NWP REPORT ON CYCLONIC STORMS OVER THE NORTH INDIAN OCEAN DURING 2013

Prepared by: S. D. Kotal, Sumit Kumar Bhattacharya,

S. K. Roy Bhowmik, Y. V. Rama Rao and Arun Sharma

India Meteorological Department

(Numerical Weather Prediction Division)

Earth System Science Organization (ESSO)

Ministry of Earth Sciences (MoES)

Lodi Road, New Delhi-110003

February 2014

NWP REPORT ON CYCLONIC STORMS OVER THE NORTH INDIAN OCEAN DURING 2013

Prepared by: S. D. Kotal, Sumit Kumar Bhattacharya,

S. K. Roy Bhowmik, Y. V. Rama Rao and Arun Sharma

India Meteorological Department

(Numerical Weather Prediction Division)

Earth System Science Organization (ESSO)
Ministry of Earth Sciences (MoES)

Lodi Road, New Delhi-110003

February 2014

CONTENT

1. Introduction

India Meteorological Department (IMD) operationally runs two regional model WRF and Hurricane WRF (HWRF) model for short-range prediction and Global model T574L64 for medium range prediction (7 days). As part of WMO Program to provide a guidance of tropical cyclone (TC) forecasts in near real-time for the ESCAP/WMO Member Countries based on the TIGGE Cyclone XML (CXML) data, IMD also implemented JMA supported software for real-time TC forecast over North Indian Ocean (NIO).

As a part of our effort to meet the specific requirement of the operational forecaster, IMD developed and implemented NWP based Objective Cyclone Prediction System (CPS) for the operational cyclone forecasting work (Roy Bhoiwmik and Kotal, 2010). The method comprises of five forecast components, namely (a) Cyclone Genesis Potential Parameter (GPP), (b) Multi-Model Ensemble (MME) technique for cyclone track prediction, (c) Cyclone intensity prediction, (d) Rapid intensification and (e) Predicting decaying intensity after the landfall. Genesis potential parameter (GPP) is used for potential of cyclogenesis and forecast for potential cyclogenesis zone (Roy Bhowmik, 2003; Kotal et al., 2009). A multi-model ensemble (MME) forecast of NWP models is generated in real time for predicting the track of tropical cyclones over the North Indian Seas using the outputs of member models IMD-GFS, IMD-WRF, GFS (NCEP), UKMO and JMA (Kotal and Roy Bhowmik, 2011). SCIP (statistical cyclone intensity prediction) model is run for 12 hourly intensity predictions up to 72-h (Kotal et al., 2008). A rapid intensification index (RII) is used for the probability forecast of rapid intensification (RI) (Kotal and Roy Bhowmik, 2013). A decay model has been used for real time forecasting of decaying intensity after the landfall (Roy Bhowmik et al., 2005).

In this report performance of NWP based Objective CPS (GPP, MME, SCIP, RII and Decay model) for prediction of the cyclonic storms over the north Indian Ocean during 2013 is presented. In addition, the performance of HWRF and member models IMD-GFS, IMD-WRF, GFS (NCEP), UKMO and JMA are also evaluated.

2. NWP Models

2.1 Global Forecast System

The Global Forecast System (GFS), adopted from National Centre for Environmental Prediction (NCEP) was implemented at India Meteorological Department

(IMD), New Delhi on IBM based High Power Computing Systems (HPCS).at T574L64 (~ 25 km in horizontal over the tropics) with Grid point Statistical Interpolation (GSI) scheme as the global data assimilation for the forecast up to 7 days. The model is run twice in a day (00 UTC and 12 UTC). The real-time outputs are made available to the national web site of IMD (http://www.imd.gov.in/section/nhac/dynamic/nwp/welcome.htm).

2.2. Regional Forecast System

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

The mesoscale forecast system Weather Research and Forecast WRF (version 3.2) with 3DVAR data assimilation is being operated daily twice to generate mesoscale analysis at 27 km and 9 km horizontal resolutions using IMD GFS-T574L64 analysis as first guess and forecasts as boundary conditions. Using analysis and updated boundary conditions from the WRFDA, the WRF (ARW) is run for the forecast up to 3 days with double nested configuration with horizontal resolution of 27 km and 9 km and 38 Eta levels in the vertical. The model mother domain covers the area between lat. 25º S to 45º N long 40º E to 120º E and child covers whole India. At ten other regional centres, very high resolution mesoscale models (WRF at 3 km resolution) are also operational with their respective regional setup/configurations.

(available at http://www.imd.gov.in/section/nhac/dynamic/nwp/welcome.htm)

2.2.2. Hurricane WRF Model (HWRF)

Recently under Indo-US joint collaborative program, IMD adapted Hurricane-WRF model for Tropical Cyclone track and intensity forecast for North Indian Ocean (NIO) region for its operational requirements. The basic version of the model HWRF (V3.2+) which was operational at EMC, NCEP, USA was ported on IMD IBM P-6/575 machine with nested domain of 27 km and 9 km horizontal resolution and 42 vertical levels with outer domain covering the area of $80^o x 80^o$ and inner domain $6^o x 6^o$ with centre of the system adjusted to the centre of the observed cyclonic storm. The outer domain covers most of the North Indian Ocean including the Arabian Sea and Bay of Bengal and the inner domain mainly covering the cyclonic vortex with moving along the movement of the system. The model has special features such as vortex initialization, coupled with Ocean model to take into account the changes in SST during the model integration, tracker and diagnostic software to provide the graphic and text information on track and intensity prediction for real-time operational requirement. The operational version of the model is run incorporating vortex re-location and moving nesting procedure on real time twice a day based on 00 UTC and 12 UTC initial conditions to provide 6 hourly track and intensity forecasts valid up to 120 hours. The model uses IMD GFS-T574L64 analysis/forecast as initial and boundary conditions. (available at http://202.54.31.51/hwrf/hwrf_main.htm).

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

As part of WMO Program to provide a guidance of tropical cyclone (TC) forecasts in near real-time for the ESCAP/WMO Member Countries based on the TIGGE Cyclone XML (CXML) data, IMD implemented JMA supported software for real-time TC forecast over North Indian Ocean (NIO) during 2011. The Ensemble and deterministic forecast products from UKMO (50+1 Members), NCEP (20+1 Members), UKMO (23+1 Members) and MSC (20+1 Members) are available near real-time for NIO region for named TCs. These Products includes: Deterministic and Ensemble TC track forecasts, Strike Probability Maps, Strike probability of cities within the range of 120 kms 4 days in advance. The JMA provided software to prepare Web page to provide guidance of tropical cyclone forecasts in near real-time for the ESCAP/WMO committee Members.

(available at http://202.54.31.51/cyclone/StrikeProbability.aspx)

3. NWP based Objective Cyclone Forecast System (CPS)

As statistical post processing can add skill to dynamical forecasts, following post-processed value added NWP based special products are prepared for real time cyclone forecasting.

3.1. Genesis Potential Parameter (GPP)

A cyclone genesis parameter, termed as the genesis potential parameter (GPP), for the North Indian Sea is developed (Roy Bhowmik, 2003; Kotal et al, 2009). The parameter, which is defined as the product of four variables, namely vorticity at 850 hPa, middle tropospheric relative humidity, middle tropospheric instability, and the inverse of vertical wind shear, is computed based on outputs of IMD GFS T574/L64(analysis as well as forecasts) . The parameter is operationally used for distinction between non-developing and developing systems at their early development stages. The composite GPP value is found to be around three to five times greater for developing systems than for non-developing systems.

The analysis of the parameter at early development stage of a cyclonic storm found to provide a useful predictive signal for intensification of the system. (product available at http://www.imd.gov.in/section/nhac/dynamic/gpp.pdf)

The grid point analysis and forecast of the genesis parameter up to seven days is also generated on real time (Kotal, SD and Bhattacharya SK, 2013). Higher value of the GPP over a region indicates higher potential of genesis over the region. Region with GPP value equal or greater than 30 is found to be high potential zone for cyclogenesis. The analysis of the parameter and its effectiveness during cyclonic disturbances in 2012 affirm its usefulness as a predictive signal (4-5 days in advance) for cyclogenesis over the North Indian Ocean. (product available at http://www.imd.gov.in/section/nhac/dynamic/Analysis.htm).

3.2. Dynamical-Statistical model for Cyclone Intensity Prediction (SCIP)

A dynamical statistical model (SCIP) (Kotal et al, 2008) has been implemented for real time forecasting of 12 hourly intensity up to 72 hours. The model coefficients are derived based on model analysis of past cyclones. The parameters selected as predictors are: Initial storm intensity, Intensity changes during past 12 hours, Storm motion speed, Initial storm latitude position, Vertical wind shear averaged along the storm track, Vorticity at 850 hPa, Divergence at 200 hPa and Sea Surface Temperature (SST). For the real-time forecasting, model parameters are derived based on the forecast fields of IMD GFS T574/L64. (http://www.imd.gov.in/section/nhac/dynamic/MME_TRACK_INTENSITY.htm)

3.3. Multi-model ensemble (MME) technique for track prédiction

The multi model ensemble (MME) technique (Kotal and Roy Bhowmik, 2011) is based on a statistical linear regression approach. The predictors selected for the ensemble technique are forecasts latitude and longitude positions at 12-hour interval up to 72-hour of five NWP models (IMD-GFS, IMD-WRF, NCEP GFS, UKMO, JMA. 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. 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. First, the 12 hourly predicted cyclone tracks of member models are determined using a cyclone tracking software, then MME forecast track is generated applying previously determined weight factors of each model. In the case of cyclone MADI, MME forecast tracks were generated using IMD-GFS, IMD-WRF, NCEP GFS, UKMO and JMA up to 120 hours.

http://www.imd.gov.in/section/nhac/dynamic/MME_TRACK_INTENSITY.htm)

3.5. Rapid Intensification (RI) Index

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

3.6. Decay of Intensity after the landfall

Tropical cyclones (TCs) are well known for their destructive potential and impact on human activities. The Super cyclone Orissa (1999) illustrated the need for the accurate prediction of inland effects of tropical cyclones. The super cyclone of Orissa maintained the intensity of cyclonic storm for about 30 hours after landfall. Because a dense population resides at or near the Indian coasts, the decay forecast has direct relevance to daily activities over a coastal zone (such as transportation, tourism, fishing, etc.) apart from disaster management. In view of this, the decay model (Roy Bhowmik et al. 2005) has been used for real time forecasting of decaying intensity (after landfall) of TCs.

Flow Diagram of the five-step objective Cyclone Prediction System (CPS) is shown in Fig 1.

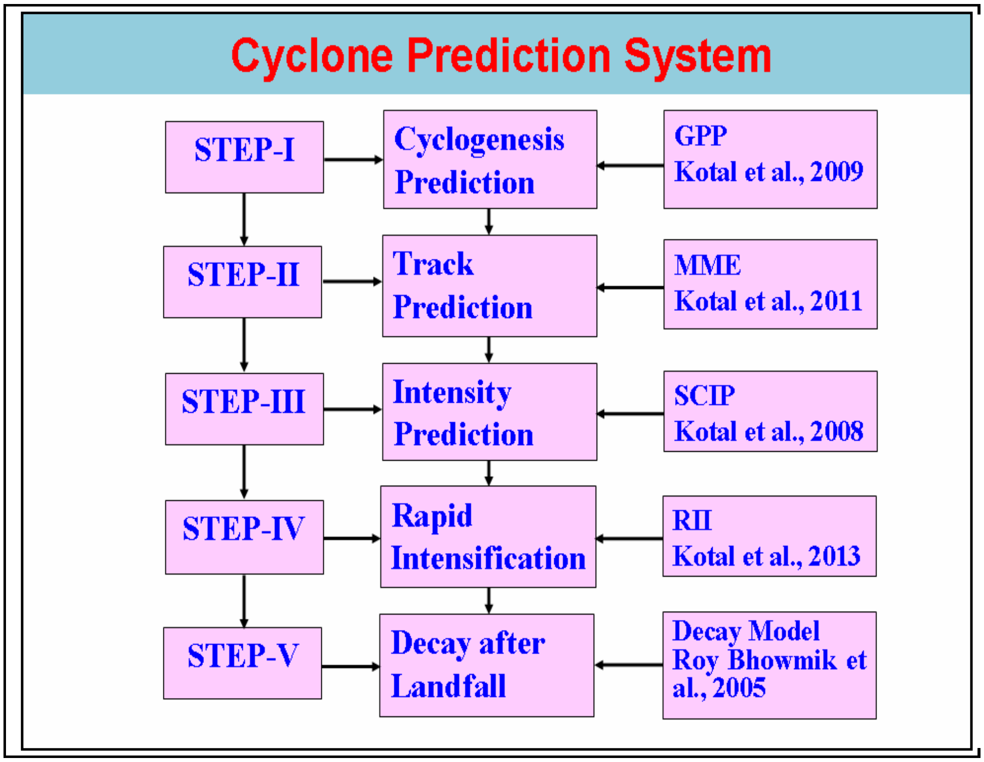


Fig. 1 Flow Diagram of Cyclone Prediction System (CPS)

4. Methodology for evaluation of track forecast error

Direct position errors (DPE), cross track (CT) and along track (AT) component of track forecast are calculated based on the following Fig. 2 adapted from Heming (1994).

