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Performance of IMD NWP based Objective Cyclone Forecast System during 2008-2009

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17	Abstract	During 2008-09, IMD experimented an objective numerical method for the operational cyclone forecasting work. The method comprising of four forecast components, namely (a) Cyclone genesis potential parameter (GPP), (b) Multi-model Ensemble (MME) technique for cyclone track prediction, (c) Cyclone intensity prediction (SCIP) model and (d) Predicting decaying intensity after the landfall. This report describes the development of objective cyclone forecast system and documents the performance skill during the cyclone season 2008-09. The study shows that the GPP analysis at early stages of development (T.No. 1.0, 1.5, 2.0) could indicate the potential of the systems for intensification. The 12-hourly track forecast by MME technique and intensity forecasts by SCIP model valid up to 72 hours and subsequent updated forecasts are found to be consistent and useful to the operational forecasters. The error statistics of the decay model shows that the model could predict the decaying intensity after landfall with reasonable success. The study has demonstrated the potential of the system for operational application.
18	Key words	NWP model, cyclone forecasting, cyclone genesis, track forecast, intensity forecast, multi-model ensemble, decay, Bay of Bengal

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PREFACE

Tropical cyclones are among the most deadly natural hazards as they are associated with very strong winds, heavy rain and storm surge. Various stages of cyclone forecasting are genesis, movement, intensity and decay after landfall. Due to the increasing human habitation near the coasts, accurate and timely forecasting of Tropical Cyclone has posed a challenging task to the operational forecasters. The synoptic methods have been the mainstay of tropical weather forecasting. Of late, NWP methods have acquired greater skills and are playing increasingly important role in delivering operational real time weather forecasts. However, limitations remain, particularly in the prediction of track and intensity of tropical cyclone. As such there has been an operational requirement to formulate an objective procedure to handle operational cyclone forecasting work in a more efficient and effective manner.

During 2008-09, IMD has used some objective methods, such as (a) Analysis of genesis potential parameter, (b) Multi-model Ensemble (MME) technique for track prediction, (c) Statistical-dynamical model for cyclone intensity prediction and (d) Empirical decay model for prediction of decaying intensity after landfall in the operational cyclone warning work. The new approach was found very useful for delivering improved operational cyclone forecast and warning.

This Meteorological Monograph describes the formulation of objective cyclone forecast system and makes a quantitative assessment of the performance skill of the new approach during 2008-09. It is strongly believed that this publication will stand out as a distinctive one in operational application as well as from scientific point of view. It may also serve as a reference of document for other scientists engage in cyclone work.

I congratulate the authors for their valued contribution in developing the objective cyclone forecasting system and bringing out this important Monograph. I am sure operational forecasters, researchers and other user community will find this publication very useful.

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CHAPTER-I

1.1 Introduction

Operational forecasting of tropical cyclones remains a challenging task. During the last two decades, weather forecasting all over the world has greatly benefited from the guidance provided by the Numerical Weather Prediction (NWP). Significant improvement in accuracy and reliability of NWP products has been driven by sophisticated numerical techniques and by the phenomenal increase in satellite based soundings. However, limitations remain, particularly in the prediction of genesis and intensity of tropical cyclones (Elsberry et al, 2007; Houze et al, 2007). Until the time when a NWP model can be used with reasonable success, there is an imperative need in the operational scenario to use statistical and empirical models in conjuntion with the dynamical models in order to take advantage of each of these procedures.

Various stages of cyclone forecasting are: (a) Genesis, (b) Track, (c) Intensity and (d) Decay after landfall. During 2008-09, IMD used an objective numerical method for the operational cyclone forecasting work. The method is comprising of four forecast components, namely (a) cyclone genesis potential parameter (GPP), (b) Multi-model Ensemble (MME) technique for track prediction, (c) cyclone intensity prediction (SCIP) model and (d) predicting decaying intensity after the landfall.

Every year about one dozen low pressure areas form over the Indian Seas, but only a few of them intensify into a cyclonic storm. So from the operational point of view, it is very important to know at the initial stage the potentiality of a low pressure system to intensify into a cyclonic storm. In a recent study, Roy Bhowmik (2003) proposed a genesis potential parameter on the basis of some dynamical parameters (such as low level divergence, vorticity and vertical wind shear between lower and upper troposphere), derived from the model analysis fields. This provides very useful information which has direct relevance to disaster management preparedness and other activities such as transportation, tourism, fishing etc. Very recently, Kotal et al. (2009) further extended the work and suggested another genesis potential parameter (GPP) which takes into account both dynamical and thermodynamical factors.

In the context of cyclone track prediction, recent studies (Krishnamurti et al. 1999, 2000a, 2000b, 2001, 2003; Goerss, J. S., 2000; Mackey and Krishnamurti, 2001; Weber, H. C., 2003; Vijaya kumar et al. 2003; Williford et al., 2003) have shown that the application of the ensemble approach is very promising to address the problem of operational forecasting of weather and tropical cyclone.

Towards this direction, a multimodel ensemble (MME) based track forecast technique is developed for the tropical cyclones over the Bay of Bengal (at 12-hour interval up to 72 hours) using the cyclone data of 2008.

In view of limitations of NWP models in the prediction of intensity of tropical cyclones (Elsberry et al, 2007; Houze et al, 2007), in a recent study, Kotal et al. (2008a) developed a statistical-dynamical cyclone intensity prediction (SCIP) model for prediction of intensity at 12-hour interval up to 72 hours to aid operational cyclone forecasting work over the Bay of Bengal. The maximum potential intensity (MPI) of a cyclone during life time of the system for the Bay of Bengal is also investigated in a recent study (Kotal et al., 2008b).

The forecast of inland wind after the landfall of a cyclone is of great concern to disaster management agencies. To address this problem, Roy Bhowmik et al. (2005) proposed an empirical decay model for predicting 6-hourly surface winds (intensity) valid till the system becomes a weak low-pressure area after the landfall over the Indian region

During the year 2008, five cyclonic systems formed over the Bay of Bengal and crossed east coast of India, Bangladesh coast and Myanmar coast and two cyclonic systems formed over the Bay of Bengal during pre-monsoon season in 2009. The aim of this work is to describe the objective cyclone forecast system and document the performance skill during the cyclone season 2008-09.

1.2 Formulation of the objective cyclone forecast system

As stated above, various features of cyclone forecasting are: (a) Genesis, (b) Track, (c) Intensity and (d) Decay after landfall. The four forecasting components of tropical cyclone are described below.

1.2.1 Genesis Potential Parameter (GPP)

The process of initiation of a cyclonic disturbance over the Sea area is called cyclogenesis. To quantify the cyclogenesis, McBride et al (1981) proposed a Daily Genesis Potential parameter (DGP) on the basis of model analysis fields over the Atlantic and Pacific Ocean basin. In their study, DGP is defined as the difference of vorticity between 900 hPa and 200 hPa. The study showed that DGP is three times greater for developing systems than that of non-developing systems. An analysis of Cyclone Genesis Parameter for the Bay of Bengal, conducted by Roy Bhowmik (2003), showed that the procedure is capable of providing useful predictive signal. Kotal et al (2009) extended the work further by defining Genesis Potential Parameter (GPP) as:

$$GPP = \frac{\xi_{850} x M x I}{S} \quad \text{if } \xi_{850} > 0,\ M > 0 \text{ and } I > 0 \qquad \text{….(1.2.1)}$$

$$= 0 \quad \text{if } \xi_{850} \le 0,\ M \le 0 \text{ or } I \le 0$$

Where , ξ_{850} = Low level relative vorticity (at 850 hPa) in 10^{-5} s^{-1}

S = Vertical wind shear between 200 and 850 hPa (knots)

$$M = \frac{[RH - 40]}{30} = \text{Middle troposphere relative humidity}$$

Where, RH is the mean relative humidity between 700 and 500 hPa

$I = (T_{850} - T_{500})$ °C = Middle-tropospheric instability (Temperature difference between 850 hPa and 500 hPa). All the variables are estimated by averaging of all grid points over an area of radius 2.5^{o} around the centre of cyclonic systems.

The study showed that GPP values are 3 to 5 times greater for the developing systems (T.No. > 2.5; maximum wind speed >35 knots) than for non-developing systems (T.No. ≤

2.5; maximum wind speed ≤ 35 knots) and is useful in differentiating between developing and non-developing systems at their early stages of development. They also showed that GPP values are equal and above 8.0 for developing systems and below 8.0 for non-developing systems in more than 85% of cases. GPP values for developing and non-developing systems as reported by Kotal et al (2009) are shown in Table 1.2.1.

Table 1.2.1. Genesis potential parameter (GPP) for Developing Systems and Non-Developing Systems.

GPP ($x10^{-5}$) →					
T.No. →	1.0	1.5	2.0	2.5	3.0
Developing	11.1	12.3	13.3	13.5	13.6
Non-Developing	3.4	4.2	4.6	2.7	-

Various thermo-dynamical parameters, which are used for real time analyzing Genesis Potential Parameter (GPP) for cyclonic storms over the Bay of Bengal during 2008-2009, are derived from the operational model analysis of the limited area model (LAM) of India Meteorological Department (IMD), New Delhi.

1.2.2 Track : Multimodel Ensemble (MME) Technique

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 of 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 Arabian Sea or Bay of Bengal. 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. In this report performance of these models during cyclone season of 2008 and pre-monsoon cyclone season of 2009 has been presented. The performance statistics of operational model QLM is shown in Table 1.2.2.

Table-1.2.2: QLM Model – Cyclone Track Error Statistics

Year	24-hour forecast (km)	36/48-hour forecast (km)	72-hour forecast (km)
1998	143	224	--
1999	119	248	--
2000	100	173	--
2001	106	183	--
2002	150	115	425
2003	187	251	280
2004	176	223	240
2005	174	306	345
2006	97	123	196
2007	136	252	408
2008	133	255	496
Mean Error (QLM)	**138**	**214**	**341**

A multimodel ensemble (MME) technique is developed using cyclone data of 2008. The technique is based on a linear statistical model. The predictors (shown in Table 1.2.3) selected for the ensemble technique are forecasts latitude and longitude position at 12-hour interval up to 72-hour of five operational models. In the MME forecasts, model-forecast latitude position and longitude position of the member models are linearly regressed against the observed latitude position and longitude position respectively for each forecast time at 12-hours intervals for the forecast up to 72-hour. 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). These coefficients are then used as weights for ensemble forecasts.

12-hourly forecast latitude (LAT^f) and longitude (LON^f) positions by multiple linear regression technique is defined as:

$$\left.\begin{aligned} LAT^f_t &= a_o + a_1 ECMWF_t^{lat} + a_2 NCEP_t^{lat} + a_3 JMA_t^{lat} + a_4 MM5_t^{lat} + a_5 QLM_t^{lat} \\ LON^f_t &= a'_o + a'_1 ECMWF_t^{lon} + a'_2 NCEP_t^{lon} + a'_3 JMA_t^{lon} + a'_4 MM5_t^{lon} + a'_5 QLM_t^{lon} \end{aligned}\right\} \text{----(1.2.2)}$$

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

The dependent variable latitude (LAT^f) in °N and longitude (LON^f) in °E.

The detailed of model predictors are given in Table 1.2.3. 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 1.2.4 and Table 1.2.5 respectively.

Table 1.2.3. *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 1.2.4. *Regression coefficients for latitude position for different forecasts hours*

Forecast hours	a_0	a_1	a_2	a_3	a_4	a_5
12 hr	1.46633	0.48327	0.08762	0.0474	-0.06954	0.34208
24 hr	0.75662	0.76242	-0.08543	-0.17727	-0.02354	0.45521
36 hr	1.28923	0.61778	-0.05394	0.04076	0.12614	0.17496
48 hr	0.60173	1.35212	0.30361	-0.3094	-0.00463	-0.27553
60 hr	0.36611	1.12986	-0.15616	0.1433	-0.11323	0.03574
72 hr	2.49751	0.37663	-0.37158	0.90057	-0.21182	0.14239

Table 1.2.5. *Regression coefficients for longitude position for different forecasts hours*

Forecast hours	a'_0	a'_1	a'_2	a'_3	a'_4	a'_5
12 hr	2.12692	0.33632	0.07031	0.10898	-0.04351	0.49902
24 hr	1.04316	0.85076	-0.14555	-0.07929	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 is implemented from 2009 and is used for real time forecasting of tropical cyclones BIJLI and AILA, which formed during pre-monsoon season over the Bay of Bengal in 2009.

1.2.3 Intensity

Roy Bhowmik et al (2007) proposed a simple empirical model for predicting cyclone intensity over the Bay of Bengal. The study is based on the assumption that tropical cyclone intensifies exponentially, where the intensification factor is determined using past 12 hours intensity changes. A major limitation of this empirical model (Roy Bhowmik et al 2007) is that it does not include parameters to take into account the physical and dynamical processes involved. The study warranted further investigation in a more general manner incorporating other synoptic and thermodynamical factors, which play important role for intensification of storms. In order to over come these shortcomings, Kotal et al (2008a) developed a Statistical Cyclone Intensity Prediction (SCIP) model for the Bay of Bengal for predicting 12 hourly cyclone intensity (up to 72 hours), applying multiple linear regression technique using various dynamical and physical parameters as predictors. The model equation (Kotal et al 2008a) is given as:

$$dv_t = a_o + a_1 IC12 + a_2 SMS + a_3 VWS + a_4 D200 + a_5 V850 + a_6 ISL + a_7 SST + a_8 ISI$$

for t= forecast hour 12, 24, 36, 48, 60 and 72 -------------(1.2.3)

dv_t = Intensity change during the time interval t

The detailed of model predictors are given in Table 1.2.6. The constant term a_0 and coefficients a_1, a_2, ….., a_8 for a 12 hourly forecast interval are given in Table 1.2.7.

Table 1.2.6. Model parameters

S.No.	Predictors	Symbol of Predictors	Unit
1.	Intensity change during last 12 hours	IC12	Knots
2.	Vorticity at 850 hPa	V850	x 10^5 s^{-1}
3.	Storm motion speed	SMS	ms^{-1}
4.	Divergence at 200 hPa	D200	x10^5 s^{-1}
5.	Initial Storm intensity	ISI	Knots
6.	Initial Storm latitude position	ISL	°N
7.	Sea surface temperature	SST	°C
8.	Vertical wind shear	VWS	Knots

Table 1.2.7. Regression coefficients for different forecasts hours

Forecast hours	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8
12	-9.54983	0.31517	0.6749	- 0.18668	0.865	0.75918	0.16853	0.24186	0.04103
24	-14.66671	0.58485	1.42963	-0.54507	1.58903	1.46658	0.5017	0.36094	0.14683
36	-7.61006	0.57747	3.03779	-0.8867	2.51223	2.28032	1.02698	-0.072297	0.22346
48	4.4943	0.54152	5.0484	-1.18528	3.29409	2.63681	1.66914	-0.71783	0.3127
60	18.75396	0.37624	6.66114	-1.33578	3.14652	2.85734	1.95777	-1.08646	0.1684
72	24.58879	0.19425	7.87951	-1.31717	5.09006	2.49177	2.22359	-1.30808	0.10789

The thermodynamic parameters used as predictors for the Statistical Cyclone Intensity Prediction (SCIP) model are derived from the forecast fields of ECMWF (European Center for Medium Range Weather Forecast) model and Sea Surface Temperature (SST) analysis at 1° latitude-longitude grid interval from NCEP (National Center for Environmental Prediction) is used in real time forecasting.

The SCIP model is implemented from April 2008 and is used for real time forecasting of the cyclones during 2008-2009 except for the cyclone NISHA as the system was very close to Sri-lanka coast and coast of Tamilnadu.

1.2.4. Decay of intensity after the Landfall

The forecast of inland wind after the landfall of a cyclone is of great concern to disaster management agencies. To address this problem, Roy Bhowmik et al. (2005) proposed an empirical model for predicting 6-hourly maximum sustained surface winds (intensity) that is valid till the system becomes a weak low pressure area after the landfall over the Indian region. According to the decay equation (Roy Bhowmik et al., 2005), the maximum sustained surface wind speed (MSSW) after the landfall at time t is given by:

$V_{t+6} = V_b+(V_t-V_b)*R_1$, for t=0 ------------------- (1.2.4)

$= V_b+(V_t-V_b)*R_2$, for t=6,12,18 and 24 ---- (1.2.5)

Where, reduction factors

$R_1 = exp(-a_1*6.0)$ ---------------------------------(1.2.6)

and, $R_2 = exp(-a_2*6.0)$ ----------------------------(1.2.7)

Decay constant a_1 for the first six hours after the landfall (for t= 0 to 6) is given by:

$a_1 = [ln \{(V_o - V_b)/(V_6-V_b))\}]/6$ ------------------(1.2.8)

The decay constant a_2 for the remaining 12 hours (for t= 6 to 18 hours) is taken as:

$a_2 = [ln \{(V_6 - V_b)/(V_{18}-V_b))\}]/12$ ----------------(1.2.9)

Regression equation relating R_1 and R_2 as given below:

$R_2 = 0.982*R_1-0.081$ ---------(1.2.10)

Where, V_0 is the maximum sustained surface wind speed at the time of landfall, V_t is the wind speed at time t after the landfall and V_b is the background wind speed. After landfall, tropical cyclone decays to some background wind speed. The background wind speed V_b and the reduction factors R_1 & R_2 as determined (Table 1.2.8) in the decay model (Roy Bhowmik et al, 2005) are used in this study.

The steps suggested by Roy Bhowmik et al (2005) for the operational forecasting are:

(i) At the time of landfall (at t=0), employ the observed landfall intensity V_0 and the values of R_1, R_2 and V_b, that are obtained based upon the sample average decay rate (Table 1.2.8), to make a six hourly prediction of V_t using equation (1.2.4).

(ii) Six hours after the landfall (at t=6), use V_0 and V_6 from observation and V_b from Table 1.2.8 to compute actual R_1 from equations 1.2.6 and 1.2.8. Then get new R_2 from equation 1.2.10 and use equation (1.2.5) to revise the forecast for 12 hours after the landfall and later times.

(iii) Twelve hours after the landfall (at 12), employ observed V_{12} to make a six hourly prediction using equation 1.2.5.

