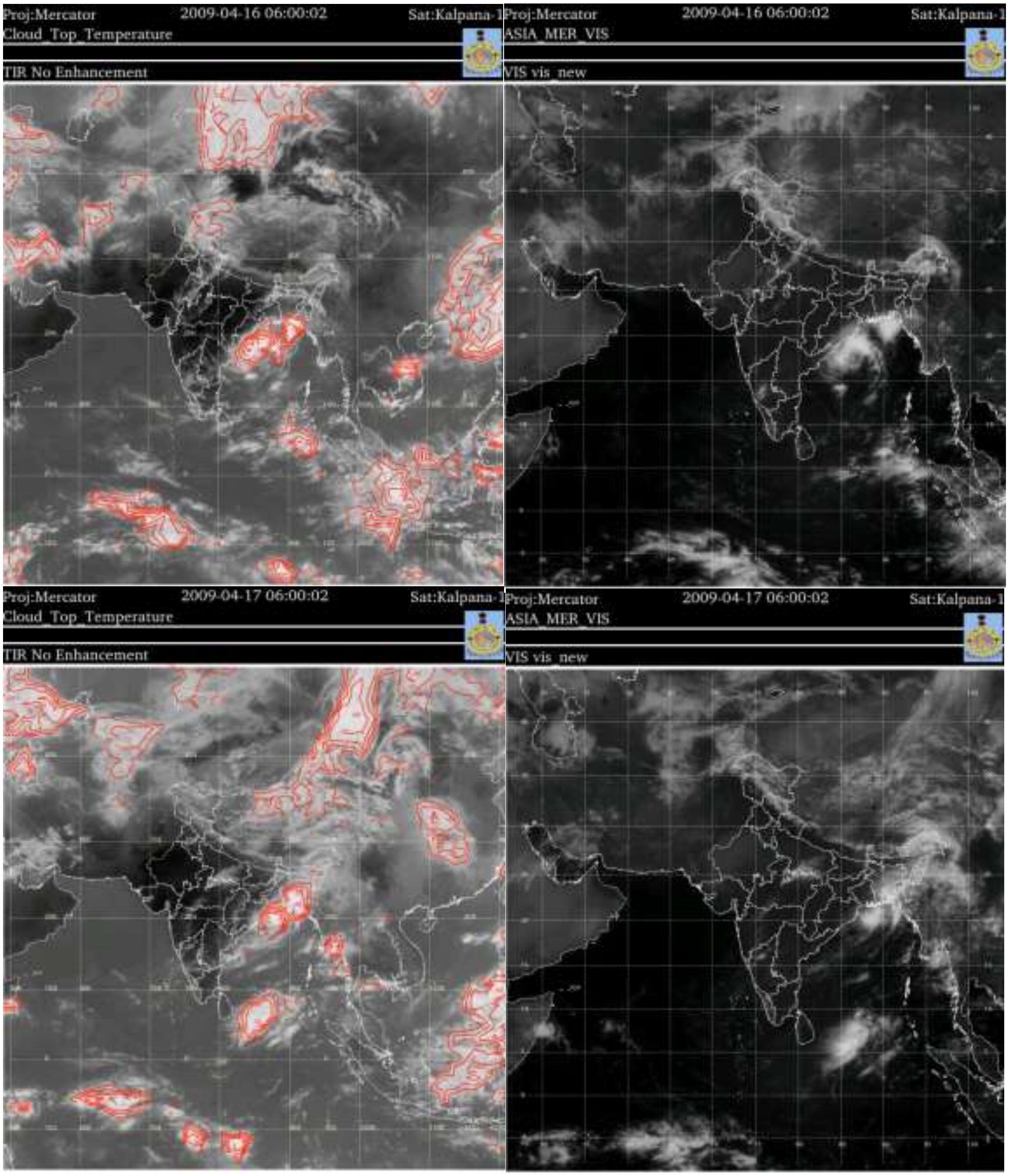


Fig.2.1.4. INSAT IR with CTT and visible imageries of the system at 0600 UTC of 17 April 2009.

Table 2.1.1: Best track Positions and other parameters for cyclonic storm, 'BIJLI' over Bay of Bengal during 14-17 April 2009

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
14.04.2009	0900	12.5/88.0	1.5	1004	25	3	D
	1200	12.5/88.0	1.5	1002	25	3	D
	1800	12.5/88.0	1.5	1002	25	4	D
15.04.2009	0000	13.0/88.0	1.5	1000	25	4	D
	0300	13.5/87.5	1.5	1000	25	4	D
	0600	14.0/87.5	2.0	1000	30	6	DD
	1200	15.0/86.5	2.5	996	35	8	CS
	1500	15.5/86.5	2.5	996	40	8	CS
	1800	16.0/86.5	2.5	996	40	8	CS
	2100	16.0/86.5	2.5	996	40	8	CS
16.04.2009	0000	16.5/86.0	2.5	996	40	8	CS
	0300	17.0/86.0	2.5	996	40	8	CS
	0600	17.5/86.0	2.5	996	40	8	CS
	0900	18.0/86.0	2.5	996	40	8	CS
	1200	18.5/86.5	2.5	996	40	8	CS
	1500	18.5/86.5	2.5	996	40	8	CS
	1800	19.5/87.0	2.5	996	40	8	CS
	2100	20.0/87.5	2.5	996	40	8	CS
17.04.2009	0000	20.5/88.0	2.5	996	40	8	CS
	0300	20.5/88.5	2.5	996	35	6	CS
	0600	21.0/89.0	2.5	996	35	6	CS
	0900	21.5/89.5	2.0	996	30	5	DD
	1200	21.5/90.0	1.5	996	25	4	D
	1500	22.0/91.5	1.5	996	25	4	D
	1800	Depression crossed Bangladesh coast near 22.2^{0}N./91.8^{0}E, close to south of Chittagaon around 1600 UTC of 17 April 2009.					
		Weakened and lay as well marked low pressure area over Bangladesh and adjoining Mizoram & Tripura					

2.1.4. Pressure and wind characteristics:

2.1.4.1. Pressure Change in 24 hours:

Considering 0300 UTC observations, during the period of cyclogenesis (14 & 15, April) , there was no significant 24 hours change in Mean Sea Level Pressure (MSLP) along the east coast of India, Bangladesh and Myanmar as the system was away from these coasts. On 16 April, as the system moved north-northwest and came closer to east coast of India, the MSLP along the east coast responded and maximum 24 hrs pressure fall of 3.4 hPa was reported over Gopalpur. On 17 April, the pressure fall was maximum over coastal area of West

Bengal with 4.9 hPa reported over Diamond Harbour By 0900 UTC of 17 April, the maximum pressure fall of 5.9 hPa was reported by Khepupara (Bangladesh). At 1200 UTC of the same day, maximum pressure fall was 5.8 hPa reported by Cox Bazar (Bangladesh). All these observations indicate that place of maximum pressure fall shifted northeastwards along the coast. Till 0900 UTC of 17 April, there was no tongue like shape in pressure change distribution along the east coast of India and Bangladesh. From 0900 UTC of 17 April, tongue like shape appeared towards Bangladesh with pressure fall becoming maximum near the landfall point.

2.1.4.2. Pressure departure from normal:

The pressure departure from normal was of the order of -4 to -5 hPa along Tamil Nadu at 0300 UTC of 14 & 15 April. The negative pressure departure was maximum over north coastal Andhra Pradesh and adjoining south coastal Orissa (Visakhapatnum -5.6 hPa and Gopalpur -5.7 hPa) at 0300 UTC of 16 April. The negative pressure departure from normal was more than 5 hPa along Orissa, West Bengal and Bangladesh coast at 0300 UTC of 17 April being maximum over Balasore (-5.9 hPa). As the system moved skirting the coast, the zone of higher negative pressure departure shifted from north to south along the east coast of India. The pressure departure along Bangladesh coast was relatively less on 17 April, as the system weakened over the Sea and crossed coast as depression.

2.1.4.3. Estimated central pressure and maximum sustained surface wind:

The minimum estimated central pressure was reported at 1200 UTC of 15April and it continued to remain same till the landfall of the system. However, the pressure drop at the centre was maximum (-8 hPa) during 1200 UTC of 15 to 0000 UTC of 17 April. It gradually increased thereafter. The sustained maximum surface wind speed in association with the system was 40 knots during 1200 UTC of 15 to 0000 UTC of 17 April. Considering the wind along the coast, the maximum wind of 30 knots from westerly direction was reported by Cox Bazar (Bangladesh) at 1500 UTC of 17 April.

2.1.5 Characteristics as observed in Radar:

The system was tracked by conventional cyclone detection radar (CDR) at Paradip and Doppler Weather Radar (DWR), Visakhapatnam**.** The brief reports on the characteristics of the system as observed in these radars are discussed below.

2.1.5.1 Radar observations from DWR, Visakhapatnam:

The DWR at Visakhapatnam was on continuous mode of operation with observations at 10 minutes intervals. The Cyclonic Storm was kept under watch from 1200 UTC of 15 April 2009. The centre of the storm was estimated from the spiral Bands. A few DWR imageries of 'BIJLI' are shown in fig 2.1.5. However, the confidence was poor. No eye wall was observed during the observation. The track of cyclone BIJLI as observed by DWR Visakgatnam is given in Table 2.1.5.2. According to the radar nobservations the system moved north-northeastweards on 16 April 2009.

2.1.5.2 Radar observations from CDR, Paradip

Special Radar observations were taken from 0100 UTC of 16 to 1200 UTC of 17 April.

Curved lines with some banding features of outer storm area could be seen at 0100 UTC of 16 April when the system was more that 400 kms away from the station. Centre was reported at Lat. 17.7 Deg. N and Long. 86.3 Deg. E with poor confidence. Prominent spirals were seen from 0300 UTC of 16 April and centres could be fixed with fair confidence. Echo was strength observed to be reduced from 2000 UTC of 16 April and no centers could be defined from 2200 UTC of 16 April to 0200 UTC 17 April. Organisation of cloud mass was seen at 0300 UTC of 17 April with one spiral and centres were given from 0300 to 0700 UTC of 17 April. As the system was moving away from station echo intensity and spatial distribution reduced gradually from 17/0800 UTC and no centre could be defined due to absence of prominent features. The track of the cyclone " BIJLI" is given in Table 2.1.3. according to CDR Paradip obsevations. According to these observations, the system moved north-northeastwards on 16 and 16 April 2009.

Table 2.1.2: Track of cyclonic storm BIJLI observed by DWR Visakhapatnam

Date	Time in UTC	Azimuth in degrees	Range in Km	Lat.	Long.	Confidence
15-04-09	2300Z	120	320	16.2	86.0	|
16-04-09	0000Z	118	282	16.5	85.7	|
16-04-09	0100Z	113	280	16.7	85.8	P
16-04-09	0200Z	109	294	16.7	86.0	O
16-04-09	0300Z	105	297	17.0	86.0	O
16-04-09	0400Z	98.6	301	17.3	86.2	R
16-04-09	0500Z	95.1	303	17.5	86.2	|
16-04-09	0600Z	91.5	300	17.7	86.2	|
16-04-09	0700Z	88.4	300	17.8	86.2	|
16-04-09	0800Z	84.7	313	18.0	86.3	|
16-04-09	0900Z	82.5	321	18.1	86.4	|
16-04-09	1000Z	82.5	343	18.2	86.6	|
16-04-09	1100Z	77.8	348	18.3	86.6	|
16-04-09	1200Z	74.7	360	18.6	86.7	|

Table 2.1.3: Track of cyclonic storm BIJLI observed by CDR, Paradip

Date	Time(UTC)	Latitude ^{0}N	Longitude^{0}E	Confidence	Character/Feateres
16-04-09	0100	17.7	86.3	Poor	Spiral
	0200	17.7	86.3	Poor	Spiral
	0300	17.4	86.2	Poor	Spiral
	0600	17.7	86.2	Fair	Spiral
	0700	18.1	86.4	Fair	Spiral
	0800	18.3	86.5	Fair	Spiral
	0900	18.6	86.5	Fair	Spiral
	1000	18.6	86.6	Fair	Spiral
	1100	18.6	86.6	Fair	Spiral
	1200	18.7	86.7	Fair	Spiral
	1300	18.8	86.8	Fair	Spiral
	1400	19.0	86.8	Fair	Spiral
	1500	19.0	87.0	Fair	Spiral
	1700	19.2	87.2	Fair	Spiral
	1800	19.4	87.3	Fair	Spiral
	1900	19.6	87.3	Fair	Spiral
	2000	21.0	88.2	Poor	Curved LN was not distinct system appeared to be weakening
	2100	21.4	88.8	Poor	Curved LN was not distinct
	2200	NOT	DEFINED		
17-04-09	0300	20.7	88.2	Poor	
	0400	20.8	88.4	Fair	Curved LN was seen
	0500	20.9	88.6	Fair	Spiral
	0600	21.1	88.7	Fair	Spiral
	0700	21.1	88.8	Fair	Spiral
	0800	Centre could not be defined			Isolated echoes seen

2.1.6 Realized weather:

As the system moved north-northeastwards it did not cause any heavy rainfall along east coast of India. However, after the landfall, it caused isolated heavy rainfall over Mizoram with Lenpui reporting 7 cm of past 24 hours rainfall at 0300 UTC of 18 April. Squally winds of speed reaching 30-35 knots prevailed along Bangladesh coast at the time of landfall.

As per the decision of last WMO/ESCAP Panel meeting held at Muscat during Feb. 2009, the storm surge guidance was issued by RSMC, New Delhi to Bangladesh based on IIT, Delhi model when the system was a cyclonic storm. According to their guidance a storm surge of meters above the astronomical tide was predicted near the landfall point based on observation. As the system weakened over the sea, the storm surge guidance was subsequently withdrawn at UTC.

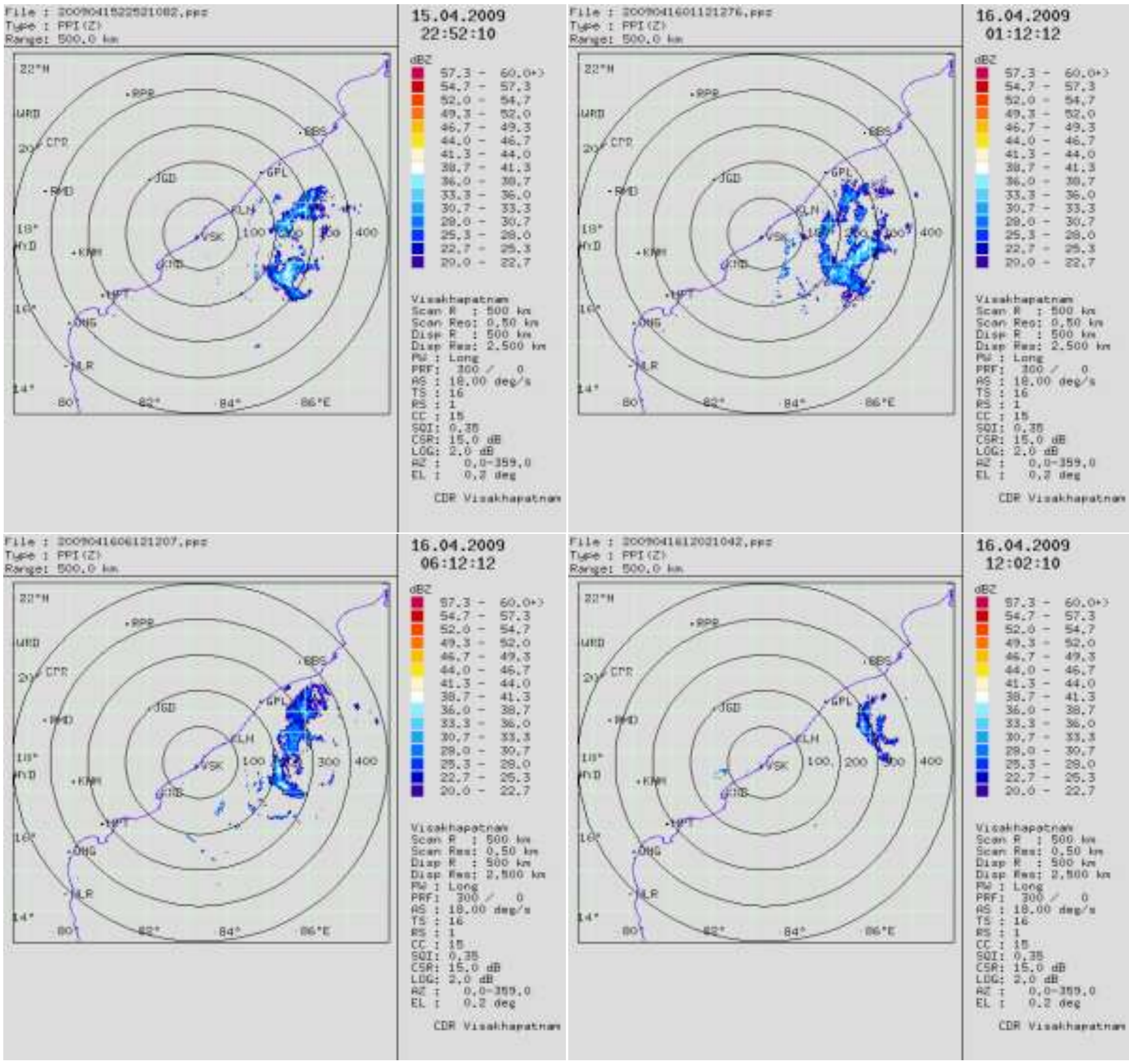


Fig.2.1.5 A few DWR imageries as observed by DWR Visakhapatnam on 15 and 16 April, 2009.

2.1.7 Damage:

There was no damage over Indian region. However, it caused death of 3 persons and loss of some properties in Bangladesh.

2.2 Severe Cyclonic Storm, 'AILA" over the Bay of Bengal (23-26 May, 2009)

2.2.1. Introduction

A severe cyclonic storm (SCS), **AILA** crossed West Bengal coast near Sagar Island between 0800 and 0900 UTC of 25 May 2009. It caused loss of about 100 human lives and left several injured in West Bengal. It also caused about 175 human deaths and left several injured in adjoining Bangladesh. The special features of this storm are as follows.

- The system moved in a near northerly direction throughout its life period.
- Its intensification was rapid only a few hours before landfall.
- The system maintained cyclone intensity even upto 15 hours after the landfall.

The brief life history depicting genesis, intensification, movement and landfall characteristics are presented and discussed below. Also, the utilities of satellite, Radar and automatic weather stations are also analysed and discussed. The disastrous weather and the damage are also presented.

2.2.1. Genesis

Southwest monsoon set in over Andaman Sea and adjoining south Bay of Bengal on 20 May 2009. In its association, 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. It led to the development of the upper air cyclonic circulation extending upto mid-tropospheric level on 21 May over the southeast Bay of Bengal and associated convective cloud clusters persisted over the region. Under the influence of the cyclonic circulation, a low pressure area formed over the southeast Bay of Bengal on 22 May morning. It lay over eastcentral & adjoining westcentral Bay of Bengal on 22 May evening. It concentrated into a depression and lay centered at 0600 UTC of 23 May near Lat. 16.5º N/Long 88.0º E, about 600 km south of Sagar Island. The best track parameters of the system are shown in Table 2.2.1. The track of the system is also shown in Fig. 2.1.

According to INSAT imageries, a low level circulation developed over South Bay of Bengal on 21 May 2009 at 0300 UTC. It developed into a Vortex with center 11.5^0 N/85.5^0 E and intensity T1.0 at 1200 UTC of the same day. It gained intensity of T1.5 corresponding to depression with centre at 16.5^0N/88.0^0E at 0600 UTC of 23 May. It was the shear pattern at the time of cyclogenesis with maximum convection lying to the southwest of the system centre. The INSAT imagery of the system at the stage of depression is shown in Fig.2.2.1.

Considering the environmental factors for cyclogenesis, the wind shear between the layers (150-300) hpa & (700-925) hPa was 05-10 knots on 21 and 22 May according to METEOSAT observations. It became 10-20 knots on 23 May over the region except northeast sector where it continued to be 05-10 knots. The sea surface temperature (SST) was warmer (about 28^0 C) over central and north Bay of Bengal, being 0.5 to 1^0 C above normal. There was maximum lower level convergence to the southeast of the system centre. Similarly, the upper level divergence and the lower level relative vorticity was higher around the system centre. The system could gain upper level divergence as the upper tropospheric ridge roughly ran along 17^0. In association with an anti-cyclonic circulation located near lat. 17^0 N and long. 94^0E. The quickscat derived wind speed at surface level was about 10-15 knots on 21 and 22 May. It became 15-20 knots on 23 May. However, the observations indicated the wind speed 25-30 knots on 23 May. The wind speed was relatively stronger in the southeast sector due to strong southerly surge of the monsoon current. All these observations indicated that the environmental factors were favourable for genesis and intensification of the system.

Table 2.2.1 Best track Positions and other parameters for severe cyclonic storm, "AILA" over the Bay of Bengal during 23-26 May, 2009

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
23-05-2009	0600	16.5/88.0	1.5	998	25	3	D
	1200	16.5/88.0	1.5	994	25	3	D
	1800	17.0/88.5	1.5	996	25	4	D
24-05-2009	0000	17.0/88.5	1.5	996	25	4	D
	0300	18.0/88.5	2.0	992	30	5	DD
	0600	18.0/88.5	2.0	988	30	5	DD
	0900	18.0/88.5	2.0	986	30	5	DD
	1200	18.5/88.5	2.5	986	35	6	CS
	1500	19.0/88.5	2.5	986	35	8	CS
	1800	19.0/88.5	2.5	986	35	8	CS
	2100	20.0/88.0	2.5	984	40	8	CS
25-05-2009	0000	20.0/88.0	2.5	980	40	10	CS
	0300	20.5/88.0	3.0	978	50	12	CS
	0600	21.5/88.0	3.5	974	55	15	SCS
	The system crossed West Bengal coast close to east of Sagar Island near 21.8^0N/88.0^0E between 0800 & 0900 UTC.						
	0900	22.0/88.0	---	968	60	20	SCS
	1200	22.5/88.0	---	970	50	16	SCS

	1500	23.0/88.0	---	978	45	14	CS
	1800	23.5/88.0	---	980	40	12	CS
	2100	24.0/88.0	---	981	35	10	CS
26-05-2009	0000	25.0/88.0	---	982	30	08	CS
	0300	25.5/88.0	---	988	25	06	DD
	0600	27.0/88.5	---	992	20	04	D
	0900	The System weakened into a well marked low pressure area over Sub-Himalayan West Bengal and neighbourhood					

2.2.2. Intensification and movement

Under the favourable conditions as discussed above, the depression moved mainly in a northerly direction and intensified into a deep depression and lay centred at 0300 UTC of 24 May near Lat. 18.0ºN/Long 88.5ºE. It further intensified into a cyclonic storm, 'ALIA' at 1200 UTC of 24 May and lay centred near Lat. 18.5ºN/Long 88.5ºE. It continued to move in northerly direction and intensified into a severe cyclonic storm at 0600 UTC of 25 May and lay centred over northwest Bay of Bengal near Lat. 21.5ºN/Long 88.0ºE close to Sagar Island. The system crossed West Bengal coast close to the east of Sagar Island between 0800 & 0900 UTC as a severe cyclonic storm with wind speed of 100 to 110 kmph. The lowest estimated central pressure was about 967 hPa at the time of landfall. After the landfall, the system continued to move in a northerly direction, gradually weakened into a cyclonic storm and lay centred at 1500 UTC of 25 May over Gangetic West Bengal, close to Kolkata. While it continued its northerly movement, it further weakened into a deep depression and lay centred at 0300 UTC of 26 May over Sub-Himalayan west Bengal & Sikkim, close to Malda. It weakened into a depression and lay centred at 0600 UTC of 26 May over the same region close to Bagdogra. It further weakened and lay as a well marked low pressure area over Sub-Himalayan West Bengal and neighbourhood at 0900 UTC of 26 May and became less marked on 27 May.

To compare with the climatology, the tracks of the systems developing within +/- 2^0 Lat/long. from the system location (lat. 16.5^0 N/ long. 88.5^0 E) on 23 May were analyzed. It indicated that any depression forming over this region (lat. 14.5-18.5^0 N and long. 86.5-90.5^0 E) in the month of May becomes a cyclone and most of them move northward/northeastward towards West Bengal/Bangladesh coasts (Fig. 2.2.1).

Considering the environmental factors, the vertical wind shear continued to be 10-20 knots till 0600 UTC of 24 May. It then fell and was about 05-10 knots thereafter till the landfall. The low level relative vorticity and convergence increased gradually from 24 May. The SST continued to be above normal and about 28^0 C. The upper tropospheric ridge lay very close to the system centre throughout the life of the system. It interacted with the system and moved gradually northward with northward movement of the system. The anticyclonic circulation located to the east-northeast of the system centre also shifted gradually northward. A feeble trough in upper tropospheric westerlies roughly ran along 75^0 E to the north of 20^0 N on 23 May and gradually moved eastward and intensified, roughly running along 80^0 E on 25 May. It provided required upper level divergence for intensification of the system. Under the influence of the above mentioned trough and anti-cyclonic circulation/ridge, the system continued its nearly northerly movement throughout its life.

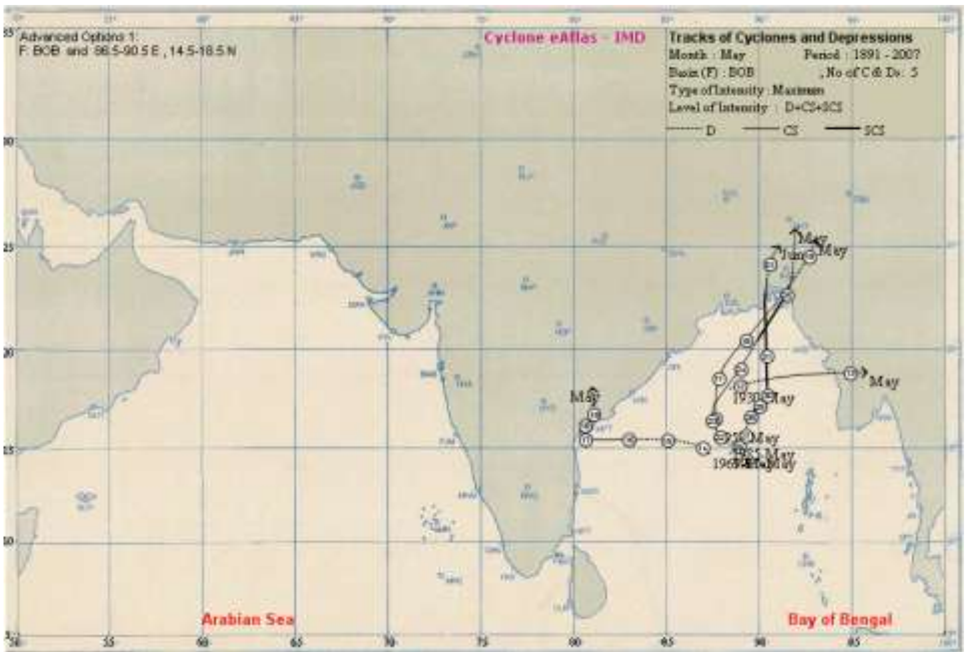


Fig. 2.2.1: The cyclonic storm developing within +/- 2^0 Lat/long from the system location (lat. 16.5^0 N/ long. 88.5^0 E) during May over the period 1891-2008.