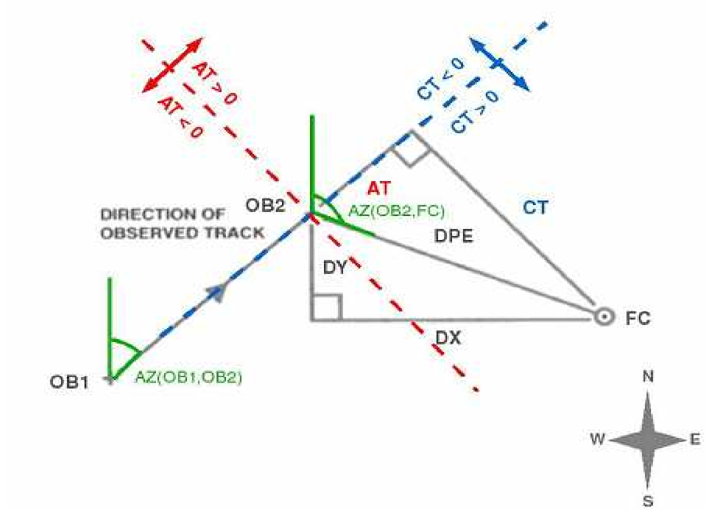


Fig 2: Types of positional forecast errors.

5. Cyclonic storm 'MAHASEN' over the Bay of Bengal-(10-16) May 2013

A low pressure system that formed over southeast Bay of Bengal on 8th May 2013 intensified into depression at 0900 UTC of 10th May 2013 near latitude 5.0° N and longitude 92.0° E. Initially it moved northwestwards and intensified into a deep depression at 1200 UTC of the same day and further intensified into a cyclonic storm (T.No. 2.5), MAHASEN at 0300 UTC of 11th May 2013. The cyclonic storm recurved to north-northeasterly direction on 13th and 14th May and further intensified from T.No.2.5 to T.No. 3.0 at 0600 UTC of 16th May 2013. Moving north-northeastward direction the cyclonic storm crossed Bangladesh coast near lat. 22.8° N and long. 91.4° E, around 0800 UTC of 16th May 2013. After landfall, it continued to move north-northeastwards and weakened into a deep depression over Mizoram at 1200 UTC into a depression over Manipur at 1800 UTC of 16th. It further weakened into a well marked low pressure area over Nagaland at 0000 UTC 17th May 2013. The observed track of the cyclone MAHASEN is shown in Fig. 3.

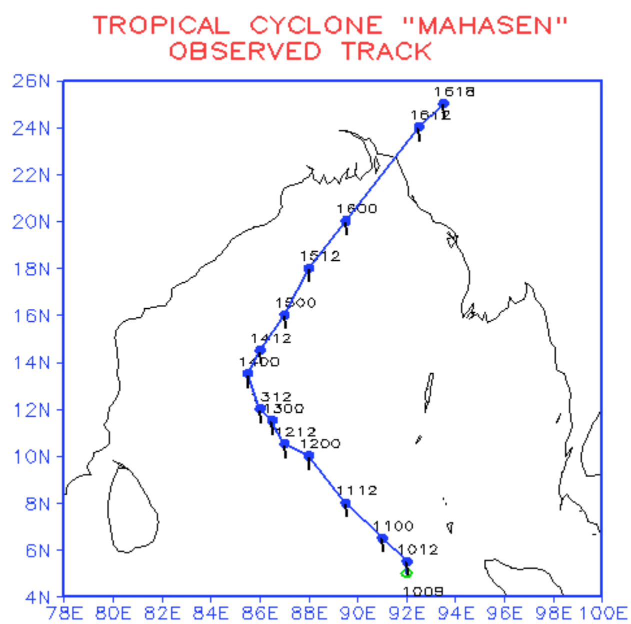
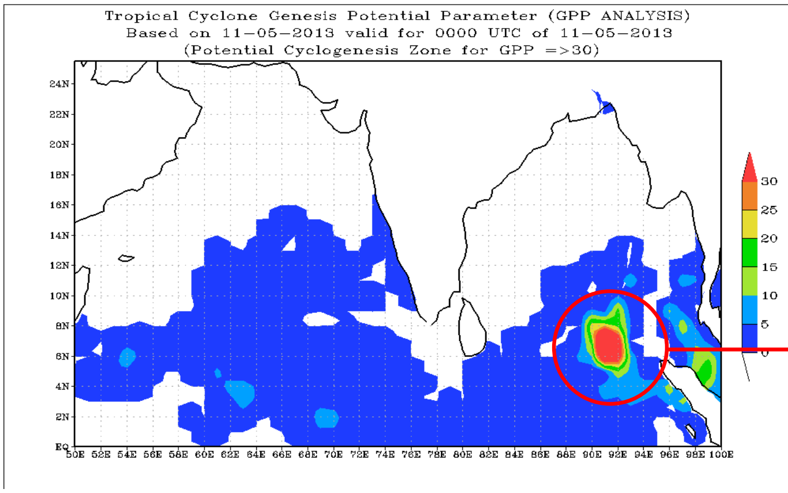


Fig. 3 Observed track of the cyclone MAHASEN

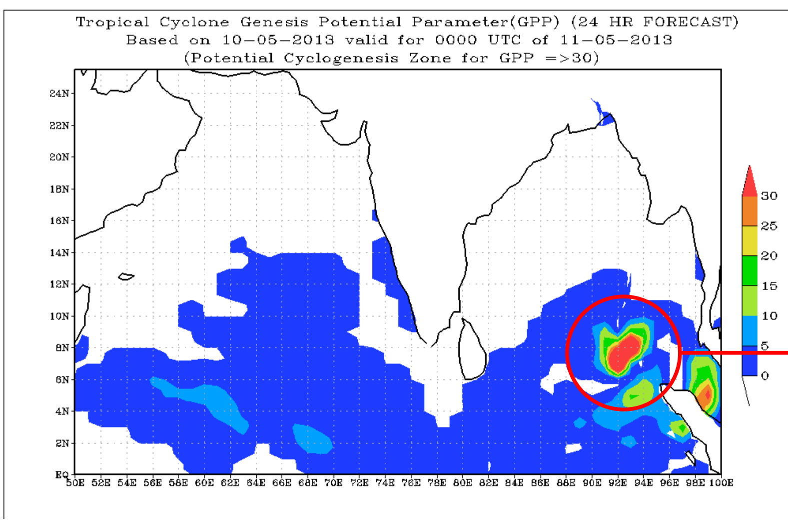
5.1 Grid point analysis and forecast of GPP

Objective: Grid point analysis and forecast of GPP is used to identify potential zone of cyclogenesis.



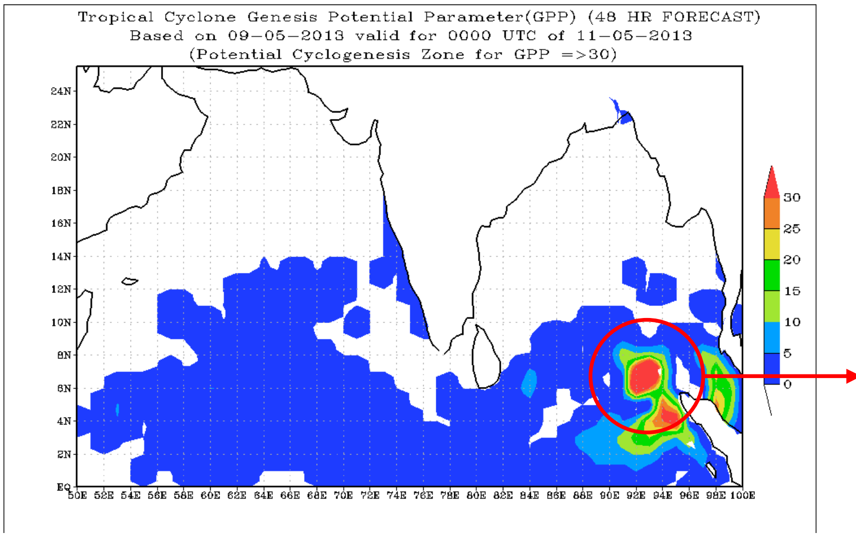
Analysis of GPP on 00 UTC 11 May 2013 indicates the location of DD.

Fig. 4a



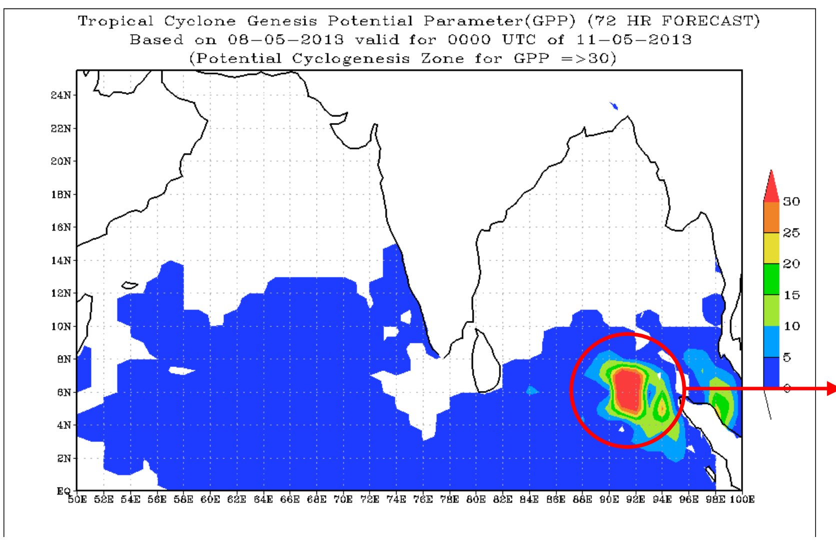
24 hour forecast of GPP valid for 00 UTC 11 May 2013 indicated the potential cyclogenesis zone, where DD formed on that date.

Fig. 4b



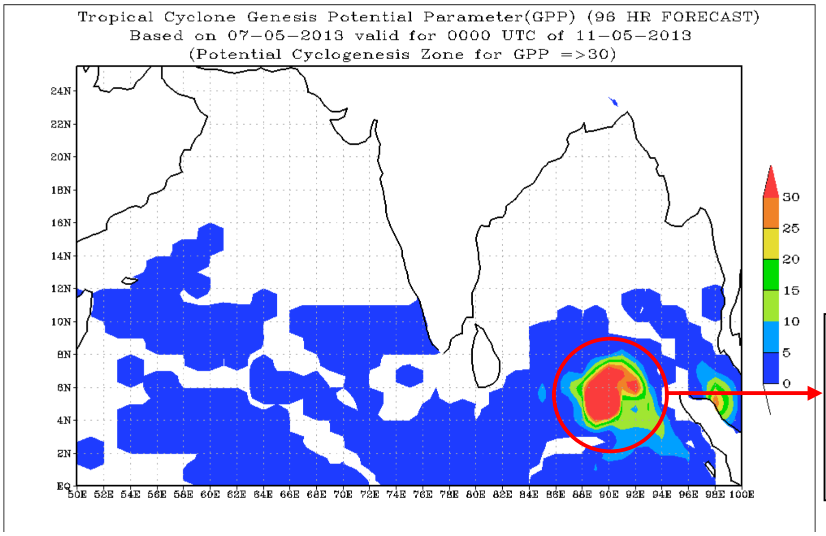
48 hour forecast of GPP valid for 00 UTC 11 May 2013 indicated the potential cyclogenesis zone, where DD formed on that date.

Fig. 4c



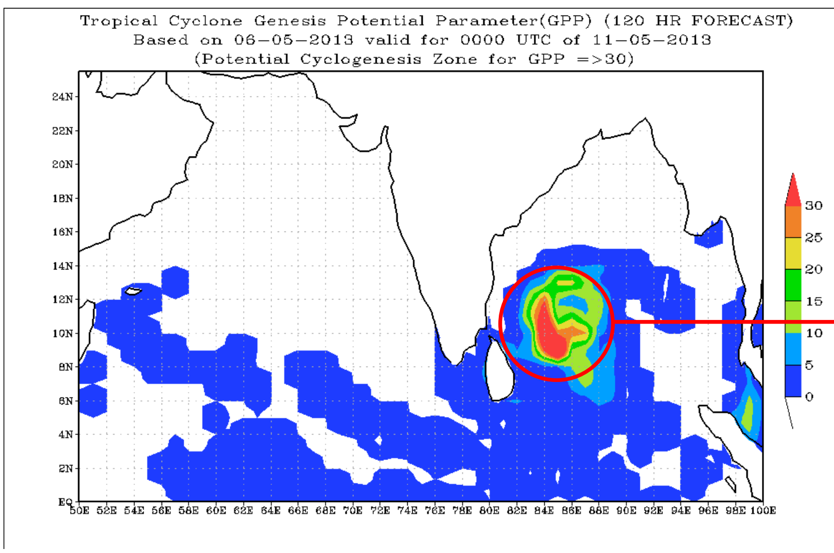
72 hour forecast of GPP valid for 00 UTC 11 May 2013 indicated the potential cyclogenesis zone, where DD formed on that date.

Fig. 4d



96 hour forecast of GPP valid for 00 UTC 11 May 2013 indicated the potential cyclogenesis zone, where DD formed on that date.

Fig. 4e



120 hour forecast of GPP valid for 00 UTC 11 May 2013 indicated the potential cyclogenesis zone, but on the north-west side of actual position of DD on that date.

Fig. 4f

Fig. 4 Grid point analysis of GPP for Cyclone "MAHASEN"

Grid point analysis and forecasts of GPP (Fig.4(a-f)) shows that it was able to predict the formation and location of the system before 120 hours of its formation.

(Product available at http://www.imd.gov.in/section/nhac/dynamic/Analysis.htm).