(iv) Eighteen hours after the landfall, employ observed values of V_0, V_{18} to calculate actual R_2 from equations 1.2.7 and 1.2.9 and revise the forecast for 24 hours and beyond using equation 1.2.5.

(v) Twenty fours hours after the landfall, use observed V_{24} to make a final forecast for V_{30}.

Table 1.2.8. Decay parameters of mean curve

MSSW (knots)	**a_1 (h^{-1})**	**R_1 $(6\ h)^{-1}$**	**a_2 (h^{-1})**	**R_2 $(6\ h)^{-1}$**	**V_b (knots)**
< 65	0.099	0.552	0.149	0.408	19.0
≥65	0.154	0.339	0.194	0.311	21.0

The decay model is used for real time forecasting of decaying intensity (after landfall) of cyclone RASHMI, NISHA and AILA over the Bay of Bengal during the period 2008-2009. The cyclone KHAI MUK weakened into deep depression and BIJLI weakened into depression before landfall and the cyclone NARGIS re-curved to northeast direction and crossed Myanmar coast.

This report comprises of nine chapters. The Chapter I is introductory. Chapter II, Chapter III, Chapter IV, Chapter V, Chapter VI, Chapter VII and Chapter VIII deals with description of observational characteristics and corresponding forecast fields and errors of cyclone NARGIS, RASHMI, KHAIMUK, NISHA, Deep Depression during 4-7 December 2008, BIJLI and AILA respectively.
Finally concluding remarks are given in Chapter IX.

CHAPTER-II

Cyclone “NARGIS” during 27 April-04 May 2008

2.1 The Cyclonic Storm “NARGIS”

The low pressure system over the east-central Bay of Bengal on 26 April 2008 concentrated into a depression at 0300 UTC of 27 April and lay centered at latitude 12.0° N, longitude 87° E. Moving in a westerly direction, the system intensified into deep depression at 1200 UTC of same day over east-central and adjoining west-central Bay of Bengal near Latitude 12.0° N and longitude 86.5° E. The system further moved in a Northwesterly directions and intensified into a cyclonic storm “NARGIS” (T.No. 2.5) over west-central Bay of Bengal at 0000 UTC of 27 April and lay centered at latitude 13.0° N, longitude 85.5° E. Thereafter the system remained practically stationary and intensified into severe cyclonic storm (T.No 3.5) at 0900 UTC of same day. Then the system moved slightly Northerly direction and further intensified into a very severe cyclonic storm (T.No 4.0) at 0300 UTC of 27 April near latitude 13.5° N, longitude 85.5° E. Thereafter the system moved in a Northeasterly directions and intensified to T.No 4.5 at 0000 UTC of 2 May near latitude 16.0° N, longitude 92.5° E. Moving easterly direction the system further intensified to T.No 5.0 at 0600 UTC of same day near latitude 16.0° N, longitude 93.5° E. The system further moved in an easterly direction and crossed southwest Coast of Myanmar between 1200 UTC to 1400 UTC of 2 May. There after the system further moved in a Northeasterly direction and weakened gradually. The observed track of the system is presented in Figure 2.1.

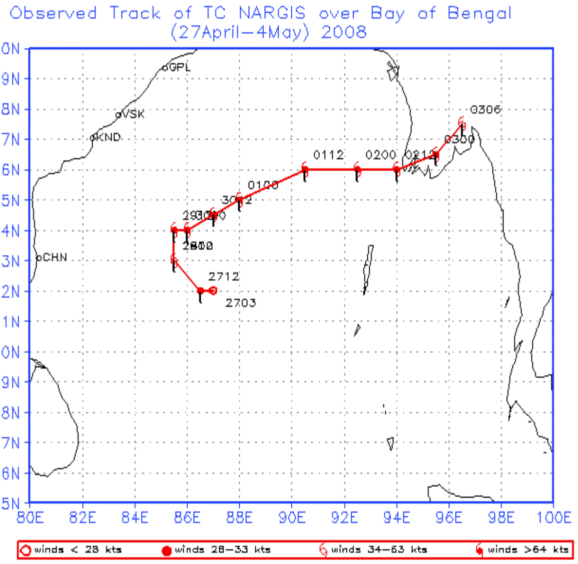

Observed Track of TC NARGIS over Bay of Bengal
(27April–4May) 2008

Figure 2.1

2.2 Analysis of GPP

GPP values computed (using equation 1.2.1) for this cyclone on the basis of real time model analysis fields along with the GPP values for Developing Systems and Non-Developing Systems are shown in Table 2.2.1. The higher GPP values (> 8.0, the threshold value) at early stages of development (T.No. 1.0, 2.0, 2.5) have clearly indicated that the cyclone “NARGIS” had enough potential to intensify into a developing system (>35 knots).

Table 2.2.1. Genesis potential parameter (GPP) for Developing System, Non-Developing System and Cyclone “NARGIS”

GPP (x10^{-5}) →			
T.No. →	1.0	2.0	2.5
Developing	11.1	13.3	13.5
Non-Developing	3.4	4.6	2.7
Cyclone “NARGIS”	11.1 (00UTC/27.04.2008)	16.5 (12UTC/27.04.2008)	13.3 (00UTC/28.04.2008)

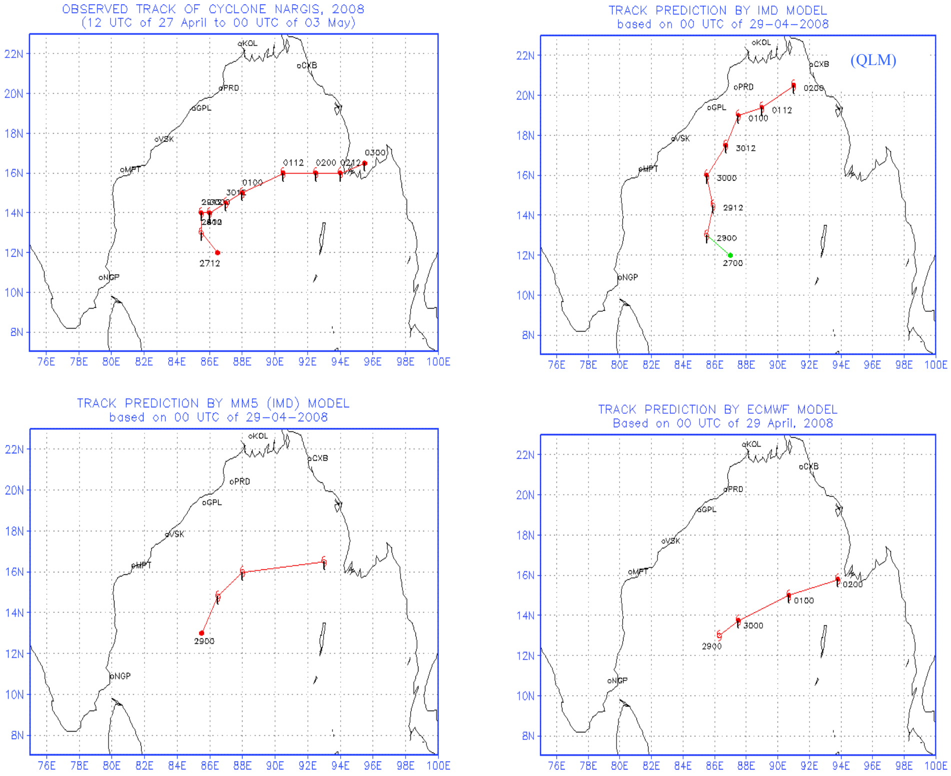
2.3 Track prediction by NWP models

Figure 2.3.1, Figure 2.3.2 and Figure 2.3.3, display the forecast track positions of the system by various NWP models (QLM, MM5 and ECMWF) with the initial condition of 29 April, 30 April and 1 May 2008. Observed track of NARGIS is included in the diagrams to visualize the performance of the models. It is encouraging to note that all the NWP models consistently indicated that the very severe cyclonic storm Nargis would not hit Indian coast. The QLM model showed northerly movement initially, but during subsequent forecast hours it showed northeast to easterly movement. MM5 model showed northeasterly to easterly movement. ECMWF showed northeasterly movement initially and during subsequent forecast hours it showed easterly movement.

In Table 2.3.1, landfall errors of different models are presented. The landfall errors in the 24 hours to 48 hours forecasts by MM5 and ECMWF are found to be between 10 km to

110 km and landfall time error is between 1 hour to 8 hours. The landfall errors in the 24 hours to 48 hours forecasts by QLM is found to be between 300 km to 430 km and landfall time error is between -5 hour to 12 hours

The corresponding forecast errors are summarized in Table 2.3.2. The QLM showed mean forecast error of 245 km to 285 km for the forecast range 12 hours to 48 hours. MM5 showed mean forecast error of 150 to 160 km for the 72 hours forecast range. ECMWF showed mean forecast error of 140 to 170 km for the forecast range up to 72 hours.


OBSERVED TRACK OF CYCLONE NARGIS, 2008
(12 UTC of 27 April to 00 UTC of 03 May)

TRACK PREDICTION BY IMD MODEL
based on 00 UTC of 29-04-2008

(QLM)

TRACK PREDICTION BY MM5 (IMD) MODEL
based on 00 UTC of 29-04-2008

TRACK PREDICTION BY ECMWF MODEL
Based on 00 UTC of 29 April, 2008

Figure 2.3.1: 72 hours forecast tracks based on initial condition of 29 April 2008

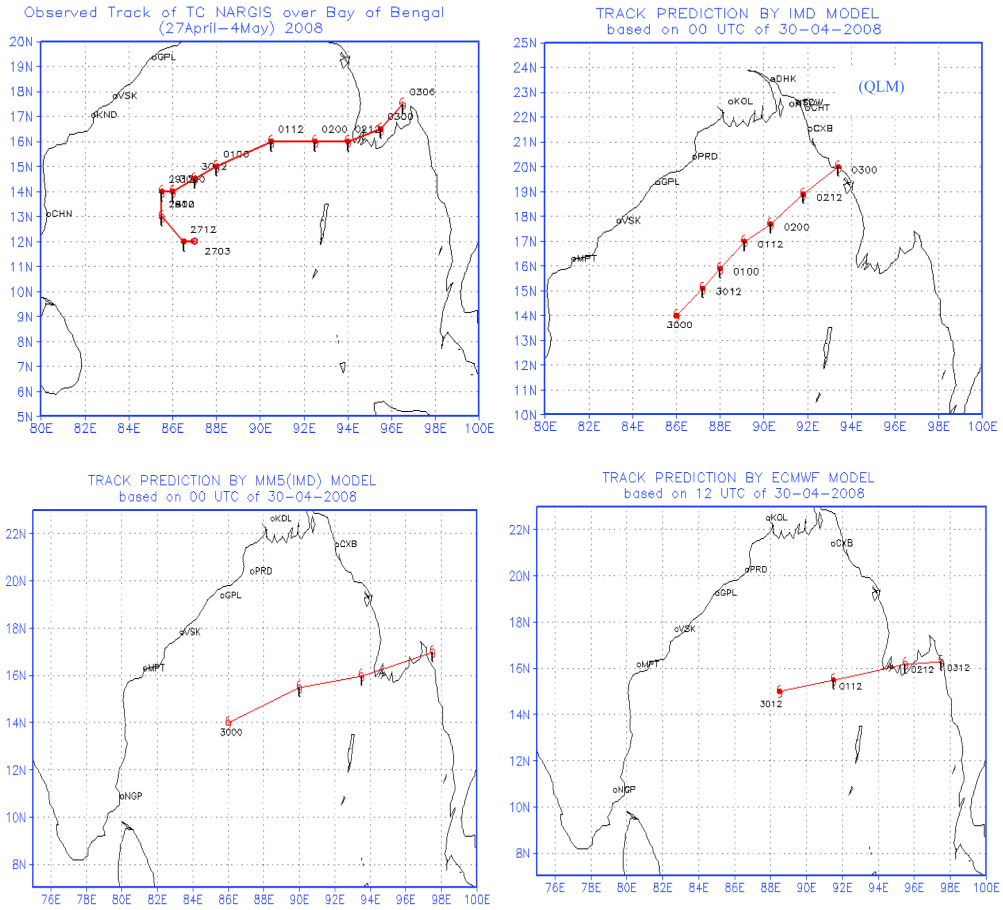
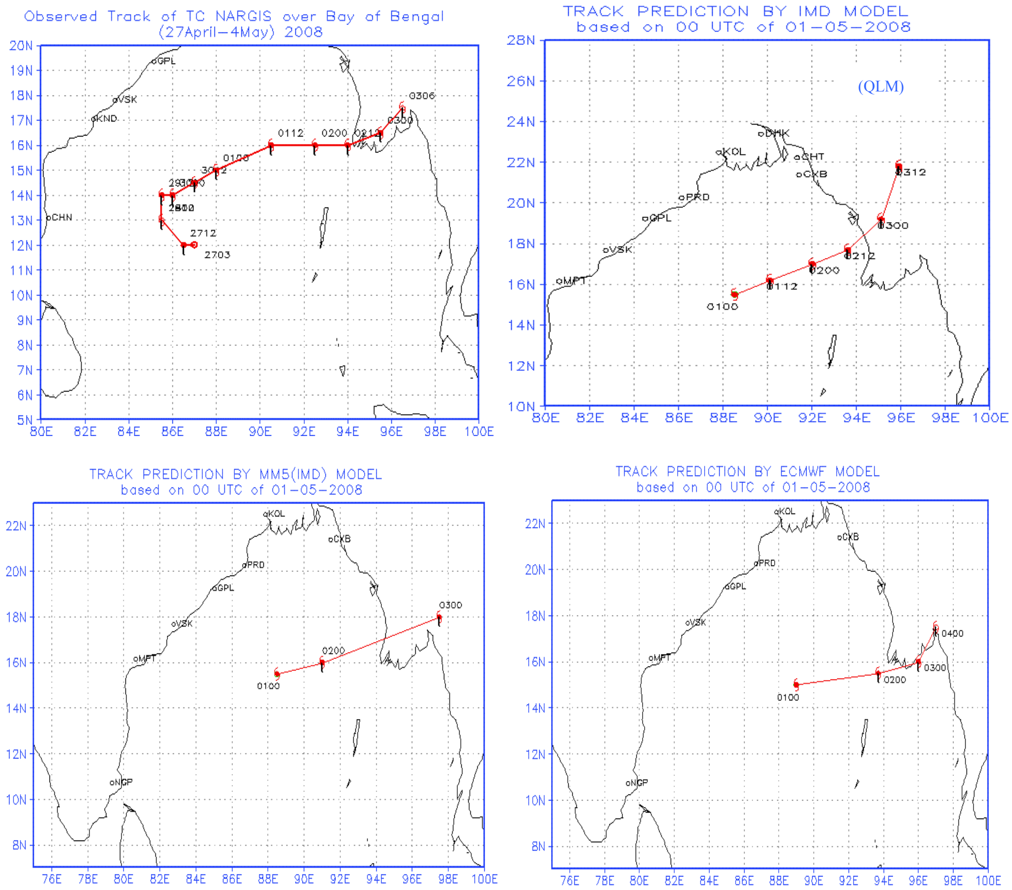


Figure 2.3.2: Model Performance: 48 hours forecast tracks based on initial condition of 30 April 2008



Observed Track of TC NARGIS over Bay of Bengal (27April–4May) 2008

TRACK PREDICTION BY IMD MODEL based on 00 UTC of 01–05–2008

TRACK PREDICTION BY MM5(IMD) MODEL based on 00 UTC of 01–05–2008

TRACK PREDICTION BY ECMWF MODEL based on 00 UTC of 01–05–2008

Figure 2.3.3: Model Performance: 24 hours forecast tracks based on initial condition of 1 May 2008

Table 2.3.1: Forecast Landfall Errors of “NARGIS”

Models	**Forecast hour**	**Initial Date/time (UTC)**	**Landfall Lat/Lon**	**Landfall Position Error (Km)**	**Landfall time error**
QLM	i) 72hr FC	2904/00	No landfall	-	-
	ii) 48hrFC	3004/00	20.0/93.5	430 km	12 hrs early
	iii) 24hr FC	0105/00	18.5/94.5	300 km	5 hr delay
MM5	i) 72hr FC	2904/00	No landfall	-	-
	ii) 48hrFC	3004/00	Close to obs.	10 km	8 hrs early
	iii) 24hr FC	0104/00	17.0/94.7	110 km	1 hr early
ECMWF	i) 72hr FC	2904/00	No landfall	-	-
	ii) 48hrFC	3004/12	Close to obs.	10 km	8 hrs early
	iii) 24hr FC	0104/00	15.8/95.2	50 km	7 hrs early

Table 2.3.2: Track forecast errors of “NARGIS”

Models	**Initial Date/time**	**24 hr error (km)**	**48 hr error (km)**	**72 hr error (km)**
QLM	2904/00	240	435	940
	3004/00	380	120	432
	0105/00	120	305	-
MM5	2904/00	104	111	77
	3004/00	220	105	220
	0105/00	160	270	-
ECMWF	2904/00	164	275	140
	3004/12	120	162	-
	0105/00	140	77	-

2.4 Intensity prediction by SCIP model

Based on initial condition of 0000 UTC of 28 April:

The cyclone "NARGIS" intensified rapidly during the period 00UTC on 28 April to 1200 UTC on 28 April (by 20 knots in 12 hours). The 12 hourly intensity forecast valid up to 72 hours (Table 2.4.1) shows that during the initial forecast hours the model could not indicate rapid intensification. However, as the forecast hour increases, the model could peak up the intensity increase at the 60 hour and 72 hour forecasts with an underestimation of 2 knots and overestimation of 14 knots respectively.

Table 2.4.1. Model (SCIP) performance based on 0000 UTC of 28 April 2008

Forecasts hours →	00 hr	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
Observed (knots)	35	55	55	65	65	65	65
Forecasts (knots)	35	39	41	49	53	63	79
Error (knots)	-	-16	-14	-16	-12	-2	+14

Updated forecast based on 1200 UTC of 29 April:

The cyclone "NARGIS" shows no intensification during the 48 hours period (12 UTC on 29 April to 1200 UTC on 1 April). Thereafter it intensified to 77 knots during next 12 hours and to 90 knots during next 12 hours. The model could pick up intensity up to next 24 hours (Table 2.4.2) with a maximum error of 6 knots (overestimation) at 24 hour. However the model overestimated the wind speed for next 48 hours with errors ranging from 16 knots to 34 knots.