According to INSAT observations, the system intensified with intensity T2.0 at 0300 UTC of 24 May with shear pattern of convection changing to curved band pattern. The curved band pattern continued till the landfall of the system. The INSAT imageries at different stages of the system like depression, deep depression, cyclonic storm and severe cyclonic storm are shown in Fig.2.2.2. The system attained the intensity of T2.5 corresponding to cyclonic storm at 1100 UTC of 24, T3.0 at 0300 UTC of 25 and T3.5 corresponding to severe cyclonic storm at 0600 UTC of 25 May.

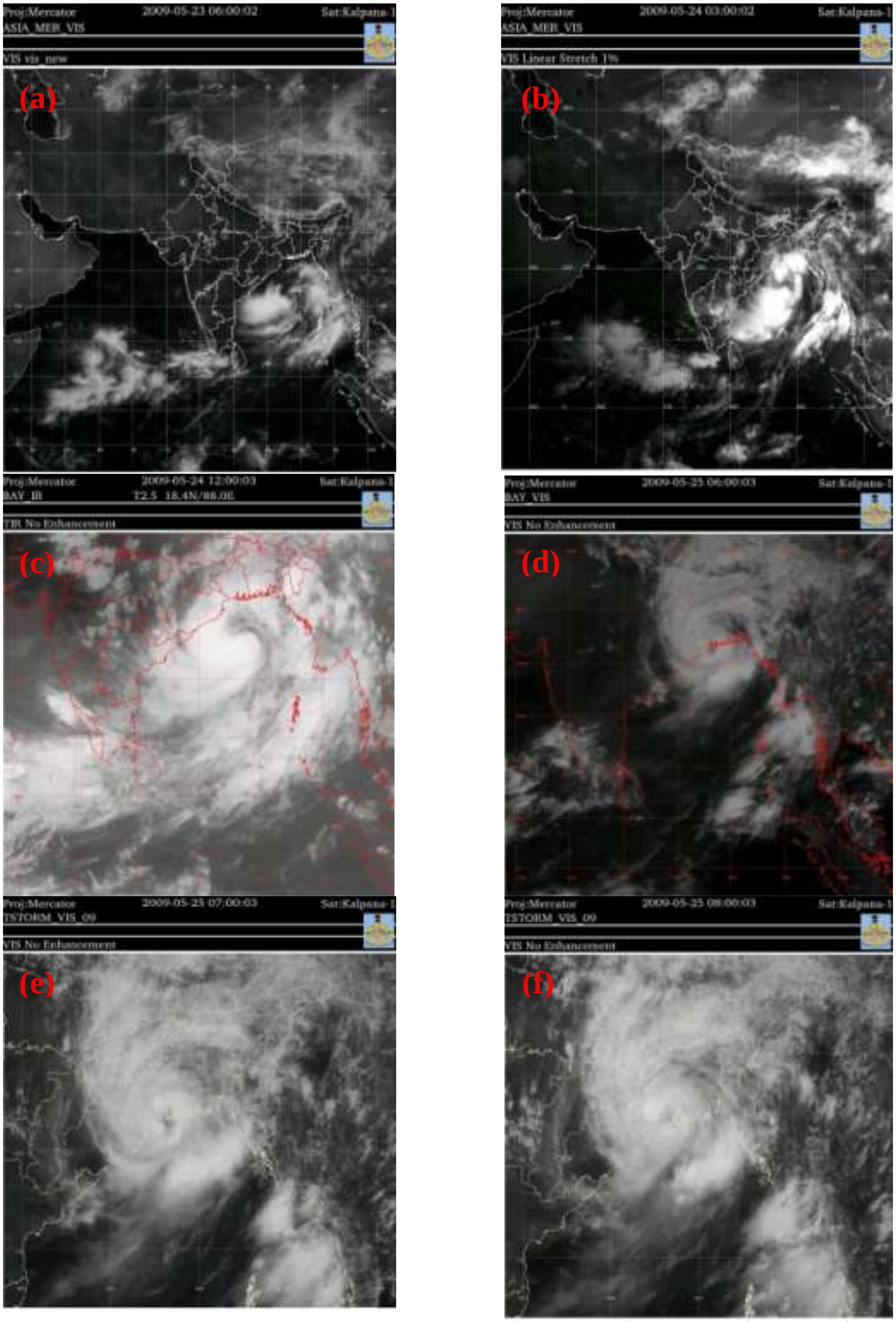


Fig.2.2.2. INSAT imageries of the system at different stages of intensification and landfall Depression, (b) deep depression, (c) cyclonic storm, (d) severe cyclonic storm, (e) prior to landfall and (f) during landfall

The system could retain its intensity of cyclone for about 15 hrs after the landfall, as it lay close to the Bay of Bengal and lay centred over the Gangetic deltaic region for quite sometime, thus ascertaining the availability of moisture. However, the system gradually weakened due to interaction with land surface.

There were mainly two intense zones of convection in association with the system, one lying to the northwest and the other to the southeast. There was a weak convection zone at the centre. It was also supported by the rainfall distribution. As the system moved inland in a northerly direction and weakened gradually, the two convective zones went apart from each other with one lying over sub-Himalayan West Bengal and neighbourhood and the other lying over Bangladesh. The minimum cloud top temperatures were about -70 to -80^0 C in association with the system.

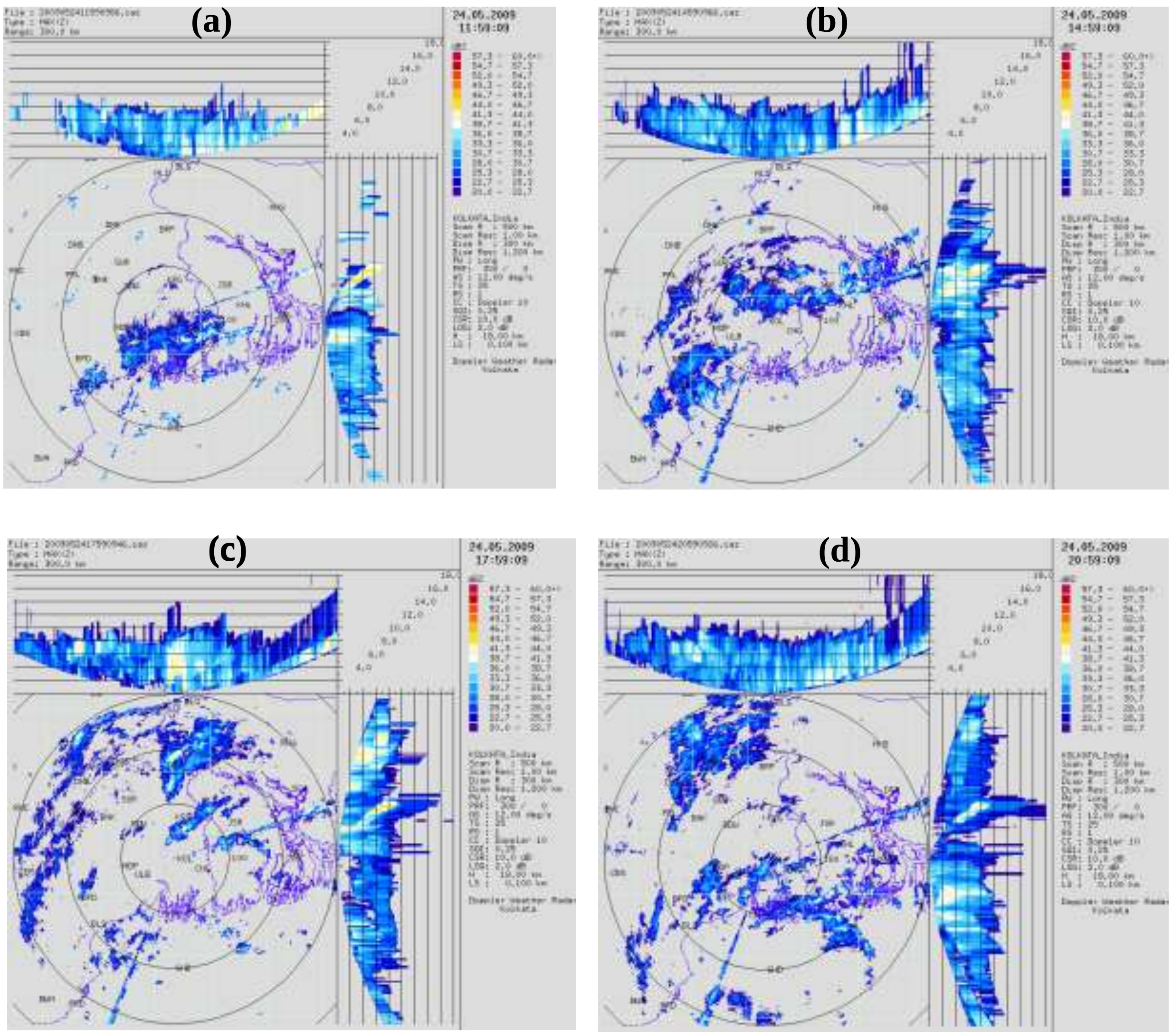
2.2.4 Features observed through Radar

The severe cyclonic storm, **AILA** was tracked by conventional cyclone detection radar CDR Paradip and Doppler weather DWR, Kolkata. Both the radars could find out the system centre as the system moved nearer to the radar centre. The centres as fixed by the CDR, Paradip based on the Curved line(LN) / Spiral band echoes are furnished below in table 2.2.2. It suggested north-northwesterly movement of the system. However, the confidence of fixation of cemtre was poor to fair.

Table 2.2.2. Centre of the cyclone, AILA according to CDR, Paradip

Date	Time (UTC)	Latitude (Deg.)	Longitude (Deg.)	Confidence	Character
24-May-09	0600	18.0 N	88.4 E	Poor	LN
24-May-09	0700	18.8 N	88.5 E	Poor	LN
24-May-09	0900	18.8 N	88.5 E	Poor	LN
24-May-09	0900	18.7 N	88.4 E	Poor	LN
24-May-09	1000	18.7 N	88.4 E	Poor	LN
24-May-09	1100	18.8 N	88.4 E	Poor	LN
24-May-09	1200	18.8 N	88.4 E	Poor	LN
24-May-09	1300	19.2 N	88.2 E	Poor	LN
24-May-09	1400	19.2 N	88.2 E	Poor	LN
24-May-09	1500	19.3 N	88.0 E	Fair	LN
24-May-09	1600	19.3 N	88.0 E	Fair	LN
24-May-09	1900	19.3 N	87.9 E	Fair	Spiral
24-May-09	2000	19.3 N	87.9 E	Fair	Spiral
24-May-09	2100	19.6 N	87.8 E	Fair	Spiral
24-May-09	2200	19.6 N	87.7 E	Fair	Spiral
24-May-09	2300	19.8 N	87.6 E	Fair	Spiral

25-May-09	0000	20.3 N	87.8 E	Fair	Spiral
25-May-09	0100	20.4 N	87.8 E	Fair	Spiral
25-May-09	0200	20.5 N	87.7 E	Fair	Spiral
25-May-09	0300	20.7 N	87.6 E	Fair	Spiral
25-May-09	0400	20.9 N	87.6 E	Fair	Spiral
25-May-09	0500	21.0 N	87.6 E	Fair	Spiral
25-May-09	0600	21.1 N	87.7 E	Fair	Spiral
25-May-09	0700	Not Defined			Weak echoes
25-May-09	0900	Not Defined			Weak echoes



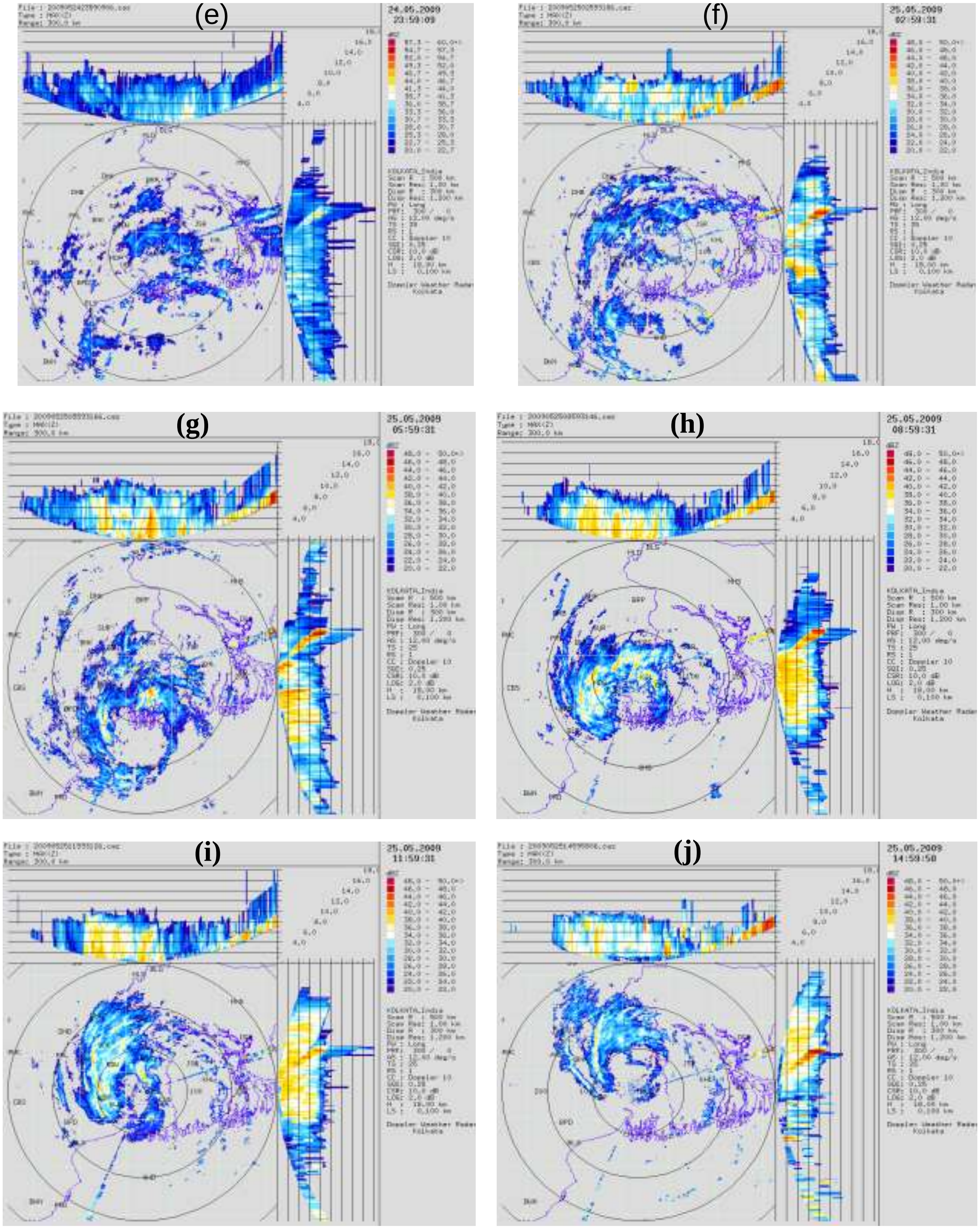


Fig.2.2.3 (a-j) A few DWR, Kolkata imageries depicting the landfall of AILA over West Bengal near Sagar Island and movement across West Bengal

Considering the period, when the radar could fairly determine the system centre, the system moved in near northerly direction with longitudinal displacement of about 0.3^0 and latitudinal displacement of about 1.8^0. The spiral bands were observed by CDR Paradip.

The DWR Kolkata also showed near northerly movement of the system during its period of track (Fig.2.2.3) DWR, Kolkata was observing the system continuously since 0000 UTC of 24 May 2009 in every 15 minutes interval. The weak echoes were seen from 1100 UTC of 24 May. The first echo associated with deep depression was seen by DWR at 2200 UTC of 24 May with organized cloud mass of 42 dBz and height of 8 – 10 km over Gangetic West Bengal and adjoining Bangladesh. The spiral band with semicircular eye of the storm with diameter about 100 km was observed at 0400 UTC of 25 May. The seventy five percent closed spiral bands of diameter 125 km were seen at 0600 UTC with reflectivity 40 dBz. Convective clouds with increased reflectivity in the subsequent observation were seen but the centre of cyclone could not be ascertained as no closed circular eye of the storm could be observed in any DWR observation. Spiral bands were also organized but not clearly defined and the storm centre was determined from the bands with poor confidence. The system weakened slightly after landfall but again intensified as seen in 1100 UTC observation. At 1200 UTC, all the echoes moved over land. The estimated centres of the system are given in Table 2.2.3.

According to this radar, there were two main regions of convection, one to the northwest and the other to the southeast. These two convective regions also went apart from each other as the system moved northward. Hence it was similar to convection observed by the satellite and was supported by the rainfall distribution. Another feature observed by the DWR, Kolkata was the pre-cyclone squall line. It was observed on 24 May (night) when the system was over the Sea and centred near Paradip latitude. The occurrence of this pre-cyclone squall line improved the confidence of the forecasters to expect the northerly movement of the system.

Table 2.2.3. Centre of the cyclone, AILA according to DWR, Kolkata

Time (UTC)	Latitude in degree North	Longitude in degree East	Confidence	Character
03 00	20.6	88.2	Fair	Spiral band
04 00	20.9	88.2	Fair	Semi circular eye
05 00	21.1	88.2	Fair	$3/4^{th}$ Close eye
06 00	21.4	88.2	Fair	Spiral band
07 00	21.6	88.2	Poor	Spiral band
07 30	21.7	88.2	Poor	Spiral band
08 00	21.8	88.2	Poor	Spiral band
09 00	22.1	88.2	Poor	Spiral band
10 00	22.3	88.1	Poor	Spiral band
11 00	22.6	88.1	Poor	Spiral band
12 00	22.8	88.0	Poor	Spiral band
13 00	22.9	88.0	Poor	Spiral band
14 00	23.1	88.2	Poor	Spiral band
15 00	23.3	88.3	Poor	Spiral band
16 00	23.5	88.3	Poor	Spiral band
17 00	23.7	88.3	Poor	Spiral band

The maximum radial wind recorded by DWR Kolkata is as follows.

Date	Time (UTC)	Maximum Radial wind (MPS)	Height (km)	Azimuth	Distance from Kolkata
25-5-2009	0507	51	1.66		140 km of Kolkata
25-5-2009	0920	33	0.19		20 km of Kolkata
25-5-2009	0820	45	2.0		Near Kolkata

Maximum horizontal wind observed was 75 knots from easterly to southeasterly direction at heights from 0.6 km to 4.5 km. during 0620 to 0835 UTC of 25 May.

2.2.5: Performance of AWS:

The observations from AWS and coastal observatories from Orissa and West Bengal helped in monitoring and predicting the intensification and movement of the system. They were especially very helpful to monitor the landfall point and time.

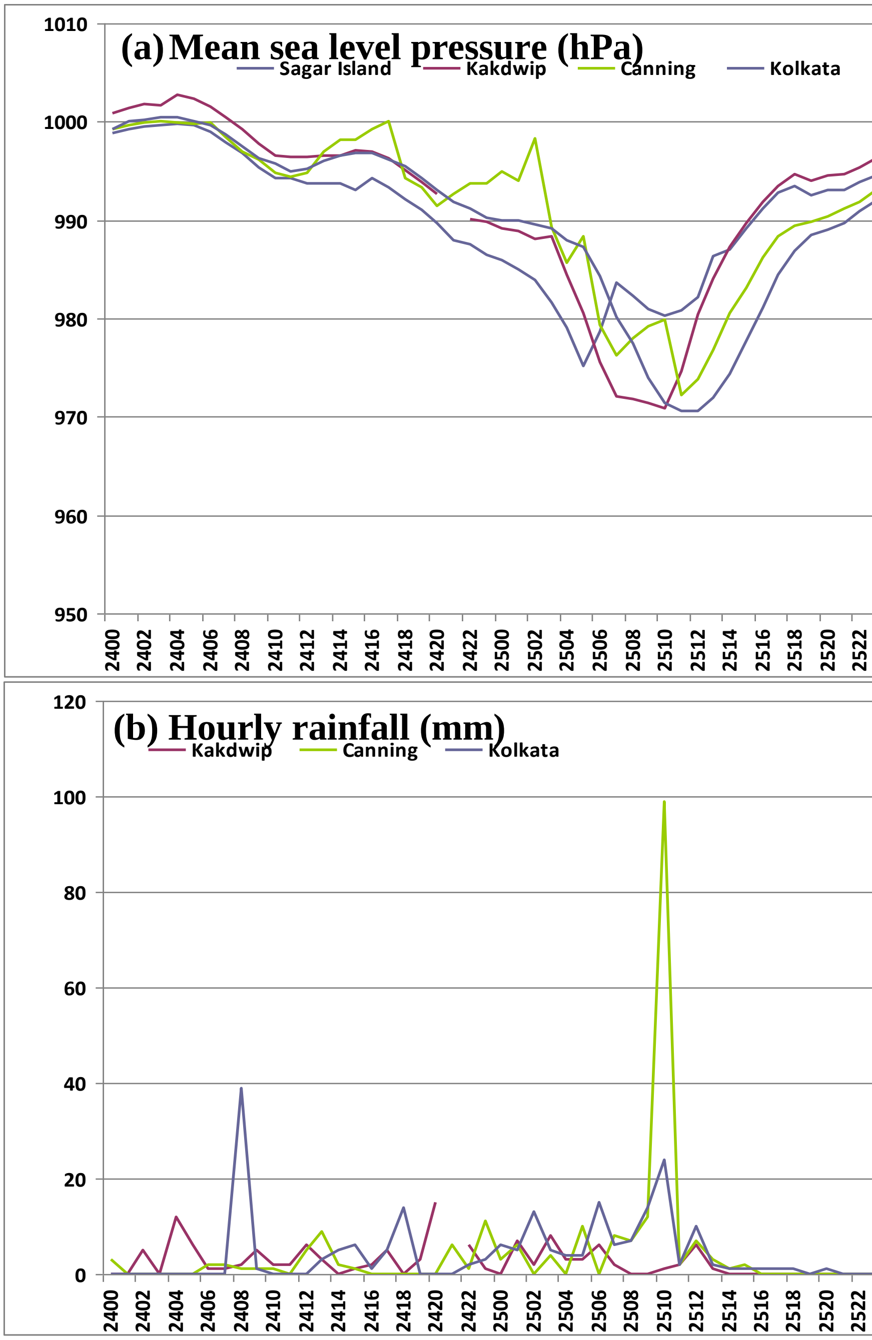


Fig.2.2.4 (a & b). Performance of AWS during cyclone AILA (0000UTC of 24 may to 2300 UTC of 25 May 2009
(a) Mean sea level pressure (hPa) and (b) Hourly rainfall (mm)

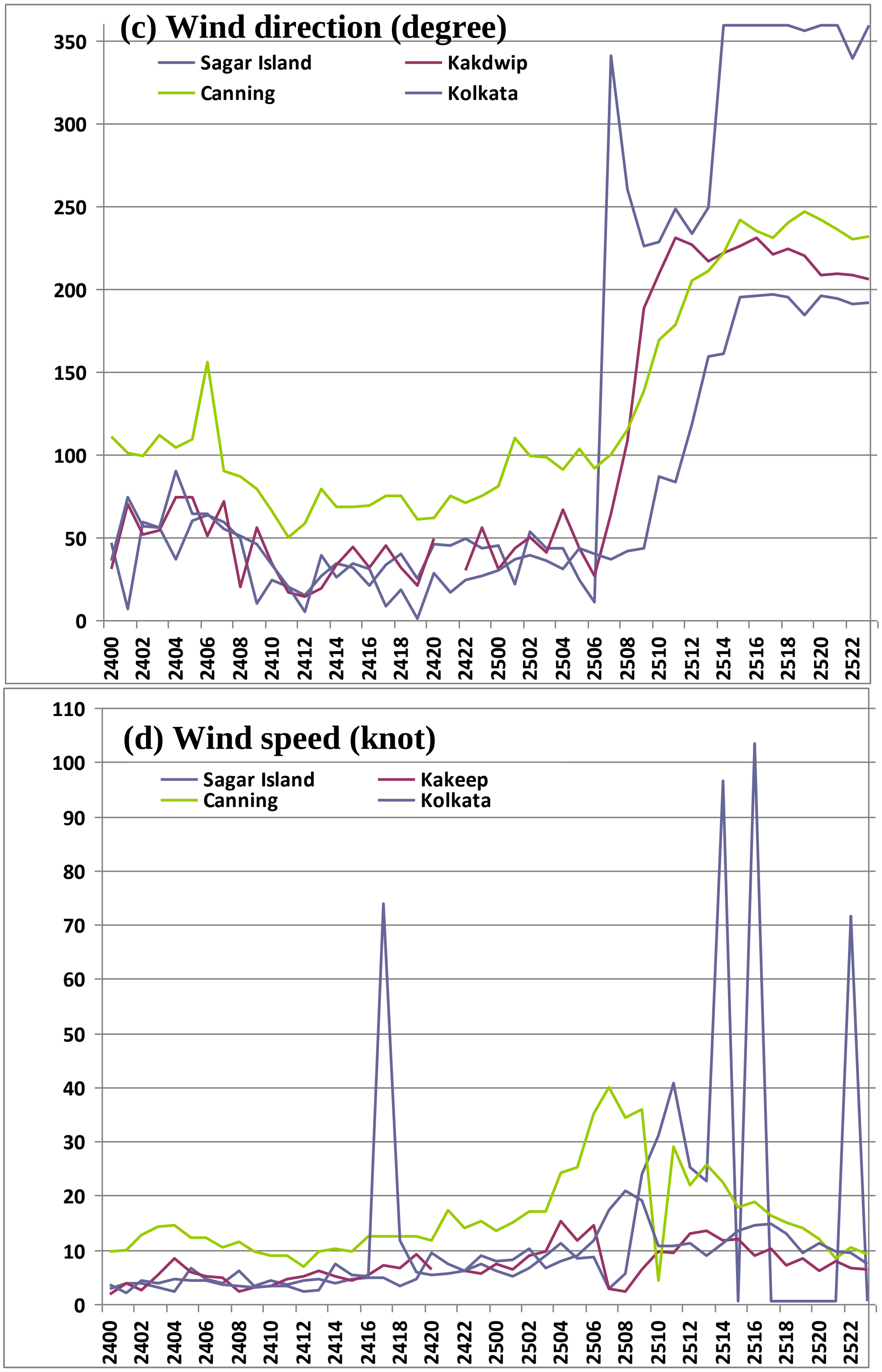


Fig.2.2.4(c & d). Performance of AWS during cyclone AILA (0000UTC of 24 may to 2300 UTC of 25 May 2009 (c)Wind direction (degrees) and (d) wind speed (knots)

These observations indicated that the system crossed West Bengal coast close to the east of Sagar Island between 0800 and 0900 UTC (Fig.2.2.4). The observations from AWS also could help in estimating the maximum wind and lowest ECP of the system. The lowest MSLP of 967 hPa was recorded by Kakdwip AWS in Sunderban delta which lies close to the north of Sagar Island. To compare the performance of the AWS, the hourly plots of observations from Sagar Island, Kakdwip, Canning and Kolkata AWS are shown in Fig.2.2.4. There were natural variations in different parameters like pressure, wind direction and speed and rainfall, as expected in association with a cyclone. However, the wind observations were erratic and may be erroneous in respect of Sagar Island AWS after the landfall of the system. As expected, the lowest pressure was recorded by the AWS located from south to north with lowest pressure being first observed over Sagar Island followed by Kakdwip, Canning and Kolkata. The surface wind over Sagar Island was northeasterly at 0700, northerly at 0800 and westerly at 0900 UTC indicating landfall between 0800 and 0900 UTC.