5.2. Area average analysis and forecast of GPP

Analysis of Genesis Potential Parameter (GPP) values computed (Kotal et al, 2009) for cyclone 'MAHASEN' on the basis of real time model analysis fields along with the GPP values for Developing Systems and Non-Developing Systems are shown in Fig.2(a-b). The higher GPP values (> 8.0, the threshold value) at early stages of development (T.No. 1.0) have clearly indicated that the cyclone "MAHASEN" had enough potential to intensify into a developing system.

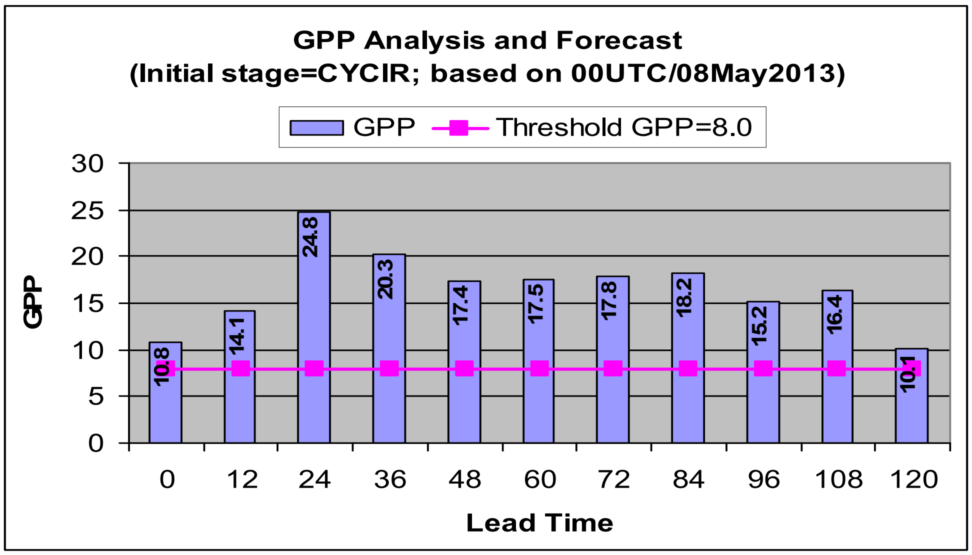


Fig 5a: Analysis and forecasts of GPP shows that GPP $\geq$ 8.0 at very early stage of development (**CYCIR**) indicated its potential to intensify into a cyclone.

Fig.5a

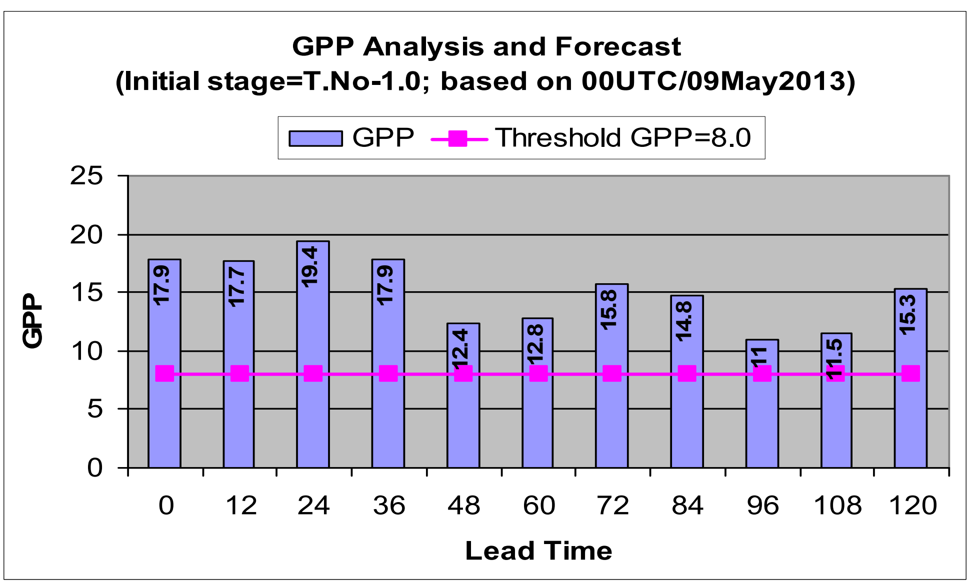


Fig 5b: Analysis and forecasts of GPP shows that GPP $\geq$ 8.0 at very early stage of development (**T.No. 1.0**) indicated its potential to intensify into a cyclone.

Fig. 5b

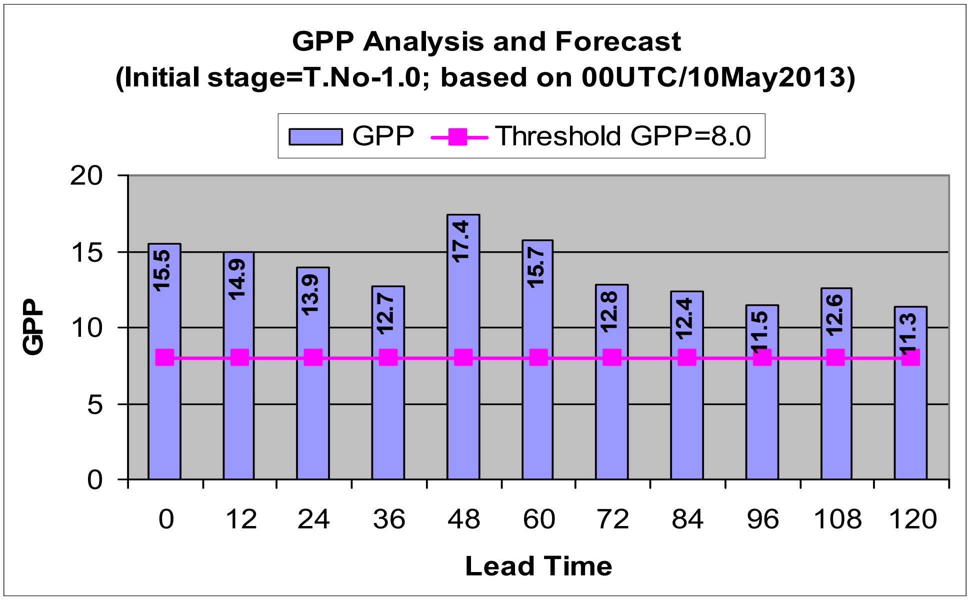


Fig 5c: Analysis and forecasts of GPP shows that GPP ≥ 8.0 at very early stage of development (**T.No. 1.0**) indicated its potentiial to intensify into a cyclone.

Fig. 5c

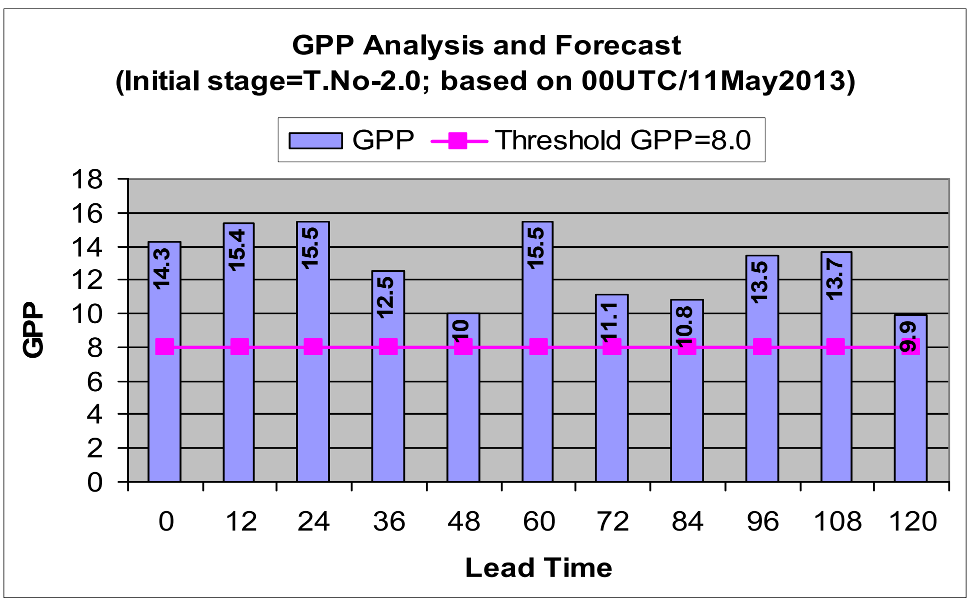


Fig 5d: Analysis and forecasts of GPP shows that GPP ≥ 8.0 at early stage of development (**T.No. 2.0**) indicated its potentiial to intensify into a cyclone.

Fig. 5d

Fig.5 Analysis and forecasts of GPP for cyclone MAHASEN

5.3. Track prediction

The average track forecast errors of NWP models along with the consensus forecast by MME and IMD official (OFFICIAL) forecast is presented in the Table 1. The landfall point error (km) and landfall time (hour) is presented in Table-2 and Table-3 respectively. The MME forecasts track based on different initial conditions along with the observed track is depicted in Fig.6. The figure shows that from the day1 (00 UTC 10 May 2013), MME was able to predict the recurvature and landfall at southeast coast of Bangladesh near Chittagong.

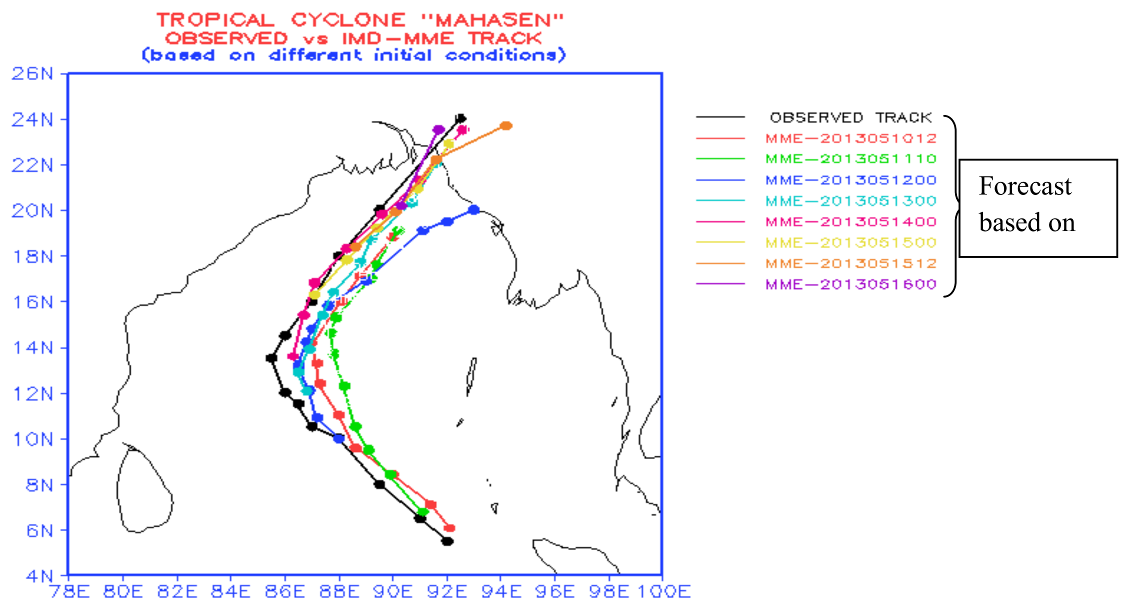


Fig. 6. MME forecasts track based on different initial conditions for MAHASEN

Table-1. Average track forecast errors (km) (Number of forecasts verified) of MAHASEN

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
IMD-GFS	69(7)	114(7)	217(6)	257(4)	425(4)	388(3)	573(3)	553(2)	433(1)	453(1)
IMD-WRF	101(8)	196(7)	318(6)	373(5)	536(5)	402(4)	-	-	-	-
IMD-QLM	163(7)	230(6)	292(5)	252(4)	289(4)	238(3)	-	-	-	-
JMA	110(8)	150(7)	191(6)	158(5)	207(5)	196(4)	339(4)	-	-	-
NCEP-GFS	102(8)	81(7)	143(6)	154(5)	210(5)	190(4)	232(4)	229(3)	300(2)	307(2)
ECMWF	105(8)	149(7)	202(6)	153(5)	199(5)	173(4)	224(4)	104(3)	255(3)	233(2)
IMD-MME	79(8)	120(7)	168(6)	122(5)	189(5)	169(4)	253(4)	245(3)	295(3)	176(2)
IMD-HWRF	77(10)	186(9)	299(8)	392(7)	516(6)	635(5)	753(4)	836(3)	892(2)	1008(1)
IMD-OFFICIAL	90(24)	152(22)	189(20)	205(18)	208(16)	268(14)	251(10)	308(8)	291(6)	222(4)

The consensus forecast MME outperformed all the forecasts upto 72 h, and it ranged from 79 km at 12 h to 169 km at 72 h. ECMWF model forecast is superior to other model forecasts for 84 h to 108 h forecast (104 km-255km) and again MME forecast error (176 km) is lowest at 120 h.

Table-2. Landfall point forecast errors (km) at different lead time (hour) (LF = Landfall) of MAHASEN

Model	FC based on 00 UTC/14.05.2013	FC based on 00 UTC/15.05.2013	FC based on 12 UTC/15.05.2013	FC based on 00 UTC/16.05.2013
	Lead time: 56 h	Lead time: 32 h	Lead time: 20 h	Lead time: 8 h
IMD-GFS	NO LF	NO LF	136	-
IMD-WRF	NO LF	147	49	45
IMD-QLM	NO LF	63	137	243
JMA	137	63	98	49
NCEP-GFS	289	169	136	136
ECMWF	259	274	127	15
IMD-MME	63	63	63	25
IMD-HWRF	84	174	121	-

Land fall point error shows that MME forecast error is least, 63 km to 25 km before 56 h to 8 h of landfall respectively.