Table 2.4.2. Model (SCIP) performance based on 1200 UTC of 29 April 2008

Forecasts hours →	00 hr	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
Observed (knots)	65	65	65	65	65	77	90
Forecasts (knots)	65	67	59	92	96	110	106
Error (knots)	-	+2	-6	+27	+34	+33	+16

Updated forecast based on 0000 UTC of 30 April, 1200 UTC of 30 April and 0000 UTC of 1 May:

It is very encouraging to note that all the12-hourly forecasts based on observations of 0000 UTC of 30 April (Table 2.4.3), 1200 UTC of 30 April (Table 2.4.4) and 0000 UTC of 1 May (Table 2.4.5) valid up to 60 hours, 48 hours and 36 hours (till landfall) respectively are considerably improved. The model could capture the intensification with errors ranging from 2 knots to 7 knots. This shows that the updated forecast could provide improved forecast values.

Table 2.4.3 Model (SCIP) performance based on 0000 UTC of 30 April 2008

Forecasts hours →	00 hr	12 hr	24 hr	36 hr	48 hr	60 hr
Observed (knots)	65	65	65	65	77	90
Forecasts (knots)	65	67	71	71	80	86
Error (knots)	-	+2	+6	+6	+3	-4

Table 2.4.4 Model (SCIP) performance based on 1200 UTC of 30 April 2008

Forecasts hours →	00 hr	12 hr	24 hr	36 hr	48 hr
Observed (knots)	65	65	65	77	90
Forecasts (knots)	65	69	69	84	84
Error (knots)	-	+4	+4	+7	-6

Table 2.4.5 Model (SCIP) performance based on 0000 UTC of 01 May 2008

Forecasts hours →	00 hr	12 hr	24 hr	36 hr
Observed (knots)	65	65	77	90
Forecasts (knots)	65	69	73	86
Error (knots)	-	+4	-4	-4

CHAPTER-III

Cyclone “RASHMI” during 25-27 October 2008

3.1 The Cyclonic Storm “RASHMI”

The system was located as a low pressure area over the west-central Bay of Bengal at 0000 UTC of 24 October 2008. The low pressure system concentrated into a depression at 0300 UTC of 25 November and lay centered at latitude 16.5 °N, longitude 86.5 °E. Moving in a north-north-easterly direction, the system intensified into deep depression at 0000 UTC of 26 October over west-central and adjoining north Bay of Bengal near Latitude 18.0° N and longitude 87.0° E about 500 km southwest of Kolkata. The system further moved in a North-Northeasterly directions and intensified into a Cyclonic storm “RASHMI” (T.No. 2.5) over Northwest Bay of Bengal at 1200 UTC of same day and lay centered at latitude 19.5 °N, longitude 88.0 °E. Thereafter the system moved fast in a North-Northeasterly direction and intensified into T.No 3.0 at 2100 UTC and crossed Bangladesh Coast near latitude 21.8° N and longitude 89.5° E between 2200 to 2300 UTC of 26 October. The system further moved in a North-Northeasterly direction, weakened rapidly into a deep depression at 0300 UTC of 27 October over Northern part of Bangladesh and adjoining parts of West Meghalaya. The observed track of the system is presented in Figure 3.1.

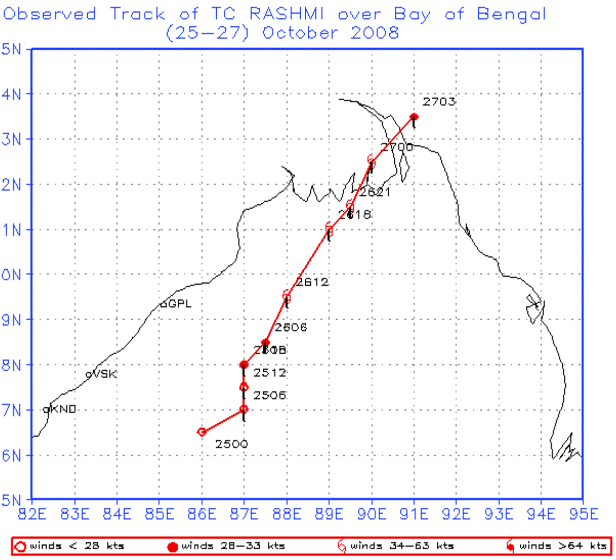


Figure 3.1

3.2 Analysis of GPP

GPP values computed (using equation 1.2.1) for this cyclone on the basis of real time model analysis fields along with the GPP values for Developing Systems and Non-Developing Systems are shown in Table 3.2.1. The higher GPP values (> 8.0, the threshold value) at early stages of development (T.No. 1.0, 1.5, 2.0) have clearly indicated that the cyclone "RASHMI" had enough potential to intensify into a developing system.

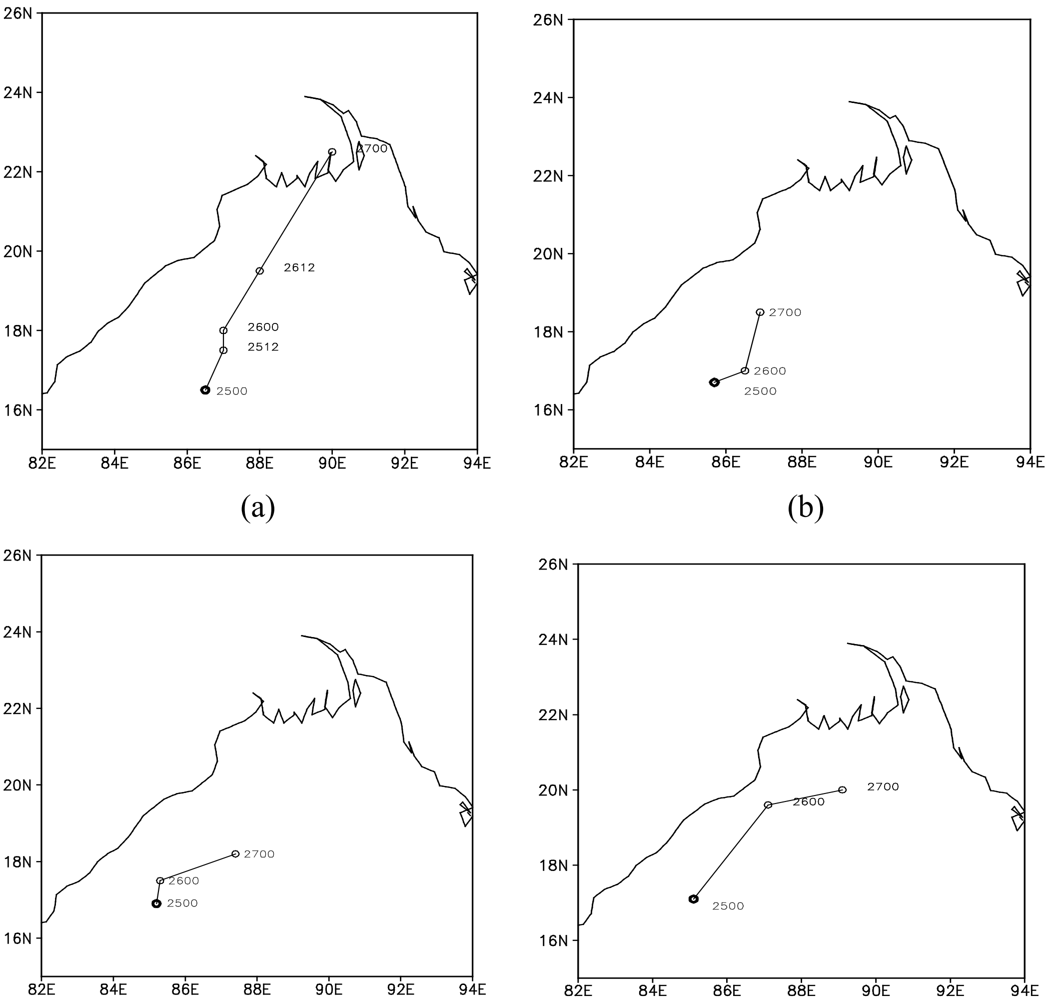
Table 3.2.1. Genesis potential parameter (GPP) for Developing System, Non-Developing System and Cyclone "RASHMI".

GPP ($x10^{-5}$) →			
T.No. →	1.0	1.5	2.0
Developing	11.1	12.3	13.3
Non-Developing	3.4	4.2	4.6
Cyclone "RASHMI"	10.9 (00UTC/24.10.2008)	15.8 (00UTC/25.10.2008)	10.6 (00UTC/26.10.2008)

3.3 Track prediction by NWP models

Figure 3.3.1 (a-e) displays the observed track and forecast tracks of the cyclone by the operational NWP models based on 0000 UTC of 24 October 2008 up to 72 hours. The QLM model tracks are not included in figure 3.3.1 as the product was not available on the day. Figure 3.3.2 (a-f) and Figure 3.3.3 (a-f) displays the observed track and forecast tracks based on 0000 UTC of 25 and 26 October 2008 up to 48 hours and 24 hours (till landfall) respectively. Observed track of RASHMI is included in the diagrams to visualize the performance of the models. The corresponding 24-hourly track prediction errors of NWP models and landfall forecast errors are summarized in Table 3.3.1 and Table 3.3.2 respectively. The 72 hours forecasts based on 0000 UTC initial conditions of 24 October depicted large error by all these models except the JMA (Japan Meteorological Agency). The 48 hours forecasts error varies from around 15 km to 190 km with lowest error of JMA and largest error of MM5 model. The 24 hours forecasts error varies from around 40 km to 115 km with lowest error of ECMWF and largest error of GFS model. Forecasts based on initial conditions of 0000 UTC of 25 October depicted wide variation of errors. The 48 hours forecasts error varies from around 45 km to 310 km with lowest error of MM5 and largest error of QLM model. The 24 hours forecasts error varies from around 85 km to 315 km with lowest error of ECMWF and largest error of GFS model. The 24 hours forecasts error based on 00 UTC initial conditions of 26 October varies from near landfall to 100 km with lowest error of GFS and largest error of MM5 and QLM model.

In the case of landfall errors (position and time), based on 0000 UTC of 24 October all models show no landfall till 0000 UTC of 27 October except JMA with an error of around 55 km and 5 hours early. Based on 0000 UTC of 25 October, the landfall errors are varies from around 10 km to 95 km and time error varies from 12 hours early to 5 hours delay. The lowest error is found to be for the model JMA with an error of around 10 km and 1 hour delay and largest error of MM5 model of around 95 km and around 12 hours delayed landfall by QLM model. Updated forecast based on 0000 UTC of 26 October shows improvement of landfall error for all models. The maximum landfall error is found to around 45 km of JMA model. The landfall time error varies from 6 hours early to 2 hours delay. The lowest error is found to be for the model QLM and JMA and largest error of MM5 model.

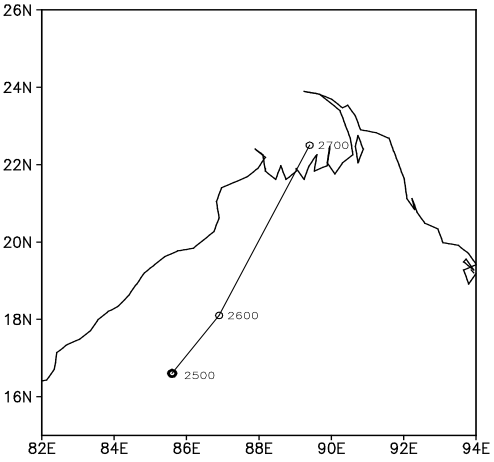


(a)

(b)

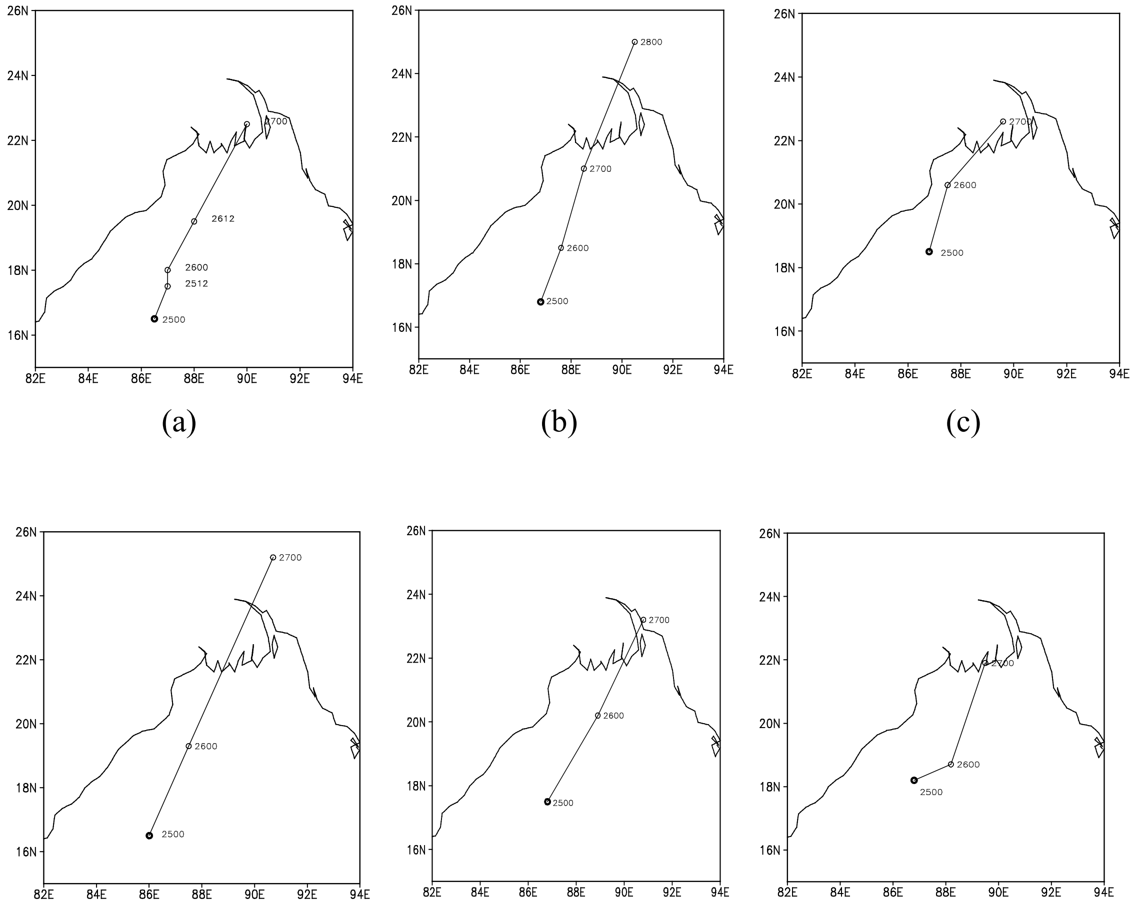
(c)

(d)



(e)

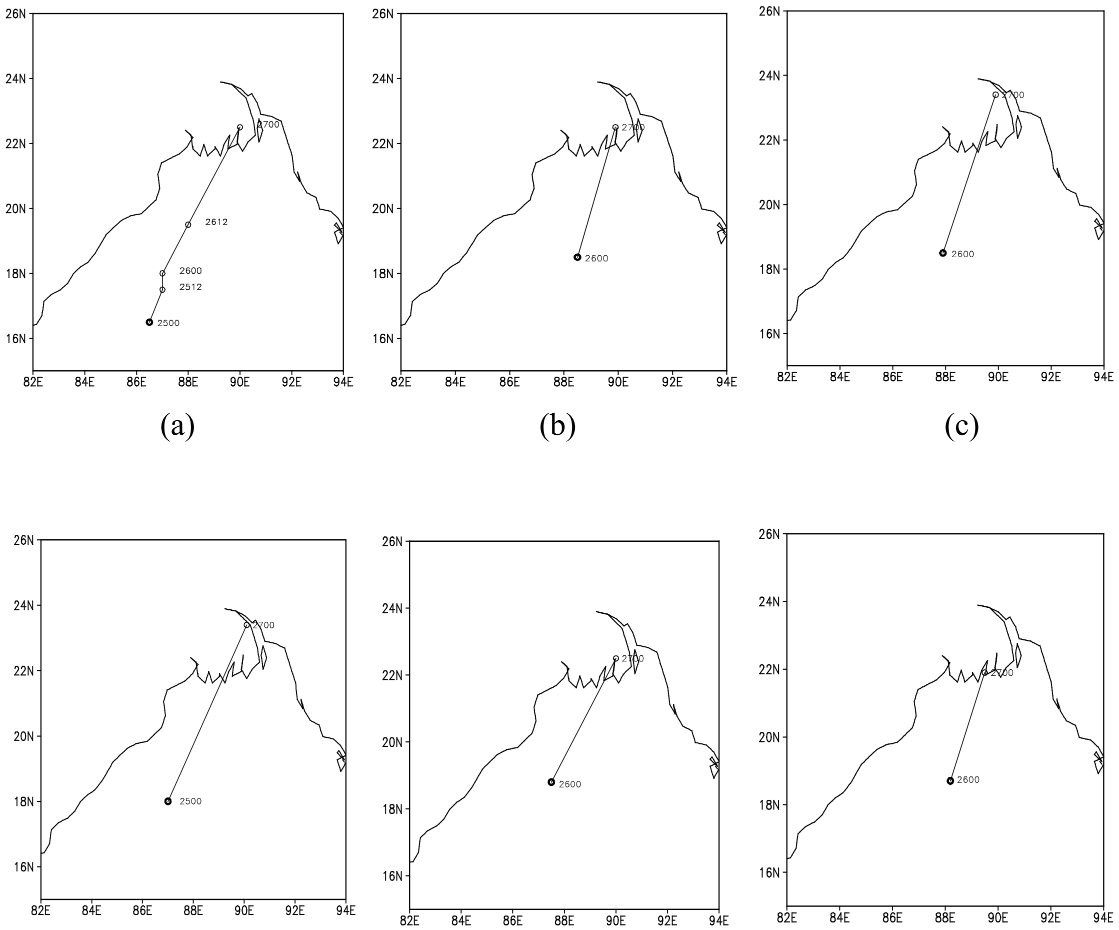
Figure 3.3.1: Inter-comparison of observed track of cyclone "RASHMI"and track predicted by different operational NWP models based on 0000 UTC of 24 October 2008 (a) Observed (b) ECMWF (c) MM5 (d) GFS (e) JMA



(a) (b) (c)

(d) (e) (f)

Figure 3.3.2 Inter-comparison of observed track of cyclone "RASHMI" and track predicted by different operational NWP models based on 0000 UTC of 25 October 2008 (a) Observed (b) ECMWF (c) MM5 (d) QLM (e) GFS (f) JMA



(a) (b) (c)

(d) (e) (f)

Figure 3.3.3: Same as Figure 3.3.2 except based on 0000 UTC of 26 October 2008

Table 3.3.1: Forecast Landfall errors of Rashmi

Based on →	**0000 UTC of 24.10.2008**				**0000 UTC of 25.10.2008**			**0000 UTC of 26.10.2008**	
Models	**00 hr (Km)**	**24hr (Km)**	**48hr (Km)**	**72hr (Km)**	**00 hr (Km)**	**24hr (Km)**	**48hr (Km)**	**00 hr (Km)**	**24hr (Km)**
ECMWF	NA	39	123	549	63	84	227	168	10
MM5	NA	91	188	549	228	294	43	110	100
QLM	-	-	-	-	0	154	308	0	100
GFS	NA	117	178	293	123	315	113	103	0
JMA	NA	44	15	61	207	148	84	160	68

Table 3.3.2: Track forecasts errors of Rashmi

Based on →	**0000 UTC of 24.10.2008**		**0000 UTC of 25.10.2008**		**0000 UTC of 26.10.2008**	
Models	**Landfall Position Error (Km)**	**Landfall time error**	**Landfall Position Error (Km)**	**Landfall time error**	**Landfall Position Error (Km)**	**Landfall time error**
ECMWF	No landfall	-	76	5 hrs delay	30	2 hrs delay
MM5	No landfall	-	95	10 hrs early	10	6 hrs early
QLM	-	-	20	12 hrs early	25	1 hr early
GFS	No landfall	-	66	8 hrs early	0	2 hrs early
JMA	56	5 hrs early	10	1 hr delay	46	1 hr early

3.4 Intensity prediction by SCIP model

The 12-hourly wind speed forecasts based on 0000 UTC of 26 October 2008 along with observed wind speed is given in the Table 3.4.1. The model forecasts show that there is an underestimation of intensity by 2 knots and 8 knots at 12 hour and 24 hour respectively. The statistical-dynamical cyclone intensity prediction model (SCIP) could predict the intensification into cyclonic storm of the system.