2.2.6 Disastrous weather

The heavy rainfall, strong wind and storm surge are the disastrous weather associated with cyclone. The realised weather are summarised below.

2.2.6.1 Heavy rainfall

Widespread rain/thundershowers with scattered heavy to very heavy rainfall and isolated extremely heavy rainfall (≥ 25 cm) occurred over Orissa on 25 May, over West Bengal & Sikkim on 25 & 26 May. Widespread rainfall with isolated heavy to very heavy rainfall also occurred over Assam & Meghalaya on 26 & 27 May. The significant amount of rainfall realised over these regions are shown in Table 2.2.4. Apart from India and Bangladesh, Nepal also could get heavy rain due to northward movement of the system.

Table 2.2.4(a). Chief amounts of rainfall (7 cm or more) over India due to SCS, AILA

Met Sub-Division	25th May	26th May	27th May
Orissa	Paradip– 26 Kakatpur– 18 Chandbali , Alipingal– 15 Neemapara, Patamundai–14, Rajkanika -1 0, Cuttack, Akhuapada – 9 Bhubneswar, Soro, Gathgaon-8, Jajpur, Bangiriposhi, Gop– 7,		--
Gangetic West Bengal	Digha- 7	Panagarh A/F, Kaliakunda A/F , Sriniketan – 17 Midnapur, Digha – 14 Barrackpur – 12 Barampur– 10 Barrackpur, Dumum – 9 Bankura ,Krishannagar – 7.	---
Sub Himalayan West Bengal & Sikkim	Barobhisa – 10	Singlabazar – 14 Malda- 13 Gazoledobo – 11, Khanitar- 10 Jalpiaguri – 9 Domohani, Champasari – 8 Pushvihar, Alipur Dwar – 7,	Darjeeing -27 Singlabazar, Lava – 18 Bijanbari - 15 Sukhiapokhari - 11 Sevoke - 10 Baghdogara – 7
Arunachal Pradesh			Bhalukpong - 7
Assam & Meghalaya		Cherrapunji – 21 Shillong – 12 Kokrajhar – 9 Golpara – 8 Bhalpur – 7	Manas Nh – 12 Cherrapunji – 9 Shillong – 8 Beki Raod Bridge – 7
Nagaland Manipur Mizoram & Tripura		Dharmanagar, Paniagarh - 8	Belonia-13

Table 2.2.4(b) Chief amounts of rainfall (7 cm or more) over Bangladesh and Nepal due to SCS, AILA

Country	25th May	26th May	27th May
Bangladesh		Teknaf , Dinajpur – 14, Sandwip , Feni – 12, Cox's Bazar – 9, M.Coat, Ranpur, Mogla– 8,	Chittagong ,Sandwip – 13 Feni -10 M. Coat – 7
Nepal	-	Dang – 8	Biratnaagr – 12, Dharan- 9 Daankuta - 8

2.2.6.2 Strong wind

According to wind observed over the coastal region, the sustained maximum wind at the time of landfall was about 60 knots (112 kmph). Wind reported by different stations are as follows.

Kolkata :95, Panagarh : 97, Kalaikunda : 112, Barrackpore : 102, Kakdwip, Sagar, Island : 75 kmph.

2.2.6.3 Storm surge

According to survey report of IMD, a storm surge of 3 m (10 ft) impacted western regions of Bangladesh, submerging numerous villages. The Sunderbans, was inundated with 6 m (20 ft) of water as per the media reports. Considering the astronomical tidal wave at the time of landfall, which was about 4-5 meters, the maximum storm surge over Sunderban area may be estimated to be about 2 m. The storm surge predicted by IITD model is shown in fig. 2.2.5 which suggested about 2-3 meters of storm surge near Sagar Island and adjoining areas of West Bengal and Bangladesh.

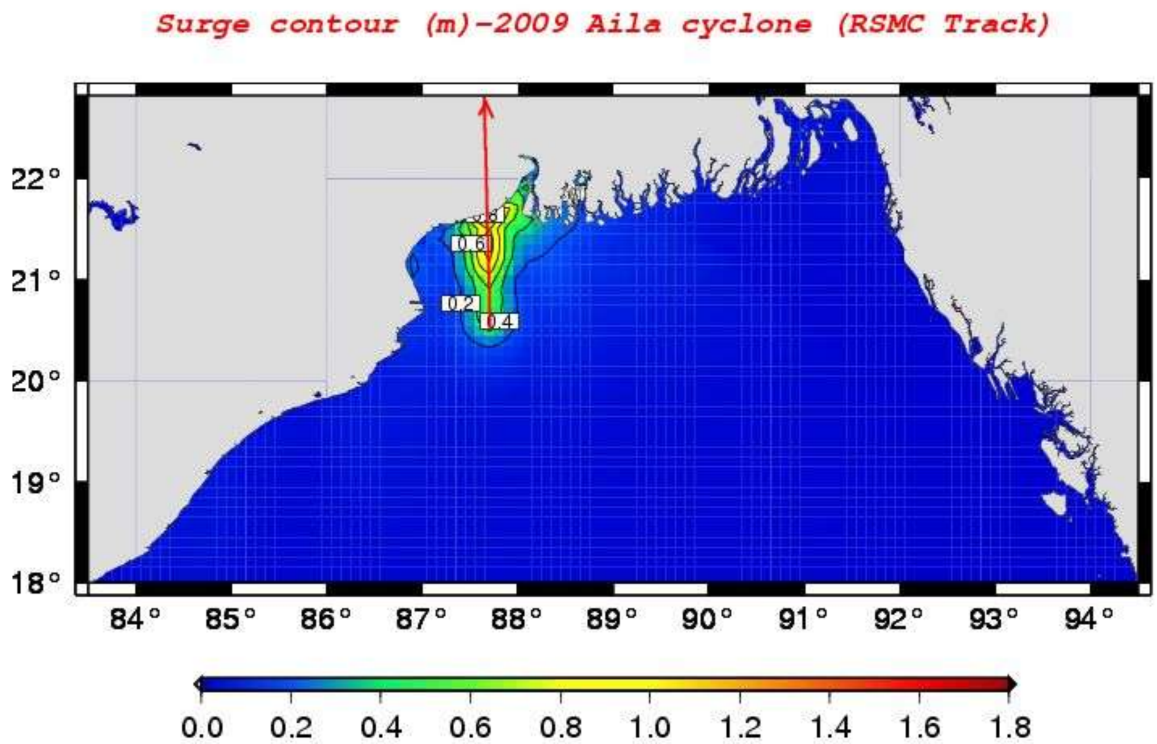


Fig. 2.2.5 Storm surge predicted by IITD model for cyclone Aila

2.2.7 Damage

The severe cyclonic storm, **AILA** affected both India and Bangladesh. A brief report on damages due to **AILA** in these two countries are summarized below.

2.2.7.1 India

West Bengal:

Mainly West Bengal was damaged due to severe cyclonic storm, **AILA**. According to State Govt. report, the number of storm-affected people was about 2.2 million. More than 61,000 houses collapsed and more than 132,000 houses were partially damaged. About 100 people died in the state due to **AILA**.

It caused extensive damage to rice and other crops. In Sundarbans, heavy downpour raised river levels while the gushing waters of flooded mangroves burst mud embankments in the extensive delta region, destroying hundreds of houses. The Sunderbans mangrove forest area, home to the highly endangered Royal Bengal tiger, was fully inundated and high-speed winds destroyed all communication and transportation infrastructure. The entire Sunderbans biosphere reserve area of 9600 square kilometers suffered extensive damage under the impact of cyclone **AILA**. A few damage photographs are shown in Fig.2.2.6. The SCS, **AILA** affected Sub-Himalayan West Bengal and Sikkim causing uprooting of trees due to strong wind and land slide and flood due to heavy rain.

Orissa:

The outer bands of the storm also produced torrential rains and high winds in several parts of north coastal Orissa, with the heaviest rainfall being recorded at Paradip at 260 mm (10 in) and winds peaked at 90 km/h (56 mph). Numerous trees were uprooted and power lines were down. High waves produced by the storm inundated coastal villages, forcing residents to evacuate to safer areas. However, there was no report of human death in the state. An estimated 1,000 acres of Orissa cropland were affected due to cyclone **AILA**.

Meghalaya:

The remnants of cyclone **AILA** produced gusty winds and heavy rains in Meghalaya between 25 and 26 of May. Rainfall amounts peaked at 213.4 mm and winds reached 60 km/h. Several homes were damaged in the area and power was cut off due to fallen trees and power lines. No injuries were reported in the state. Several streets were flooded and some homes were reported to have standing water.

Fig. 2.2.6 Photographs showing damage due to AILA (a) Uprooting of trees in Kolkata, (b) Damage to embankments in Birbhum district, (c) damaged hutments along the coast, (d) land slide in Darjiling.

2.2.5.2 Bangladesh

In Bangladesh, more than three million people were hit by the cyclone. The death toll from cyclone **AILA** in Bangladesh was around 175. According to Bangladeshi authorities, over 5,400 people were injured and nearly 842,000 were forced to take refuge on rooftops and rafts. Several rivers broke through embankments, causing widespread inland flooding. An estimated 58,950 animals were killed by the storm.

2.3 Depression over the Arabian Sea (23-24 June, 2009)

2.3.1. Introduction

During the onset phase of monsoon, a depression formed over the Arabian Sea and crossed Gujarat coast near Diu between 1300 and 1400 UTC of 23 June. Under its influence, the southwest monsoon advanced over the country especially along west coast after a long hiatus during 08-22 June. The track of the system is shown in Fig.2.1. The genesis, intensification and movement along with the associated weather are discussed below. The important features of this system is that it was mainly detected by satellite and synoptic analysis and most of the NWP models failed to detect this system. Though it revived the monsoon its significant impart on rainfall was confined to Saurashtra & Kutch and adjoining areas.

2.3.2. Genesis

The off shore trough at mean sea level from Konkan coast to Kerala coast persisted during 18-20 June with gradual increase in pressure gradient. An embedded cyclonic circulation extending upto mid-tropospheric level lay over the eastcentral Arabian Sea off Karnataka coast on 19 June and off Karnataka and Konkan coast on 20 and 21 June. Under its influence, a low pressure area formed over the eastcentral Arabian Sea off konkan coast on 22 June. It concentrated into a depression and lay centred at 0000 UTC of 23 June near lat. 18.0^0N/long. 71.5^0E, about 300 Km southwest of Mumbai. The vertical wind shear of horizontal wind over the region was low to moderate (about 10-20 kt). The sea surface temperature was also favourable for cyclogenesis, as they were above normal by 0.5 to 1.0 deg.C.

2.3.3. Intensification and movement

The system lay embedded in the southwesterly flow in lower and middle levels. The upper tropospheric ridge roughly ran along 21.0^0N. The depression moved in a near northearly direction and crossed Gujarat coast near Diu between 1300 and 1400 UTC of 23 June 2009. It then moved north-northwestwards and gradually weakened and lay as a well marked low pressure area over Saurashtra & Kutch and neighbourhood at 0300 UTC of 24 June.

The typical INSAT imageries of this system are shown in Fig.2.3.1. The best track parameters are shown in Table 2.3.1.

2.3.4. Realised Weather:

Under the influence of the system heavy to very heavy rainfall occurred at isolated places in Saurashtra & Kutch. Isolated heavy rainfall also occurred over Gujarat region. The chief amounts of rainfall (≥ 5 cm) are given below:

23-06-2009:

Gujarat Region: Dharampur-7, Jhagadia and Vapi-5 each
Saurashtra, Kutch & Diu: Maliya-5

24 -06-2009:

Saurashtra, Kutch & Diu: Sutrapada and Veraval-17 each Mangrol-15, Porbandar-7, Dwarka-6, Manavadar and Jamnagar- 5 each

25-0602009:

Saurashtra, Kutch & Diu: Kalyanpur-16, Okha-15, Mangrol-12, Bhanvad-10, Keshod, Ranavav, Lalpur-9 each, Sutrapada, Porbandar, Dwarka-8 each, Kutch Mandvi-6, Kodinar, Talala and Veraval-5 each.

2.3.5. Damage:

No damage was reported due to this system.

Table 2.3.1. Best track Positions and other parameters for depression over the Arabian Sea 23-24 June, 2009

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
23-06-2009	0000	18.0/71.5	1.5	998	25	4	D
	0300	19.0/71.5	1.5	1000	25	4	D
	0600	19.0/71.5	1.5	1000	25	4	D
	0900	20.0/71.5	1.5	1000	25	4	D
	1200	20.5/71.0	1.5	998	25	4	D
	Depression crossed Gujarat coast near Diu between 1300 and 1400 UTC.						
	1500	21.0/71.0	-	998	25	4	D
24-06-2009	0000	21.5/70.5	-	998	25	4	D
	0300	The system weakened into a well marked low pressure area over Saurashtra & Kutch and neighbourhood.					

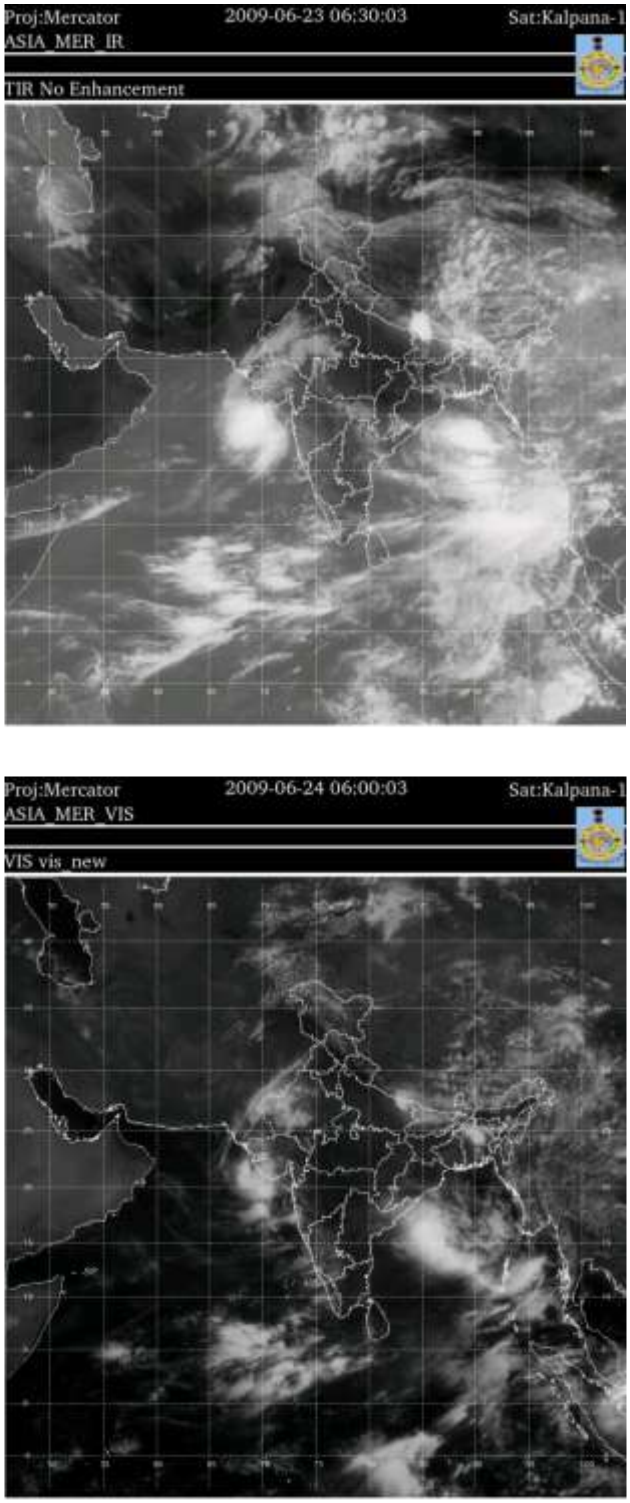


Fig. 2.3.1. INSAT imagery of depression over the Arabian Sea at 0630 UTC of 23-6-2009 and 0600 UTC of 24 June ahoqwing maximum convection in the southwest sector of the system.

2.4 Depression over the Arabian Sea (25-26 June, 2009)

2.4.1. Introduction

The remnant of the depression discussed in sec.2.3 emerged into Arabian Sea and reintensified into a depression at 0900 UTC of 25 June 2009. It moved northward, weakened and lay as a well marked low pressure area over Kutch and neighbourhood at 0000 UTC of 26 June 2009. Saurashtra and Kutch experienced active monsoon condition under the influence of this system. The genesis, intensification, movement and associated weather are discussed below. Like its parent system, it was mostly monitored by the synoptic and satellite analysis. It was short lived system with a life period of about 15 hours. As a result it did not have any significant impact on rainfall except over Saurashtra & Kutch.

2.4.2. Genesis, intensification and movement

Moving in a north-northwesterly direction, the well marked low pressure area over Saurashtra and Kutch and neighbourhood, which was the remnant of the depression discussed in previous section, re-intensified into the depression over northeast Arabian Sea and lay centred near lat. 22.5^0N/long. 68.5^0E about 50 km west-northwest of Dwarka and 300 km south-southeast of Karachi at 0900 UTC of 25 June. Moving slowing in a northerly direction, the system weakened into a well marked low pressure area at 0000 UTC of 26 June over Kutch and neighbourhood. The best track of the system is shown in Fig.2.1. The best track parameters are shown in Table 2.4.1. A typical INSAT imagery of the system is shown in Fig.2.4.1.

Table 2.4.1

Best track Positions and other parameters for depression over the Arabian Sea 25-26 June, 2009

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
25-06-2009	0900	22.5/68.5	1.5	996	25	4	D
	1200	22.5/68.5	1.5	996	25	4	D
	1800	23.0/68.5	1.5	996	25	4	D
26-06-2009	0000	The system weakened into a well marked low pressure area over Kutch and neighbourhood.					

2.4.2. Realised Weather:

Under the influence of the system, heavy to very heavy rainfall occurred at isolated places Saurashtra & Kutch and isolated heavy rainfall occurred over Gujarat region. The chief amounts of rainfall are given below:

26-06-2009:

Saurashtra, Kutch & Diu: Ranavav-7, Dwarka-5

27-6-2009:

Gujarat Region: Kamrej-7, Umargoan-5
Saurashtra, Kutch & Diu: Mangrol-13, Maliya-12, Bagsra and Keshod-8

Damage: No damage reported.

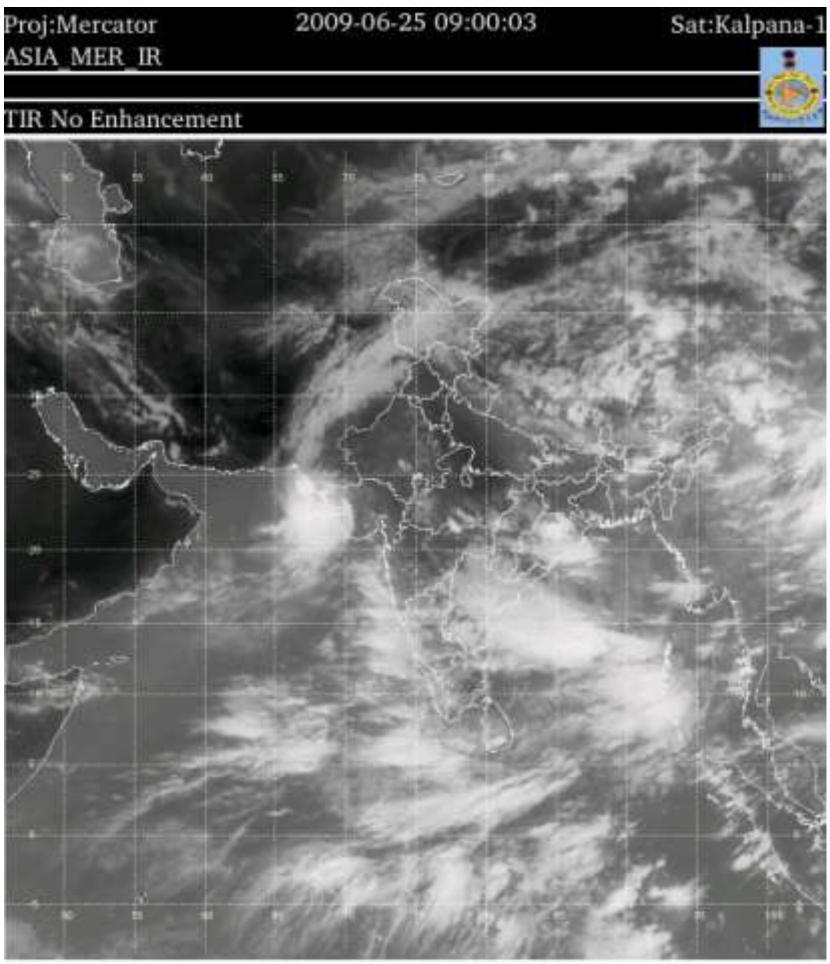


Fig. 2.4.1. INSAT imagery showing the re-intensification of the system into a depression over the Arabian Sea at 0900 UTC of 25-6-2009.

2.5 Deep depression over the Bay of Bengal (20-21 July, 2009)

2.5.1 Introduction:

A deep depression formed over the north Bay of Bengal at 0300 UTC of 20 July and crossed north Orissa-West Bengal coast between Balasore and Digha during 1600 and1700 UTC of the same day. It caused good rainfall activity over central parts of country as it led to active monsoon condition. The genesis, intensification, movement and associated weather are described below. One of the main features of this system was that though it followed a climatological track moving in a west-northwesterly direction. Its westward displacement was limited to the east of long. 80^0E.

2.5.2 Genesis:

An Upper air cyclonic circulation lay over Gangetic West Bengal & neighbourhood extending upto mid-tropospheric level and tilting southwestwards with height on 17 July. Under its influence, a low pressure area formed over northwest Bay of Bengal and adjoining coastal areas of north Orissa and West Bengal on 18 July. It persisted over the same region and became well marked on 19^{th}. It concentrated into a depression and lay centred at 0300 UTC of 20 July over northwest Bay of Bengal near Lat. 21.0^oN/Long. 88.5^oE, about 120 Km southeast of Digha.

Vertical wind shear of horizontal wind over the region was low to moderate (around 10-20 knots). Sea surface temperature was about 29.0^0 c. The system was supported by upper level divergence and lower level convergence. Strong east-southeasterly winds prevailed over the region in the upper tropospheric level. As observed at 1200 UTC of 19 July, the 24 hours pressure fall was higher in the west-northwesterly direction.

2.5.3 Intensification & movement:

It further intensified into a deep depression at 1200 UTC of 20 July, moved west-northwestwards and crossed north Orissa-West Bengal coast between Balasore and Digha during 1600-1700 UTC of 20 July. While moving west-northwestwards, it weakened gradually and lay as a well marked low pressure area at 0900 UTC of 21 July over north Chhattisgarh & neighbourhood. The well marked low pressure area lay over East Madhya Pradesh & neighbourhood on 22 July. The best track parameters of the system are given in table 2.5.1. The track is also shown in Fig. 2.1. A few INSAT imageries of the system are show in Fig. 2.5.1. The westward travel of the system was limited as the system dissipated to the east of long.80^0E.

2.5.4 Realised weather:

The system mainly caused floods due to the heavy to extremely heavy rainfall over Orissa, Madhya Pradesh, Maharashtra and Gujarat region. The chief amounts of heavy rainfall (≥7 cm) are given below as recorded at 0300 UTC of date..

21-07-2009

Orissa: Binika-22, Sambalpur-21, Bijepur-19, Altuma, Khandapara, Hindol, Sohela, Chandbali & Hirakud- 17 each, Paikmal, Keonjhargarh, Kamakshyanagar & Dunguripalli-16 each, Daringibadi, Ambabhona, Bargarh-15 each, Rajkanika, Ghatagaon & Swam-patna- 14 each, Batagaon, Padampur, Bolangir, Khairamal, Angul, Ranpur & Pattamundai-13 each, Rengali, Akhuapada & Naktideul- 12 each, Talcher, Rajkishorenagar, Sonepur, Sukinda, Athgarh & Chendipada- 11 each, Deogarh, Tensa, Jajpur, Boudhgarh & Kuchinda-10 each, Athmalik, Deogaon,Kotagarh, Reamal, Barmul, Narsinghpur, Kantamal, Bonth, Patnagarh, Jharsuguda & Hemgiri- 9 each, Naraj, Dhenkanal, Kendrapara, Telkoi, Cuttack & Nawana -8 each, Soro, Sundargarh, Tikabali, Nilgiri & Phulbani- 7 each.

East Madhya Pradesh: Jabalpur-16, Narsinghpur-13, Amarwara-12.

Chhattisgarh: Saraipali-17, Gharghoda-16, Mahasamund-10, Sarangarh-9, Janakpur- 8, Raigarh-7.

22-07-2009:

ORISSA : Ambabhona-11, Udala-8, Paikmal-7.

Chhattisgarh: Kasdol-28, Bilaigarh, Pithora-18 each, Basna-17, Simga, Mahasamund -15 each; Tilda-14, Patan, Arang, Shivarinarayan-13 each, Kurud, Raipur, Saraipali- 12 each, Bagbahara, Baloda Bazar, Palari, Bemetara-11 each, Mana, Sarangarh -10 each, Chura -9, Durg-8, Baramkeh, Rajim, Dhamtari -7 each

East Madhya Pradesh: Amarwara-17, Keolari-13, Malanjkhand-12, Narsinghpur-11, Kaneli- 10, Gotegaon, Seoni-8 each, Gadarwara, Chindwara-7 each.

West Madhya Pradesh: Pachmarhi-29, Chicholi- 18, Nusrulgunj-16, Biaora-15, Betul-14, Bhopal-14, Shujalpur-13, Bhainsdehi-8, Agar**,** Ujjain, Budhni**,** Raisen, Jhabua, Indore, Chachoda, Hoshangbad-7 each.

East Rajasthan: Jhalarapatan, Veja -15, Sunel- 12, Asnawar-11, Ladpura, Bharatpur, Kota, Degod-10 each, Bharatpur tehsil, Aklera, Pirawa ,Chipaboard -9

each, Malpura, Kesoraipatanam, Jhalawar, Patan-8 each, Rawatbhatta, Chambal, Partapgarh, Khanpur, Ramganjmandi, Kekri – 7 each
Gujarat Region: Dediapada-33, Mahuwa- 18, Silvassa-17, Daman, Madhbun, Vapi -16 each, Chikhli-15, Gandevi- 14, Bansda, Nanipalson-13, Sagbara-12, Dharampur-10.