Table-3. Landfall time forecast errors (hr) of MAHASEN ('+' for Delay, '-' for early, LF = landfall)

(Observed landfall time = 0800 UTC 16 may 2013)

Model	FC based on 00 UTC/14.05.2013	FC based on 00 UTC/15.05.2013	FC based on 12 UTC/15.05.2013	FC based on 00 UTC/16.05.2013
	Lead time: 56 h	Lead time: 32 h	Lead time: 20 h	Lead time: 8 h
IMD-GFS	NO LF	NO LF	-4	Dissipated
IMD-WRF	NO LF	+5	+2	+4
IMD-QLM	NO LF	+15	+4	+4
JMA	+10	+12	+4	0
NCEP-GFS	-4	+4	-5	-4
ECMWF	+4	+12	+4	+1
IMD-MME	+10	+13	+5	+1
IMD-HWRF	+10	+4	-2	-

Landfall time error shows that NCEP consistently predicted landfall at lowest landfall time error (± 4 h), but before 8 h, JMA, ECMWF, and MME predicted at near landfall time.

5.4. Intensity prediction

Average absolute error (AEE) and Root mean square error (RMSE) of SCIP and HWRF along with the official forecast error for cyclone MAHASEN is presented in the following Table-4 and Table-5. Intensity forecasts by SCIP, HWRF and OFFICIAL shows that Statistical-dynamical model forecast (SCIP) is superior to other model forecasts.

Table-4 Average absolute errors of MAHASEN (Number of forecasts verified)

Lead time →	**12 hr**	**24 hr**	**36 hr**	**48 hr**	**60 hr**	**72 hr**	**84 hr**	**96 hr**	**108 hr**	**120 hr**
IMD-SCIP	1.3 (6)	4.3 (6)	6.4 (5)	3.8 (4)	11.3 (4)	10.0 (3)	-	-	-	-
IMD-HWRF	27.2(10)	21.3(9)	8.6(8)	10.9(7)	19.2(6)	23.0(5)	29.5(4)	14.0(3)	22.0(2)	29.0(1)
IMD-OFFICIAL	3.6 (24)	6.8(22)	8.7(20)	10.0(18)	13.0(16)	15.0(14)	14(10)	13(8)	17(6)	14(4)

Table-5 Root Mean Square (RMSE) errors (Number of forecasts verified is given in the parentheses) of cyclone MAHASEN

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
IMD-SCIP	2.2 (6)	8.0 (6)	8.5 (5)	4.3 (4)	14.9 (4)	11.6 (3)	-	-	-	-
IMD-HWRF	30.0(10)	24.3(9)	12.2(8)	12.8(7)	22.8(6)	28.0(5)	31.5(4)	14.3(3)	22.4(2)	29.0(1)
IMD-OFFICIAL	4.6 (24)	8.9(22)	10.8(20)	12.5(18)	16.1(16)	17.8(14)	16.1(10)	15.7(8)	17.5(6)	16.4(4)

5.5. Probability of Rapid intensification (by RI-Index)

Rapid intensification (RI) is defined as: Increase of intensity by 30 kts or more during subsequent 24 hour.

Table-6 Probability of Rapid intensification of cyclone MAHASEN

Forecast based on	Probability of RI predicted	Chances of occurrence predicted	Occurrence
00 UTC/11.05.2013	9.4 %	VERY LOW	NO
00 UTC/12.05.2013	5.2 %	VERY LOW	NO
00 UTC/13.05.2013	2.6 %	VERY LOW	NO
00 UTC/14.05.2013	5.2 %	VERY LOW	NO
00 UTC/15.05.2013	9.4 %	VERY LOW	NO
12 UTC/15.05.2013	22.0 %	LOW	NO
Inference: RI-Index was able to predict non-occurrence of Rapid Intensification of cyclone MAHASEN during its lifetime.			

5.6. Decay after landfall

Decay (after landfall) prediction curve (6-hourly) (Fig. 5) of cyclone MAHASEN shows slow decay compared to observed decay. The error is -8 kt and -7 kt at 6 h and 12 h respectively.

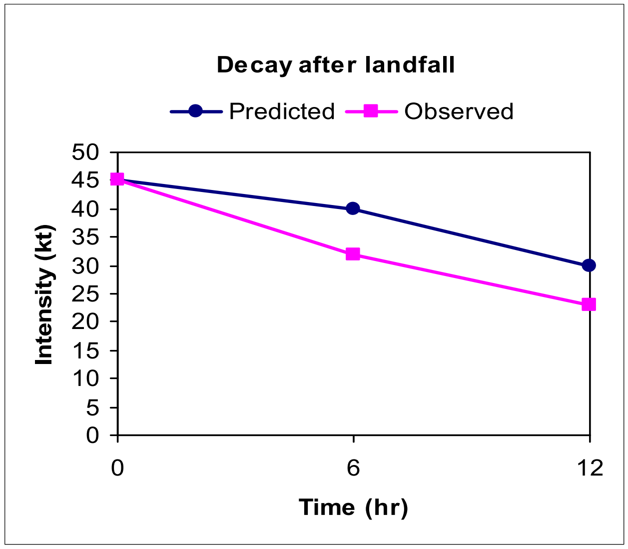
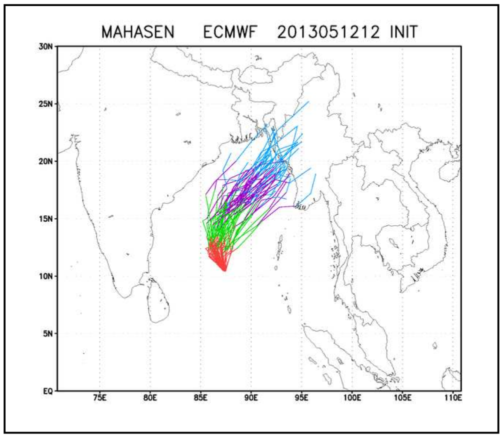
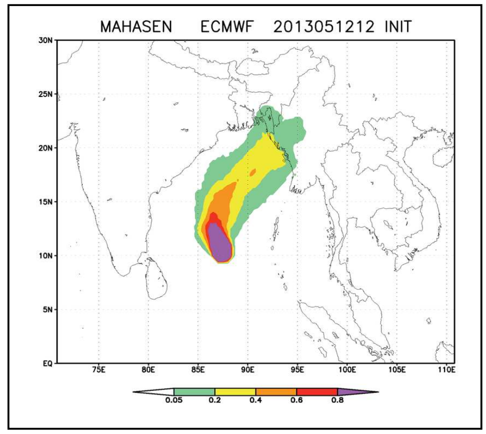


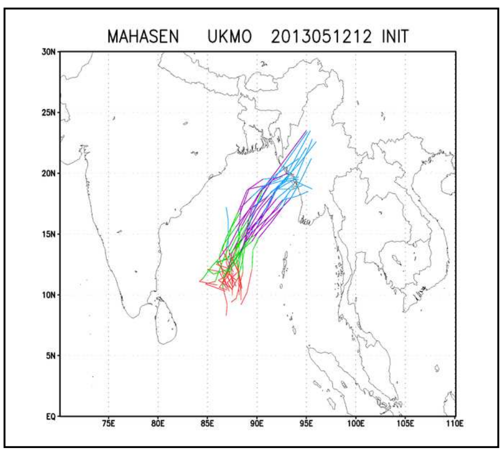
Fig.7 Decay after landfall for MAHASEN

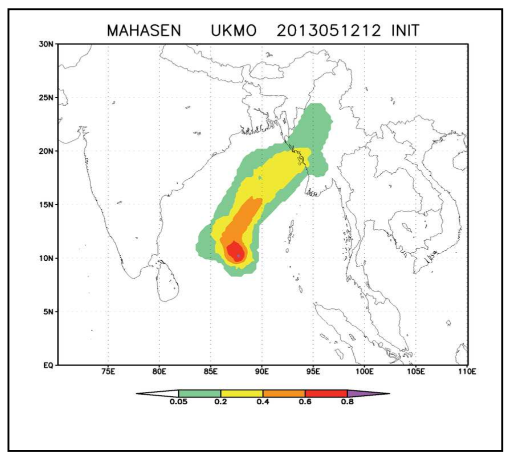
5.7. Ensemble track and Strike Probability forecast of cyclone MAHASEN

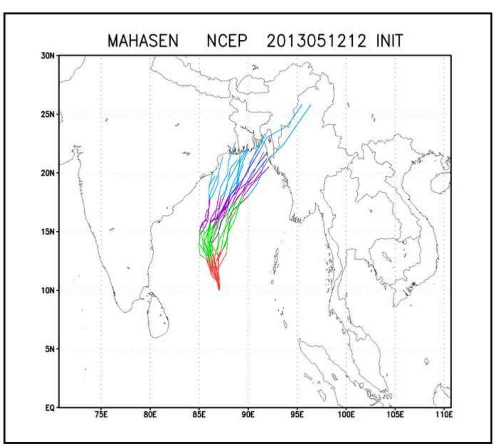
a. Based on 1200 UTC 12.05.2012

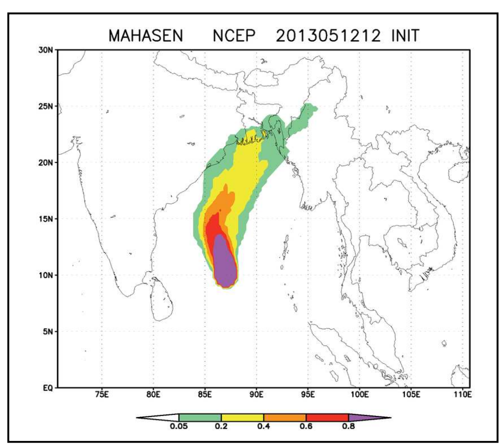












b. Based on 0000 UTC 13.05.2012

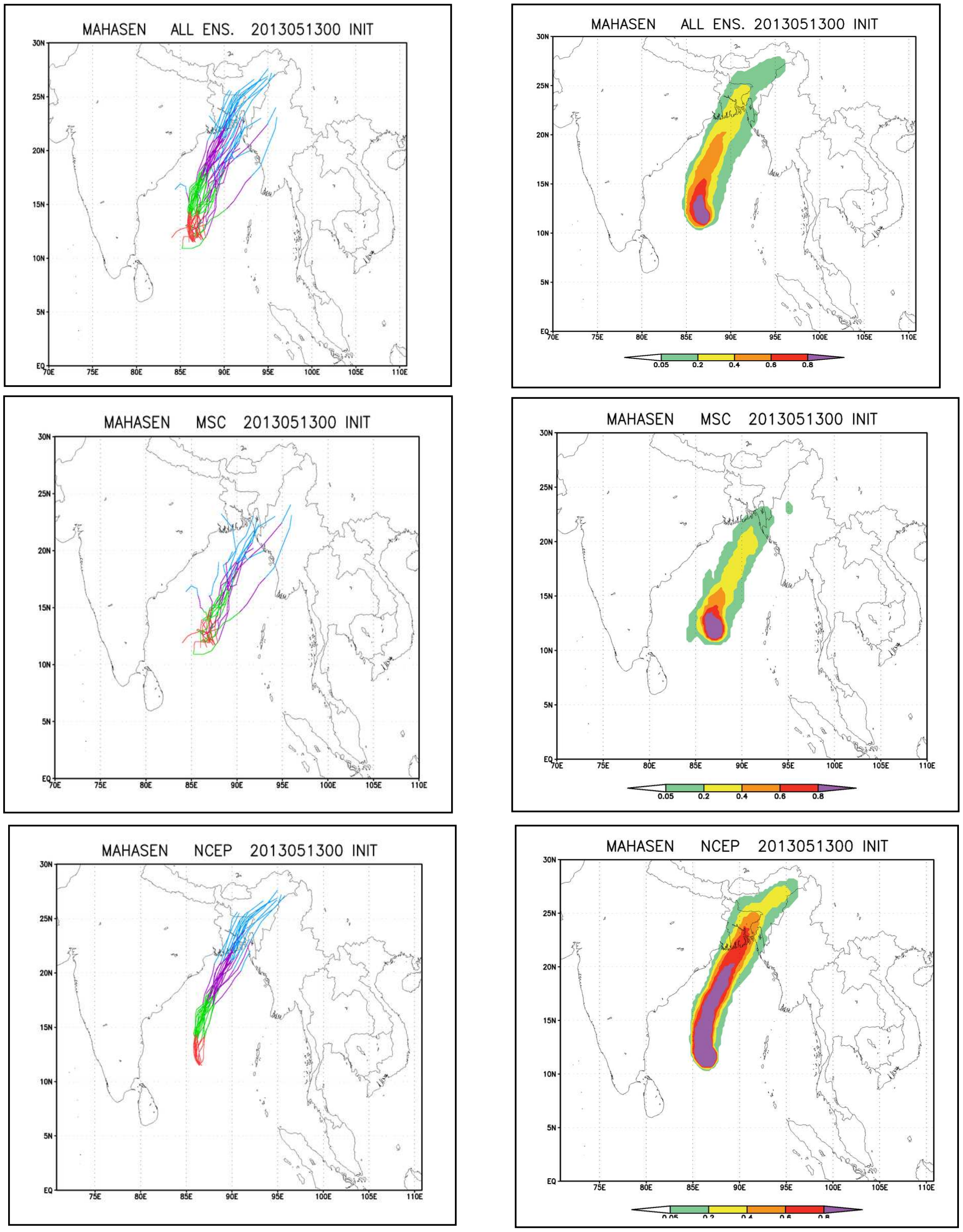


Fig. 8 Ensemble track prediction and Strike Probability for MAHASEN

Ensemble track and strike probability forecast based on 12 UTC 12.05.2013 and 00 UTC 13.05.2013 shows that ECMWF, UKMO, MSC and NCEP all predicted re-curvature and to cross south of actual landfall point except NCEP, which predicted landfall near actual landfall point.