Table 3.4.1 Model (SCIP) performance based on 0000 UTC of 26 October 2008

Forecasts hours →	00 hr	12 hr	24 hr
Observed (knots)	30	35	45
Forecasts (knots)	30	33	37
Error (knots)	-	-2	-8

3.5 Decay of RASHMI after landfall

After landfall the cyclone RASHMI decayed rapidly. Figure 3.5.1 shows the decay curves on the basis of observations (line with solid squares) and 6-hourly forecast intensity (using equation 1.2.4) up to 12 hours after the landfall (line with open circles). Forecast errors (Table 3.5.1) at 6 hour and 12 hour after the landfall (at t=0, Intensity=45 knots) are found to be around 6 knots and 10 knots (over estimation) respectively.

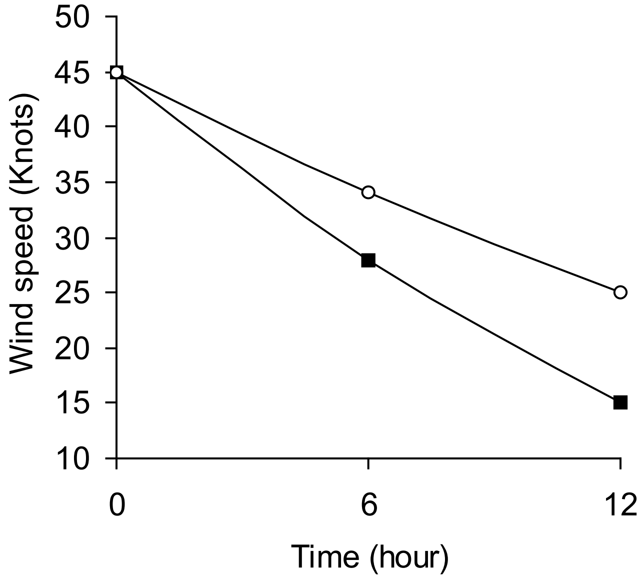


Figure 3.5.1: Decay of intensity of RASHMI after landfall

Table 3.5.1. Decay model performance (at time of landfall)

Forecasts hours →	00 hr	6 hr	12 hr
Observed (knots)	45	28	15
Forecasts (knots)	45	34	25
Error (knots)	--	+6	+10

CHAPTER-IV

Cyclone “KHAI MUK” during 13-16 November 2008

4.1 The Cyclonic Storm “KHAI MUK”

Under the influence of upper air cyclonic circulation, a low-pressure area formed over southeast Bay of Bengal on 12 November. It became well marked on 13th and lay over southeast and adjoining southwest Bay of Bengal. It concentrated into a depression over the same region at 1200 UTC of 13th. The system moved in a northwesterly direction, intensified into a deep depression at 0300 UTC of 14th near lat. 12.5° N and long. 85.0° E. The system further intensified into a cyclonic storm, “KHAI MUK” over west central and adjoining southwest Bay of Bengal at 1200 UTC of same day near lat. 14.0° N and long. 84.0° E. It reached its maximum intensity near lat. 14.5° N and long. 83.0° E around 2100 UTC of 14th with maximum sustained wind speed of 40 knots. The system moved in a westerly direction and weakened into a deep depression at 0600 UTC of 15th near lat. 14.5° N and long. 82.0° E. It then moved in a west-northwesterly direction and crossed south Andhra Pradesh coast, close to the north of Kavali between 2200 UTC to 2300 UTC of 15 November. It weakened into a depression at 0300 UTC of 16 November over Rayalaseema. It further moved in a west northwesterly direction and weakened into a well-marked low pressure area over Rayalaseema and adjoining Telangana and interior Karnataka at 0900 UTC of 16 November. The observed track of the system is presented in Figure 4.1.

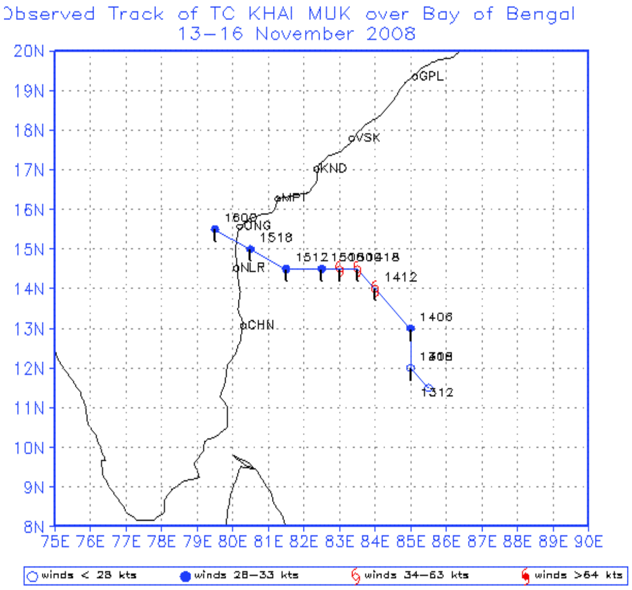


Figure 4.1

4.2 Analysis of GPP

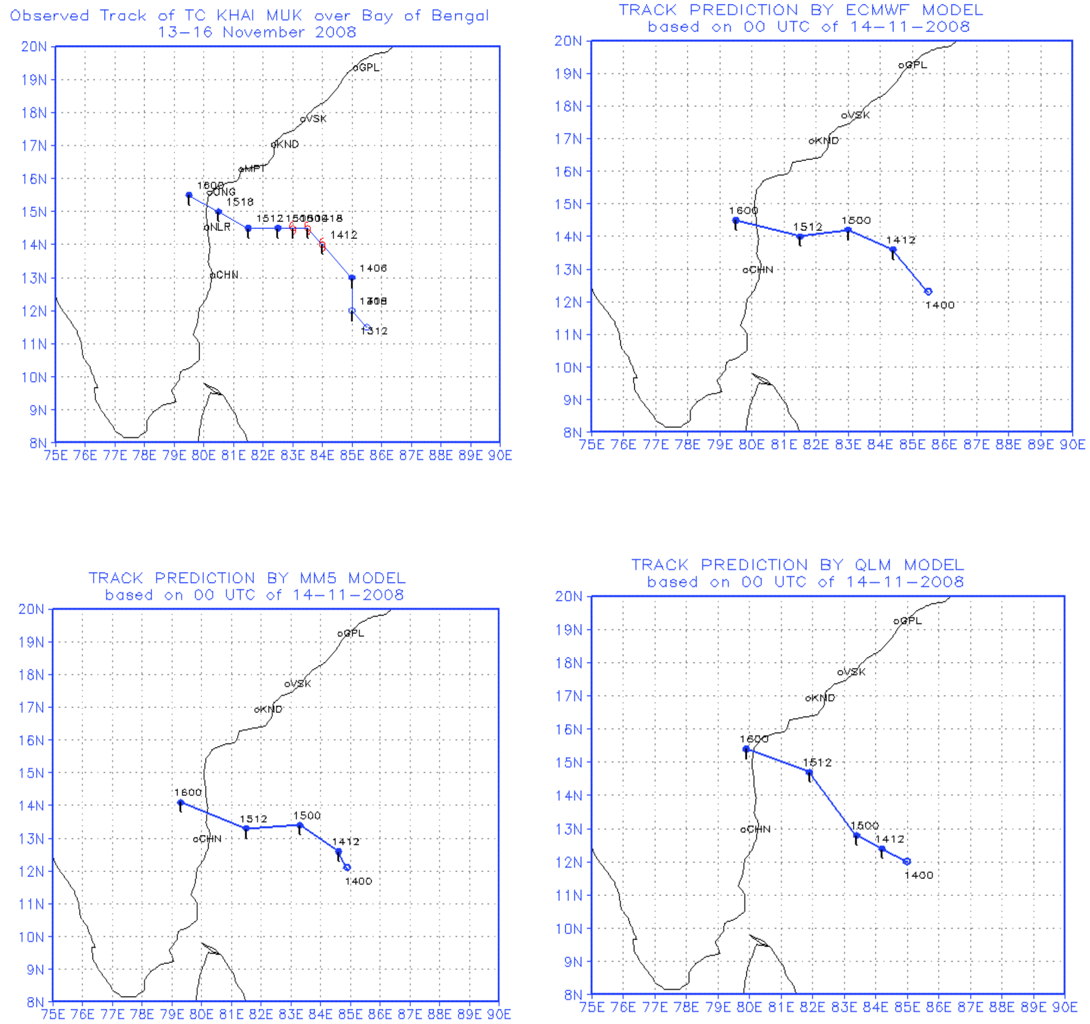
GPP values computed for this cyclone on the basis of real time model analysis fields are shown in Table 4.2.1. The higher GPP values (> 8.0, the threshold value) at early stages of development have clearly indicated that the cyclone “KHAI MUK” had enough potential to intensify into a developing system (>35 knots).

Table 4.2.1. Genesis potential parameter (GPP) for Developing System, Non-Developing System and Cyclone “KHAI MUK”

GPP (x10^{-5}) →			
T.No. →	1.0	1.0	1.5
Developing	11.1	12.3	12.3
Non-Developing	3.4	4.2	4.2
Cyclone “KHAI MUK”	12.5 (00UTC/12.11.2008)	12.3 (00UTC/13.11.2008)	8.3 (00UTC/14.11.2008)

4.3 Track prediction by NWP models

The forecast track and the observed track based on 0000UTC of 14 and 15 November 2008 are shown in Figure 4.3.1 and Figure 4.3.2. Corresponding forecast track errors and landfall errors are presented in Table 4.3.1 and Table 4.3.2.



Observed Track of TC KHAI MUK over Bay of Bengal 13–16 November 2008

TRACK PREDICTION BY ECMWF MODEL based on 00 UTC of 14–11–2008

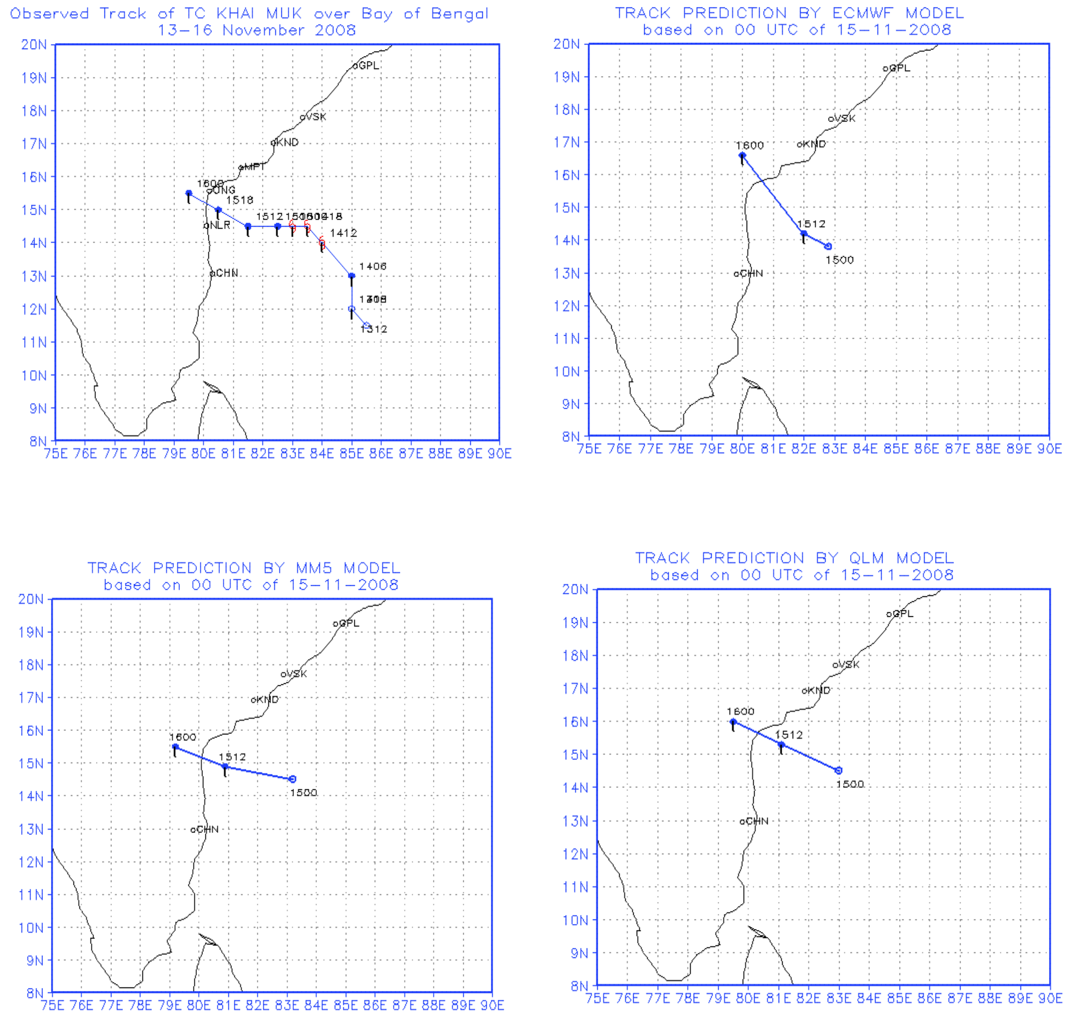
TRACK PREDICTION BY MM5 MODEL based on 00 UTC of 14–11–2008

TRACK PREDICTION BY QLM MODEL based on 00 UTC of 14–11–2008

Figure 4.3.1: Forecast tracks of NWP models based on 0000 UTC of 14 November 2008.

Table 4.3.1: Track Forecast Errors (km) of Khai-Muk based on initial condition of 0000 UTC of 14 November

Model	**Initial error**	**24hr forecast**	**48hr forecast**
QLM	00	202	58
ECMWF	65	144	78
MM5	00	126	166



Observed Track of TC KHAI MUK over Bay of Bengal
13–16 November 2008

TRACK PREDICTION BY ECMWF MODEL
based on 00 UTC of 15–11–2008

TRACK PREDICTION BY MM5 MODEL
based on 00 UTC of 15–11–2008

TRACK PREDICTION BY QLM MODEL
based on 00 UTC of 15–11–2008

Figure 4.3.2: Forecast tracks of NWP models based on 0000 UTC of 15 November 2008.

Table 4.3.2: Track Forecast Errors (km) of Khai-Muk based on initial condition of 0000 UTC of 15 November

Model	**Initial error**	**24hr forecast**
QLM	00	57
ECMWF	78	80
MM5	65	85

Table 4.3.3: Landfall errors (km) of Khai-Muk

Model	**Based on 14/0000UTC**		**Based on 15/0000UTC**	
	Landfall position error	**Landfall time error**	**Landfall position error**	**Landfall time error**
ECMWF	100 km	Close to landfall	31 km	1 hr delay
MM5	178 km	1hr early	56 km	1hr delay
QLM	15 km	1hr early	31 km	2hr delay

4.4 Intensity prediction by SCIP model

The statistical-dynamical cyclone intensity prediction model (SCIP) could predict the intensification into cyclonic storm of the system. The 12–hourly intensity prediction based on 0000 UTC on 14 November 2008 shows that the model (SCIP) could pick up the intensification of the low pressure system into cyclonic storm of intensity 35 knots at 12 hour and there is an underestimation of intensity by 5 knots and overestimation of 6 knots at 24 hour and 36 hour respectively. The 12-hourly wind speed forecasts based on 0000 UTC of 14 November 2008 along with observed wind speed is given in the Table 4.4.1.