Konkan & Goa: Dahanu-22, Jawahar-21, Mokhada-17, Palghar, Vikramgadh- 16 each, Talasari-15, Wada-13, Sahapur, Bhira, Poladpur-10 each, Mahad & Matheran-9 each, Bhiwandi, Karjat & Mandangad-7 each

Madhya Maharashtra: Mahabaleshwar-15, Radhanagari-13, Trimbak-12, Langpai & Peint -11 each, Surgana-10

2.5.5. Damage:

Bhadrak, Cuttack, Ganjam, Kalahandi, Koraput, Keonjhar, Nayagarh and Sundergarh districts of Orissa were affected with large area submerged:.
Human death = 43.
(According to the report of Revenue deptt., Govt. Of Orissa)

Table 2.5.1 Best track Positions and other parameters for deep depression over the Bay of Bengal (20-21 July, 2009)

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
20-07-2009	0300	21.0/88.5	1.5	992	25	3	D
	0600	21.0/88.5	1.5	992	25	3	D
	1200	21.0/88.0	2.0	988	30	4	DD
	The system crossed north Orissa – West Bengal coast between Balasore and Digha during 1600- 1700 UTC.						
	1800	21.5/87.0	--	992	30	4	DD
21-07-2009	0000	22.0/85.0	--	992	30	4	DD
	0300	22.0/84.5	--	992	30	4	DD
	0600	22.0/84.0	--	994	25	3	D
	0900	The system moved west-northwestwards and weakened into a well marked low pressure area.					

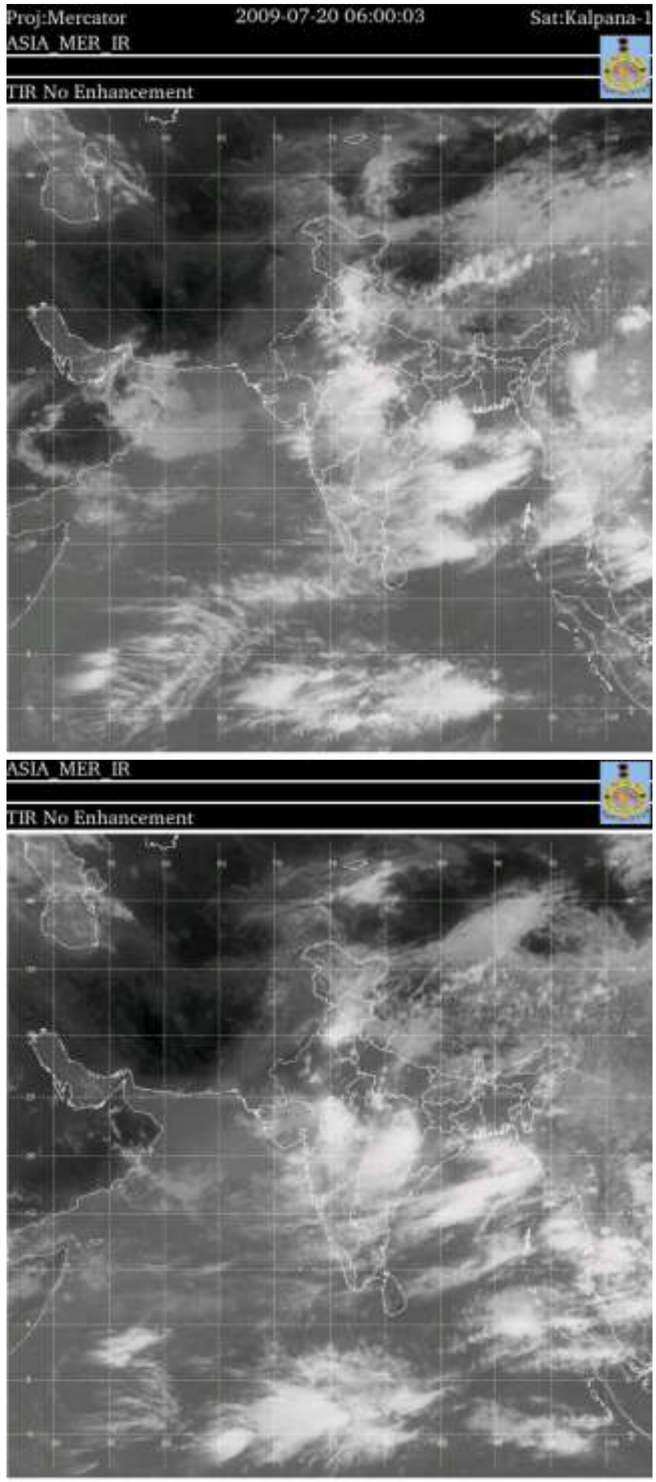


Fig. 2.5.1 INSAT imageries of deep depression over the Bay of Bengal at 0600 UTC of 20, 21 July 2009 indicating shear pattern of the cloud.

2.6 Deep depression over the Bay of Bengal (5-7 September, 2009)

2.6.1 Introduction:

A depression formed over the westcentral and adjoining northwest Bay of Bengal off Orissa coast at 0000 UTC of 5 September, 2009. Moving in a north-northwesterly direction, the system intensified into deep depression at 0300 UTC and crossed West Bengal coast near Digha between 0700 and 0800 UTC on 5 September, 2009. Afterwards, it moved in a west-northwesterly direction and weakened gradually into a low pressure area over north Jharkhand and neighbourhood at 1200 UTC of 7 September 2009.

2.6.2 Genesis:

A convective cloud cluster developed over northwest and adjoining central Bay of Bengal on 2 September, 2009. An upper air cyclonic circulation lay over westcentral and adjoining northwest Bay of Bengal on 2 September. It slowly organized with persistence of the convection over the region. The southwesterly winds over the Bay of Bengal increased in intensity leading to a lower level convergence and cyclonic circulation over the region embedded with the monsoon trough over the northwest Bay of Bengal on 3 and 4 September. The MSLP fell by about 2 hPa along west Bengal and Orissa coast at 0300 UTC of 3 September. Under the influence of the cyclonic circulation, a low pressure area has formed over westcentral and adjoining northwest Bay of Bengal off Orissa coast on 3 Septenmber and it become well marked on 4 september over the same area.

The adequate upper level divergence continued to support the deep convection over the region. Upper air difluence gave the potential for further intensification of the system. As a result, it concentrated into a depression and lay centred at 0000 UTC of 5 September, 2009 over northwest Bay of Bengal near lat. 20.5^0 N and long. 88.0^0 E.

2.6.3 Intensification and Movement:

The system further intensified into a deep depression at 0300 UTC of 5 September over the same region. The system initially moved in a north-northwesterly direction and crossed West Bengal coast near Digha between 0700 and 0800 UTC of the same day. Thereafter, it moved in a west-northwesterly direction and lay centred over Jharkhand, about 50 km northeast of Ranchi at 0900 UTC of 6 September and near Daltonganj 0300 UTC of 7 September. Its movement slowed down and the system lay over the same area up to the evening of 7 September. The system weakened into a well marked low pressure area over Jharkhand and adjoining north Chhattisgarh, northeast Madhya Pradesh, southeast Uttar Pradesh and southeast Bihar at 1200 UTC of 7 September 2009. As well marked low pressure area, it moved upto the Madhya Pradesh and neighbourhood till 11 September and become unimportant thereafter. The track of the system is shown in Fig. 2.1. The INSAT and DWR Kolkata imageries are shown in Fig. 2.6.1 and 2.6.2 respectively.

Table 2.6.1 Best track Positions and other parameters for deep depression over the Bay of Bengal during 5-7 September, 2009

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
05-09-2009	0000	20.5/88.0	1.5	990	25	3	D
	0300	21.0/87.5	2.0	988	30	4	DD
	0600	21.5/88.0	2.0	988	30	4	DD
	The system crossed West Bengal coast near Digha between 0700 & 0800 UTC.						
	0900	22.0/87.5	--	988	30	4	DD
	1200	22.5/87.5	--	988	30	4	DD
	1800	23.0/87.0	--	988	30	4	DD
06-09-2009	0000	23.0/86.5	--	988	30	4	DD
	0300	23.5/86.0	--	988	30	4	DD
	0900	23.5/85.5	--	988	30	4	DD
	1200	24.0/85.0	--	988	30	4	DD
	1800	24.3/84.5	--	988	30	4	DD
07-09-2009	0000	24.5/84.0	--	988	30	4	DD
	0300	24.5/84.0	--	990	30	4	DD
	0900	24.5/84.0	--	994	25	3	D
	1200	The system weakened into a well marked low pressure area over Jharkhand and adjoining north Chhattisgarh, northeast Madhya Pradesh, southeast Uttar Pradesh and southwest Bihar.					

2.6.4 Realized weather:

Under the influence of the system, fairly widespread to widespread rainfall with isolated heavy to very heavy rainfall occurred over Orissa, Jharkhand, north Chhattisgarh, northeast Madhya Pradesh, southeast Uttar Pradesh and southwest Bihar.

Chief rainfall amounts (>7 cm) as recorded at 0300 UTC of date are as follows:

6-09-2009:

Orissa: Nawana-18, Jaipur,Soro, Nilgiri- 10 each Balasore-9, Rairangpur-8, NH5 Gobindpur, Tiring-7 each.

Jharkhand: Jamshedpur(City)-10 and Jamshedpur(AP)-8.

Gangetic West Bengal: Berhampur-21, Midnapore(CWC)-18, Midnapur and Mohanpur-17 each, Kalaikunda-16, Diamond Harbour-14, Phulberia, Durgachak and Haldia-13 each Krishnanagar and Kolkata(Alipore)-12 each, Tusuma and Dengarparaghat-11 each, Kharidwar, Bagati and Canning-10 each Kansabati Dam and Simulia-9 each, Kolkata(Dum Dum), Basirhat and Barrackpur-8 each Bankura and Digha -7 each

07-09-2009

Gangetic West Bengal: Bankura(CWC)-17, Asansol-15, Bankura-14, Kansabati Dam-11.

Jharkhand: Jamatara-23, Tilaiya-22, Hindigir and Konner-19 each Nandadih and Panchet-17, Ramgarh-16, Mython and Vandera-15 each, Tenughat-14, Ranchi and Kuru-13, Daltonganj and Kisko-11 each; and Pupunki-10.

Bihar: Gaya-17, Palmerganj-12, Matihani-9, Dehri, Makhdumpur, Sono and Koilwar-8 each Bhabhua, Colgaon and Indrapuri-7 each.

08-09-2009:

Chhattisgarh: Janakpur-13, Wadrafnagar-9.

East Madhya Pradesh: Umaria-15, Maihar-9, Sidhi and Rewa-7 each

Orissa: Soro-14, Nilgiri-9.

Bihar: Dehri-8, Palmerganj-7.

East Uttar Pradesh: Meja-12, Mirzapur (FMO)-9, Chhatnag-7.

2.6.5 Damage:

Crop area of 5005 hectare in the three blocks of Balasore districts of Orissa was affected.

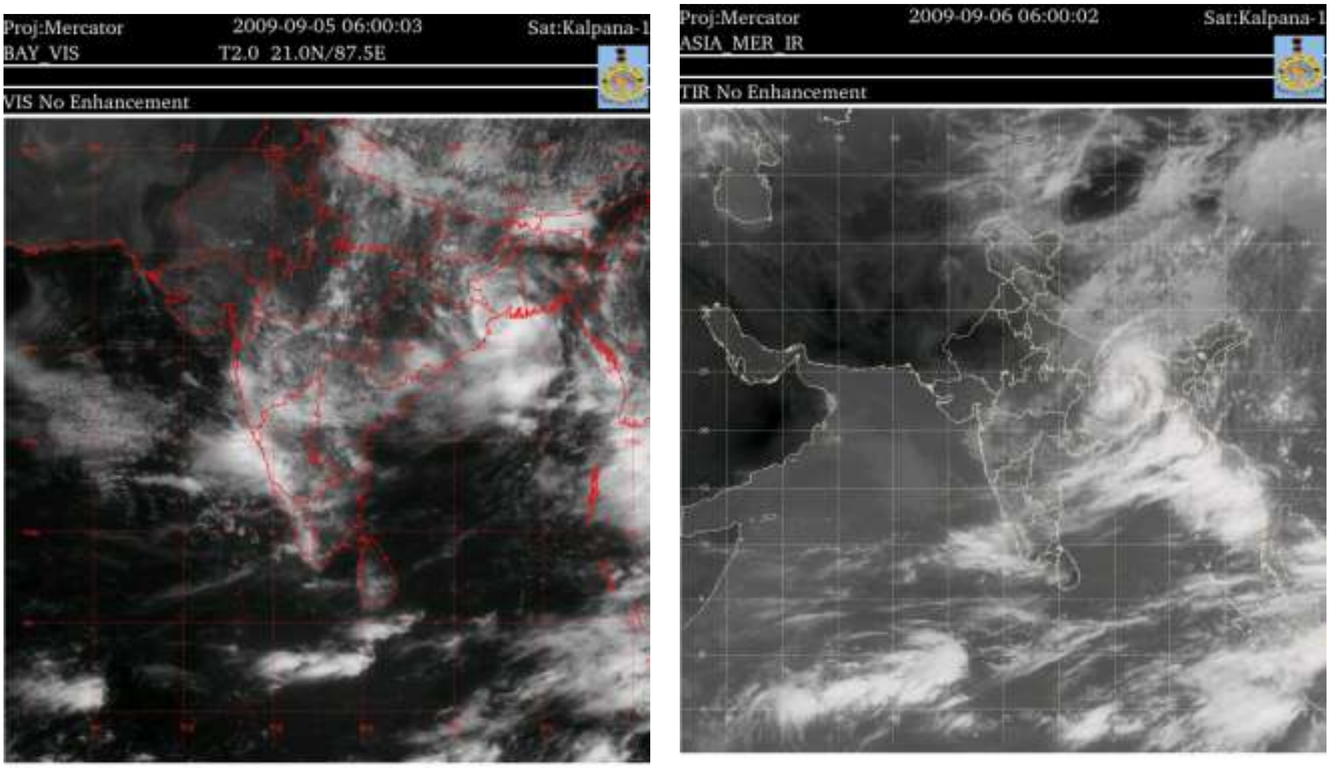


Fig. 2.6.1 INSAT imageries at 0600 UTC of 5 and 6 September 2009 showing the convection in association with deep depression over the Bay of Bengal.

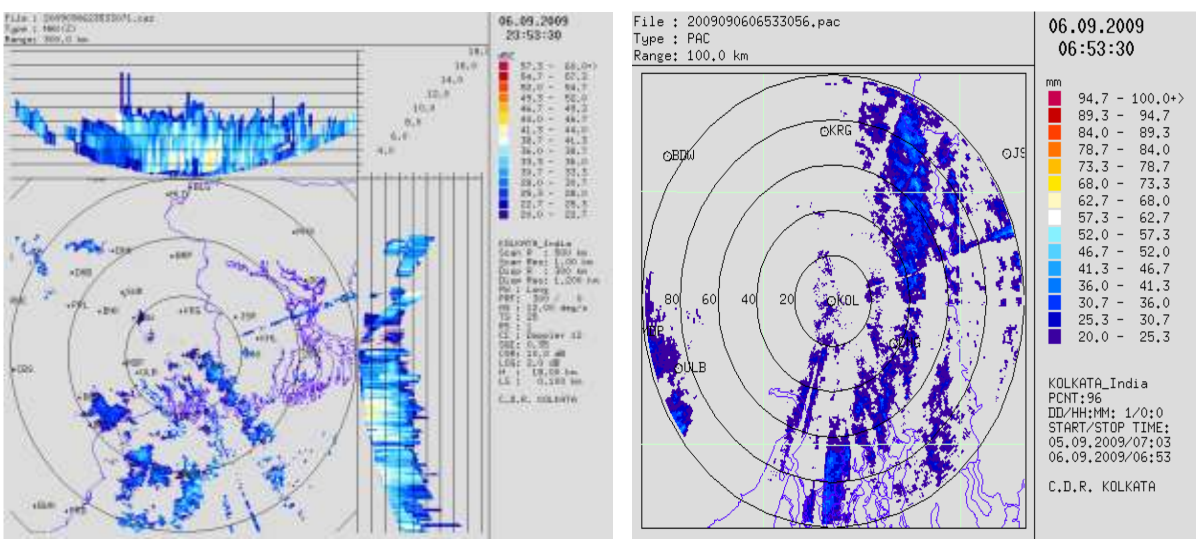


Fig. 2.6.2 DWR Kolkata imageries of deep depression over the Bay of Bengal on 06 September 2009.

2.7 Cyclonic storm ‘Phyan’ over the Arabian Sea (09-12 November, 2009)

2.7.1 Introduction

A cyclonic storm, **‘Phyan’** crossed Maharashtra coast between Alibag and Mumbai during 1000 and 1100 UTC of 11 November, 2009. It caused loss of seven human lives and many fishermen missing in Maharashtra and Goa areas. The main features of this cyclone are as follows.

(i) Cyclone, ‘Phyan’ moved very fast prior to landfall. It moved about 450 km during 0000 to 1200 UTC of 11 November 2009.

(ii) Though it crossed as a cyclonic storm, it slightly weakened before the landfall.

The genesis, intensification and movement of the cyclonic storm, **‘Phyan’,** along with satellite observation, realized weather and associated damages are described below.

2.7.2 Genesis

In association with active northeast monsoon surge, a low pressure area formed over Comorin area on 7 November, 2009. It became well marked over Lakshadweep area on 8 November. The environmental features like sea surface temperature, vertical wind shear of horizontal wind, mid-tropospheric humidity, low level convergence and upper level divergence were favourable for cyclogenesis over the southeast Arabian Sea. The sea surface temperature was about 28-30 deg. C. over southeast and east central Arabian Sea. The vertical wind shear of horizontal wind was low to moderate (10-20 knots). In addition, the Madden Julian Oscillation was also favourable, as its active phase lay over west equatorial Indian Ocean and adjoining Arabian Sea region during the period of cyclone leading to enhanced and persistent convection required for cyclogenesis and intensification. Due to all these the system concentrated in to a depression and lay centred at 0900 UTC of 9 November, 2009 over southeast and adjoining east central Arabian Sea near lat. 11.0^0N and long. 72.0^0E, about 70 km west of Amini Divi.

2.7.3 Intensification and movement:

It moved initially in a north-northwesterly direction till 10 November morning and then recurved north-northeastwards. The track of the system is shown in Fig. 2.1. It intensified into a deep depression at 0300 UTC and into a cyclonic storm **‘Phyan’** at 1800 UTC of 10 November, 2009. Continuing its north-northeastward movement, the cyclonic storm **‘Phyan’** crossed north Maharashtra coast between Alibag and Mumbai during 1000 and 1100 UTC of 11 November. It moved then northeastwards and weakened into a deep depression and lay centred at 1200 UTC of 11 November, 2009 over north Konkan, about 100 km northeast of Mumbai. It further weakened into a depression and lay centred at 1800 UTC of 11 November over Madhya Maharashtra, near Nasik. It weakened into a well marked low pressure area over north Madhya Maharashtra and neighbourhood at 0000 UTC of 12th November 2009. The cyclone, **'Phyan'** moved faster before crossing the coast. It moved about 450 km in 12 hours between 0000 and 1200 UTC of 11th November, 2009.

The system lay to the south of the upper tropospheric ridge at the time of cyclogenesis as the ridge roughly ran along 14^{0}N on 9 November. However, the system came closer to the ridge position on 10 November and lay to the north of the ridge position on 11 November morning leading to acceleration of the system in northeasterly direction. The upper tropospheric winds at 0000 UTC of 9, 10 and 11 November 2009 are shown in Fig. 2.7.1.

The vertical wind shear increased to become moderate to high, (15-25 knots) on 10 November and similar condition prevailed on 11 November (20-25 knots). However, the system still intensified till 0600 UTC of 11 November. It may be due to large Ocean heat content in the thermo cline layer in association with the higher sea surface temperature (28-30^0 C) over southeast and east central Arabian Sea. This aspect needs further study. The slight weakening of the system before landfall may be attributed to impact of orographic interaction, which needs also further examination. The vertical wind shear at 0000 UTC of 09, 10 and 11 November are shown in Fig. 2.7.2.

The best track data of the system are shown in Table 2.7.1. The estimated central pressure (ECP) of the system fell from 1000 hPa at 0900 UTC of 09 to 988 hPa at 0600 UTC of 11 November. Considering the coastal observations, the lowest pressure of 987.9 hPa was reported by Harnai at 0500 UTC of 11th, when the system was located at about 50 km southwest of Harnai. The sustained maximum wind at surface is estimated to be about 45 knots for a temporary period during 11th morning. Though the maximum intensity of the system is T 2.5 according to Dvorak's technique, the coastal observations indicate that it may be T 3.0 during this period. The sustained maximum surface wind decreased after 0600 UTC and it may be 40 knots at the time of landfall, which is supported by actual observations.

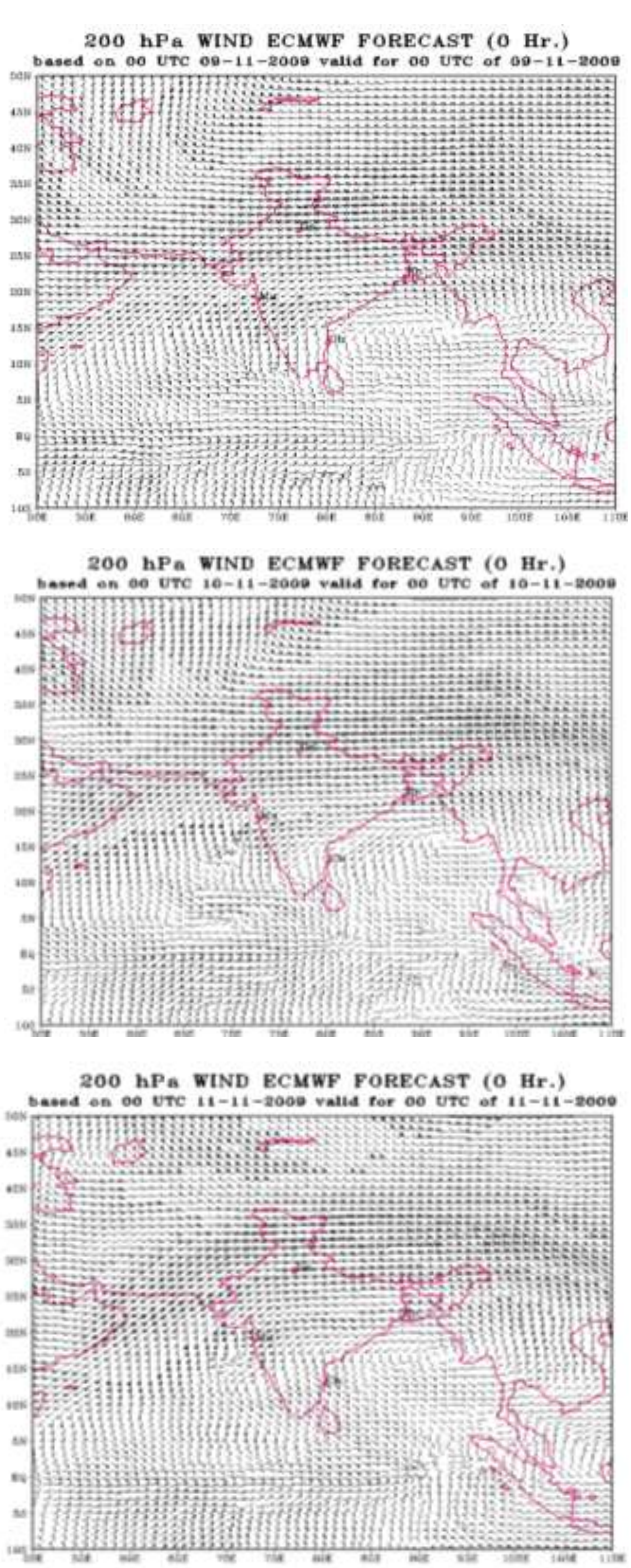


Fig.2.7.1.Upper tropospheric winds at 0000 UTC of 9, 10 and 11 November 2009

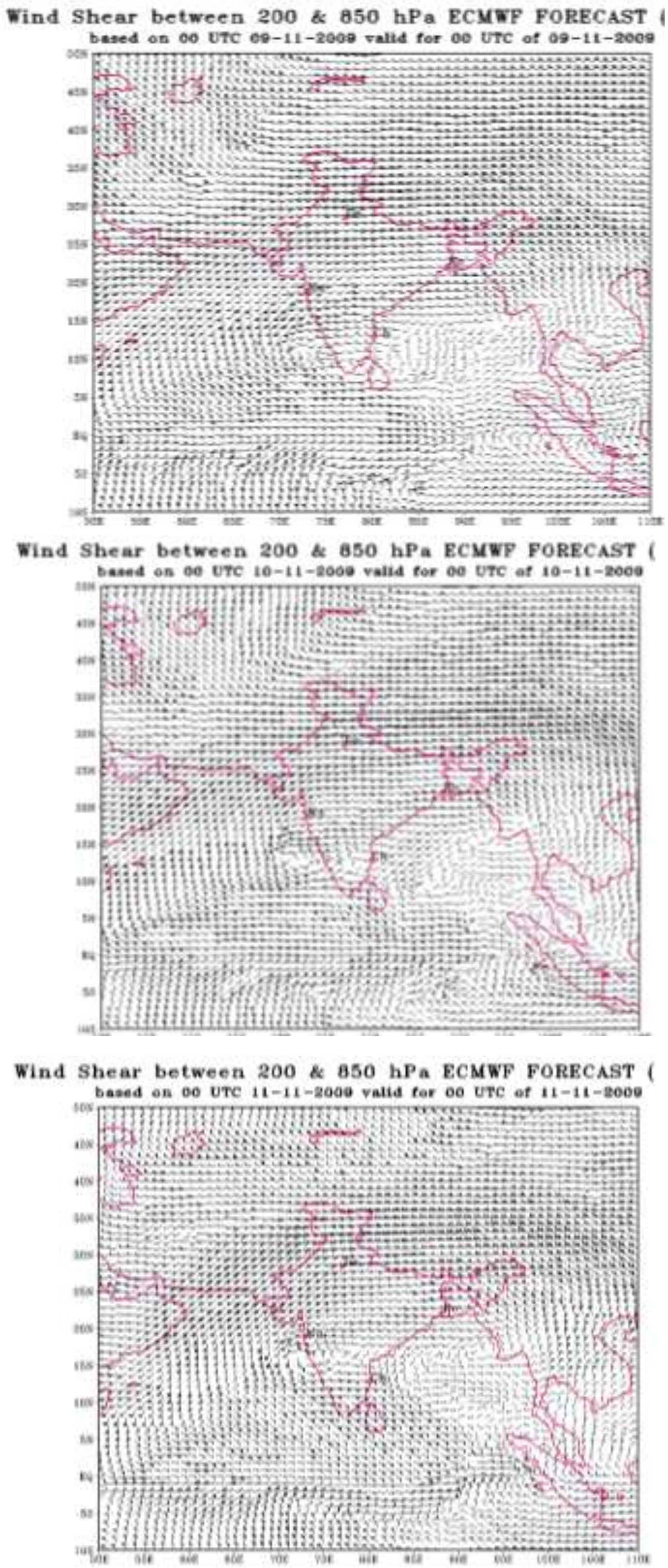


Fig.2.7.2.Vertical wind shear at 0000 UTC of 09, 10 and 11 November 2009

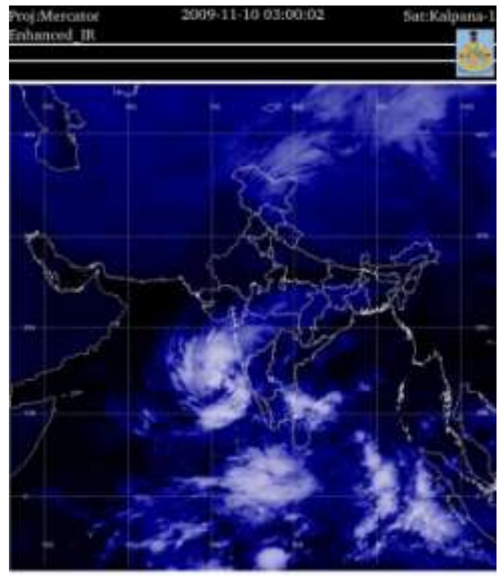
Table 2.7.1. Best track Positions and other parameters of cyclonic storm PHYAN over the Arabian Sea during 09-12 November 2009