6. Very Severe Cyclonic storm 'PHAILIN' (8-14 October 2013)

A low pressure system that formed over North Andaman Sea on 7 October 2013 intensified into depression at 0300 UTC of 8 October 2013 near latitude 12.0° N and longitude 96.0° E. It moved northwestwards and intensified into a deep depression at 0000 UTC of 9 October 2013 and further intensified into a cyclonic storm (T.No. 2.5), PHAILIN at 1200 UTC of the same day. The cyclonic storm continued to move in northwesterly direction and intensified into severe cyclonic storm (T.No. 3.5) at 0300 UTC of 10 October 2013 and subsequently intensified into very severe cyclonic storm (T. No. 4.0) at 0600 UTC of same day. Moving northwestward direction the system further rapidly intensified to T.No. 4.5, T.No. 5.0, and T.No. 5.5 at 1200 UTC, 1500 UTC and 2100 UTC of same day (10 October 2013) respectively. At 0300 UTC of 11 October 2013 the system intensified to T.No. 6.0 and continued to move northwesterly direction with same intensity towards Odisha and crossed coast near Gopalpur at around 1700 UTC of 12 October 2013. The system maintained its intensity of very severe cyclonic storm upto seven hours after landfall and cyclonic storm intensity till 1200 UTC of 13 October 2013. The system continued to decay and weakened to deep depression at 1800 UTC of 13 October 2013 and further to depression at 0300 UTC of 14 October 2013. The observed track of the cyclone PHAILIN is shown in Fig. 2.

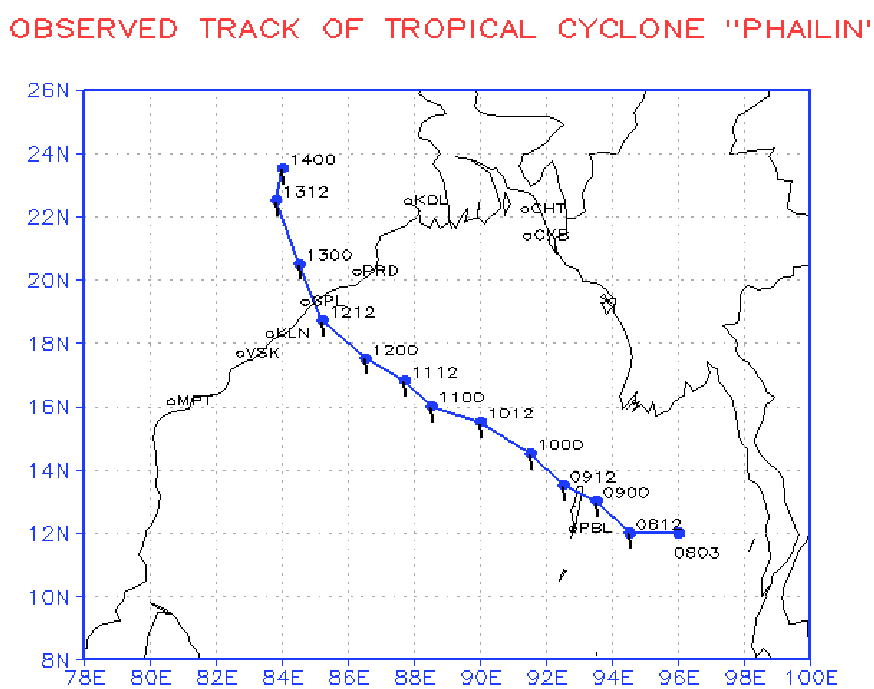
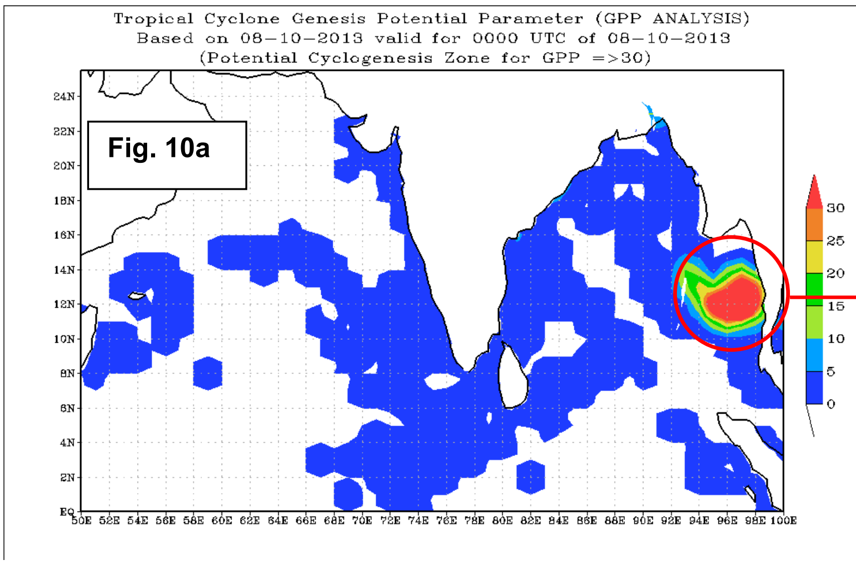


Fig. 9 Observed track of the cyclone PHAILIN

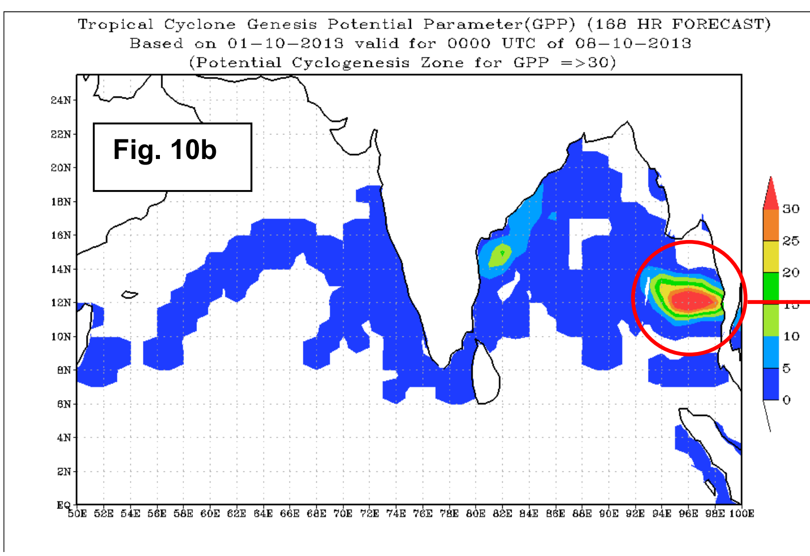
6.1. Grid point analysis and forecast of GPP

Objective: Grid point analysis and forecast of GPP is used to identify potential zone of cyclogenesis.

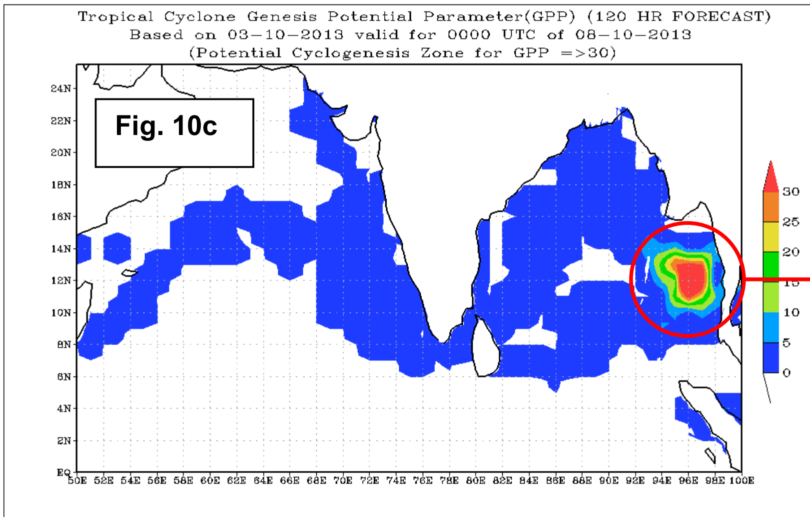
Figure 10(a-e) below shows the analysis and predicted zone of formation of cyclogenesis.



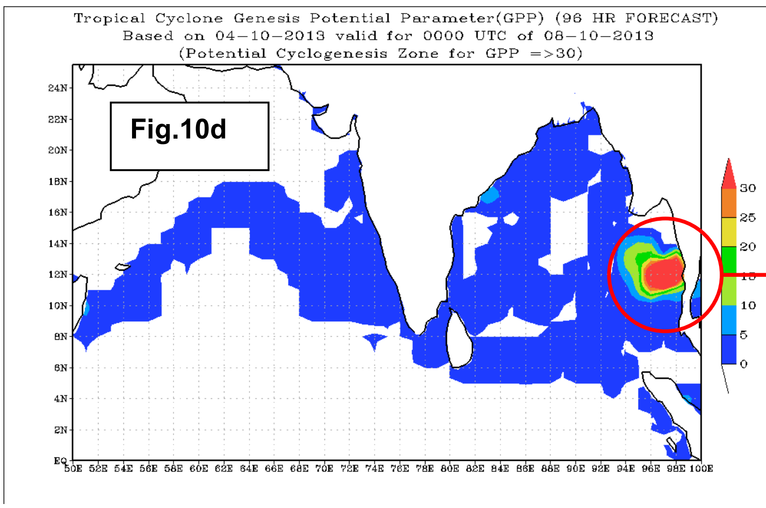
Analysis of GPP valid for 00 UTC 08 October 2013, where Depression formed on that day.



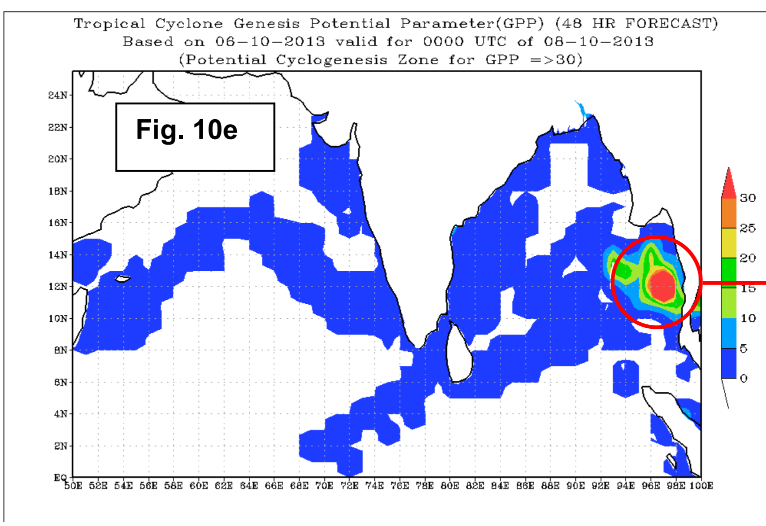
168 hour forecast of GPP valid for 00 UTC 08 October 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



120 hour forecast of GPP valid for 00 UTC 08 October 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



96 hour forecast of GPP valid for 00 UTC 08 October 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



48 hour forecast of GPP valid for 00 UTC 08 October 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.

Figure 10(a-e): Predicted zone of cyclogenesis for PHAILIN.

Inference: Grid point analysis and forecasts of GPP (Fig.10(a-e)) shows that it was able to predict the formation and location of the system before 168 hours of its formation.

(Product available at http://www.imd.gov.in/section/nhac/dynamic/Analysis1.htm)

6.2. Area average analysis of GPP

Objective: Since all low pressure systems do not intensify into cyclones, it is important to identify the potential of intensification (into cyclone) of a low pressure system at the early stages of development.

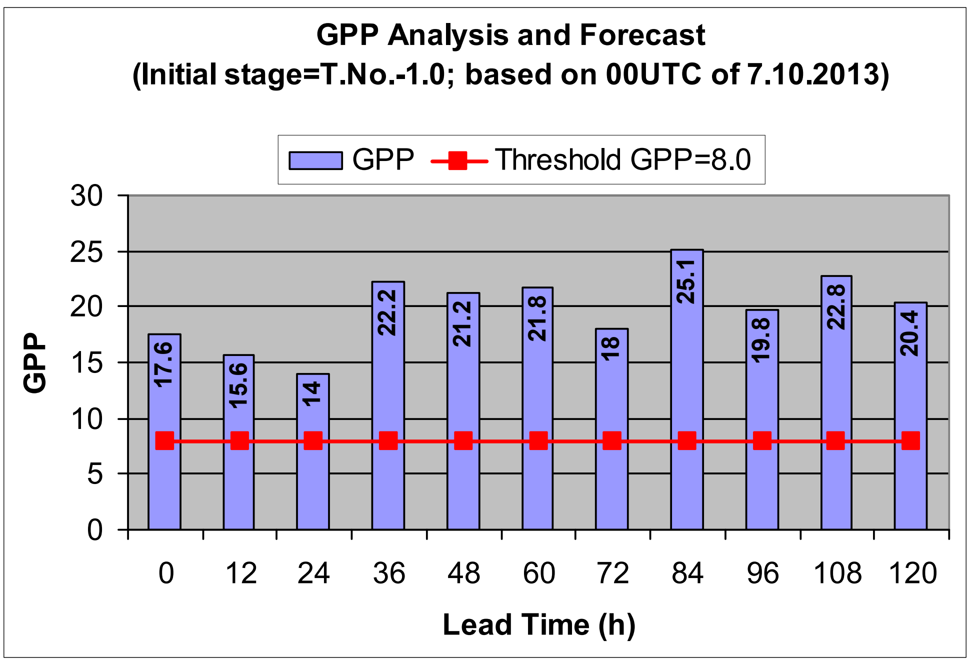


Fig 11a: Analysis and forecasts of GPP shows that GPP ≥ 8.0 (Threshold) at very early stage of development **(T.No.-1.0)** indicated its potentential to intensify into a cyclone.