Table 4.4.1 Model (SCIP) performance based on 0000 UTC of 14 November 2008

Forecasts hours →	00 hr	12 hr	24 hr	36 hr
Observed (knots)	30	35	40	30
Forecasts (knots)	30	35	35	36
Error (knots)	-	0	-5	6

CHAPTER-V

Cyclone “NISHA” during 25-27 November 2008

5.1 The Cyclonic Storm “NISHA”

A low pressure area formed over Sri Lanka and neighborhood on 24 November. It concentrated into a depression and lay centered at 0900 UTC of 25th over Sri Lanka near lat. 8.5° N and long. 81.0° E. It remained practically stationery and intensified into a deep depression at 1200 UTC of 25 November. It then moved north-northwestwards and intensified into a cyclonic storm (T.No. 2.5) “NISHA” over southwest Bay of Bengal and lay centered at 0300 UTC of 26th near latitudes 10.5°N and long. 80.0°E, close to Vedaranniyam. The system further intensified to T.No. 3.0 over the same area at 0900 UTC of same day. It then moved very slowly north-northwestwards and crossed Tamil Nadu and Puducherry coast, close to the north of Karaikal between 0000 UTC to 0100 UTC of 27 November with same intesity. It further moved in a northwesterly direction and weakened into a deep depression at 0900 UTC of 27 November. Then it moved westwards and weakened into a depression at 0900 UTC of 27 November. The system further weakened into a well-marked low pressure area over north interior Tamil Nadu and adjoining areas of south interior Karnataka and Rayalseema at 0000 UTC of 28 November. The observed track of the system is presented in Figure 5.1.

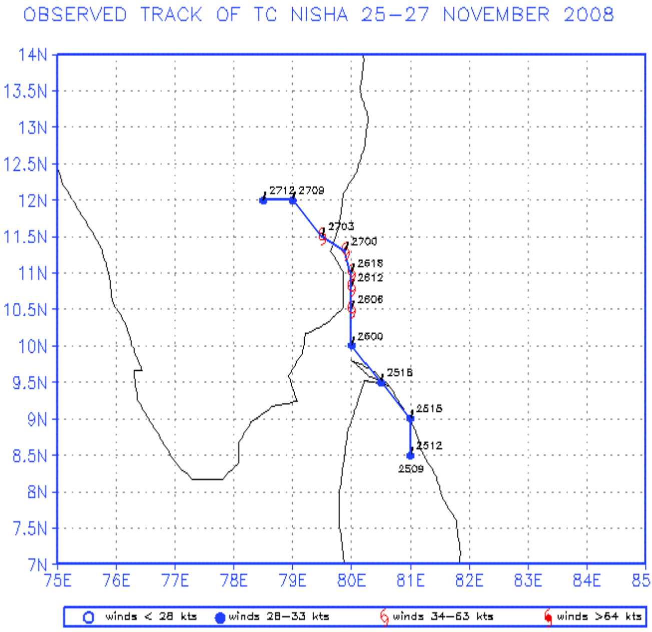


Figure 5.1

5.2 Analysis of GPP

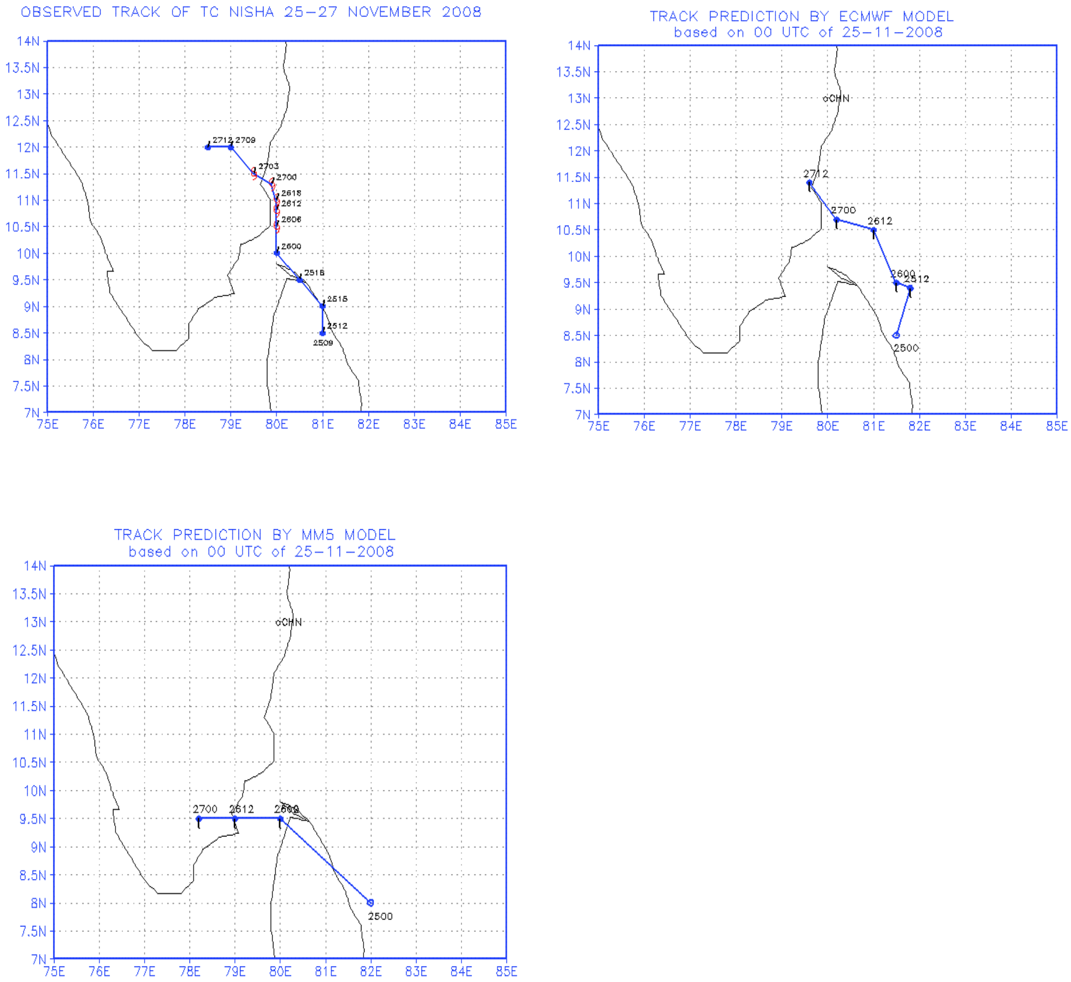
GPP values computed for this cyclone on the basis of real time model analysis fields are shown in Table 5.2.1. The higher GPP values (> 8.0, the threshold value) at early stages of development (T.No. 1.0, 2.0) have clearly indicated that the cyclone “NISHA” had enough potential to intensify into a developing system.

Table 5.2.1. Genesis potential parameter (GPP) for Developing System, Non-Developing System and Cyclone “NISHA”

GPP ($x10^{-5}$) →			
T.No. →	1.0	1.5	2.0
Developing	11.1	12.3	13.3
Non-Developing	3.4	4.2	4.6
Cyclone “NISHA”	14.5 (00UTC/24.11.2008)	- (00UTC/25.11.2008)	21.7 (00UTC/26.11.2008)

5.3 Track prediction by NWP models

The observed track and the forecast track based on 0000 UTC of 25 November 2008 and 0000 UTC of 26 November 2008 are shown in Figure 5.3.1. Corresponding forecast track errors and landfall errors are presented in Table 5.3.1 and Table 5.3.2.


OBSERVED TRACK OF TC NISHA 25–27 NOVEMBER 2008

TRACK PREDICTION BY ECMWF MODEL
based on 00 UTC of 25–11–2008

TRACK PREDICTION BY MM5 MODEL
based on 00 UTC of 25–11–2008

Figure 5.3.1: Forecast tracks based on 0000 UTC of 25 November 2008

Table 5.3.1: Track Forecast Errors (km) of Nisha with initial condition of 25 November 0000 UTC

Model	**24hr forecast**	**48hr forecast**
ECMWF	113 km	49 km
MM5	55 km	273 km
QLM	---	---

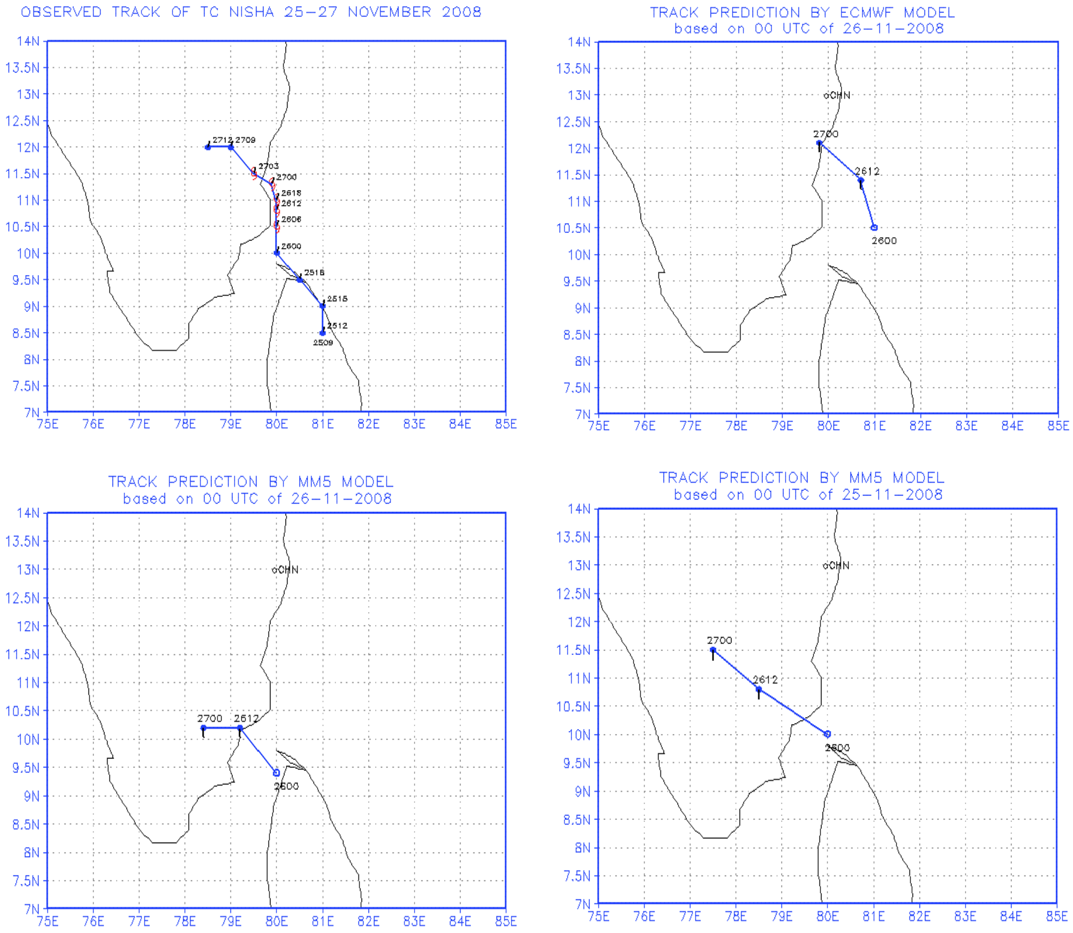


Figure 5.3.2: Forecast tracks based on 0000 UTC of 26 November 2008

Table 5.3.2: Track Forecast Errors (km) of Nisha with initial condition of 26 November 0000 UTC

Model	**24hr forecast**
ECMWF	84 km
MM5	94 km
QLM	235 km

Table 5.3.3: Landfall Errors (km) of Nisha

Model	**Based on 25/0000UTC**		**Based on 26/0000UTC**	
	Landfall position error	**Landfall time error**	**Landfall position error**	**Landfall time error**
ECMWF	25 km	3 hrs delay	33 km	3 hrs early
MM5	218 km	8 hrs early	77 km	6 hrs delay
QLM	---	---	133 km	12 hrs early

5.4 Decay of NISHA after landfall:

Figure 5.4.1 shows the decay curves on the basis of observations (line with solid squares) and 6-hourly forecast intensity (using equation 1.2.4) up to 12 hours after the landfall (line with open circles). Forecast errors (Table 5.4.1) at 6 hour and 12 hour after the landfall (at t=0, Intensity=45 knots) are found to be around -1 knots and 0 knots respectively.

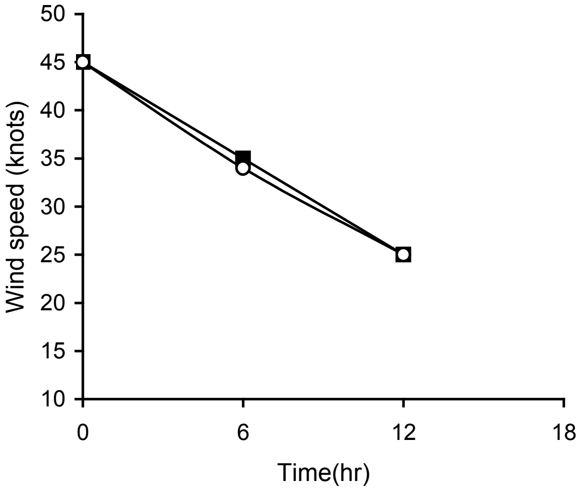


Figure 5.4.1: Decay of intensity of NISHA after landfall

Table 5.4.1. Decay model performance (at time of landfall)

Forecasts hours →	00 hr	6 hr	12 hr
Observed (knots)	45	35	25
Forecasts (knots)	45	34	25
Error (knots)	--	-1	0

CHAPTER-VI

The Deep Depression during 4 -7 December 2008

6.1 The Deep Depression

A low pressure area formed over southeast Bay of Bengal and adjoining south west Bay of Bengal on 3 December. It concentrated into a depression and lay centered at 0300 UTC of 4th near lat. 6.5° N and long. 90.0° E. The system moved northwestwards and intensified into a deep depression at 0000 UTC of 5th near lat. 7.5° N and long. 88.5° E. The system further moved northwestwards till 1200 UTC of same day, thereafter the system moved westwards till 1800 UTC of 6th without further intensification. Then it weakened into a depression at 0000 UTC of 7 December and moving further westwards it crossed Sri-Lanka cost at around 1200 UTC of same day. Due to interaction with land surface the system weakened into a well-marked low-pressure area over Sri Lanka and adjoining southwest Bay of Bengal at 1500 UTC of 7 December. The observed track of the system is presented in Figure 6.1.

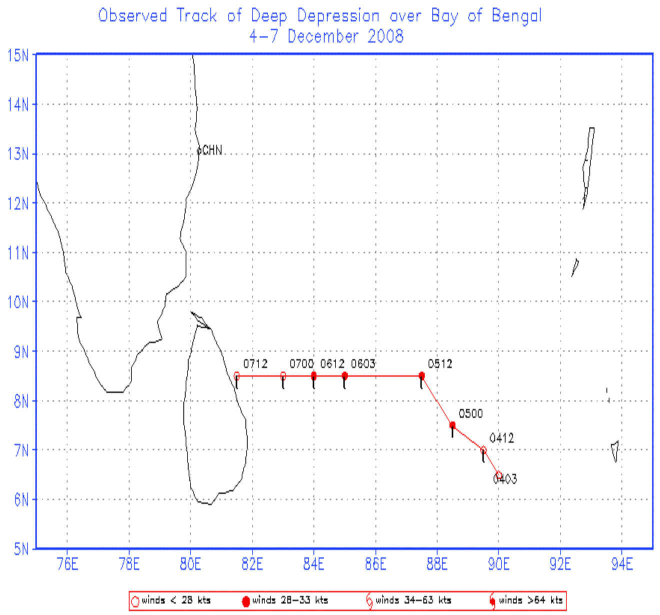


Figure 6.1.

6.2 Analysis of GPP

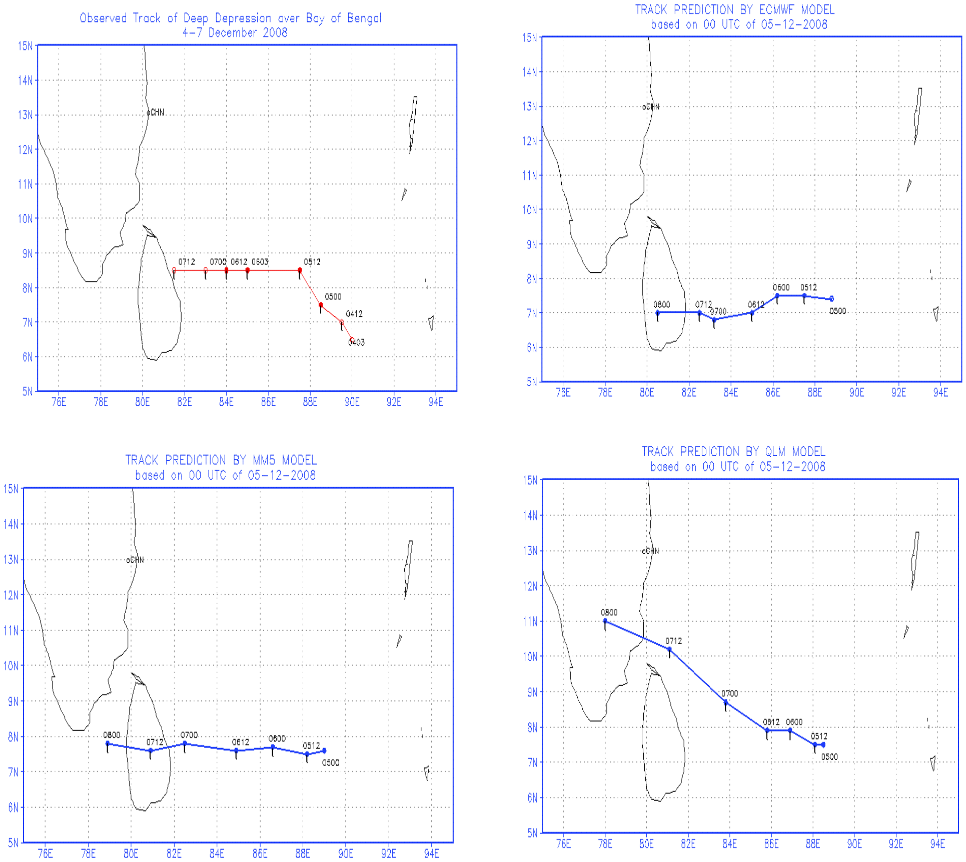
GPP values computed for this cyclone on the basis of real time model analysis fields are shown in Table 6.2.1. Analysis of genesis parameter (< 8.0, the threshold value) at early development stage (0000 UTC of 04.12.2008 & 6.12.2008) of "**Deep Depression**" suggested that the system has not enough potential to intensify into a developing system (>35 knots) but it showed greater than the threshold value on 0000 UTC of 05.12.2008.