Date	Time (UTC)	Centre (lat.^{0} N/ long. ^{0} E)	C.I. NO.	Estimated Central Pressure (hPa)	Estimated Pressure drop at the Centre (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Grade
9-11-2009	0900	11.0/72.0	1.5	1000	4	25	D
	1200	11.5/71.5	1.5	1000	4	25	D
	1800	12.0/71.0	1.5	1000	4	25	D
10-11-2009	0000	12.5/70.5	1.5	998	4	25	D
	0300	13.0/70.5	2.0	998	5	30	DD
	0600	13.5/70.5	2.0	998	5	30	DD
	1200	14.5/71.0	2.0	996	5	30	DD
	1800	15.0/71.0	2.5	996	6	35	CS
	2100	15.5/71.5	2.5	994	6	35	CS
11-11-2009	0000	16.0/71.5	2.5	992	8	40	CS
	0300	17.0/72.0	3.0	990	10	45	CS
	0600	17.5/72.5	3.0	988	12	45	CS
	0900	18.5/72.5	2.5	992	8	40	CS
	Cyclonic storm "PHYAN" crossed Maharashtra coast during Alibag and Mumbai near lat. 18.7^0/ long.73.0^{0}E during 1000 and 1100 UTC of 11 November, 2009.						
	1200	19.5/73.5	--	996	5	30	DD
	1500	20.0/74.0	--	998	5	30	DD
	1800	20.0/74.0	--	1000	4	20	D
12-11-2009	0000	The system weakened into a well marked low pressure area over north Madhya Maharashtra					

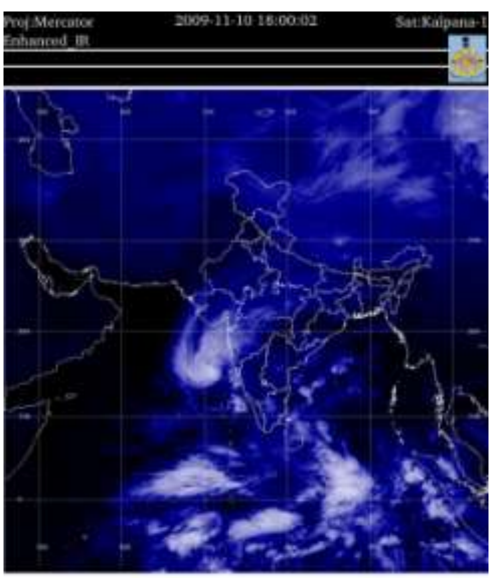
The satellite imageries of the system at different stages of intensity are shown in Fig.2.7.3. In association with deep convective cloud clusters, a low level circulation (LLC) developed over Gulf of Mannar and neighbourhood on 3 November. It lay over Comorin area and neighbourhood on 4 November. It persisted over the same region and gradually organised during 4 to 7 November. It became a vortex with T 1.0 at 0000 UTC of 7 November according to Dvorak's technique. It further organized while moving northwestward and curved band features appeared at 0900 UTC of 09 November when the system was located over Lakshadweep area. Hence, the intensity of the system at 0900 UTC of 09 November was upgraded to T1.5 corresponding to depression. From 10 November onwards, the system moved nearly northward till 2300 UTC of 10 November. It then moved north-northeastward. It intensified with T 2.0 corresponding to deep depression at 0300 UTC and to T 2.5 at 1600 UTC of 10 November corresponding to cyclonic storm. The curved band pattern of the cyclone was replaced with central dense over cast (CDO) pattern in the early morning of 11 November. However, the system slightly weakened from 0600 UTC of 11 November as it came close to the coast due to northeastward movement. The CDO pattern disorganised and curved band pattern reappeared. It made landfall with intensity of T 2.5. Further, the northeastward outflow from the system increased on 11 November with cirrus clouds extending upto Chhattisgarh.

(a) Depression

(b) Deep Depression



(c) Cyclone



(d) Cyclone at landfall

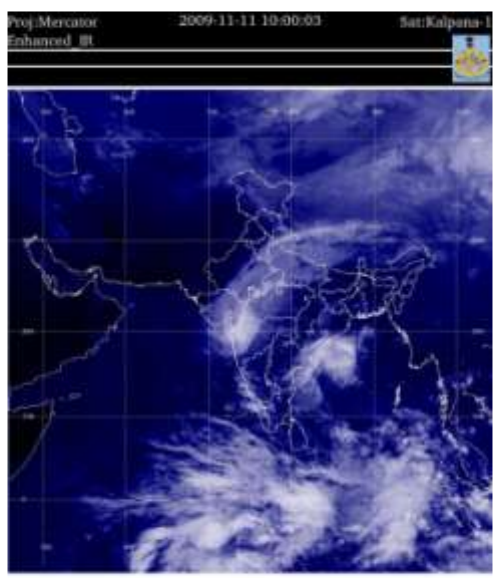


Figure 2.7.3. INSAT Kalpana I imageries at different stages of intensity of cyclone, 'Phyan'

2.7.4 Realised weather

2.7.4.1 Rainfall

Widespread rainfall with isolated heavy to very heavy falls occurred over Goa, Konkan and Madhya Maharashtra on 10 and 11 November. Fairly widespread rainfall also occurred over south Gujarat region due to the cyclone on 11 November. Chief amounts of rainfall (7cm and above) recorded at 0300 UTC of 11 and 12 November over Maharashtra and Goa are given below.

11. 11. 2009

Goa: Canacona and Marmagao -8 each, Dabolim-7.

Maharashtra: Pune Airport (Lohegaon) -13; Mahabaleshwar, Bhor, Paud, Vadgaon Maval -10 each; Wai, Pune city -9 each; Ghodegaon-8; Chandwad, Satara, Uran, Islampur, Akola -7 each.

12-11-2009:

Maharashtra : Chandwad – 17; Akola-14; Nandgaon, Sinnar, Yeola -13 each; Ghodegaon – 12; Mahabaleshwar, Mandangad -11 each, Kopargaon, Sudhagad-10 each; Chiplun, Malegaon, Mhasla, Chopda, Edalabad, Erandol, Pachora, Harnai, Kalvan, Khandala, Paud – 9 each; Shrirampur, Shirpur, Vadgaon Maval – 8 each; Bahadgaon, Shriwardhan, Niphad, Soegaon, Kalvan – 7 each.

2.7.4.2 Wind:

The maximum wind (Kmph) reported at observatory stations of IMD at the time of land fall are given below:

Pune : 68,

Goa 63,

Colaba 56.

According to Survey report on damage using Beaufort scale the maximum surface wind was estimated to be about 75 kmph along Maharashtra and Goa coast at the time of landfall.

2.7.4.3 Storm Surge:

Based on nomograms developed by IMD and Storm surge prediction model developed by IIT, Delhi, IMD predicted maximum storm surge of about 1 meter above the astronomical tide over Sindhudurg, Raigad, Greater Mumbai and Thane districts of Maharashtra and adjoining Valsad distrist of Gujarat at the time of landfall. However, no stormsurge could be extimated after the landfall.

2.7.5 Damage:

According to state government Newspaper reports, the cyclone 'Phyan' caused damage to lives, crops and properties in Goa and Konkan region especially in Ratnagiri, Sindhudurg, Raigad and Thane districts. About 1000 houses in these districts suffered damages. Seven persons died and about 44 fishermen missing due to cyclone. A few photographs showing damage in Maharashtra are shown in fig 2.7.4

Fig. 2.7.4. A few photographs showing the damage due to strong wind and storm surge along the coastal areas of Maharashtra and Goa.

2.8 Cyclonic Storm 'WARD' over the Bay of Bengal (10-15 December, 2009)

2.8.1 Introduction:

A cyclonic storm, 'WARD' (10-15 December) developed over the south Bay of Bengal and crossed northeast Sri Lanka coast, close to south of Trincomalee as a deep depression between 0800 and 0900 UTC of 14 December 2009. It weakened into a well marked low pressure area over north Sri Lanka at 0300 UTC of 15 December. It then emerged into Gulf of Mannar and became insignificant on 16 December. The main features of this cyclone are as follows.

(i) Cyclone, 'WARD' followed a rare track, as it moved initially in a northerly direction and then moved west-southwestwards across Sri Lanka.
(ii) It was a slow moving system, as it travelled at the average rate of 200 km per day (8 km per hour).
(iii) It weakened into deep depression over the Sea before the landfall.

The system was mainly monitored with the satellite imageries and other derived products during its genesis, intensification and movement towards Sri Lanka coast, as there were a very few observations from the buoys and ships. However, the surface synoptic data in every three hourly intervals were received from Sri Lanka, which helped immensely to monitor the system, especially during and prior to its landfall over Sri Lanka, its gradual weakening, emergence to Gulf of Mannar and dissipation. The genesis, intensification, movement, and realized weather are described below.

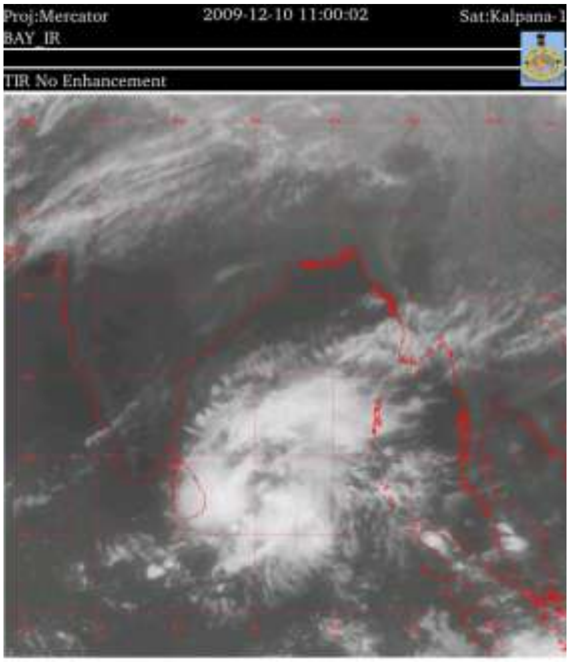
2.8.2 Genesis

In association with an active inter-tropical convergence zone (ITCZ), the convective cloud clusters persisted over the southeast Bay of Bengal during first week of December 2009. As a result, a low pressure area formed over the southeast Bay of Bengal on 7 December 2009. It slowly moved westwards and became well marked over southwest and adjoining southeast Bay of Bengal on 10 December morning. Under the favourable conditions like warmer sea surface temperature (28-30 deg. C), higher Ocean thermal energy (>100 KJ/sec), low vertical wind shear (10-15 konts) between lower and upper tropospheric levels, higher upper level divergence and increasing lower level vorticity over the region, the well marked low pressure area intensified into a depression at 0900 UTC of 14 December over southwest Bay of Bengal and adjoining southeast Bay of Bengal near Latitude 6.5ºN & Longitude 85.0º E.

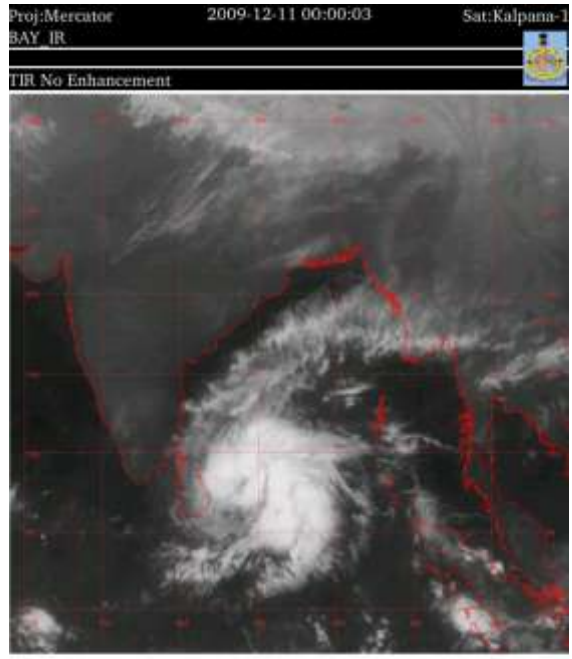
Table 2.8.1 Best track Positions and other parameters of Cyclonic Storm "WARD" over the Bay of Bengal during 10-15 December, 2009

Date	Time (UTC)	Centre lat.^{0} N/ long. ^{0} E	C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
10-12-2009	0900	6.5/85.0	1.5	1004	25	3	D
	1200	6.5/85.0	1.5	1004	25	3	D
	1800	6.5/85.0	1.5	1003	25	4	D
11-05-2009	0000	7.0/84.5	2.0	1000	30	5	DD
	0300	7.0/84.5	2.0	1000	30	5	DD
	0600	8.0/84.5	2.0	1000	30	5	DD
	0900	8.5/84.5	2.5	998	35	6	CS
	1200	8.5/84.5	2.5	998	35	6	CS
	1500	9.0/84.5	2.5	998	35	6	CS
	1800	9.0/84.5	2.5	998	40	8	CS
	2100	9.5/84.5	3.0	996	45	10	CS
12-12-2009	0000	10.0/84.5	3.0	996	45	10	CS
	0300	10.0/84.5	3.0	996	45	10	CS
	0600	10.0/84.5	3.0	996	45	10	CS
	0900	10.0/84.0	2.5	998	40	8	CS
	1200	10.0/83.5	2.5	998	35	6	CS
	1500	10.0/83.5	2.5	998	35	6	CS
	1800	9.5/83.5	2.0	1000	30	5	DD
13-12-2009	0000	9.5/83.0	2.0	1000	30	5	DD
	0300	9.5/83.0	2.0	1000	30	5	DD
	0600	9.0/83.0	2.0	1002	30	5	DD
	1200	9.0/83.0	2.0	1002	30	5	DD
	1800	9.0/82.5	2.0	1002	30	5	DD
14-12-2009	0000	9.0/82.0	2.0	1002	30	5	DD
	0300	8.5/81.5	2.0	1004	30	5	DD
	0600	8.5/81.5	2.0	1004	30	5	DD
14-12-2009	The system crossed the north Sri Lanka coast near Trincomalee (43336) (lat. 8.7^{0}N/ long. 81.3^{0}E) between 0800 & 0900 UTC.						
	0900	8.5/81.0	--	1004	25	4	D
	1200	8.5/81.0	--	1004	25	3	D
	1800	8.5/81.0	--	1005	25	3	D
15-12-2009	0000	8.5/80.5	--	1007	25	3	D
	0300	The system weakened into a well marked low pressure area over Sri Lanka .					

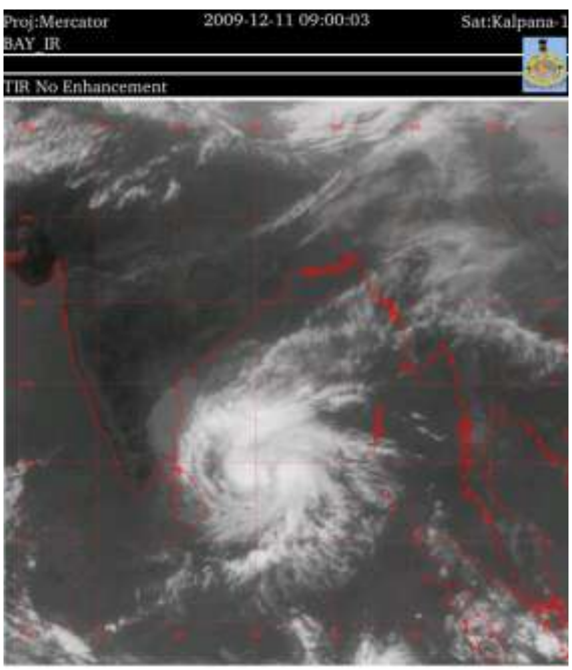
(a) Depression : T 1.5



(b) Deep Depression : T 2.0



(c) Cyclonic storm : T 2.5



(d) Cyclonic storm : T 3.0

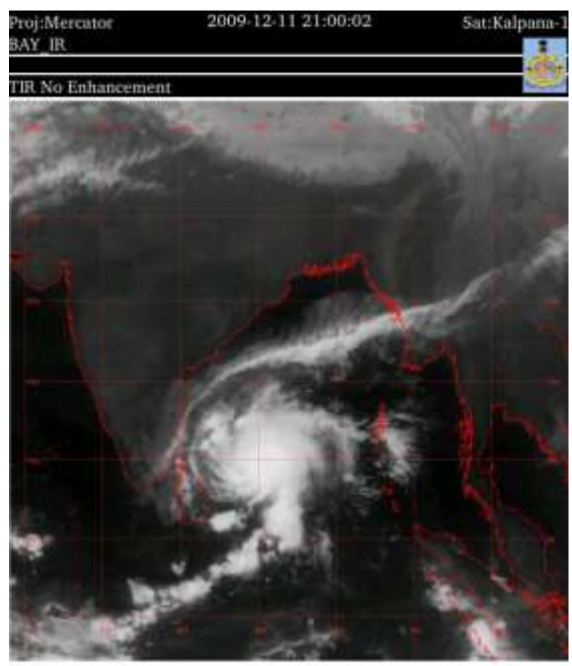


Fig.2.8.1 INSAT Kalpana imageries during different stages of intensification of the system

2.8.3 Intensification and movement:

It further intensified into a deep depression near Latitude 7.0ºN & Longitude 84.5º E at 0000 UTC of 11 December. While moving northward, it intensified into a cyclonic storm 'WARD' at 0900 UTC of the same day near latitude 8.5º N & Longitude 84.5º E.. It continued as a cyclonic storm and moved slowly northward till 0600 UTC of 12 December. It then moved west-southwestwards and weakened into a deep depression and lay over southwest Bay of Bengal at 1800 UTC of 12 December near Latitude 9.5º N & Longitude 83.5º E. Continuing to move in a west-southwesterly direction, it crossed northeast Sri Lanka coast close to the south of Trincomalee between 0800 and 0900 UTC of 14 December as a deep depression. It weakened further into a depression over north Sri Lanka close to Trincomalee at 0900 UTC of 14 December and into a well marked low pressure area over Sri Lanka at 0300 UTC of 15 December. It emerged into Gulf of Mannar as a low pressure area at 1200 UTC of the same day and became less marked at 0900 UTC of 16 December .

The track of the system is shown in Fig.2.1. The best track data of the system are shown in Table 2.8.1. The estimated central pressure (ECP) of the system fell from 1004 hPa at 0900 UTC of 10 December to 996 hPa at 2100 UTC of 11 December. The sustained maximum wind at surface is estimated to be about 45 knots for a temporary period during 2100 UTC of 11 December to 0600 UTC of 12 December. The maximum intensity of the system was T 3.0 according to Dvorak's technique The sustained maximum surface wind at the time of landfall over Sri Lanka was about 30 knots gusting to 40 knots. Along Tamil Nadu coast, Pamban reported the maximum wind of 25 knots for a temporary period on 15^{th} morning.

The satellite imageries of the system at different stages of intensity are shown in Fig.2.8.1. In association with deep convective cloud clusters, a low level circulation (LLC) developed over southeast Bay of Bengal at 1800 UTC of 6 December 2009. Under the favourable conditions, the convective cloud clusters merged with each other and a vortex with T 1.0., as per Dvorak's intensity classification based on pattern recognition, formed at 0900 UTC of 8 December over the same region. It further organized with development of curved bands around 10^{th} noon when the system was assigned with T number of 1.5. It gradually intensified further into T 2.5 at 0700 UTC of 11 December and T 3.0 at 2100 UTC of the same day corresponding to intensity of cyclonic storm. Throughout its cyclone stage, curved band pattern was observed. The system slightly weakened from 1200 UTC of 12 December due to increased wind shear and further weakened to T2.0 at 1800 UTC of 12 December as the system moved closer to Sri Lanka coast and interacted with land surface. The upper tropospheric winds and vertical wind shears are shown in Fig.2.8.2 and Fig.2.8.3 respectively.

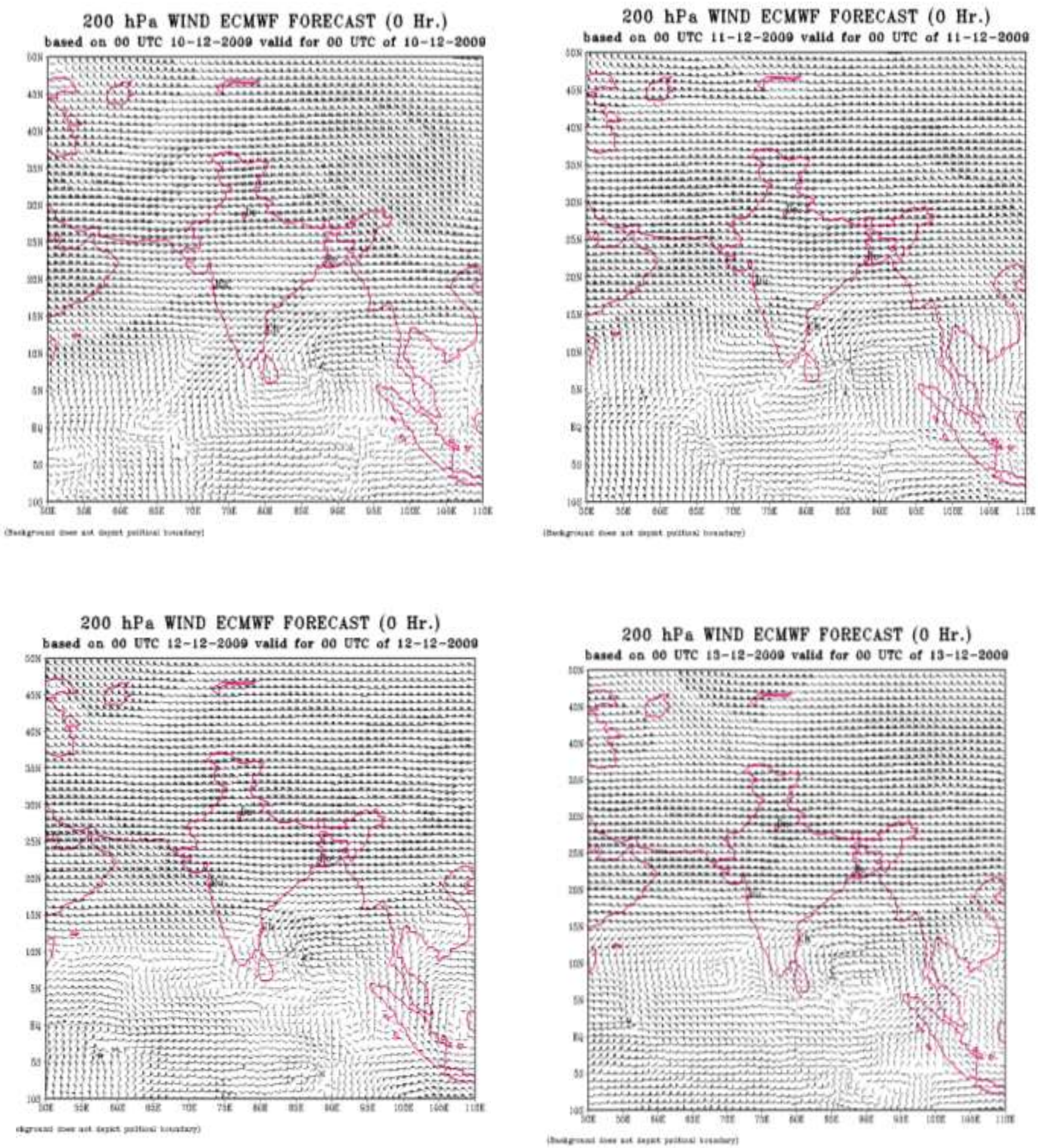


Fig.2.8.2.Upper tropospheric winds at 0000 UTC of 10, 11, 12 and 13 December 2009

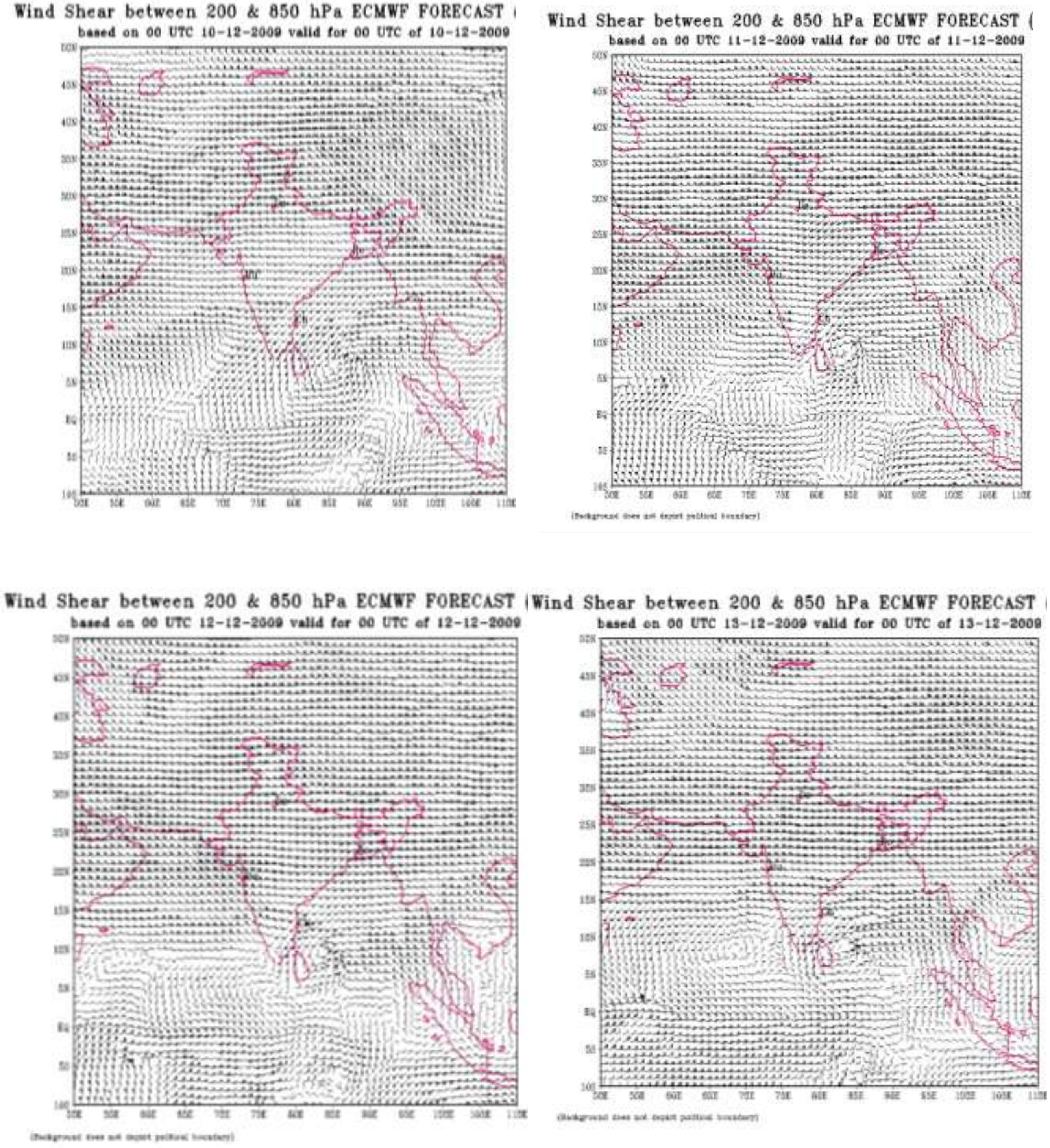


Fig.2.8.3.Vertical wind shear at 0000 UTC of 10, 11, 12 and 13 December 2009

2.8.4 Realised weather

2.8.5.1 Rainfall

In association with the cyclone, the northeast monsoon was vigorous over coastal Tamil Nadu and Puducherry during 13-16 December 2009. Widespread rainfall with isolated heavy to very heavy falls occurred over this region during this period. Details of the 24 hrs heavy rainfall events (7 cm or more) ending at 0300 UTC of date over coastal Tamil Nadu and Puducherry are given below.