Fig.11a

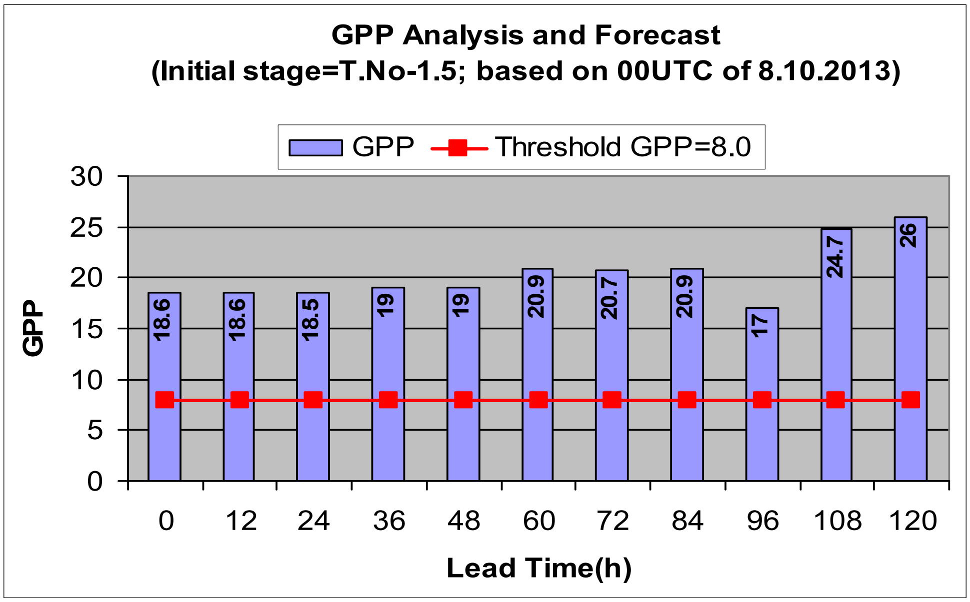


Fig 11b: Analysis and forecasts of GPP shows that GPP ≥ 8.0 (Threshold) at very early stage of development (**T.No. 1.5**) indicated its potential to intensify into a cyclone.

Fig. 11b

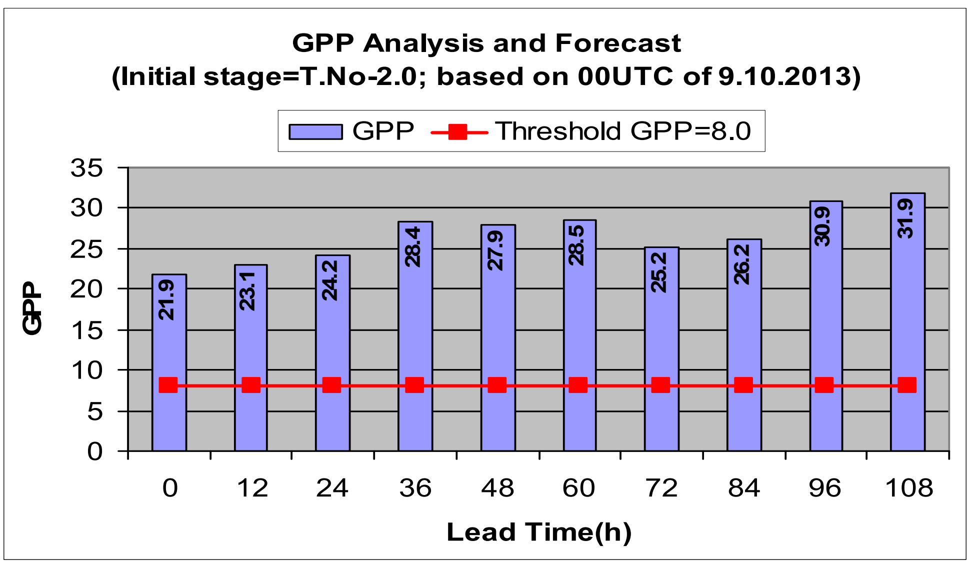


Fig 11c: Analysis and forecasts of GPP shows that GPP ≥ 8.0 (Threshold) at very early stage of development (**T.No. 2.0**) indicated its potential to intensify into a cyclone.

Fig. 11c

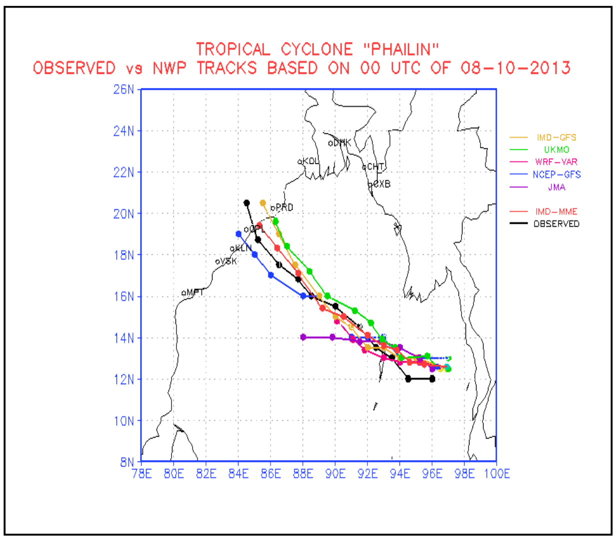
Fig. 11(a-c) Area average analysis of GPP for PHAILIN

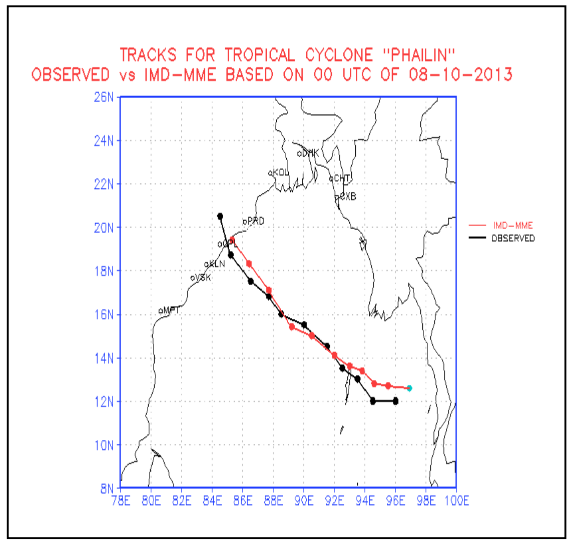
(Product available at http://www.imd.gov.in/section/nhac/dynamic/gpp.pdf)

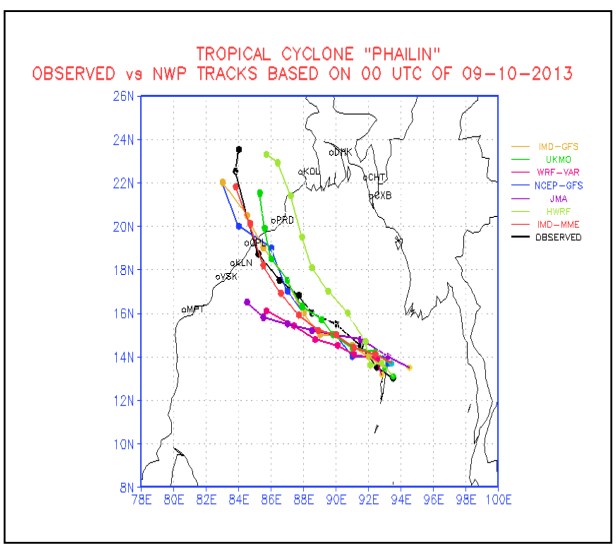
Inference: Analysis and forecasts of GPP (Fig.11(a-c)) shows that GPP ≥ 8.0 (threshold value for intensification into cyclone) indicated its potential to intensify into a cyclone at early stages of development (T.No. 1.0, 1.5, 2.0).

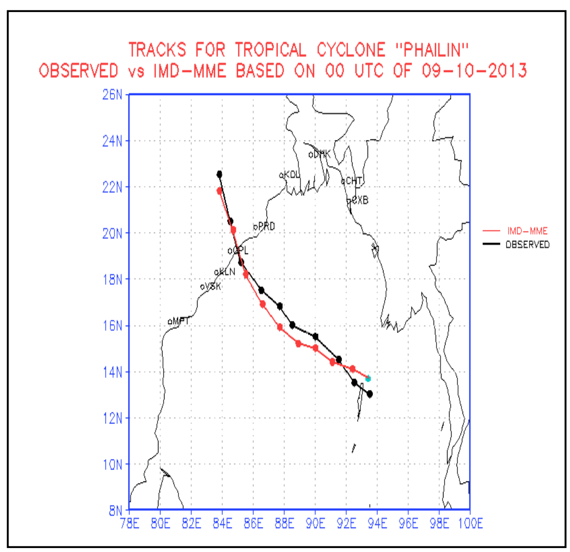
6.3 Track prediction

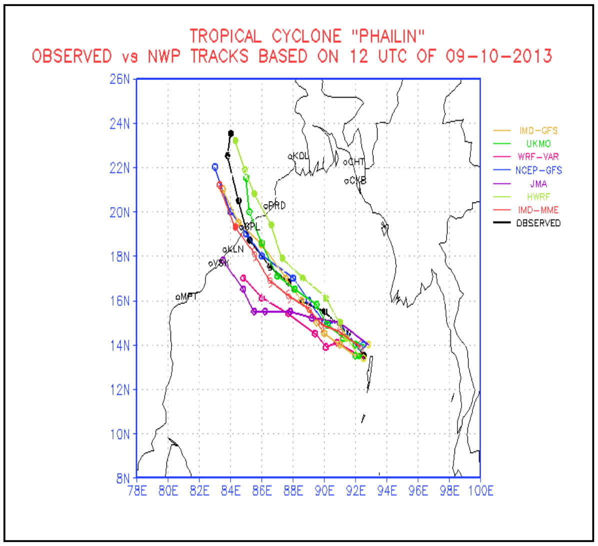
Direct position errors (DPE), cross track (CT) and along track (AT) component of track forecast are calculated based on the Heming (1994). The average track forecast errors (DPE, CTE, ATE) of NWP models along with the consensus forecast by Multi-model ensemble (MME) forecast are presented in the Table 7, Table 8 and Table 9 respectively. Landfall forecast of MME is presented in Table 10. The landfall point error (km) and landfall time (hour) is presented in Table-11 and Table-12 respectively. The MME forecasts track based on different initial conditions along with the observed track is depicted in Fig 12. The figure shows that from the day1 (00 UTC 8 October to 12 UTC 12 October 2013), MME was able to predict correctly and consistently the landfall at Gopalpur (Odisha).