Table 6.2.1. Genesis potential parameter (GPP) for Developing System, Non-Developing System and the "**Deep Depression**"

GPP ($x10^{-5}$) →			
T.No. →	1.0	2.0	2.0
Developing	11.1	13.3	13.3
Non-Developing	3.4	4.6	4.6
"Deep Depression"	5.2 (00UTC/04.12.2008)	14.3 (00UTC/05.12.2008)	7.2 (00UTC/6.12.2008)

6.3 Track prediction by NWP models

The observed track and the forecast track based on 0000 UTC of 5 December and 0000 UTC of 6 December 2008 are shown in Figure 6.3.1 and Figure 6.3.2 and corresponding forecast track errors are presented in Table 6.3.1 and Table 6.3.2



Observed Track of Deep Depression over Bay of Bengal 4-7 December 2008

TRACK PREDICTION BY ECMWF MODEL based on 00 UTC of 05-12-2008

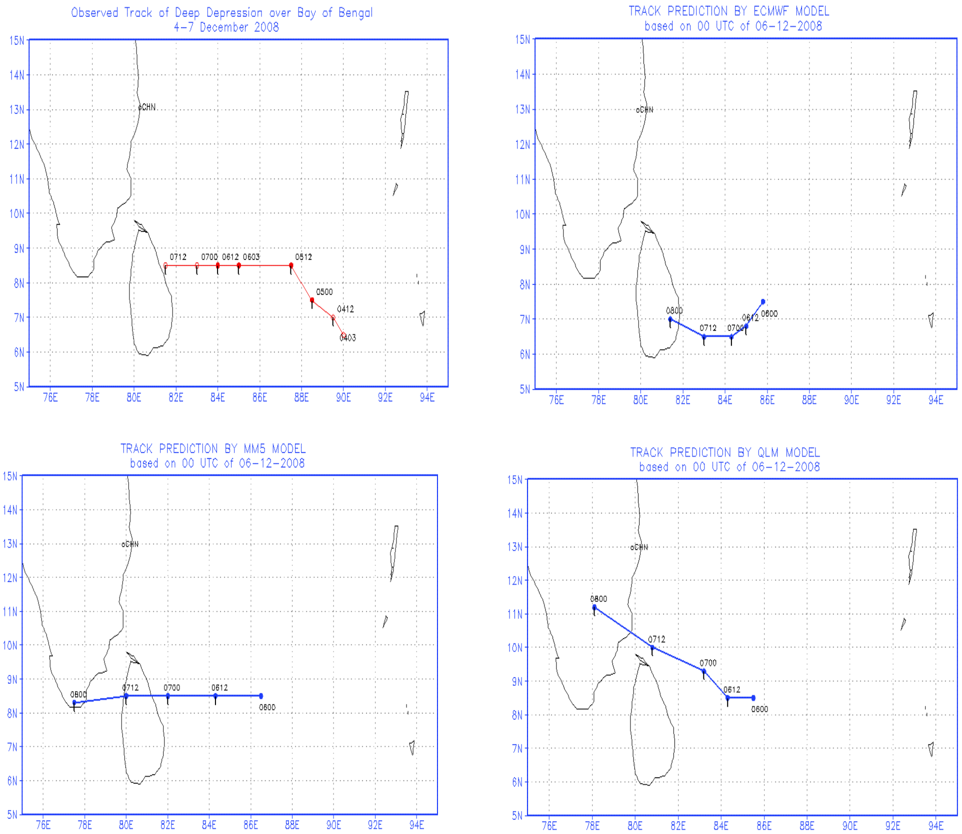
TRACK PREDICTION BY MM5 MODEL based on 00 UTC of 05-12-2008

TRACK PREDICTION BY QLM MODEL based on 00 UTC of 05-12-2008

Figure 6.3.1: Forecast tracks based on 0000 UTC of 5 December 2008

Table 6.3.1: Track Forecast Errors (km) of **Deep Depression** with initial condition of 0000 UTC of 5 December

Model	**24hr**	**48hr**
ECMWF	173 km	190 km
MM5	197 km	95 km
QLM	219 km	91 km



Observed Track of Deep Depression over Bay of Bengal
4-7 December 2008

TRACK PREDICTION BY ECMWF MODEL
based on 00 UTC of 06-12-2008

TRACK PREDICTION BY MM5 MODEL
based on 00 UTC of 06-12-2008

TRACK PREDICTION BY QLM MODEL
based on 00 UTC of 06-12-2008

Figure 6.3.2: Forecast tracks based on 0000 UTC of 6 December 2008

Table 6.3.2: Track Forecast Errors (km) of **Deep Depression** with initial condition of 0000 UTC of 6 December

Model	**24hr**
ECMWF	264 km
MM5	55 km
QLM	126 km

6.4 Intensity prediction by SCIP model

The 12–hourly intensity prediction based on 0000 UTC on 5 December 2008 shows that the statistical-dynamical cyclone intensity prediction model (SCIP) could pick up the intensity correctly up to 36 hour but unable to pick up the weakening thereafter with an over estimation of 8 knots and 12 knots at 48 hr and 60 hr respectively (Table 6.4.1). The updated wind speed forecasts (based on 0000 UTC of 6 December 2008) could pick up the weakening and captured the 12-hourly wind speed with reasonable success. The 12-hourly wind speed forecasts along with observed wind speed is given in Table 6.4.2.

Table 6.4.1 Model (SCIP) performance based on 0000 UTC of 5 December 2008

Forecasts hours →	00 hr	12 hr	24 hr	36 hr	48 hr	60 hr
Observed (knots)	30	30	30	30	25	25
Forecasts (knots)	30	31	30	33	33	37
Error (knots)	-	+1	0	+3	+8	+12

Table 6.4.2 Model (SCIP) performance based on 0000 UTC of 6 December 2008

Forecasts hours →	00 hr	12 hr	24 hr	36 hr
Observed (knots)	30	30	25	25
Forecasts (knots)	30	32	30	29
Error (knots)	-	+2	+5	+4

CHAPTER-VII

Cyclone "BIJLI" during 14-17 April 2009

7.1 Bay of Bengal Very Severe Cyclonic storm "BIJLI " of May 2009

The system was located as a low-pressure area over the southeast Bay of Bengal on 14 April 2008. The low pressure system concentrated into a depression at 0900 UTC of 14 April and lay centered at latitude 12.5 °N, longitude 88.0 °E. Moving in a northwesterly direction, the system intensified into deep depression at 0060 UTC of 15 April over west-central Bay of Bengal near Latitude 14.0° N and longitude 87.5° E. The system further moved in a Northwesterly direction and intensified into a Cyclonic storm "BIJLI" (35 knots) at 1200 UTC of same day and lay centered at latitude 15.0 °N, longitude 86.5 °E. The system further moved in a North-northwesterly direction and intensified into 40 knots at 1500 UTC of 15 April. Thereafter the system moved in a North-Northeasterly direction and maintained the same intensity (40 knots) till 0000 UTC of 17 April. The system further moved in a North-Northeasterly direction, weakened into a deep depression at 0900 UTC and into depression at 1200 UTC of same day. The Depression crossed Bangladesh 22.2^0 N / 91.8^0 E close to south of Chittagaon around 1600 UTC of 17 April 2009. It weakened and laid as well marked low-pressure area over Bangladesh and adjoining Mizoram & Tripura at 1800 UTC of 17 April 2009. The observed track of the system is presented in Figure 7.1.

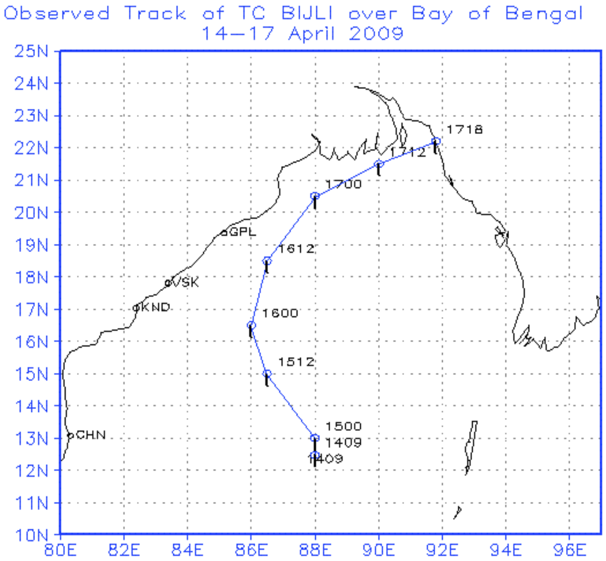


Figure 7.1

7.2. Analysis of GPP

GPP values computed (Kotal et al, 2009) for this cyclone on the basis of real time model analysis fields along with the GPP values for Developing Systems and Non-Developing Systems are shown in Table 7.2.1. The higher GPP values (> 8.0, the threshold value) 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 7.2.1. Genesis potential parameter (GPP) for Developing System, Non-Developing System and Cyclone “BIJLI”

GPP (x10^{-5}) →				
T.No. →	1.0	1.5	1.5	2.5
Developing	11.1	12.3	12.3	13.5
Non-Developing	3.4	4.2	4.2	2.7
Cyclone “BIJLI”	13.8 (0000 UTC /14.04.2009)	12.4 (1200 UTC /14.04.2009)	10.6 (0000 UTC /15.04.2009)	9.9 (1200 UTC /15.04.2009)

7.3 Track prediction by NWP models

Figure 7.3.1, Figure 7.3.2 and Figure 7.3.3 display the forecast track positions of the cyclone BIJLI by various NWP models (ECMWF, GFS (NCEP), JMA, MM5, QLM, and MME) with the initial conditions of 0000 UTC of 15 April, 16 April and 17 April 2009 respectively. It is encouraging to note that all the NWP models consistently indicated that the cyclonic storm BIJLI was going to recurve in the northeast direction. Although the GFS model based on 0000 UTC 0f 15.04.2009 showed westerly movement and the QLM model and MME showed marginally touching Orissa coast initially during recurvature, but during subsequent forecast hours it showed northeast movement.

The forecast errors of member models based on different initial conditions and the corresponding consensus forecasts (MME) are summarized in Table 7.3.1, Table 7.3.2 and Table 7.3.3. The tables show that consensus forecasts could provide useful guidance under the circumstances of wide variations of individual models.

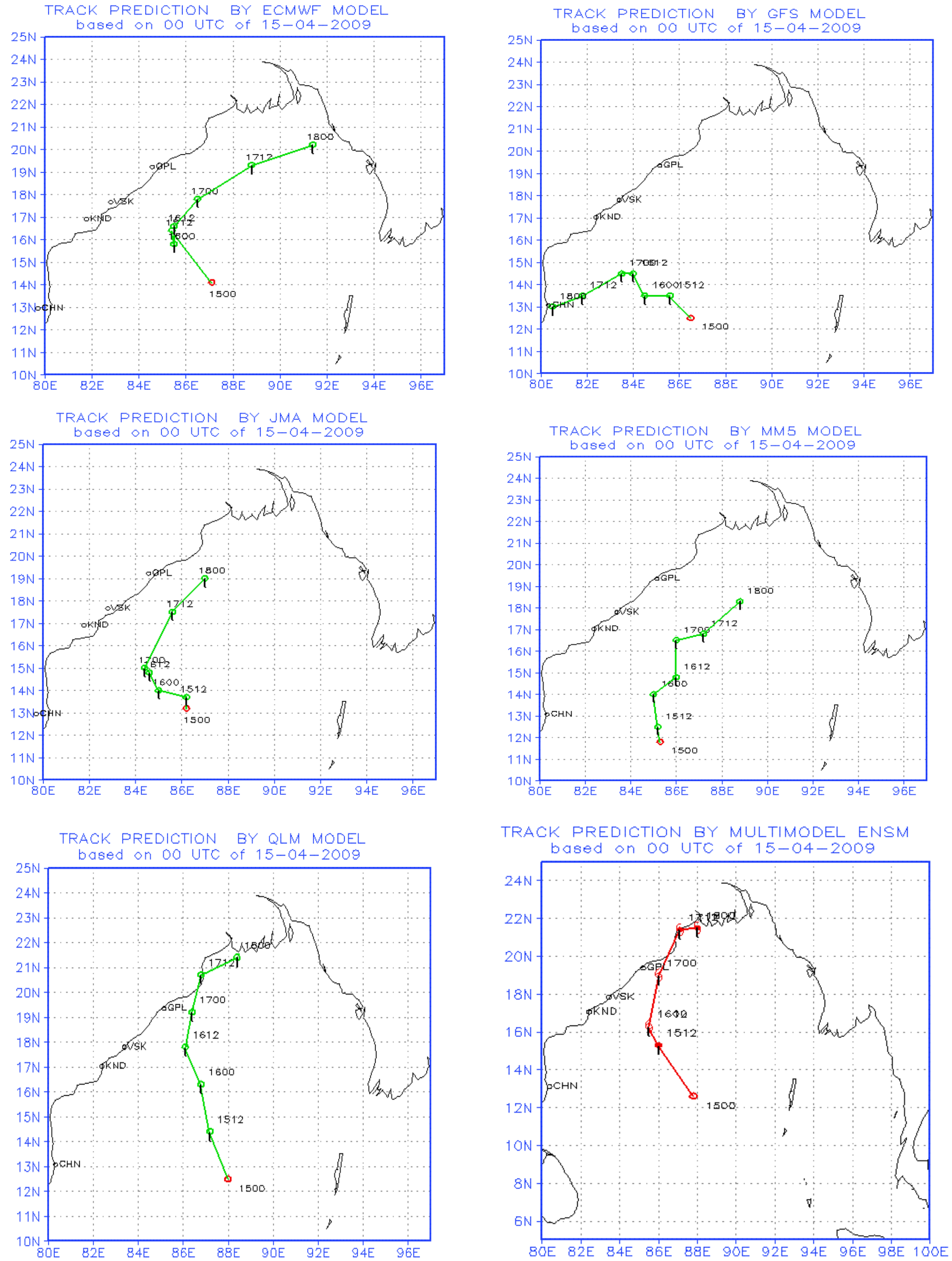


Figure 7.3.1 Forecast track of multi-model ensemble and its member models based on 0000 UTC of 15.4.2009

Table 7.3.1 Track forecast error (km) of multimodel ensemble and its member models based on 00 UTC/15.4.2009

HOUR	ECMWF	GFS	JMA	MM5	QLM	MME
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

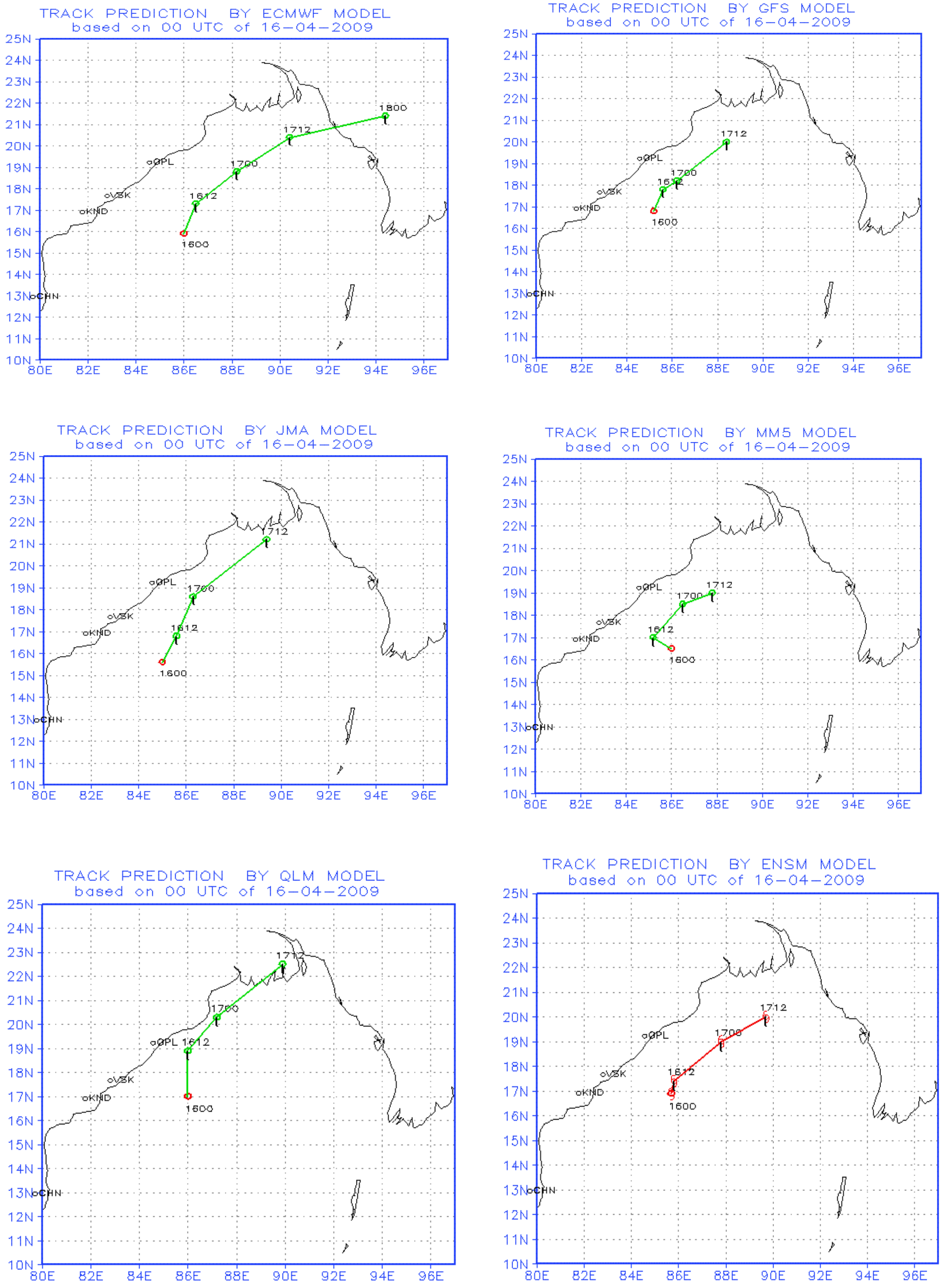


Figure 7.3.2 Forecast track of multi-model ensemble and its member models based on 0000 UTC of 16.4.2009