13. 12. 2009
Sriperumbudhur (Kanchipuram district) and Vallam (Thanjavur district) 8 each and Poonamallee (Thiruvallur district) 7 cms.

14.12. 2009 : No heavy rainfall

15. 12. 2009
Sirkali(NPT)14, Thrangambadi (NPT), Rameshwaram (RMD) and Karaikal 11 each, Kollidam and Vedaranyam (both NPT) 10 each, Mayiladuthurai (NPT) and and Chidambaram (Cuddalore dt) 9 each, Kodavasal, Thiruthuraipoondi, Valangaiman (all Thiruvarur district) 7 each.

16. 12. 2009: No heavy rainfall

17. 12. 2009 :
Orathanadu and Vallam (both Thanjavur district) 11 each, Alangudi (Pudukottai district) 10, Parangipettai 9, Vedaranyam and Thirumayam(Pudukottai district) 8 each, Thozhudhur (Cuddalore district) Aranthangi and Arimalam (both Pudukottai district), Cheyyar (Thiruvannamalai district) 7 each.

2.8.5.2 Wind:

The maximum wind of 25 knots was reported by Pamban observatory in coastal Tamil Nadu during 15th December morning.

2.8.6 Damage:

As the system weakened and crossed north Sri Lanka coast as a deep depression, it did not cause any damage over the region.

CHAPTER – III

Performance of operational NWP models during the year 2009

3.1 Introduction:

India Meteorological Department operationally runs three regional models, Limited Area Model (LAM), MM5 model and Quasi-Lagrangian Model (QLM) for short-range prediction. The 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. Initial and boundary conditions are obtained from the NCEP Global Forecast System (NCEP GFS) readily available on the Internet at the resolution of 1 ^{o} x1 ^{o} lat. /long. The boundary conditions are updated at every six hours interval. The LAM is integrated up to 48 hours at the horizontal resolution of 0.75^{o}x0.75^{o} lat/long with 16 sigma levels in the vertical over the same domain using the initial and boundary conditions provided by T-80 Global operational model run at NCMRWF. The model is also made flexible to run with NCEP GFS outputs as initial and boundary conditions. The QLM model is used for cyclone track prediction in case of cyclone situation in the north Indian ocean. IMD also makes use of NWP products prepared by some other operational NWP Centres like, ECMWF (European Centre for Medium Range Weather Forecasting), GFS (NCEP), JMA (Japan Meteorological Agency) etc. A multimodel ensemble (ENSM) for predicting the track of tropical cyclones for the Indian Seas is developed. The ENSM 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 ENSM forecasts for four cyclones during 2009 are presented and discussed.

3.2 Cyclonic storm, "BIJLI "(14-17 April 2009)

3.2.1 Track and Landfall:

Fig. 3.1(a-c) display the forecast tracks of the cyclone, "BIJLI" by various NWP models (ECMWF, GFS, JMA, MM5, QLM, and ENSM) with the initial conditions of 00 UTC of 15, 16 and 17 April 2009 respectively. It is encouraging to note that all the NWP models consistently indicated that the cyclonic storm "BIJLI" would recurve towards the north-east. Although based on 00 UTC 0f 15.04.2009 GFS model showed westerly movement and the QLM model & ENSM track showed marginally touching Orissa coast, but during subsequent forecast hours they showed northeastward movement.

The forecast errors of member models based on different initial conditions and the corresponding consensus forecasts (ENSM) are summarized in Table 3.1. The tables show that ENSM forecasts could provide useful guidance under the circumstances of wide variations of individual models.

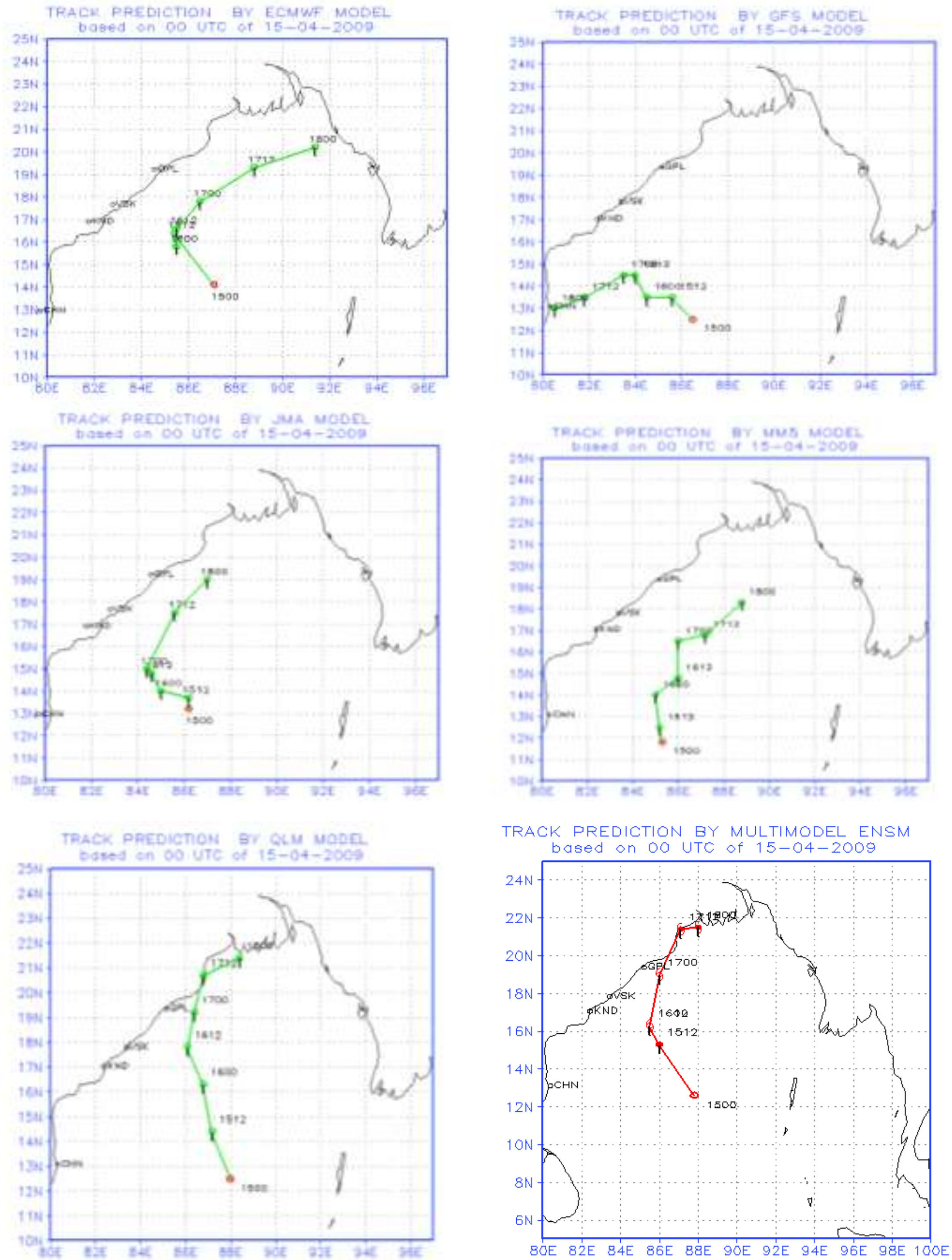


Fig.3.1 (a) Track forecasts of multimodel ENSM and its member models based on 00 UTC of 15.4.2009

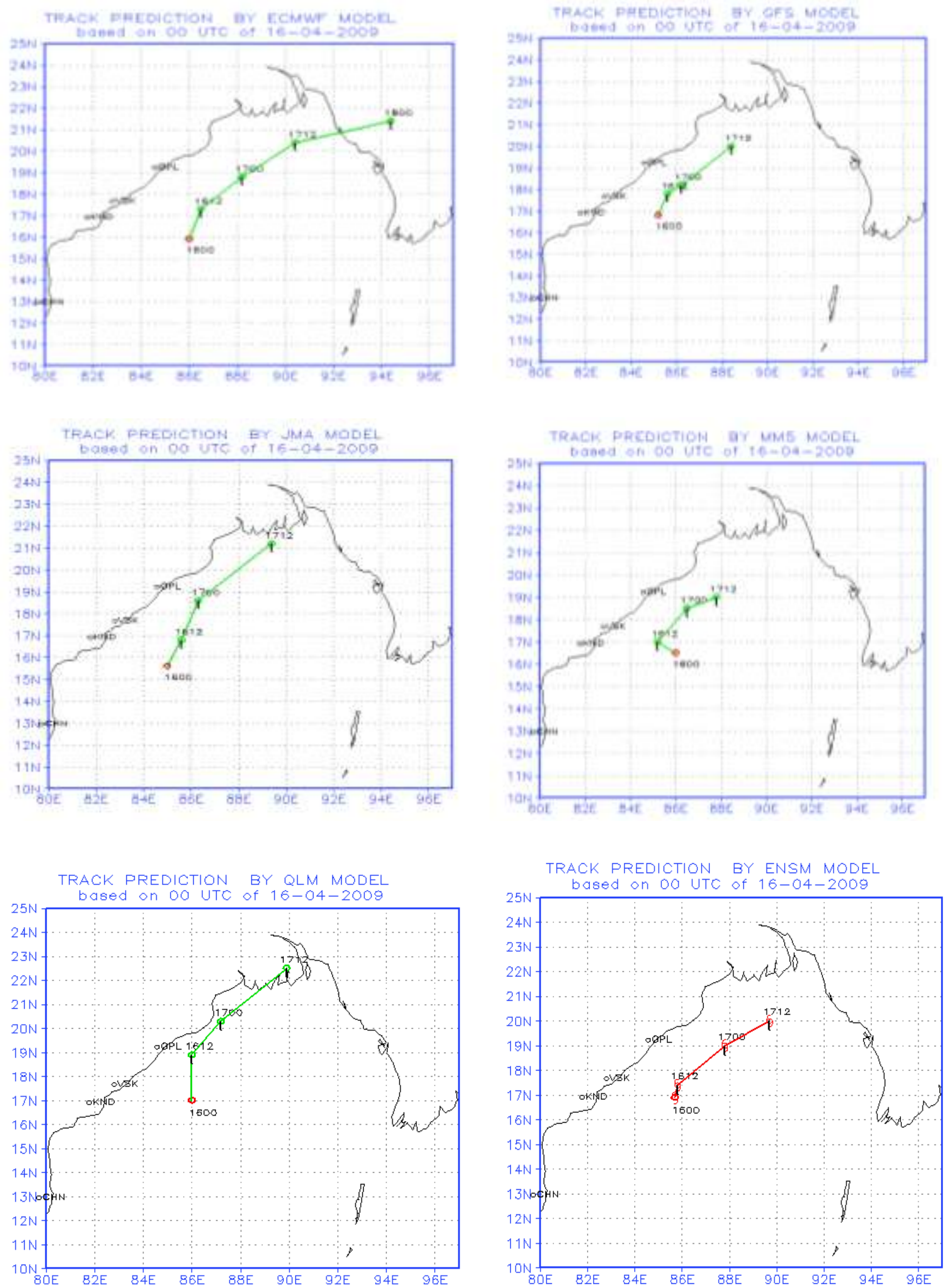


Fig.3.1 (b) Track forecasts of multimodel ENSM and its member models based on 00 UTC of 16.4.2009

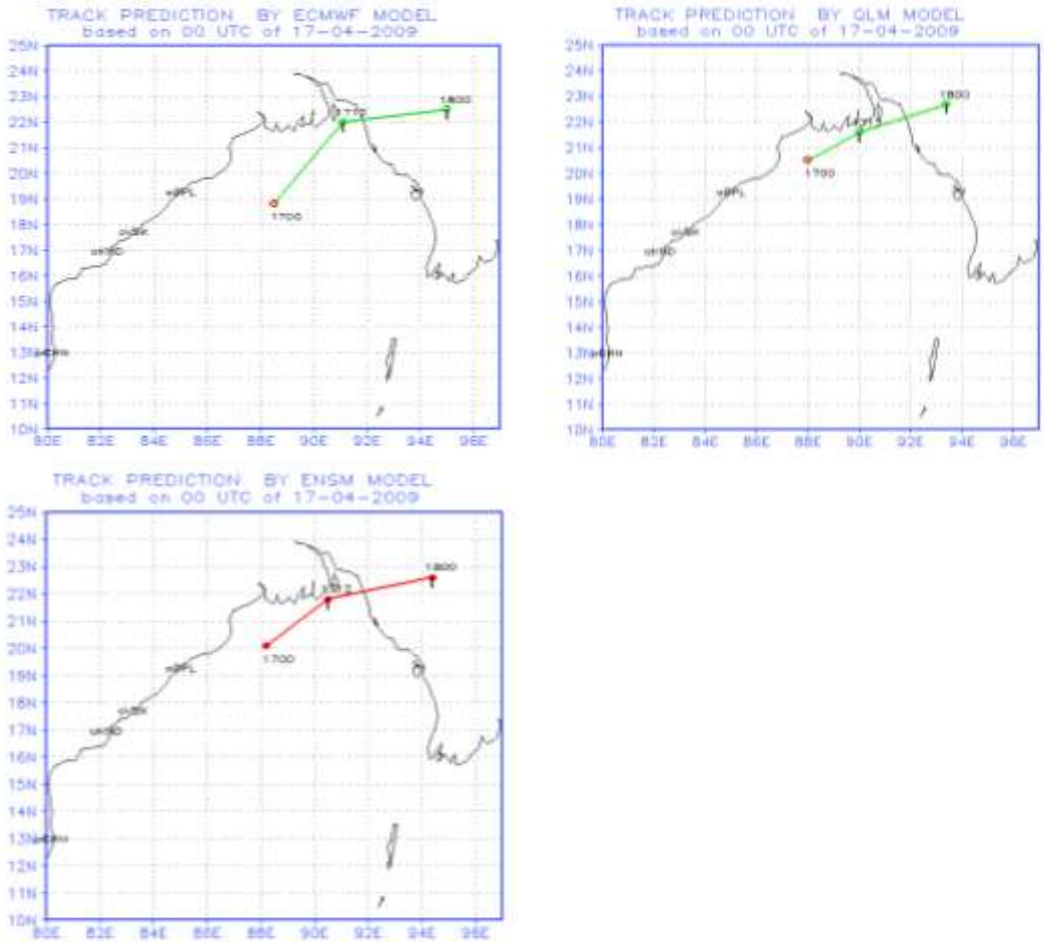


Fig.3.1(c) Track forecasts of multimodel ENSM and its member models based on 00 UTC of 17.4.2009

Table 3.1 (a) Track forecast error (km) of multimodel ENSM and its member models based on 00 UTC/15.4.2009

HOUR	ECMWF	GFS	JMA	MM5	QLM	ENSM
0	156	224	196	322	56	48
12	195	193	148	311	101	56
24	94	370	298	298	88	60
36	236	472	458	415	89	173
48	339	820	720	420	221	263
60	275	1242	640	599	343	261
LF error	NO LF	NO LF	NO LF	NO LF	582 km 9 hr early	601 km 10 hr early

L F: Landfall

Table 3.1 (b) Track forecast error (km) of multimodel ENSM and its member models based on 00 UTC/16.4.2009

HOUR	ECMWF	GFS	JMA	MM5	QLM	ENSM
0	67	92	146	0	56	55
12	133	123	212	216	69	143
24	190	318	276	272	86	168
36	129	235	71	360	112	170
LF error	167km 2h delay	Dissipated	Dissipated	Dissipated	292km 8h early	Dissipated

Table 3.1 (c) Track forecast error (km) of multimodel ENSM and its member models based on 00 UTC/17.4.2009

HOUR	ECMWF	GFS	JMA	MM5	QLM	MEAN ENSM
0	94	21	55	55	0	49
12	126	-	-	-	15	61
LF error	23km 4h Delay	Dissipated	Dissipated	Dissipated	10km 2h early	10km Close to landfall time

3.2.2. Genesis

Genesis Potential Parameters (GPP) values computed (Kotal et al, 2009) for cyclone "BIJLI" 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. The higher GPP values (> 8.0, the threshold value for T. 2.5) at early stages of development (T.No. 1.0, 1.5, 2.5) have clearly indicated that the cyclone "BIJLI" had enough potential to intensify into a developing system (>35 knots).

Table 3.2. GPP ($X10^{-5}$) for developing system, non-developing system and cyclone "BIJLI"

Date Time →	14-04-2009 0000 UTC	14-04-2009 1200 UTC	15-04-2009 0000 UTC	15-04-2009 1200 UTC
T.No. →	1.0	1.5	1.5	2.5
Developing system	11.1	12.3	12.3	13.5
Non-developing system	3.4	4.2	4.2	2.7
Cyclone, "BIJLI"	13.8	12.4	10.6	9.9

3.2.3. Intensity

The cyclone "BIJLI" intensified during the period 00UTC of 15 April to 00 UTC on 16 April and maintained its intensity with 40 knots wind for next 24 hours and weakened thereafter. The 12 hourly intensity forecast by Statistical intensity Prediction (SCIP) model valid up to 60 hours (Table 3.3) showed that the model could predict intensity up to 48 hours with reasonable success (with an error of 5 knots) but could not indicate weakening thereafter.

Forecast based on 00 UTC of 16 April and 00 UTC of 17 are shown in Table 3.3 (b) and 3.3 (c) respectively. The model showed gradual intensification and could not indicate weakening.

Table 3.3 (a). Model (SCIP) performance based on 00 UTC of 15 April 2009

Forecasts hours	00 hr	12 hr	24 hr	36 hr	48 hr	60 hr
Observed wind (knots)	30	35	40	40	40	25
Forecasts wind (knots)	30	33	35	41	45	60
Error (knots)	00	-2	-5	+1	+5	+35

Table 3.3 (b) Model (SCIP) performance based on 00UTC of 16 April 2009

Forecasts hours	00 hr	12 hr	24 hr	36 hr
Observed (knots)	40	40	40	25
Forecasts (knots)	40	44	49	60
Error (knots)	-	+4	+9	+35

Table 3.3 (c) Model (SCIP) performance based on 00 UTC of 17 April 2009

Forecasts hours	00 hr	12 hr
Observed (knots)	40	25
Forecasts (knots)	40	47
Error (knots)	-	+22

3.3 Severe Cyclonic storm "AILA" (23-26 May 2009)

3.3.2 Track and Landfall:

Fig. 3.2 (a-c) display the forecast track, of the cyclone "AILA" by various NWP models (ECMWF, GFS, JMA, MM5, QLM) and ENSM with the initial conditions at 00 UTC of 23, 24 and 25 May 2009. Most of the global NWP models consistently indicated northerly movement of the cyclonic storm "AILA". Although the based on 00 UTC 0f 23.05.2009 QLM model showed northwesterly movement and landfall over Orissa coast and MM5 model showed movement towards southeast Bangladesh coast during subsequent forecast hours they showed landfall near Indo Bangladesh border.

The forecast errors of member models based on different initial conditions and the ENSM are summarized in Table 3.4. The Tables showed that ENSM forecasts could provide useful guidance under the circumstances of wide variations of individual models.

Table 3.4 (a) Track forecast error (km) of multimodel ensemble and its member models based on 00 UTC/23.5.2009

HOUR	ECMWF	GFS	JMA	MM5	QLM	ENSM
0	123	187	201	185	0	15
12	15	86	40	216	61	31
24	81	94	115	383	85	75
36	91	33	75	341	115	67
48	50	76	0	303	199	127
60	168	152	124	372	346	114
72	270	226	224	475	559	295
LF error	20 km 10 hr delay	62 km 8 hr delay	40 km 6 hr delay	227 km 8 hr early	275 km 11 hr delay	83 km 2 hr delay

Table 3.4 (b) Track forecast error (km) of multimodel ensemble and its member models based on 00 UTC/24.5.2009

HOUR	ECMWF	GFS	JMA	MM5	QLM	ENSM
0	70	113	98	116	0	31
12	0	46	54	120	61	49
24	20	70	59	77	156	70
36	102	20	56	146	132	145
48	120	60	180	82	78	129
LF error	10km 5h delay	23km 1h delay	10km 1h delay	124km 4h delay	175km 8h early	20km 7h delay

Table 3.4(c) Track forecast error (km) of multimodel ensemble and its member models based on 00 UTC/25.5.2009

HOUR	ECMWF	GFS	JMA	MM5	QLM	ENSM
0	40	50	50	30	0	20
12	39	20	10	23	0	15
24	157	110	121	59	80	100
LF ERROR	10 km Close to LF time	15 km Close to LF time	15 km Close to LF time	20 km 2hr delay	10 km 2hr delay	15 km 2hr delay

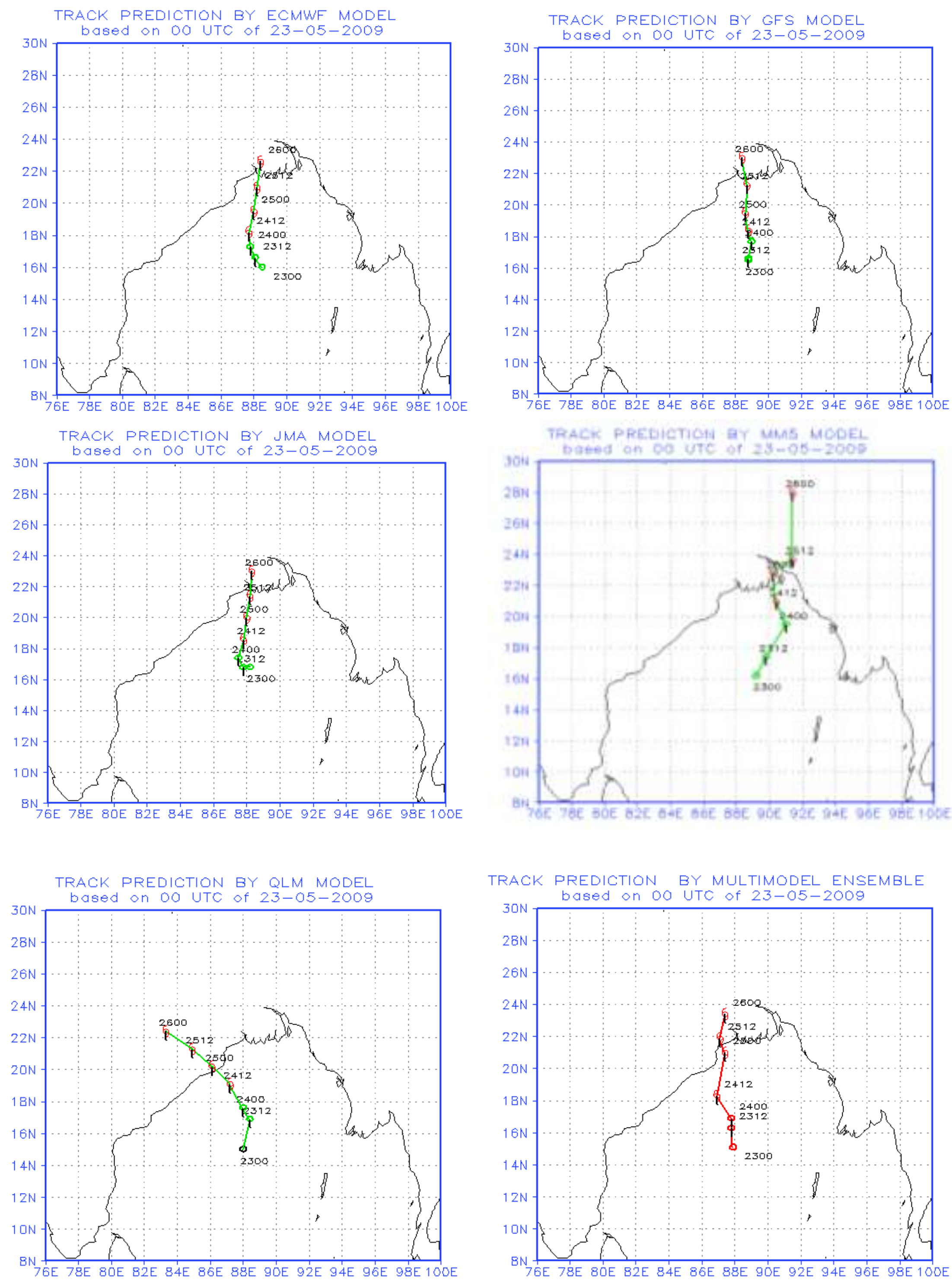


Fig.3.2 (a) Track forecasts of multimodel ensemble and its member models based on 00 UTC of 23.5.2009