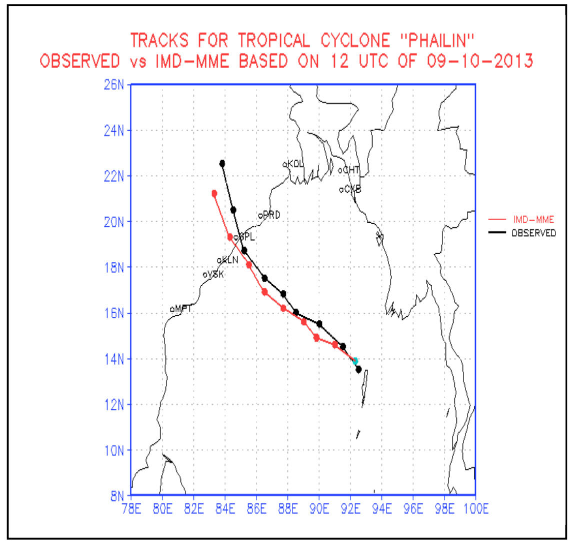


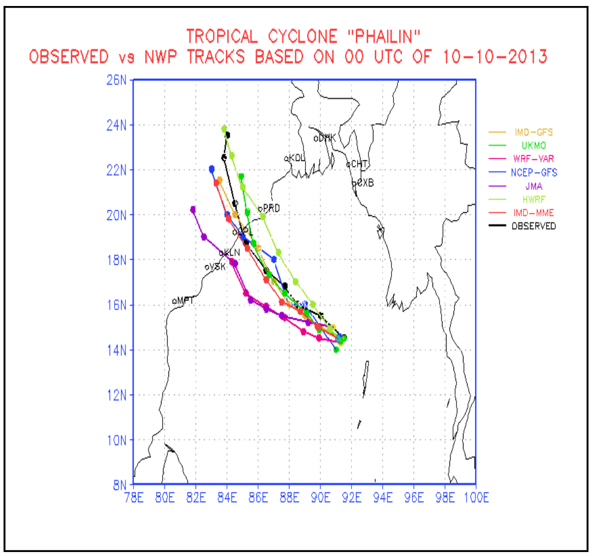


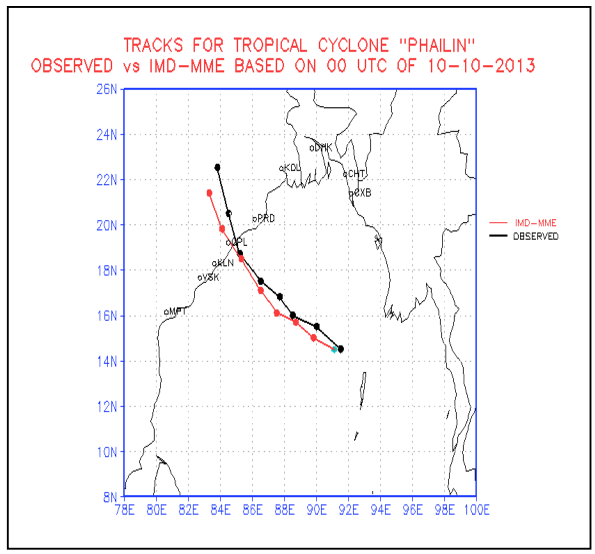


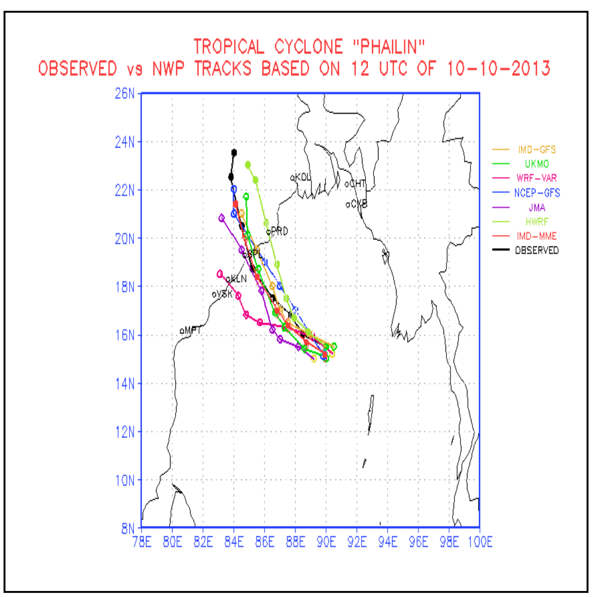


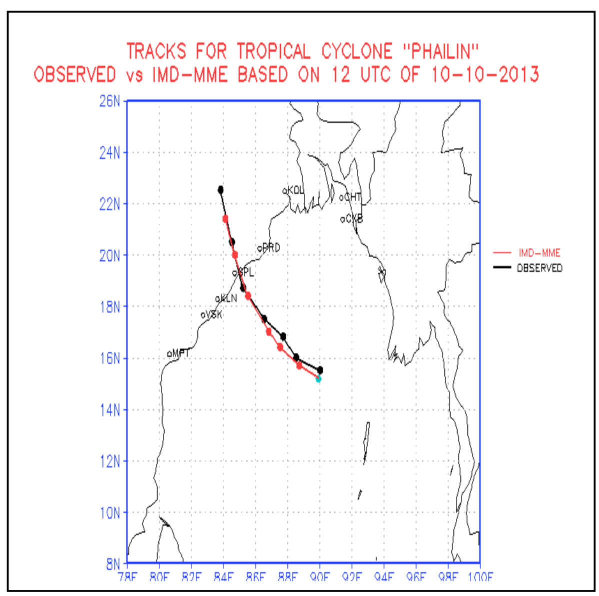

TROPICAL CYCLONE "PHAILIN"
OBSERVED vs NWP TRACKS BASED ON 12 UTC OF 09-10-2013
IMD-GFS
UKMO
WRF-VAR
NCEP-GFS
JMA
HWRF
IMD-MME
OBSERVED
KOL
CHT
CXB
PRD
GPL
KLN
VSK
MPT

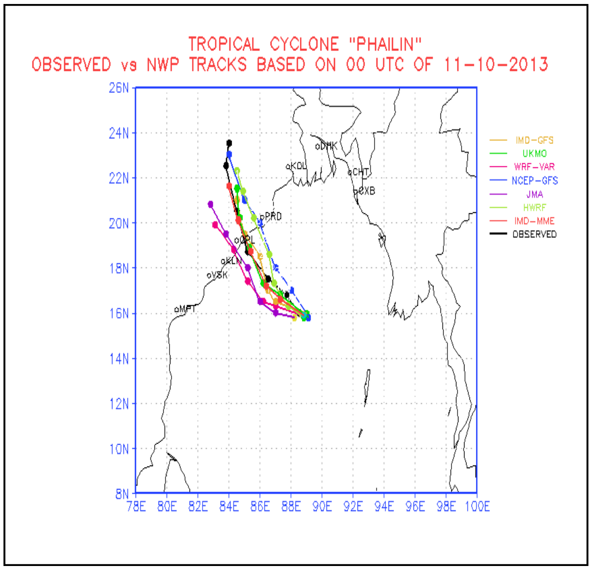

TRACKS FOR TROPICAL CYCLONE "PHAILIN"
OBSERVED vs IMD-MME BASED ON 12 UTC OF 09-10-2013
IMD-MME
OBSERVED
KOL
CHT
CXB
PRD
GPL
KLN
VSK
MPT

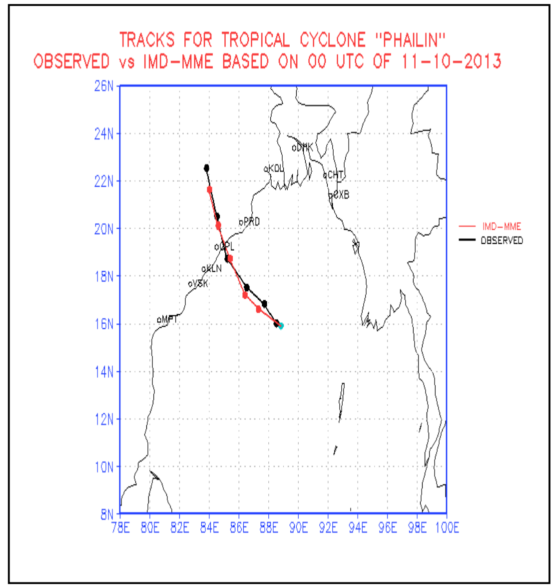

TROPICAL CYCLONE "PHAILIN"
OBSERVED vs NWP TRACKS BASED ON 00 UTC OF 10-10-2013
IMD-GFS
UKMO
WRF-VAR
NCEP-GFS
JMA
HWRF
IMD-MME
OBSERVED
DHK
KOL
CHT
CXB
PRD
GPL
KLN
VSK
MPT

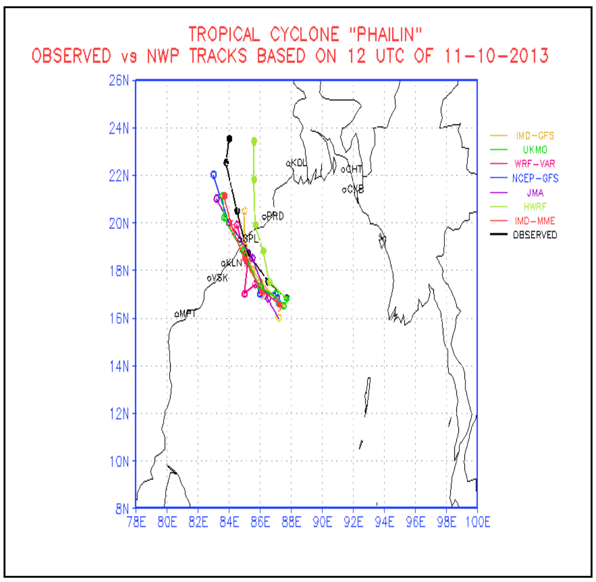

TRACKS FOR TROPICAL CYCLONE "PHAILIN"
OBSERVED vs IMD-MME BASED ON 00 UTC OF 10-10-2013
IMD-MME
OBSERVED
DHK
KOL
CHT
CXB
PRD
GPL
KLN
VSK
MPT

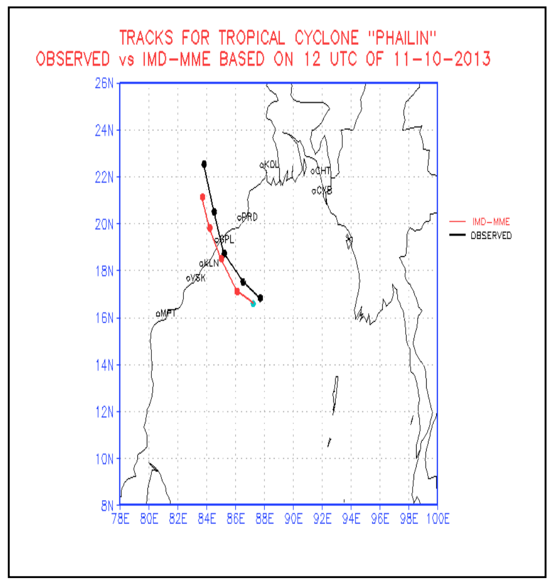

TROPICAL CYCLONE "PHAILIN"
OBSERVED vs NWP TRACKS BASED ON 12 UTC OF 10-10-2013
IMD-GFS
UKMO
WRF-VAR
NCEP-GFS
JMA
HWRF
IMD-MME
OBSERVED
KOL
CHT
CXB
PRD
GPL
KLN
VSK
MPT

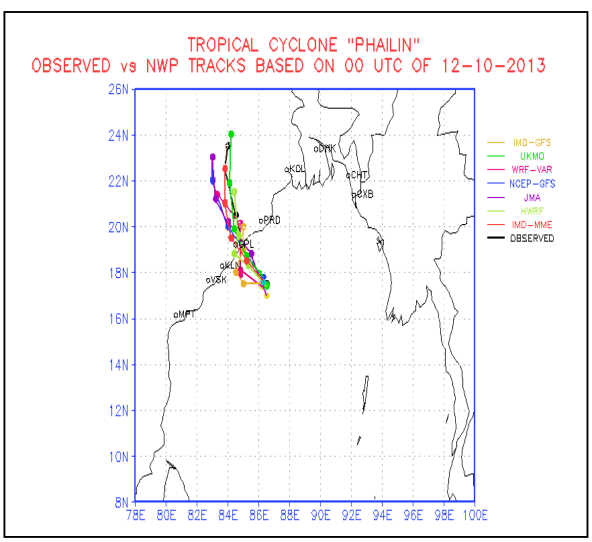

TRACKS FOR TROPICAL CYCLONE "PHAILIN"
OBSERVED vs IMD-MME BASED ON 12 UTC OF 10-10-2013
IMD-MME
OBSERVED
KOL
CHT
CXB
PRD
GPL
KLN
VSK
MPT

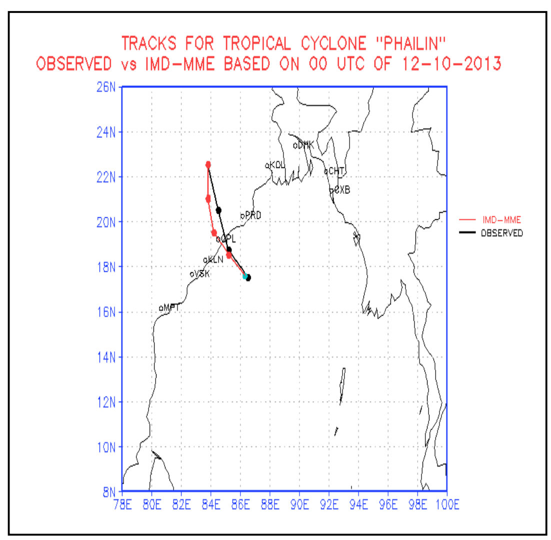

TROPICAL CYCLONE "PHAILIN"
OBSERVED vs NWP TRACKS BASED ON 00 UTC OF 11-10-2013
IMD-GFS
UKMO
WRF-VAR
NCEP-GFS
JMA
HWRF
IMD-MME
OBSERVED


TRACKS FOR TROPICAL CYCLONE "PHAILIN"
OBSERVED vs IMD-MME BASED ON 00 UTC OF 11-10-2013
IMD-MME
OBSERVED


TROPICAL CYCLONE "PHAILIN"
OBSERVED vs NWP TRACKS BASED ON 12 UTC OF 11-10-2013
IMD-GFS
UKMO
WRF-VAR
NCEP-GFS
JMA
HWRF
IMD-MME
OBSERVED


TRACKS FOR TROPICAL CYCLONE "PHAILIN"
OBSERVED vs IMD-MME BASED ON 12 UTC OF 11-10-2013
IMD-MME
OBSERVED


TROPICAL CYCLONE "PHAILIN"
OBSERVED vs NWP TRACKS BASED ON 00 UTC OF 12-10-2013
IMD-GFS
UKMO
WRF-VAR
NCEP-GFS
JMA
HWRF
IMD-MME
OBSERVED