Table 7.3.2 Track forecast error (km) of multimodel ensemble and its member models based on 0000 UTC/16.4.2009

HOUR	ECMWF	GFS	JMA	MM5	QLM	MME
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

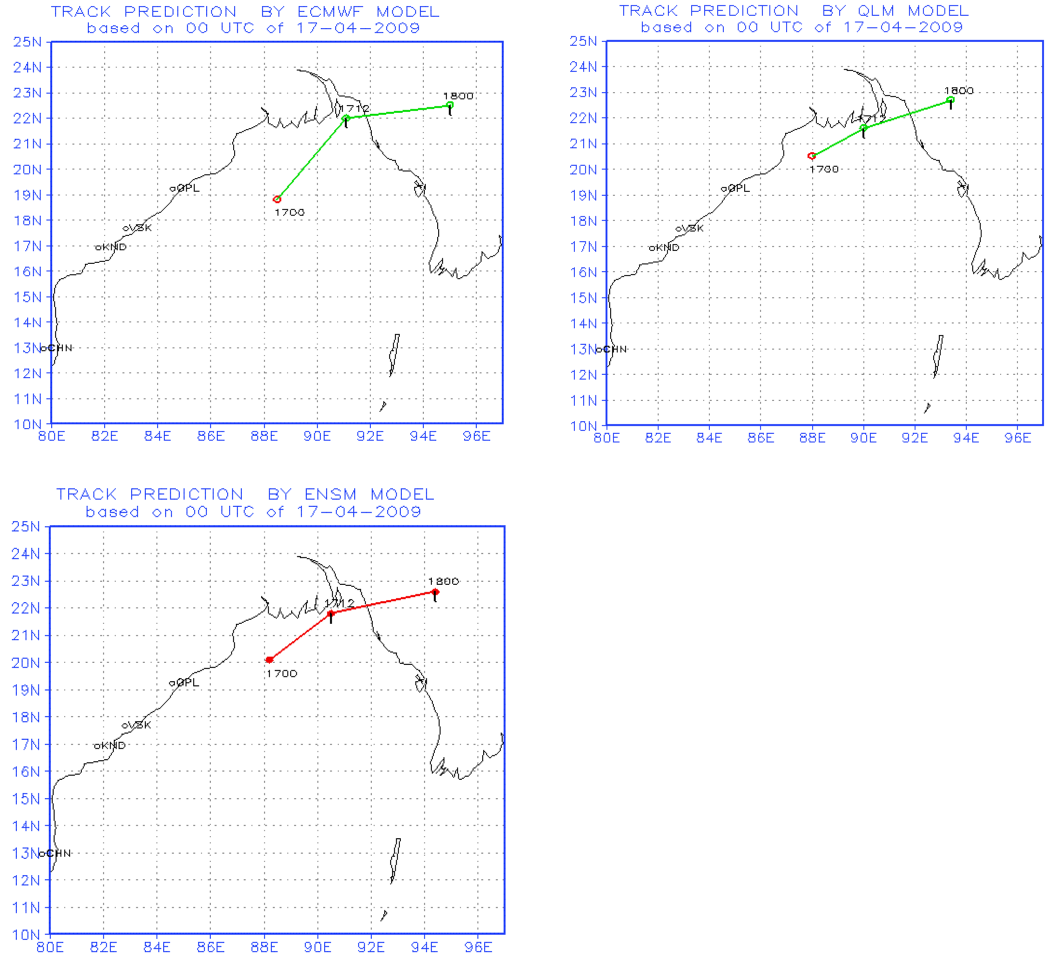


Figure 7.3.3 Forecast track of multi-model ensemble and its member models based on 0000 UTC of 17.4.2009

Table 7.3.3 Track forecast error (km) of multimodel ensemble and its member models based on 0000 UTC/17.4.2009

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

7.4. Intensity prediction by SCIP model

Based on 0000 UTC of 15 April 2009:

The cyclone "BIJLI" intensified during the period 0000UTC on 15 April to 0000 UTC on 16 April and maintained its intensity 40 knots for next 24 hours and weakened thereafter. The 12 hourly intensity forecast valid up to 60 hours (Table 7.4.1) shows that the model could predict intensity up to 48 hours with reasonable success (with a error of 5 knots) but could not indicate weakening thereafter.

Table 7.4.1. Model (SCIP) performance based on 0000 UTC of 15 April 2009

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

Forecast based on 0000 UTC of 16 April and 0000 UTC of 17 April:

The cyclone "BIJLI" shows no intensification during the 24 hours period (0000 UTC on 16 April to 0000 UTC on 17 April). The model could pick up intensity up to next 24 hours (Table 7.4.2) with a maximum error of 9 knots (overestimation) at 24 hour. However the model could not indicate weakening thereafter.

Table 7.4.2. Model (SCIP) performance based on 0000UTC 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 7.4.3. Model (SCIP) performance based on 0000 UTC of 17 April 2009

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

CHAPTER-VIII

Cyclone “AILA” during 23-26 May 2009

8.1 Bay of Bengal Severe Cyclonic storm “AILA ” of May 2009

Under the influence of the cyclonic circulation, a low-pressure area formed over the southeast Bay of Bengal on 22 May. It concentrated into a depression at 0600 UTC of 23 May and lay centered near Lat. 16.5º N/Long 88.0º E. The depression moved mainly in a northerly direction and intensified into a deep depression at 0300 UTC of 24 May and lay centred 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. The system crossed West Bengal coast close to the east of Sagar Island between 0800 UTC to 0900 UTC as a severe cyclonic storm with wind speed of 100 to 110 kmph. 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 near Kolkata. The system maintained its intensity of cyclonic storm till 0000 UTC of 26 May. Moving northerly direction, it further weakened into a deep depression and lay centred at 0300 UTC of 26th May near Malda. It weakened into a depression and lay centred at 0600 UTC of 26 May over the same region. It weakened into a well marked low pressure area over Sub-Himalayan West Bengal at 0900 UTC of 26 May and became less marked on 27 May. The observed track of the system is shown in Figure 8.1.

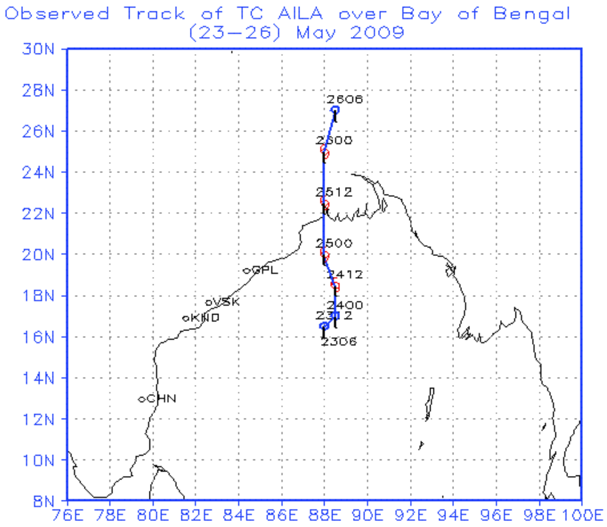


Figure 8.1

8.2. Analysis of GPP

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

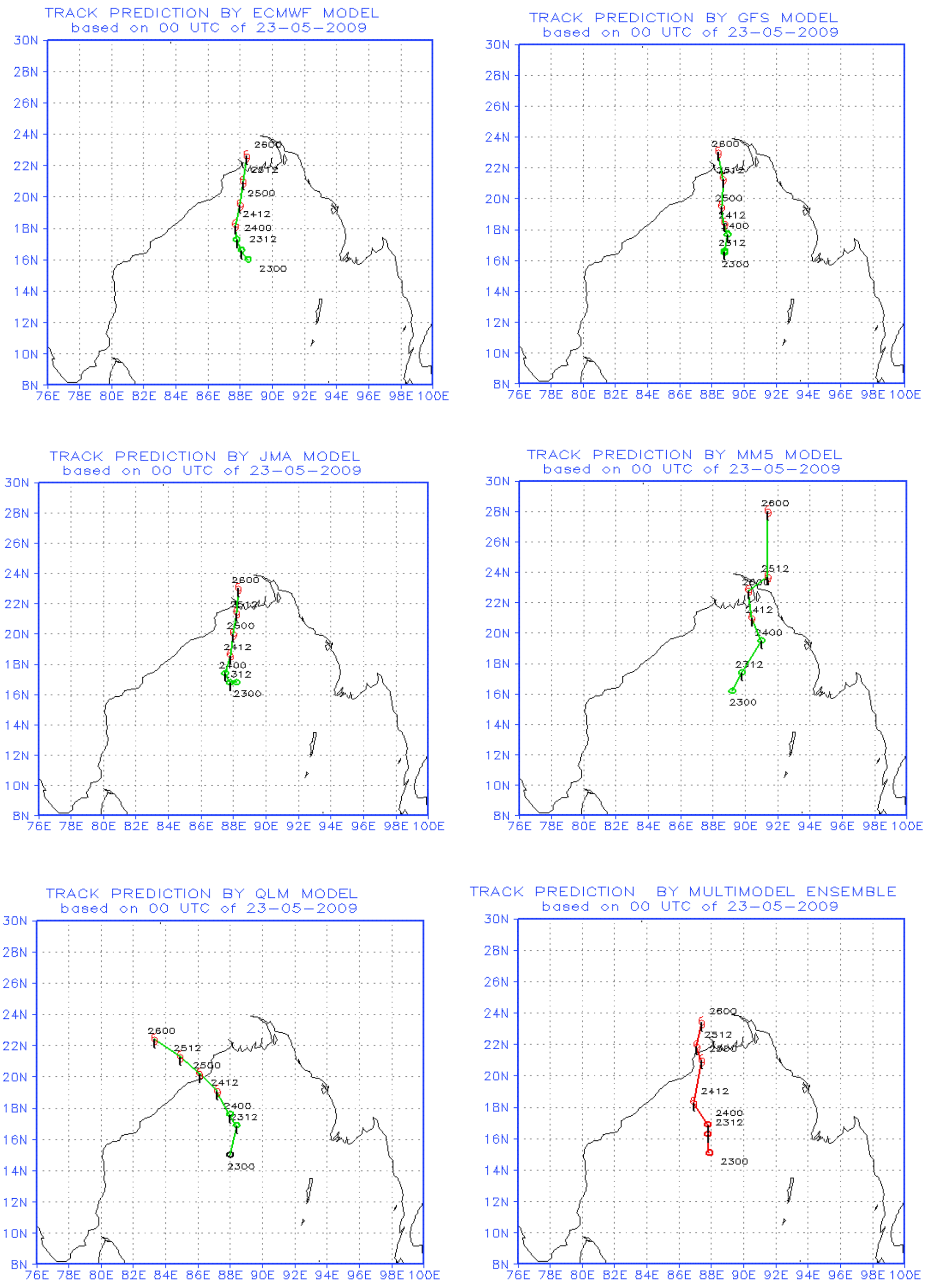
Table 8.2.1. Genesis potential parameter (GPP) for Developing System, Non-Developing System and Cyclone “AILA”

GPP (x10^{-5}) →					
T.No. →	1.0	1.0	1.0	1.0	1.5
Developing	11.1	11.1	11.1	11.1	12.3
Non-Developing	3.4	3.4	3.4	3.4	4.2
Cyclone “AILA”	20.0 (00UTC /22.05.2009)	20.0 (1200UTC /22.05.2009)	14.3 (0000UTC /23.05.2009)	14.9 (1200UTC /23.05.2009)	16.3 (00UTC /24.05.2009)

8.3 Track prediction by NWP models

Figure 8.3.1, Figure 8.3.2 and Figure 8.3.3 display the forecast track positions of the cyclone AILA by various NWP models (ECMWF, GFS (NCEP), JMA, MM5, QLM) and multimodel ensemble (MME) with the initial conditions of 0000 UTC of 23 May, 24 May and 25 May 2009 respectively. All the NWP models consistently indicated that the cyclonic storm AILA was going to move northerly direction and crossed Indo-Bangla border. Although the QLM model based on 0000 UTC 0f 23.05.2009 showed northwesterly recurvature and crossed Orissa coast and MM5 model showed southeast Bangladesh coast, but during subsequent forecast hours it showed crossing of Indo-Bangla border.

The forecast errors of member models based on different initial conditions and the corresponding consensus forecasts (MME) are summarized in Table 8.3.1, Table 8.3.2 and Table 8.3.3. The tables show that consensus forecasts could provide useful guidance under the circumstances of wide variations of individual models (e.g. QLM, MM5 based on 00 UTC 0f 23.05.2009).


TRACK PREDICTION BY ECMWF MODEL
based on 00 UTC of 23-05-2009

TRACK PREDICTION BY GFS MODEL
based on 00 UTC of 23-05-2009

TRACK PREDICTION BY JMA MODEL
based on 00 UTC of 23-05-2009

TRACK PREDICTION BY MM5 MODEL
based on 00 UTC of 23-05-2009

TRACK PREDICTION BY QLM MODEL
based on 00 UTC of 23-05-2009

TRACK PREDICTION BY MULTIMODEL ENSEMBLE
based on 00 UTC of 23-05-2009

Figure 8.3.1: Forecast track of multimodel ensemble and its member models based on 0000 UTC of 23.5.2009

Table 8.3.1: Track forecast error (km) of multi-model ensemble and its member models based on 0000 UTC/23.5.2009

HOUR	ECMWF	GFS	JMA	MM5	QLM	MME
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

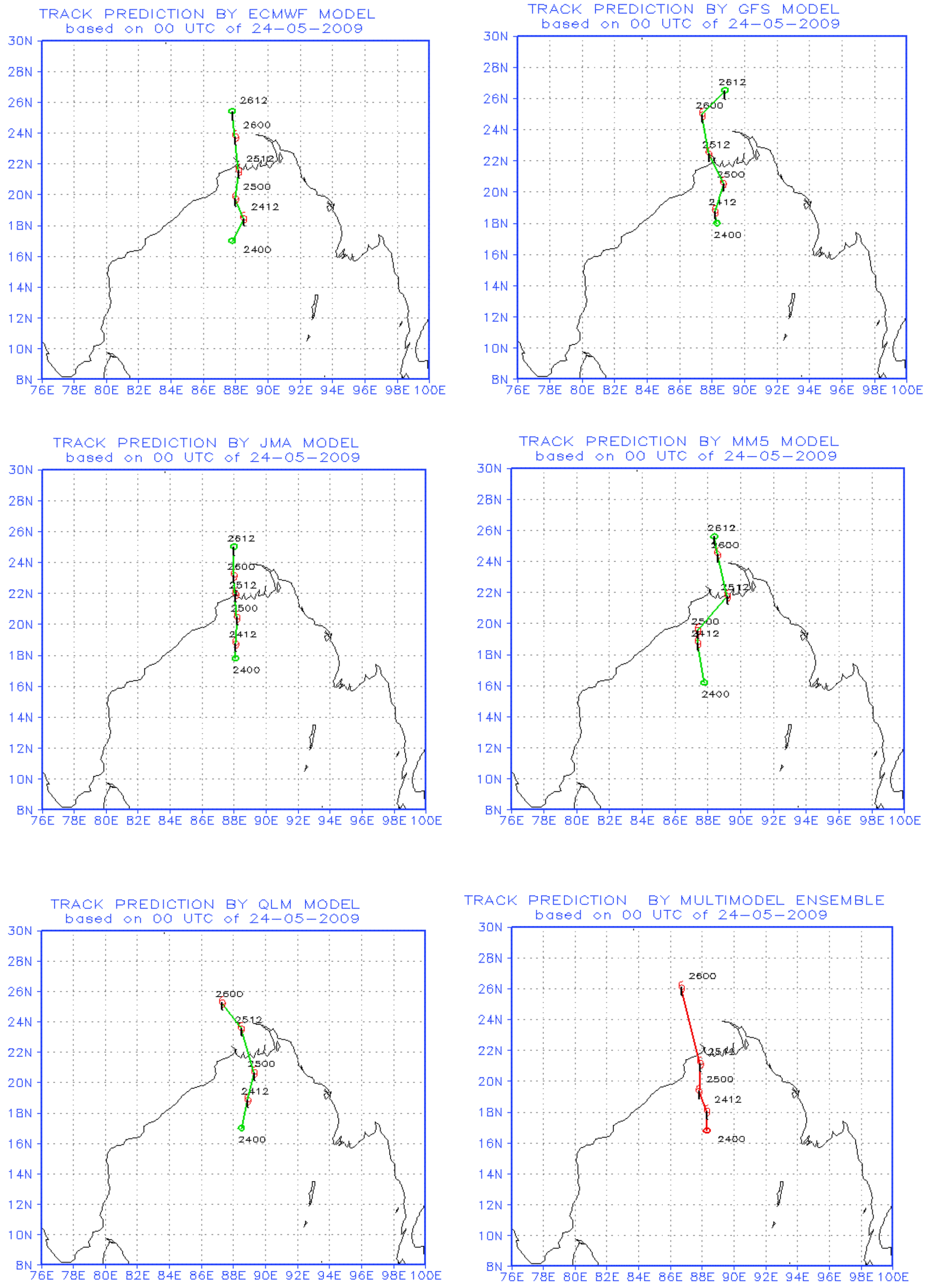


Figure 8.3.2: Forecast track of multi-model ensemble and its member models based on 0000 UTC of 24.5.2009

Table 8.3.2: Track forecast error (km) of multimodel ensemble and its member models based on 0000 UTC/24.5.2009

HOUR	ECMWF	GFS	JMA	MM5	QLM	MME
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