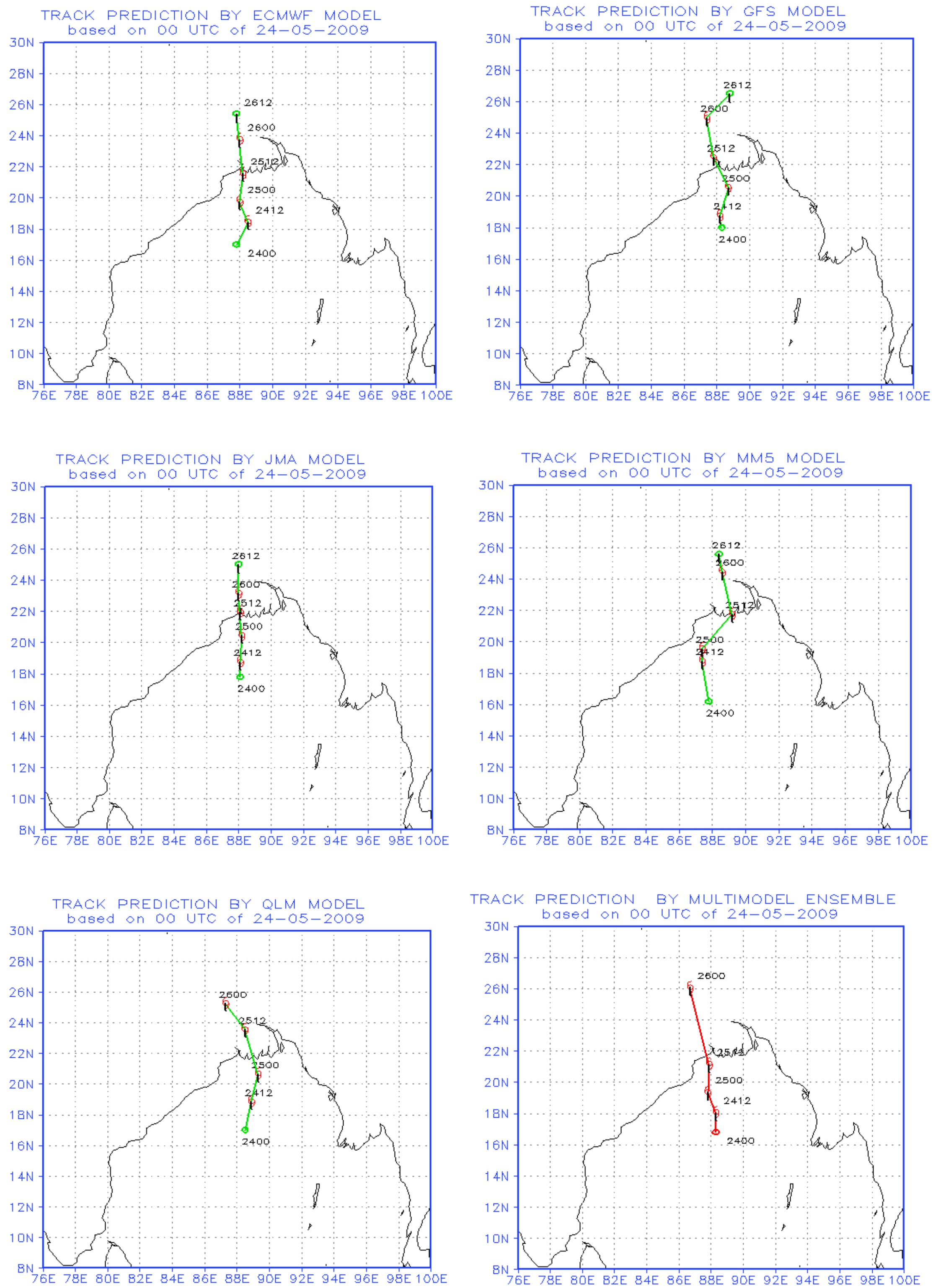


Fig.3.2(b) Track forecasts of multimodel ensemble and its member models based on 00 UTC of 24.5.2009

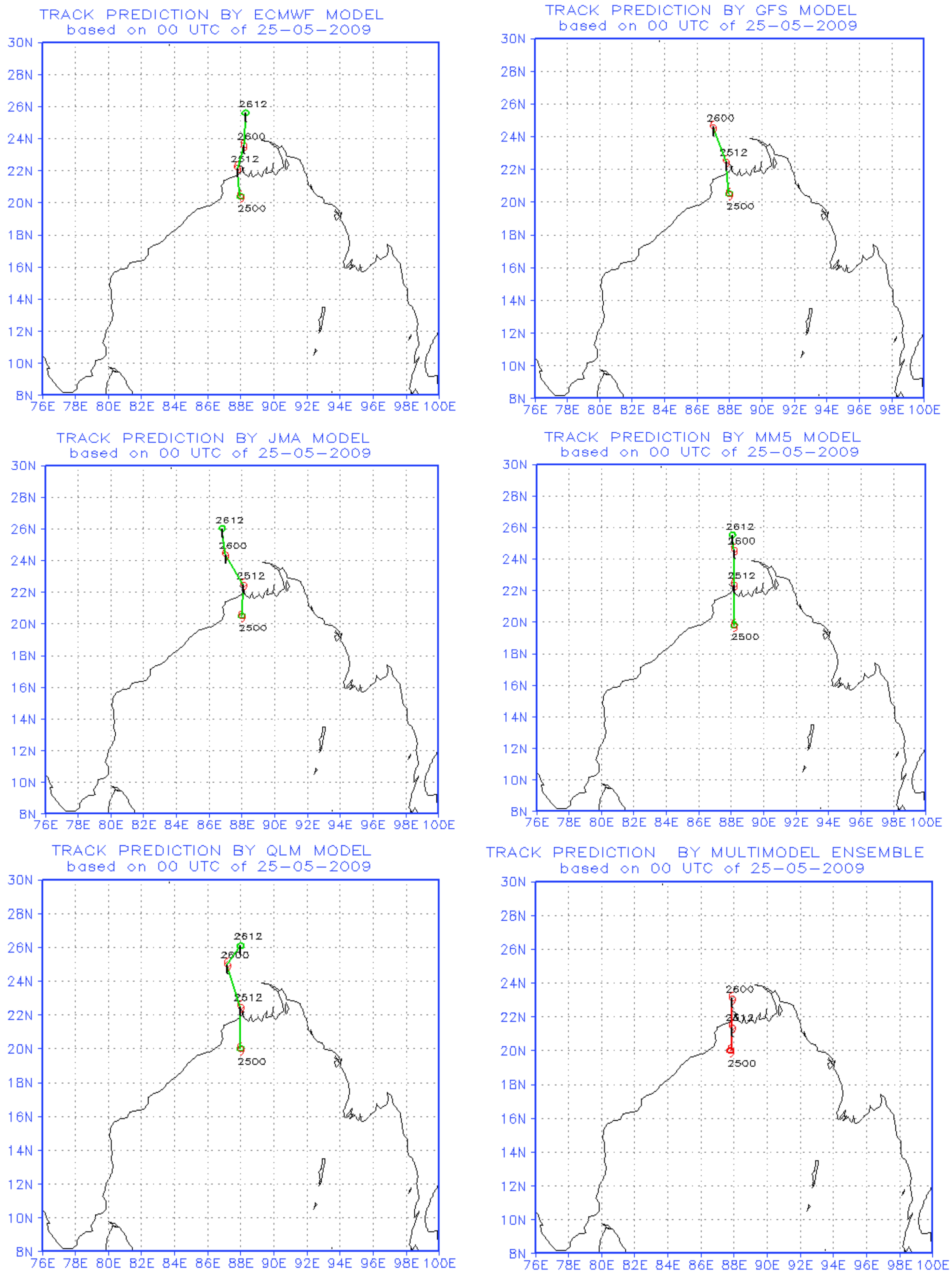


Fig.3.2 (c) Track forecasts of multimodel ensemble and its member models based on 00 UTC of 25.5.2009

3.3.1. Genesis

GPP values computed for this cyclone “AILA” 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. The higher GPP values (> 8.0, the threshold value for T>2.5) at early stages of development (T.No. 1.0, 1.5) clearly indicated that the cyclone “AILA” had enough potential to intensify into a developing system (>35 knots).

Table 3.5. Genesis potential parameter (GPP) for developing system, non-developing system and cyclone “AILA”

Date Time →	22-05-2009 0000 UTC	22-05-2009 1200 UTC	23-05-2009 0000 UTC	23-05-2009 1200 UTC
T.No. →	1.0	1.0	1.0	1.0
Developing Storm	11.1	11.1	11.1	11.1
Non-Developing Storm	3.4	3.4	3.4	3.4
Cyclone, “AILA”	20.0	20.0	14.3	14.9

3.3.3. Intensity

The cyclone “AILA” intensified gradually and maintained its intensification till landfall. It reached to its severe cyclonic storm stage at 0600 UTC of 25 May 2009. The 12 hourly intensity forecast (based on 00 UTC of 23 May 2009) valid up to 60 hours (Table 3.6) showed that the SCIP model could predict intensity with reasonable success with a maximum error of 10 knots at 48 hours.

The updated forecasts based on 00 UTC of 24 May and 00 UTC of 25 May showed improvement of error at all forecasts hour (Table 3.6).

Table 3.6 (a) Model (SCIP) performance based on 00 UTC of 23 May 2009

Forecasts hours →	00 hr	12 hr	24 hr	36 hr	48 hr	60 hr
Observed wind (knots)	20	25	25	35	40	50
Forecasts wind (knots)	20	25	31	43	50	55
Error (knots)	00	0	+6	+8	+10	+5

Table 3.6 (b). Model (SCIP) performance based on 00UTC of 24 May 2009

Forecasts hours →	00 hr	12 hr	24 hr	36 hr
Observed (knots)	25	35	40	50
Forecasts (knots)	25	32	38	49
Error (knots)	-	-3	-2	-1

Table 3.6 (c) . Model (SCIP) performance based on 00 UTC of 25 May 2009

Forecasts hours →	00 hr	12 hr
Observed (knots)	40	50
Forecasts (knots)	40	48
Error (knots)	-	+2

3.4. Cyclonic storm, "PHYAN " (9-11 November 2009)

3.4.1 Track and landfall

Fig. 3.3 (a-c) display the forecast tracks of the cyclone, "PHYAN" by various NWP models (ECMWF, GFS, JMA, MM5, QLM) and multimodel ENSM with the initial conditions at 0000 UTC of 10 November, 1200 UTC and 0000 UTC of 11 November 2009. The forecast showed northward movement by JMA model, northeastward movement by GFS model, north-northeastward movement by ECMWF model and northward movement (closely parallel to the Maharastra coast) by MM5, QLM and MME.

All the NWP models except ECMWF and GFS consistently indicated that the cyclonic storm "PHYAN" would move in a near northerly direction and cross South Gujarat coast. The ECMWF indicated north-northeastward movement with landfall over Maharastra coast near Mumbai. GFS model indicated northeastward movement with landfall over Maharastra coast near Ratnagiri. The forecast errors of member models based on different initial conditions and the corresponding MME forecasts are summarized in Table 3.7.

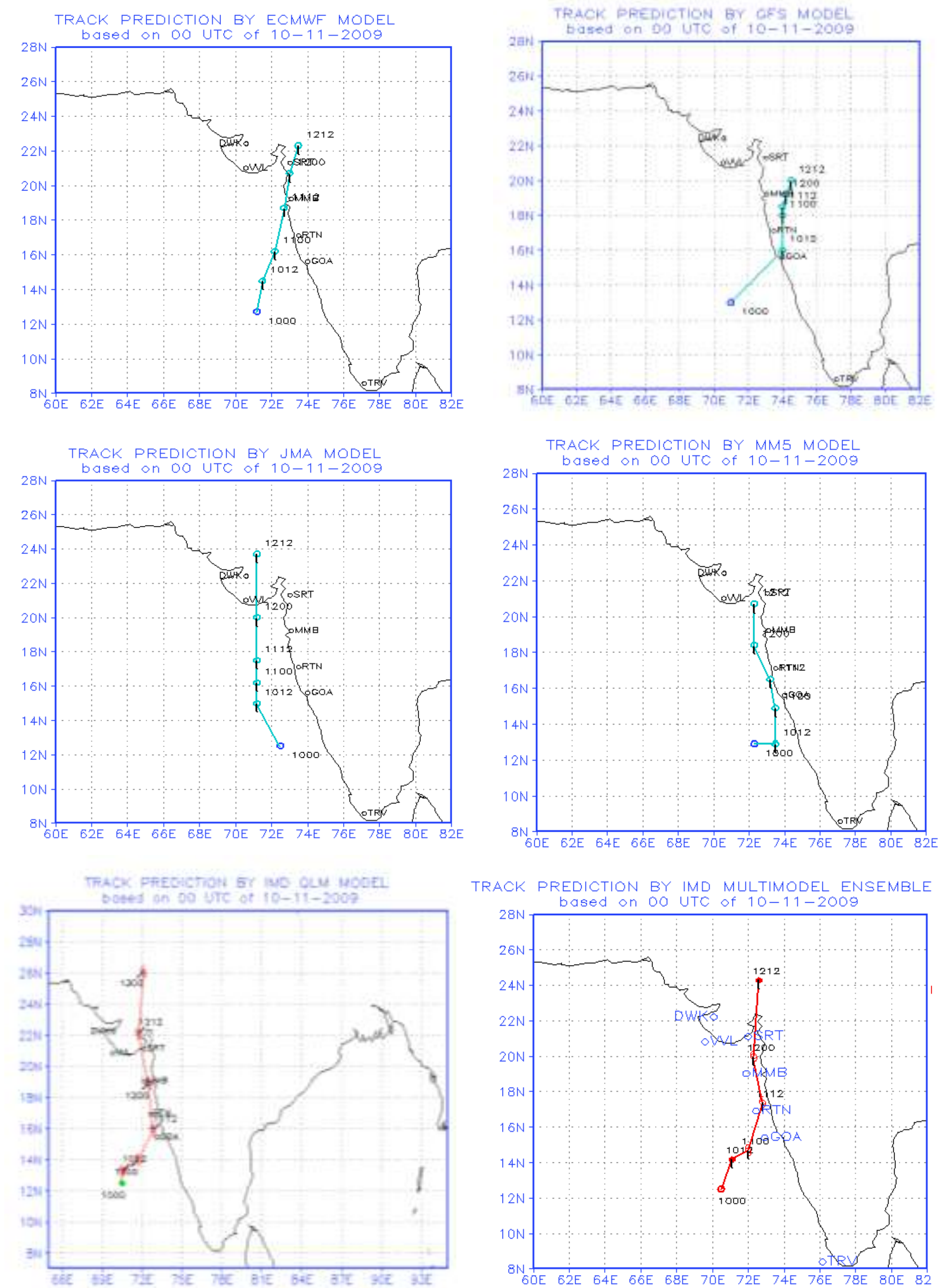


Fig.3.3 (a) Track forecasts of multimodel ensemble and its member models based on 0000 UTC of 10.11.2009

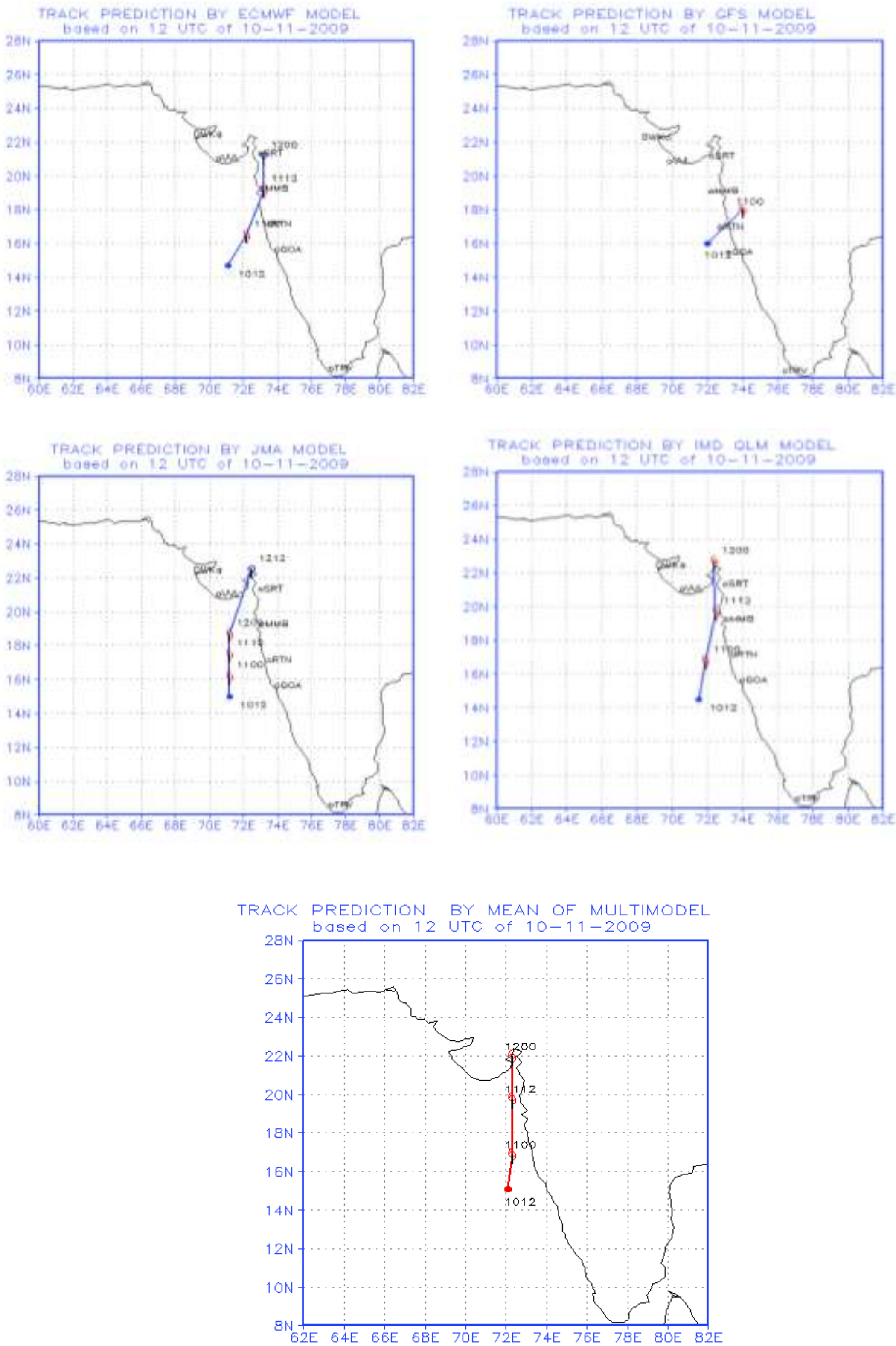


Fig.3.3 (b) Track forecasts of multimodel ensemble and its member models based on 1200 UTC of 10.11.2009

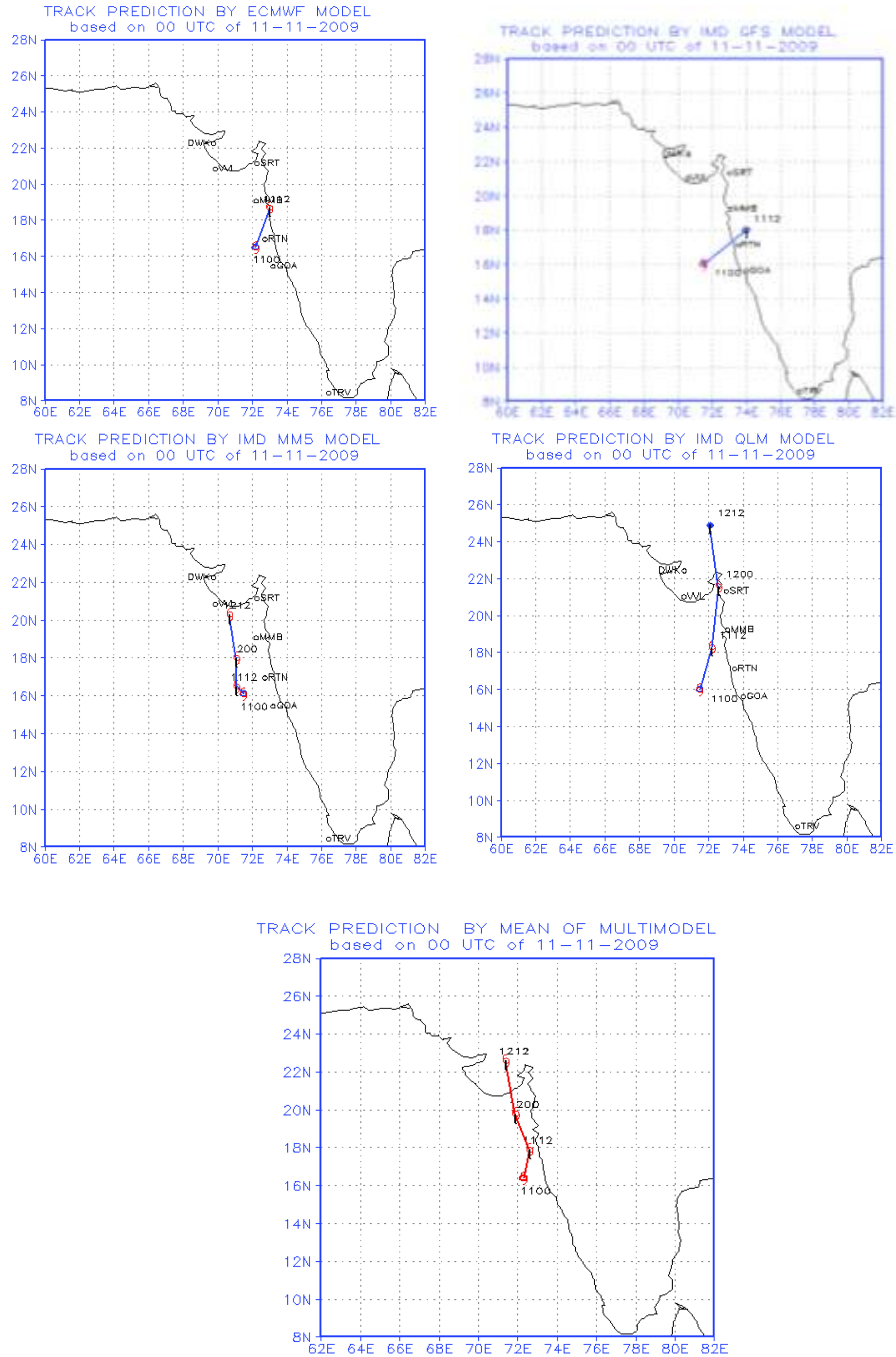


Fig.3.3 (c) Track forecasts of multimodel ensemble and its member models based on 0000 UTC of 11.11.2009

Table 3.7 (a) Track forecast error (km) of multimodel ensemble and its member models based on 0000 UTC of 10.11.2009

Forecast Period	ECMWF	GFS	JMA	MM5	QLM	MME
0	86	78	220	201	0	0
12	55	362	62	322	144	35
24	85	346	38	248	223	154
36	115	123	325	339	406	277
LF error	38 km 2 hr delay	468 km 27 hr early	271 km 16 hr delay	NO LF Till 72 hr	303 km 12 hr delay	344 km 20 hr delay

Table 3.7 (b): Track forecast error (km) of multi-model ensemble and its member models based on 1200 UTC/10.11.2009

HOUR	ECMWF	GFS	JMA	QLM	MEAN MME
0	51	362	62	55	136
12	94	346	38	99	131
24	38	-	325	107	130
LF error	Close to LF 1 hr early	220 km 15 hr early	220 km 24hr delay	265 km 10 hr delay	272 20hr delay

Table 3.7 (c) Track forecast error (km) of multi-model ensemble and its member models based on 0000 UTC/11.11.2009

HOUR	ECMWF	GFS	MM5	QLM	MEAN MME
0	97	288	15	0	96
12	99	175	421	191	201
LF ERROR	Close to LF 1 hr delay	190 km 2 hr early	Dissipated	275 km 14 hr delay	290 11 hr delay

3.4.2 Genesis

GPP values computed for this cyclone on the basis of real time model analysis fields along with the GPP values for developing and non-developing systems are shown in Table 3.8. The higher GPP values (> 8.0, the threshold value) at early stages of development (T.No. 1.0, 1.5, 2.0) clearly indicated that the cyclone “PHYAN” had enough potential to intensify into a developing system (>35 knots).

Table 3.8 Genesis potential parameter (GPP) for developing system, non-developing system and Cyclone “PHYAN”

Date Time →	07.11.09 0000 UTC	07.11.09 1200 UTC	08.11.09 0000 UTC	08.11.09 1200 UTC	09.11.09 0000 UTC	09.11.09 1200 UTC	10.11.09 0000 UTC	10.11.09 1200 UTC
T.No.	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.5**	**1.5**	**2.0**
Developing system	11.1	11.1	11.1	11.1	11.1	12.3	12.3	13.3
Non-developing system	3.4	3.4	3.4	3.4	3.4	4.2	4.2	4.6
PHYAN	8.6	10.0	13.9	11.1	11.6	28.2	18.9	17.9

3.4.3 Intensity prediction by SCIP model

The 12 hourly intensity forecast based on 0000 UTC of 10 November 2009 valid up to 24 hours (Table 3.9) along with the near landfall time intensity forecast shows that the model could predict intensity with reasonable success with a maximum error of 3 knots (underestimation) at 24 hours.

Table 3.9 Model (SCIP) performance based on 0000 UTC of 10 November 2009

Forecasts hours (	00 hr	12 hr	24 hr	At landfall Time
Observed wind (knots)	25	30	40	40
Forecasts wind (knots)	25	32	37	41
Error (knots)	00	+2	-3	+1

3.5 Bay of Bengal Severe Cyclonic storm “WARD” (10-15 December, 2009)

HYPERLINK "http://en.wikipedia.org/wiki/Cyclone_Aila" \l "cite_note-35"The cyclogenesis of the system could be well predicted by various NWP models. However, there were large variations in the prediction of intensity and track of the cyclone. While some models predicted southwestward movement across Sri Lanka, a few models predicted northwestward movement towards north Tamil Nadu coast. Initial northerly movement of the system could not be predicted by none of the NWP models. However, MM5 based on GFS predicted recurvature of the system towards northeast without making landfall over Sri Lanka or Tamil Nadu. The intensity of the system was under predicted by all the models. However, the trend in intensity variation like initial intensification and weakening thereafter was predicted by many models. The detailed performance of various models are discussed below.

3.5.1 Genesis

The GPP values computed for the cyclone”WARD” on the basis of real time model analysis fields along with the GPP values for developing and non-developing systems are shown in Table 3.10. The higher GPP values (> 8.0, the threshold value) at early stages of development (T.No. 1.0 - 2.5) have clearly indicated that the low pressure system had enough potential to intensify into a developing system.

Table 3.10 Genesis potential parameter GPP ($X10^{-5}$) for Developing Systems, Non-Developing Systems and cyclone “WARD” of (10 -15) December 2009 over Bay of Bengal.

Date/Time (UTC)	10.12.09 0000 UTC	10.12.09 1200 UTC	11.12.09 0000 UTC	11.12.09 1200 UTC
T.No. →	1.0	1.5	2.0	2.5
Developing system	11.1	12.3	13.3	13.5
Non-developing system	3.4	4.2	4.6	2.7
Cyclone “WARD”	20.5	23.2	26.0	25.7

3.5.2 Intensity

The performance of the SCIP model based on 0000 UTC of 11, 12 and 13 Dec. 2009 ate shown in Table 3.11.

Table 3.11(a) Model (SCIP) performance based on 0000 UTC of 11 December 2009

Forecasts hours →	00 hr	12 hr	24 hr	36 hr	48 hr
Observed wind (knots)	30	35	45	35	30
Forecasts wind (knots)	30	33	30	31	30
Error (knots)	00	-2	-15	-4	0

Table 3.11(b) Model (SCIP) performance based on 0000 UTC of 12 December 2009

Forecasts hours	00 hr	12 hr	24 hr	36 hr	48 hr
Observed wind (knots)	45	35	30	30	30
Forecasts wind (knots)	45	49	45	45	45
Error (knots)	00	+14	+15	+15	+15

Table 3.11(c). Model (SCIP) performance based on 0000 UTC of 13 December 2009

Forecasts hours	00 hr	12 hr	24 hr	36 hr	48 hr
Observed wind (knots)	30	30	30	25	25
Forecasts wind (knots)	30	34	34	30	27
Error (knots)	00	+4	+4	+5	+2

The initial intensification and then weakening could not be predicted on 11 December, resulting in relatively higher 24 hrs forecasts and then weakening based on 0000 UTC of 12 and 13 December, the system only gradually weakened on both the days.