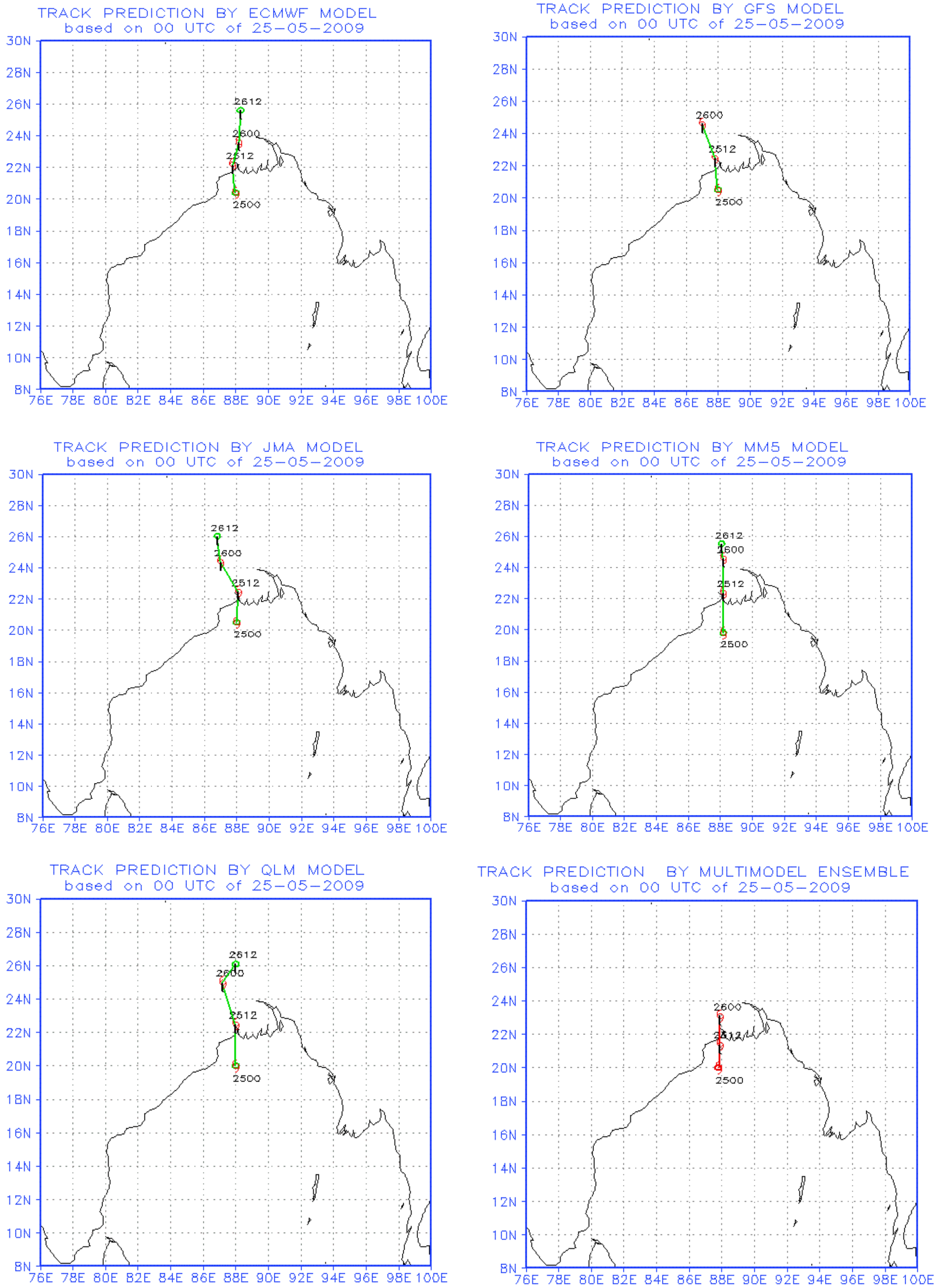


Figure 8.3.3: Forecasts track of multi-model ensemble and its member models based on 0000 UTC of 25.5.2009

Table 8.3.3 Track forecast error (km) of multimodel ensemble and its member models based on 0000 UTC/25.5.2009

HOUR	ECMWF	GFS	JMA	MM5	QLM	MME
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

8.4. Intensity prediction by SCIP model

Based on 0000 UTC of 23 May 2009:

The cyclone "AILA" intensified gradually from its depression stage and maintained its intensification till landfall. The cyclone reached to its severe cyclonic stage at 0600 UTC of 25 May 2009. The 12 hourly intensity forecast (based on 0000 UTC of 23 May 2009) valid up to 60 hours (Table 8.4.1) shows that the model could predict intensity with reasonable success with a maximum error of 10 knots at 48 hours.

Table 8.4.1. Model (SCIP) performance based on 0000 UTC of 23 May 2009

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

Updated forecasts based on 0000 UTC of 24 May and 00 UTC of 25 May:

The updated forecasts based on 0000 UTC of 24 May and 0000 UTC of 25 May show improvement of error at all forecasts hour.

Table 8.4.2. Model (SCIP) performance based on 0000UTC 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 8.4.3. Model (SCIP) performance based on 0000 UTC of 25 May 2009

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

8.5. Decay of AILA after landfall

The cyclone “AILA” maintained its intensity of cyclonic storm till 15 hours after landfall and depression stage for next 6 hour. Figure 8.5.1 shows the decay curves on the basis of observations (line with solid squares), 6-hourly forecast intensity (using equation 1.2.4) up to 18 hours after the landfall (line with open circles) and six hour after landfall, the updated forecast intensity (using equation 1.2.5) up to 12 hours (line with solid circles). The 6 hourly decay forecast (based on 0900 UTC of 25 May 2009, at the time of landfall) valid up to 18 hours (Table 8.5.1) shows that the decay model could predict intensity with reasonable success with a maximum error of 6 knots (under estimation) at 12 hours. The updated forecast (6 hour after landfall) valid up to 12 hours (Table 8.5.2) shows improvement of forecast error.

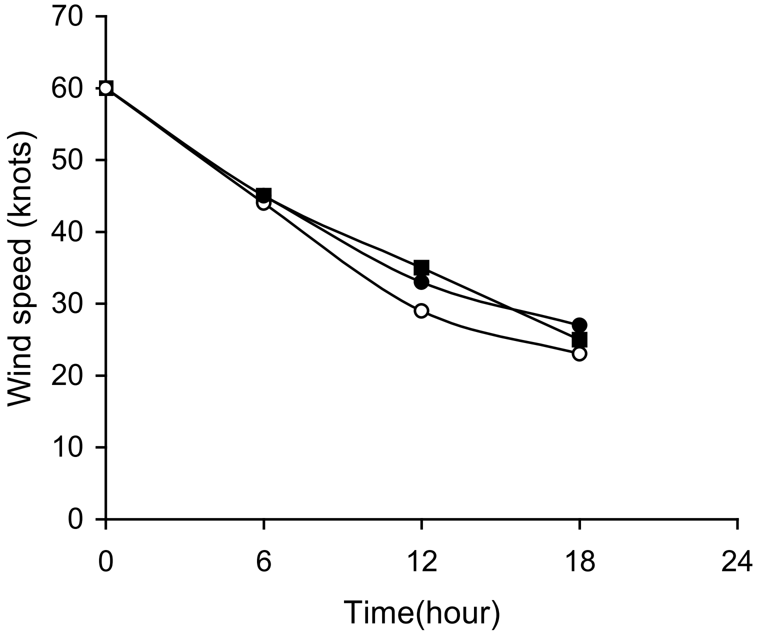


Figure 8.5.1: Decay of intensity of AILA after landfall

Table 8.5.1. Decay model performance (at the time of landfall)

Forecasts hours →	00 hr	6 hr	12 hr	18 hr
Observed (knots)	60	45	35	25
Forecasts (knots)	60	44	29	23
Error (knots)	--	-1	-6	-2

Table 8.5.2. Updated Decay forecast (6 hr after landfall)

Forecasts hours →	00 hr	6 hr	12 hr
Observed (knots)	45	35	25
Forecasts (knots)	45	33	27
Error (knots)	--	-2	+2

CHAPTER-IX

SUMMARY AND CONCLUSIONS

During 2008-09, IMD used an objective numerical method for the operational cyclone forecasting work. The method comprising of four forecast components, namely (a) cyclone genesis potential parameter (GPP), (b) MME technique for cyclone track prediction, (c) cyclone intensity prediction (SCIP) model and (d) predicting decaying intensity after the landfall. The main purpose of this work is to describe the objective cyclone forecast system and document the performance skill during the cyclone season 2008-09.

Five cyclonic systems formed over the Bay of Bengal during the year 2008 and two cyclonic systems formed over the Bay of Bengal during the pre-monsoon cyclone season 2009.

Performance statistics of GPP, MME, SCIP and Decay model are presented below:

a. Performance statistics of genesis potential parameter (GPP)

Out of seven cyclonic systems, those formed over the Bay of Bengal during the year 2008-2009, six systems were developing systems and one was non-developing system (DD). GPP analysis at early stages of development (T.No. 1.0, 1.5, 2.0) successfully indicated the potential for intensification of all the six developing systems. GPP analysis for the non-developing system showed greater than threshold value 8.0 at 0000 UTC of 05.12.2008 at T.No. 2.0, but in this case at 0000 UTC of 04.12.2008 (at T.No. 1.5) and at 0000 UTC of 06.12.2008 (at T.No. 2.0) it successfully indicated that the potential of the system is less for intensification into a developing system as shown in Table 6.2 in the text.

b. Performance statistics of NWP models and MME for track prediction

Table 9.1 shows the error statistics of the NWP models (ECMWF, GFS (NCEP), JMA, MM5 and QLM) during the year 2008 at 12 hour, 24 hour, 36 hour, 48 hour, 60 hour and 72 hour forecasts. The Average Error (AE) of the member models is ranging from 90 km to 160 km for forecasts up to 12 hours. The AE of the member models increases with the forecast period and it ranges from of the order of 100 km to 210 km, 120 km to 220 km, 140 km to 285 km, 195 km to 345 km and 200 km to 495 km for 24, 36, 48, 60 and 72 hour forecast respectively. ECMWF model is found to be the best among the member models.

Table 9.1: Track forecast error (km) of the member models during the year 2008

HOUR	ECMWF	GFS	JMA	MM5	QLM
12 hr	92	129	161	142	107
24 hr	104	186	212	175	133
36 hr	120	223	183	213	222
48 hr	142	248	249	214	286
60 hr	195	250	285	291	344
72 hr	199	329	250	366	496

Table 9.2 shows the error statistics of the member models (ECMWF, GFS, JMA, MM5 and QLM) and MME during the year 2009 at 12 hour, 24 hour, 36 hour, 48 hour, 60 hour and 72-hour forecasts. The 12 hour forecasts shows that the AE varies from around 70 km to 155 km. Corresponding MME forecast position error is 70 km. The 24-hour forecasts position error varies from 110 km to around 235 km with lowest error by ECMWF and largest error by MM5 model. Corresponding MME forecast is found to be 90 km. The 36 hour forecast position error varies from around 115 km to 320 km with lowest error by ECMWF and largest error by MM5 model, whereas, MME error is around 145 km. The 48 hours forecasts position error varies from around 95 km to 245 km with lowest error by ECMWF and largest error by MM5 model. Corresponding MME forecast error is around 200 km. The 60 hour forecasts varies from 85 km to 445 km with MME error is around 240 km. The 72 hour forecasts error varies from around 150 km to 575 km with lowest error by GFS (NCEP) and JMA and largest error by QLM model and corresponding MME forecast position error is 295 km.

Table 9.2: Track forecast error (km) of the member models and MME during the year 2009

HOUR	**ECMWF**	**GFS**	**JMA**	**MM5**	**QLM**	**MME**
12 hr	72	83	86	153	77	70
24 hr	111	191	167	234	124	90
36 hr	114	193	142	320	143	147
48 hr	93	117	86	246	242	199
60 hr	168	126	85	351	447	242
72 hr	217	151	152	415	577	293

Table 9.3 and Table 9.4 shows the landfall error (position and time) statistics of the model ECMWF, GFS, JMA, MM5 and QLM before 24 hour and 48 hour of landfall respectively during 2008.

Table 9.3 Landfall position and time error (up to 24 hours before landfall); E=early, D=delay

Cyclone	Lead Time (Hr)	ECMWF		GFS		JMA		MM5		QLM	
		Km	Time (Hr)	Km	Time (Hr)	Km	Time (Hr)	Km	Time (Hr)	Km	Time (Hr)
Nargis	24	50	7 E	-	-	-	-	110	1 E	300	5 D
Rashmi	22	30	2 D	0	2 E	46	6 E	10	6 E	25	1 E
Khaimuk	22	31	1 D	-	-	-	-	56	1 D	31	3 D
Nisha	24	33	3 E	-	-	-	-	77	6 D	133	12 E
MEAN		**36**	**3.2**	**0**	**2**	**46**	**6**	**63**	**3.5**	**122**	**5.2**

Table 9.4 Landfall position and time error (25 to 48 hours before landfall); E=early, D=delay

Cyclone	Lead Time (Hr)	ECMWF		GFS		JMA		MM5		QLM	
		Km	Time (Hr)	Km	Time (Hr)	Km	Time (Hr)	Km	Time (Hr)	Km	Time (Hr)
Nargis	48	10	8 E	-	-	-	-	10	8 E	430	12 E
Rashmi	46	76	5 D	66	8 E	10	1 E	95	10 E	20	12 E
Khaimuk	46	100	0	-	-	-	-	178	1 E	15	1 E
Nisha	48	25	3 D	-	-	-	-	218	8 E	-	-
MEAN		**53**	**4**	**66**	**8**	**10**	**1**	**100**	**6.7**	**155**	**8.3**

Table 9.5, Table 9.6 and Table 9.7 shows the landfall error (position and time) statistics of the model ECMWF, GFS, JMA, MM5, QLM and MME before 24 hour, 48 hour and 72 hour of landfall respectively during 2009.

Table 9.5 Landfall position and time error (up to 24 hours before landfall); E=early, D=delay

Cyclone	Lead Time (Hr)	ECMWF		GFS		JMA		MM5		QLM		MME	
		Km	Time (Hr)	Km	Time (Hr)	Km	Time (Hr)	Km	Time (Hr)	Km	Time (Hr)	Km	Time (Hr)
Bijli	16	23	4 D	-	-	-	-	-	-	10	2 E	10	2 E
Aila	08	10	0	15	0	15	0	20	2 D	10	2 D	15	2 D
MEAN	**-**	**16**	**2**	**15**	**0**	**15**	**0**	**20**	**2**	**10**	**2**	**12**	**2**

Table 9.6 Landfall position and time error (25 to 48 hours before landfall); E=early, D=delay

Cyclone	Lead Time (Hr)	ECMWF		GFS		JMA		MM5		QLM		MME	
		Km	Time (Hr)	Km	Time (Hr)	Km	Time (Hr)	Km	Time (Hr)	Km	Time (Hr)	Km	Time (Hr)
Bijli	40	167	2 D	-	-	-	-	-	-	292	8 E	-	-
Aila	32	10	5 D	23	1 D	10	1 D	124	4 D	175	8 D	20	7 D
MEAN	**-**	**88**	**3.5**	**23**	**1**	**10**	**1**	**124**	**4**	**233**	**8**	**20**	**7**

Table 9.7 Landfall position and time error (49 to 72 hours before landfall); E=early, D=delay

Cyclone	Lead Time (Hr)	ECMWF		GFS		JMA		MM5		QLM		MME	
		Km	Time (Hr)	Km	Time (Hr)	Km	Time (Hr)	Km	Time (Hr)	Km	Time (Hr)	Km	Time (Hr)
Bijli	64	-	-	-	-	-	-	-	-	582	9 E	601	10 E
Aila	56	20	1 D	62	8 D	40	6 E	227	8 E	275	11 D	83	2 D
MEAN	**-**	**20**	**1**	**62**	**8**	**40**	**6**	**227**	**8**	**428**	**10**	**342**	**6**

c. Performance statistics (error in knots) of Intensity prediction model (SCIP)

The SCIP model is used for real time forecasting of cyclone over the Bay of Bengal during the period 2008-2009. Fifteen forecasts were issued for the six systems (as shown in Table 9.8) based on different initial conditions (including updated forecasts).

Table 9.8 illustrates the 12-hourly forecasts error (knots) valid up to 72 hours for seven cyclones. The Average Absolute Error (AAE) is found to be 15 knots (ranging from 4.4 to 15.1 knots) for forecasts up to 72 hours as shown in Table 9.8. The error statistics shows that the model could predict the intensity with reasonable success.

Table 9.8: Forecast errors (knots) of SCIP model

Cyclone	**No. of forecasts**	**Forecasts hours →**					
		12 hr	**24 hr**	**36 hr**	**48 hr**	**60 hr**	**72 hr**
Nargis	1	-16	-14	-16	-12	-2	14
	2	2	-6	27	34	33	16
	3	2	6	6	3	-4	-
	4	4	4	7	-6	-	-
	5	4	-4	-4	-	-	-
Rashmi	6	-2	-8	-	-	-	-
Khai-muk	7	0	-5	6	-	-	-
Deep Depression	8	1	0	3	8	12	-
	9	2	5	4	-	-	-
Bijli	10	-2	-5	1	5	35	-
	11	4	9	35	-	-	-
	12	22	-	-	-	-	-
Aila	13	0	6	8	10	5	-
	14	-3	-2	-1	-	-	-
	15	2	-	-	-	-	-
	AAE	**4.4**	**5.7**	**9.8**	**11.1**	**15.1**	**15.0**

d. Performance statistics (error in knots) of decay model

The empirical decay model is used for real time forecasting of decaying intensity (after landfall) of cyclone RASHMI, NISHA and AILA over the Bay of Bengal during the period 2008-2009. Four forecasts were issued for the three systems (as shown in Table 9.9) based on different initial conditions (including updated forecasts). Table 9.9 illustrates the 6-hourly forecasts error (knots) valid up to 18 hours for three cyclones. The Average Absolute Error (AAE) is found to be ranging from 2 to 4.5 knots for forecasts up to 18 hours as shown in Table 9.9. The error statistics shows that the model could predict the decaying intensity after landfall.

Table 9.9: Forecast errors (knots) of Decay model

Cylone	**No. of forecasts**	**Forecasts hours →**		
		6 hr	**12 hr**	**18 hr**
Rashmi	1	+6	+10	-
Nisha	2	-2	+2	-
Aila	3	-1	-6	-2
	4	-1	0	-
	AAE	**2.5**	**4.5**	**2**

Though the data size of the MME study is small, but results are very promising. Further studies are required with larger data sample to bring out detailed performance statistics of the technique. We intend to include the data of cyclones 2009 to increase the sample database of MME technique for forecasting the cyclone track of 2010.

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