3.5.3 Track and landfall

The tracks of the system based on NWP models and multi-model ensemble with initial conditions at 0000 UTC of 11, 12 and 13 December 2009 are shown in Fig.3.4 (a-c). The track and landfall forecast errors are given in Table 3.12.

Table 3.12 (a) Track forecast error (km) of multimodel ensemble and its member models based on 0000 UTC/11.12.2009

HOUR	ECMWF	GFS	JMA	MM5	QLM	MME
0	201	123	83	94	0	0
12	123	330	67	55	126	163
24	173	418	259	97	192	221
36	267	110	110	121	208	197
48	317	173	333	314	343	320
60	507	223	467	466	584	353
72	296	298	358	611	716	309
LF ERROR	89 km 28 hr early	Closed 14 hr early	NO LF	NO LF	NO LF	119 km 32 hr early

Table 3.12 (b) Track forecast error (km) of multimodel ensemble and its member models based on 0000 UTC/12.12.2009

HOUR	ECMWF	GFS	JMA	MM5	QLM	MEAN MME
0	52	55	259	47	0	0
12	99	104	283	65	91	108
24	193	146	255	165	297	238
36	243	239	496	327	548	385
48	267	239	394	467	675	329
60	185	335	271	683	868	327
72	227	300	358	779	1034	271
LF ERROR	81 km 26 hr early	NO LF	10 km 44 hr early	NO LF	517 km 20 hr early	254 km 10 hr early

Table 3.12 (c) Track forecast error (km) of multimodel ensemble and its member models based on 0000 UTC/13.12.2009

HOUR	ECMWF	GFS	JMA	MM5	QLM	MEAN MME
0	114	119	187	40	0	0
12	156	160	301	144	113	112
24	124	160	388	262	135	55
36	140	78	404	492	247	78
48	210	0	393	594	336	55
LF ERROR	65 km 8 hr early	60 km 14 hr early	Closed 18 hr early	NO LF	442 km 20 hr delay	89 km Near LF Time

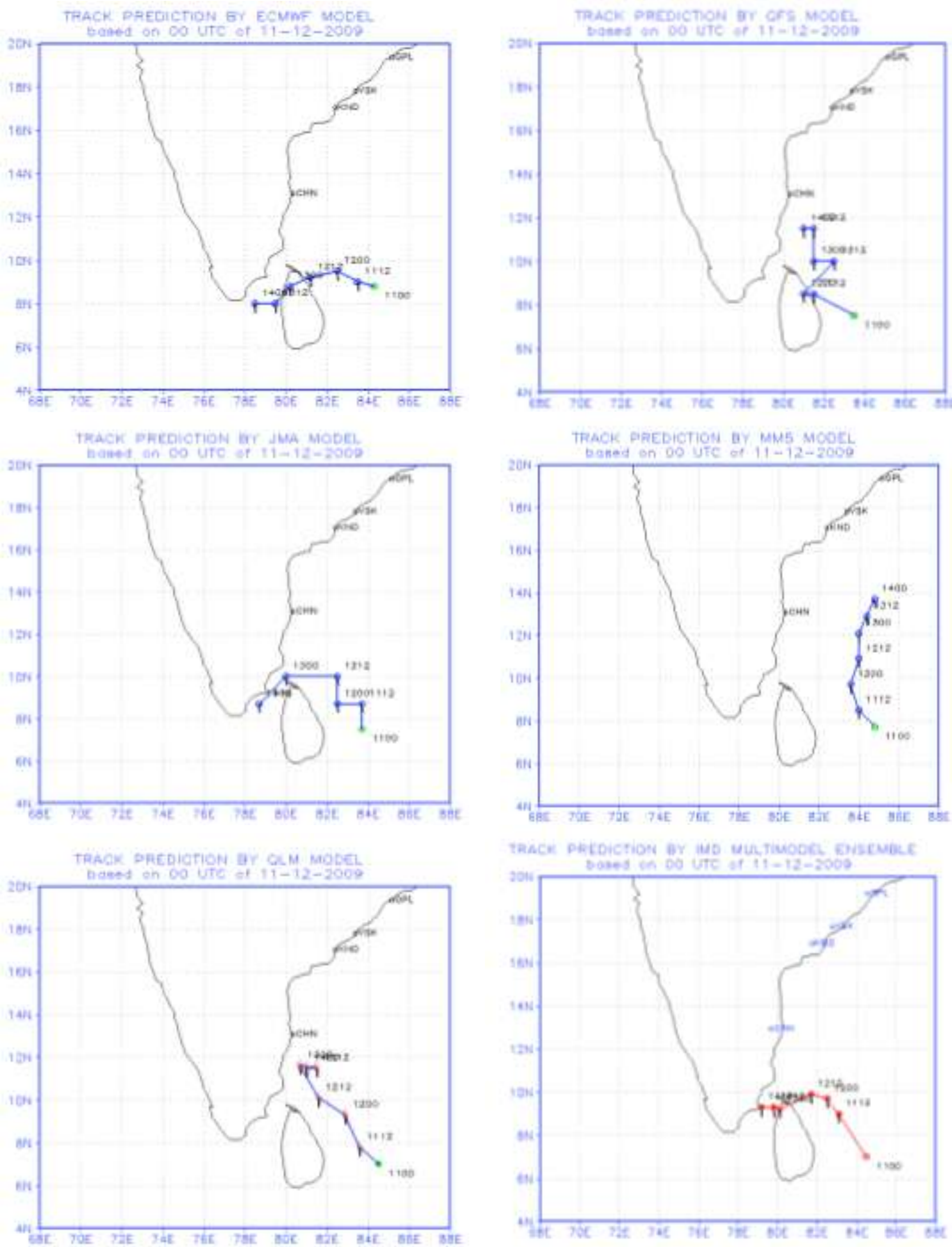


Fig. 3.4 (a) Track forecasts of multi-model ensemble (MME) and its member models based on 0000 UTC/11.12.2009

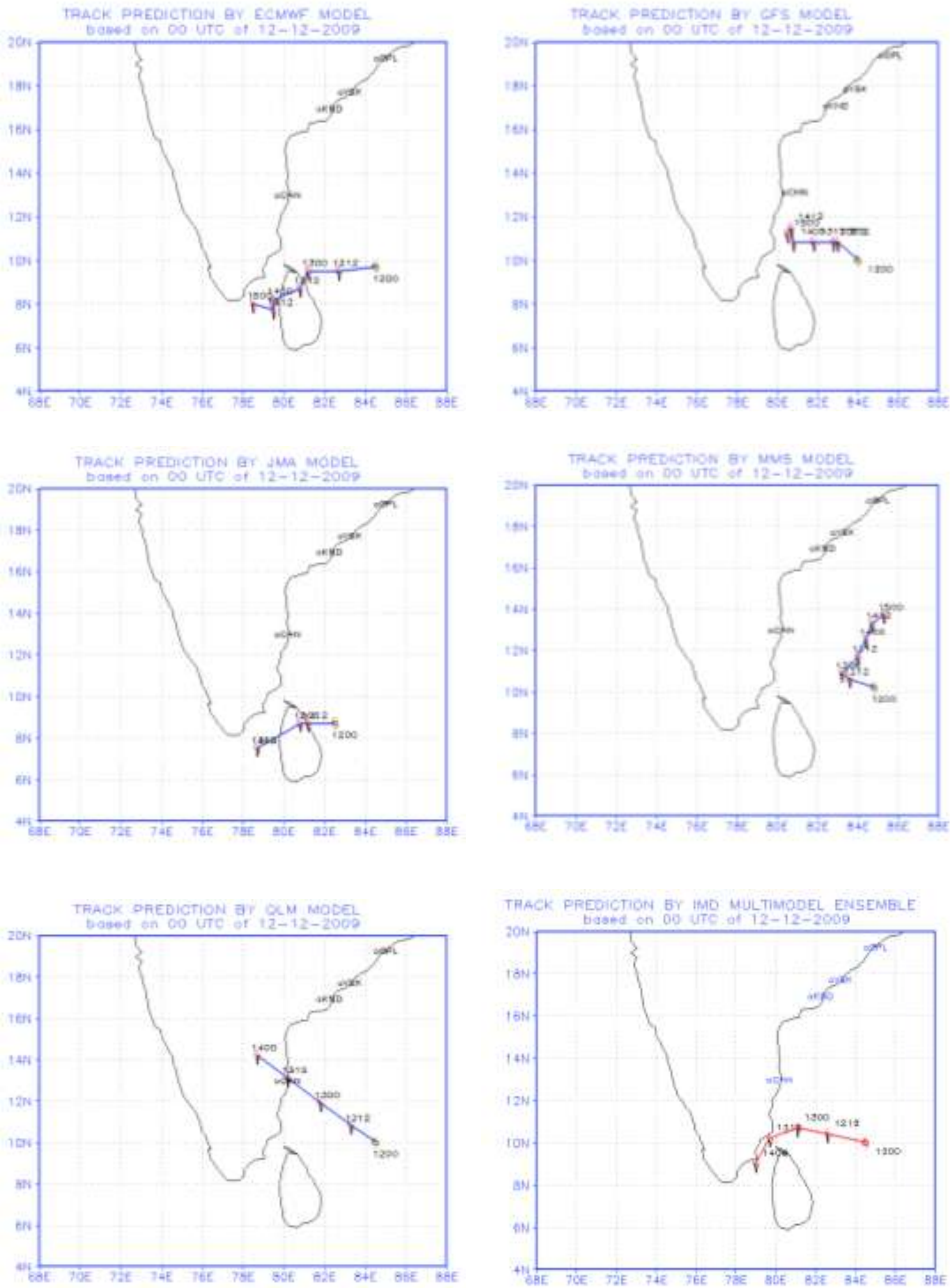


Fig.3.4 (b) Track forecasts of multi-model ensemble (MME) and its member models based on 0000 UTC/12.12.2009

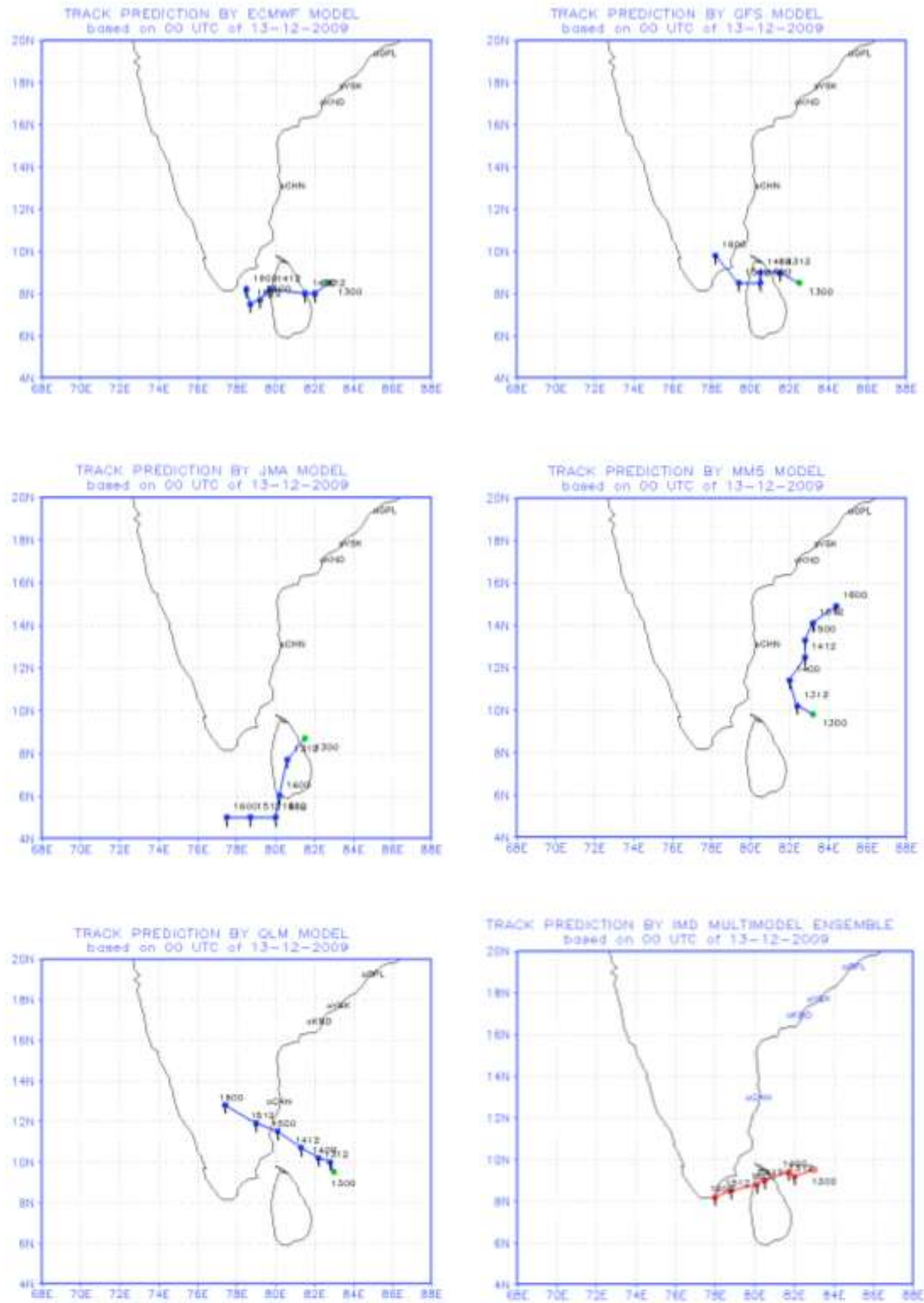


Fig.3.4 (c) Track forecasts of multimodel ensemble and its member models based on 0000 UTC/13.12.2009

CHAPTER-IV

PERFORMANCE OF CYCLONE WARNING DIVISION, NEW DELHI IN TRACK AND INTENSITY PREDICTION OF CYCLONES DURING 2009

4.1. Introduction

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. Another new initiative was the introduction of cone of uncertainty in the track forecast with effect from cyclone, WARD. The graphical display of the observed and forecast track was 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. The prognostics and diagnostics of the systems were described in the special tropical weather outlook and tropical cyclone advisory bulletins like that during 2008.

The statistics of bulletins issued by IMD, New Delhi with respect to cyclonic disturbances is presented in sec.4.2. The performance of RSMC-New Delhi in track and intensity prediction of the four cyclones during 2009 are analysed and discussed in sec.4.3.

4.2. Bulletins issued by IMD

IMD 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. AS RSMC, it issued tropical weather outlook and tropical cyclone advisories to WMO/ESCAP Panel member countries in regular intervals. As tropical cyclone advisory centre (TCAC), it also issued tropical cyclone advisories for international civil aviation purpose as per the requirement of international civil aviation organization (ICAO). The following are the statistics of bulletins issued by IMD in association with the cyclonic disturbances during 2009.

Bulletins issued during 'BIJLI'

Bulletins for Indian coast : 25
RSMC bulletin for WMO/ESCAP Panel member countries:
(Special Tropical Weather Outlook and Tropical Cyclone Advisory): 25
TCAC bulletin for international civil aviation : 08

Bulletins issued during 'AILA'

Bulletins for Indian coast : 21
RSMC bulletin for WMO/ESCAP Panel member countries:
(Special Tropical Weather Outlook and Tropical Cyclone Advisory): 13
TCAC bulletin for international civil aviation: 05

Bulletins issued during 'PHYAN'

Bulletins for Indian coast : 17
RSMC bulletin for WMO/ESCAP Panel member countries:
(Special Tropical Weather Outlook and Tropical Cyclone Advisory): 09
TCAC bulletin for international civil aviation: 03

Bulletins issued during `WARD'

Bulletins for Indian coast: 32
RSMC bulletin for WMO/ESCAP Panel member countries:
(Special Tropical Weather Outlook and Tropical Cyclone Advisory): 28
TCAC bulletin for international civil aviation: 07

Bulletins issued for all cyclones during 2009

Bulletins for Indian coast: 95
RSMC bulletin for WMO/ESCAP Panel member countries:
(Special Tropical Weather Outlook and Tropical Cyclone Advisory): 75
TCAC bulletin for international civil aviation: 23

Bulletins issued for all cyclonic disturbances during 2009

Bulletins for Indian coast: 140
RSMC bulletin for WMO/ESCAP Panel member countries:
(Special Tropical Weather Outlook and Tropical Cyclone Advisory): 89
TCAC bulletin for international civil aviation: 23

4.3. Performance of Operational Track and landfall forecast

The performance of operational genesis, track and intensity forecasts issued by IMD, New Delhi for four cyclones during 2009 are described below.

4.3.1. Cyclone, `BIJLI' (14-17 April 2009)

Genesis:

In the Weekly Weather Bulletin of 8th April 2009, it was predicted that a low pressure was likely to form over southeast & adjoining southwest Bay of Bengal around 13th April which was realized.

Intensity:

Forecast of maximum intensity	: T3.0
Actual maximum intensity	: T2.5
Intensity error (T No. /Wind speed)	: 0.5 T/ 10 knots
Forecast wind speed at the time of landfall	: 40-50 kmph gust 60 kmph along and Off Bangladesh coast
Actual wind speed at the time of landfall	: 30 knots (Cox Bazar)

Track and landfall

Based on observation and analysis at 0900 UTC of 14 April 2009 it was predicted that the system would likely move in a northwesterly direction initially. Based on observation and analysis, at 0600 UTC of 15 April 2009 indication of the recurvature of the system was predicted and its movement in north-northeasterly direction towards Bangladesh coast was predicted based on 1200 UTC of 15 April 2009. As per the actual track, the system moved initially in a northwesterly/north-northwesterly direction and then recurved north-northeastwards towards Bangladesh coast. The performance of landfall forecast is shown in Table 4.1. The track forecast errors are shown in Table 4.2.

Table 4.1: Landfall point and Time error of RSMC, New Delhi during cyclonic storm "BIJLI"

Base Chart (UTC)	Forecast hours	Landfall Forecast		Actual Landfall		Error	
		Position (Lat ON /Long° E)	Date/Time (UTC)	Position (Lat ^{O}N /Long° E	Date/Time (UTC)	Distance (Km)	Time (hrs)
151800	48	22.0/90.3	18/1000	22.2/91.8	171600	155	18 D
160600	36	22.0/92.0	18/1800	-do-	-do-	30	26D
161800	24	21.9/92.0	18/0800	-do-	-do-	40	08D
170600	12	22.2/92.0	17/1800	-do-	-do-	20	02D

D- forecast landfall time was delayed compared to actual landfall time.

Table 4.2. average track forecast errors of cyclone, BIJLI

Forecast period	Track error (km)
12 hours	79
24 hours	171
36 hours	314
48 h rs	412

4.3.2. Severe cyclonic storm, 'AILA' (23-26 May 2009)

Genesis

Likely formation of a low pressure area over central Bay of Bengal, its intensification into a depression and movement towards Bangladesh coast was predicted on All India Weekly Weather Report issued on 20 May 2009.

According to All India daily weather report, a low pressure area formed over east central Bay of Bengal on 22nd morning and concentrated into a depression at 0600 UTC of 23 May 2009.

Intensity

The likely intensification of the system into a cyclonic storm was first indicated in the warning bulletin issued by IMD at 0800 UTC based on the observation of 0600 UTC of 23 May 2009, when the system was first declared as a depression. Hence the likely intensification of the cyclonic storm was predicted about 30 hrs in advance, as the depression intensified into a cyclonic storm at 1200 UTC of 24 May 2009. Further intensification of the system was also predicted at 1400 UTC based on 1200 UTC of 24 May and the system crossed coast as a severe cyclonic storm on 25 May between 0800 and 0900 UTC. Considering the forecast in terms of T number, the maximum intensity was predicted to be T3.5 at the time of landfall. Detailed statistics are given below and Table 4.3.

Base time of issue of forecast for intensification
into a cyclonic storm : 0600 UTC of 23 May 2009
Actual time of intensification into cyclonic storm : 1200 UTC of 24 May
Forecast of maximum intensity (T No) : T3.5 at 1200 UTC of 24 May
Actual maximum intensity : T3.5 at 0600 UTC of 25 May

Table 4.3. Verification of maximum wind forecast issued by IMD

Base Time (UTC)	Forecast hours	Forecast maximum wind (kmph) at time of landfall	Actual wind (kmph)
231200	45	60-90	Kolkata :95
240300	30	75 gusting to 85	Kanagarh :Kalaikunda
240600	27	85 gusting to 95	112 Barrackpore
241200	21	95 gusting to 105	102
242100	12	100 gusting to 110	Kakdwip,
250600	03	100-110 gusting to 120	75

Considering maximum wind reported as 112 kmph, 24 hours wind forecast error was about 17 kmph (09 knots)

Track and landfall

The landfall point forecast errors and landfall time forecast errors are given in Table 4.4(a) and 4.4(b) respectively. The track forecast errors of AILA are given in Table 4.5

Table 4.4(a). Landfall forecast errors of severe cyclonic storm, AILA.

Base time (UTC)	Forecast hours	Forecast landfall point	Actual landfall point	Error (Km)
231200	45	21.8°N/89.0°E	21.8°N/88.0°E	110
240300	30	21.8°N/89.0°E	-do-	110
241200	21	21.8°N/88.5°E	-do-	55
250300	06	21.8°N/88.0°E	-do-	0

Table 4.4(b). Landfall forecast time errors of severe cyclonic storm, AILA.

Base Time (UTC)	Forecast hours	Forecast landfall time (UTC)	Actual landfall time (UTC)	Error (hrs)
231200	45	251230	250830	04
240300	30	251230	-do-	04
241200	21	251230	-do-	04
250300	06	251230	-do-	04

107

Table 4.5. Average track forecast error of severe cyclonic storm 'AILA'

Forecast period	**Track error (km)**
12 hours	78
24 hours	112
36 hours	133

It indicates that landfall point forecast errors was about 110 km with time error of about 4 hours in the forecast issued about 43 hrs in advance. Similarly, landfall point forecast errors was about 55 km with time error of about 4 hours in the forecast issued about 19 hrs in advance.

4.3.3. Cyclonic Storm, `PHYAN' (09-12 November 2009)

Genesis and intensity

The genesis of the system was predicted 2 days in advance, as likely intensification of low pressure area into a depression was indicated in the daily bulletins issued on 7 November and the system intensified into depression on 9 November. The maximum intensity was predicted to be T3.0 and actual intensity was found to be T3.0. The wind predicted at the time of landfall was 70-80 kmph and reported maximum wind was 75 kmph.

Track and landfall

The landfall and track forecast errors of cyclone, 'PHYAN' are shown in Table 4.6 and 4.7 respectively. The operational landfall forecast error for this system has been 75 km and 250 km respectively for 12 and 24 hr forecasts.

Table 4.6. Landfall forecast errors of cyclonic storm, PHYAN

Based Time (UTC)	Forecast hours	Landfall Forecast		Actual Landfall		Error	
		Position (Lat °N /Long° E)	Date/Time (UTC)	Position (Lat° N /Long° E	Date/Time (UTC)	Distance (Km)	Time (hrs)
100300	36	21.0/72.9	11/2030	18.7/72.9	11/1030	250	10D
101200	24	21.0/72.9	11/2030	18.7/72.9	11/1030	250	10D
110000	12	19.5/72.8	11/1530	18.7/72.9	11/1030	75	5D

D: Forecast landfall time is delayed compared to actual landfall time**.**

Table 4.7. Mean track forecast errors of cyclonic storm, 'PHYAN'

Forecast period	**Track error (km)**
12 hours	89
24 hours	145
36 hours	217

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

4.3.4. Cyclonic Storm, `WARD' (10-14 December 2009)

Genesis and intensity

The genesis of the system was well predicted two days in advance. The intensity of the system was well predicted by IMD in its operational forecast. The intensification into a cyclonic storm with sustained maximum surface wind of 65-75 kmph (40knots) gusting to 85 kmph was first predicted by IMD based on the observation of 0000 UTC of 11 December, while the system became cyclonic storm at 0900 UTC and attained maximum intensity of 83 kmph (45 knots) at 21 UTC of 11 December 2009.

The weakening of the system was also indicated in the bulletin. The sign of weakening was first indicated in the bulletin based on 0600 UTC of 12 December 2009.

Track and landfall

The operational landfall forecast error of RSMC, New Delhi for this system has been 78 km for both 24 and 48 hrs forecasts. The details of the landfall forecast error are given in Table 4.8. Considering the operational track forecast errors, The average errors was about 124 and 221 km for 12hr and 24 hr forecast (Table 4.9). 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 4.8. Landfall forecast error of cyclone, WARD

Forecast period And Base Date/Time (UTC)	Forecast landfall point (Deg. Lat/Long)	Actual landfall point (Deg. Lat/Long)	Landfall point error (km)	Forecast landfall Time (Date/Time in UTC)	Actual time of landfall(Date/Time in UTC)	Error (hours)
12 hours 14/0000	9.0/80.8	8.5/81.3	78	14/0630	14/0830	2 E
24 hours 13/1200	9.0/80.8	8.5/81.3	78	14/0630	14/0830	2 E
36 hours 13/0000	9.0/80.8	8.5/81.3	78	13/1230	14/0830	20 E
48 hours 12/1200	9.0/80.8	8.5/81.3	78	13/0630	14/0830	26 E

E: Forecast landfall time is earlier to actual landfall time.

Table 4.9 Mean track forecast errors of cyclone WARD

Forecast period (hours)	Track error (km)
12	124
24	221
36	308
48	401
72	481

4.3.5. Average forecast error of 2009

The average landfall forecast errors during 2009 are shown in Table 4.10. The landfall point forecast errors are quite below the long period average, as the 24 and 48 hrs long period average forecast errors are about 150 and 250 km. However, the landfall time forecast need improvement in 36 and 48 km forecast range.

Table 4.10. Average landfall forecast errors during 2009

Forecast period (hrs)	Landfall point errors (km)	Landfall time error (hrs)
12	57	03
24	120	06
36	73	15
48	114	16

The average track forecast errors during 2009 based on four cyclones are shown in Table 4.11.

Table 4.11 Average tack forecast errors of RSMC, New Delhi during 2009.

Forecast period (hrs)	Track error (km)
12	92
24	162
36	243
48	406
60	--
72	481

Compared to landfall forecast errors and track forecast errors are significantly higher in 36 and 48 hours forecast errors mainly due to large time errors. It may be due to the fact that, the tracks of all the four cyclones were unusual with two systems recurving northeastwards, one moving northward and other one moving southwestwards. While two system (BIJLI & PHYAN) moved very fast before landfall, covering about 500 km in 12 hours, the cyclone WARD moved very slow (200 km per day). The errors in case of unusual tracks are usually higher over all the ocean basins.

Uprooting of trees in Kolkata

Damage to embankments in Birbhum, West Bengal

Damaged hutments in coastal West Bengal

Land slide in Darjiling, West Bengal

Photographs showing damage due to AILA

Photographs showing damage in Ratnagiri and Harnai districts of Maharashtra due to PHYAN