TRACKS FOR TROPICAL CYCLONE "PHAILIN"
OBSERVED vs IMD-MME BASED ON 00 UTC OF 12-10-2013
IMD-MME
OBSERVED

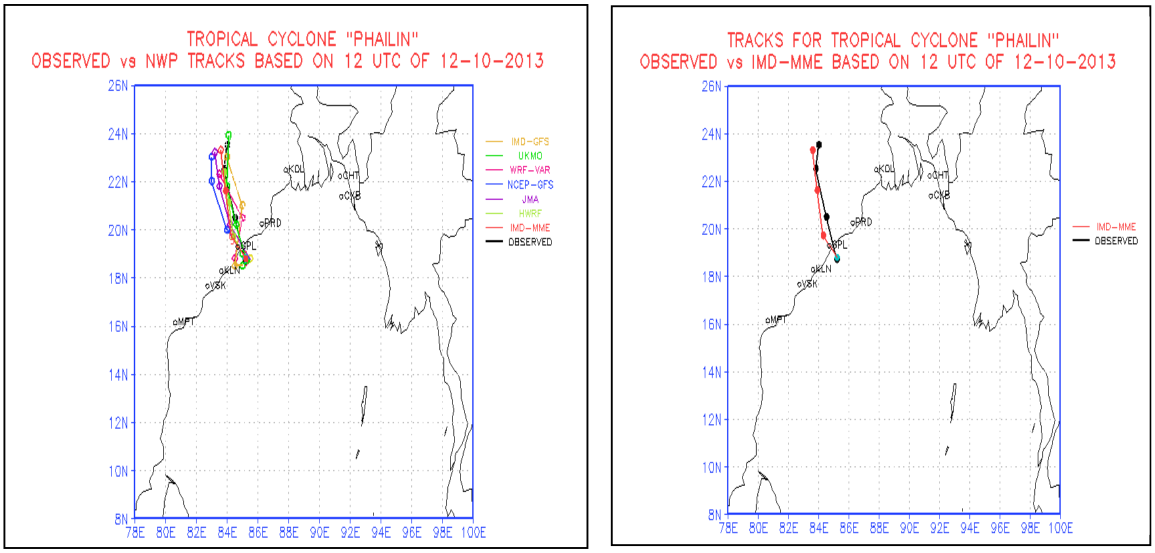


Fig. 12. MME forecasts track based on different initial conditions for PHAILIN

Direct position Error (DPE): Average track forecast error (direct position error (DPE)) of PHAILIN was highest for WRF (about 95 km at 12 h to 265 km at 72 h) and JMA (about 85 km at 12 h to 305 km at 84 h). Average DPE was lowest for UKMO, NCEP-GFS and MME up to 60 h (about 65 km at 12 h to 100 km at 60 h), thereafter NCEP-GFS lowest (about 90 km) upto 108 h. The DPE for MME was about 65 km at 12 h to 150 km at 120 h (Table-7). The DPE of all models are shown in Fig. 13.

Table-7. Average track forecast errors (DPE) in km (Number of forecasts verified)-PHAILIN

Lead time →	**12 hr**	**24 hr**	**36 hr**	**48 hr**	**60 hr**	**72 hr**	**84 hr**	**96 hr**	**108 hr**	**120 hr**
IMD-GFS	98(9)	107(9)	129(9)	173(8)	132(6)	115(5)	109(4)	92(3)	120(2)	104(1)
IMD-WRF	97(9)	150(9)	167(9)	193(8)	234(6)	266(5)	-	-	-	-
JMA	86(9)	97(9)	114(9)	149(8)	185(6)	239(5)	304(4)	-	-	-
NCEP-GFS	69(9)	63(9)	91(9)	87(8)	91(6)	61(5)	90(4)	84(3)	90(2)	175(1)
UKMO	63(9)	62(9)	71(9)	77(8)	104(6)	134(5)	134(4)	168(3)	191(2)	213(1)
IMD-MME	64(9)	67(9)	81(9)	95(8)	103(6)	119(5)	139(4)	112(3)	106(2)	148(1)
IMD-HWRF	49(8)	111(8)	169(8)	176(7)	183(6)	170(5)	154(4)	159(3)	187(2)	182(1)
IMD-OFFICIAL	63(21)	98(19)	91(17)	91(15)	90(13)	77(11)	95(7)	136(5)	112(3)	78(1)

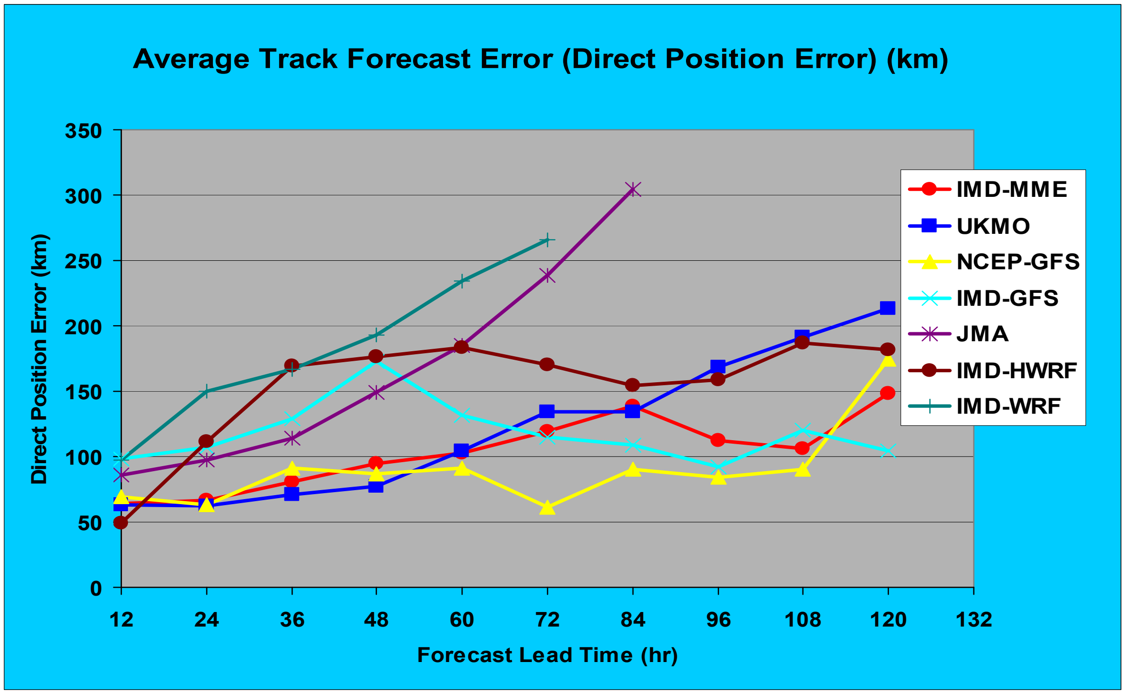


Fig. 13: Average track forecast errors (DPE) of NWP models for PHAILIN

Cross Track Error (CTE): Average cross track error (CTE) was highest for WRF (about 70 km at 12 h to 195 km at 72 h) and JMA (about 60 km at 12 h to 280 km at 84 h). Average CTE was lowest for UKMO and MME for all forecast hours (about 45 km at 12 h to 50 km at 120 h). IMD-GFS was also comparable with UKMO and MME up to 96 h (Table-8). The CTE of all models are shown in Fig. 14.

Table-8. Average cross track error (CTE) in km of PHAILIN

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
IMD-GFS	63	56	41	37	31	36	59	64	98	61
IMD-WRF	68	89	88	133	180	194	-	-	-	-
JMA	59	72	92	112	148	201	280	-	-	-
NCEP-GFS	43	51	81	71	39	31	78	83	87	166
UKMO	47	31	39	25	21	36	19	35	50	30
IMD-MME	46	41	46	43	41	46	80	61	42	50
IMD-HWRF	20	46	66	101	105	130	117	115	124	94

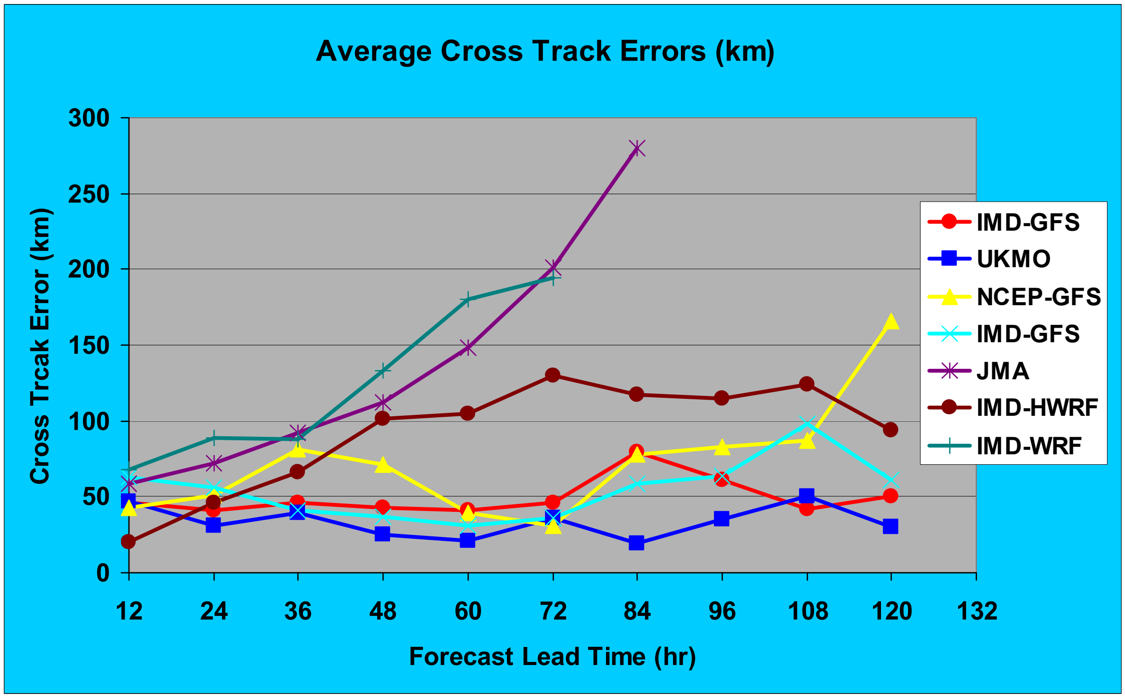


Fig. 14: Average cross track errors (CTE) of NWP models for PHAILIN

Along Track Error (ATE): Average along track error (ATE) was highest for WRF, HWRF and IMD-GFS (about 50 km at 12 h to 150 km at 48 h). ATE of WRF is largest at 72 h (about 150 km). Average ATE was highest for UKMO from 84 h to 120 h (about 130 km at 84 h to 210 km at 120 h). ATE of NCEP-GFS was lowest at all forecast hours (about 40 km at 12 h to 55 km at 120 h). The ATE for MME was about 40 km at 12 h to 140 km at 120 h (Table-9). The ATE of all models is shown in Fig. 15.

Table-9. Average along track error (ATE) in km of PHAILIN

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
IMD-GFS	63	86	120	166	126	106	76	63	60	84
IMD-WRF	56	104	127	130	138	152	-	-	-	-
JMA	48	49	57	67	77	100	104	-	-	-
NCEP-GFS	42	27	31	35	79	43	35	14	21	55
UKMO	38	46	50	69	100	127	132	163	184	211
IMD-MME	40	44	59	80	87	97	100	82	93	139
IMD-HWRF	43	97	146	140	142	111	99	102	126	156

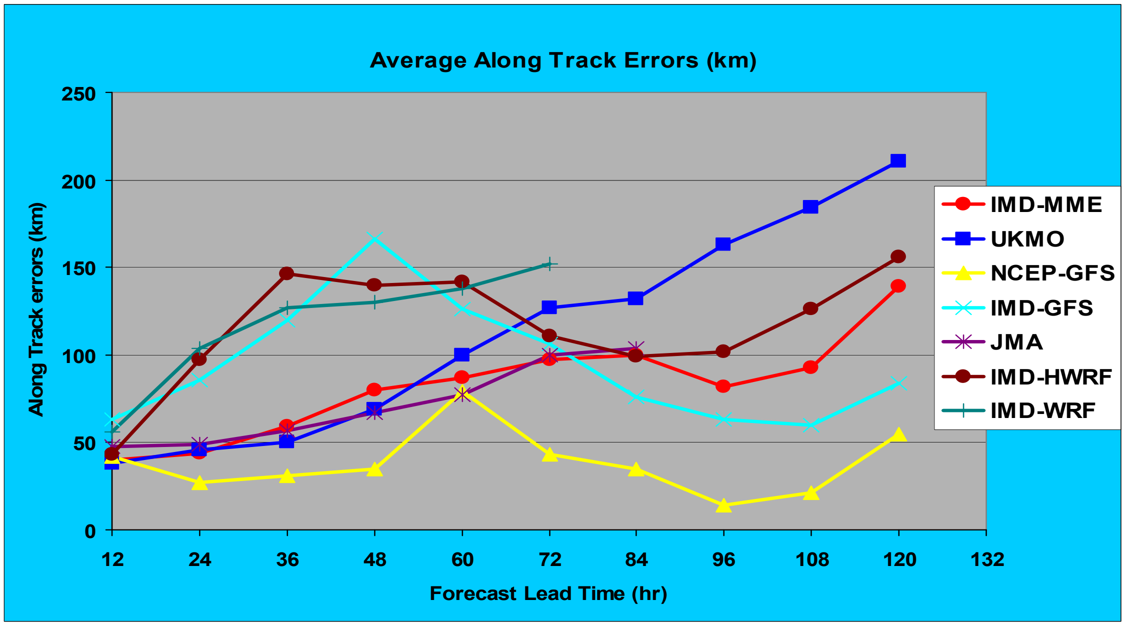


Fig. 15: Average along track errors (ATE) of NWP models for PHAILIN

Landfall Point Error: Landfall point forecasts errors of NWP model at different forecast lead times (Fig. 13) show that some model predicted north of actual landfall point and some predicted south of actual landfall point with a maximum limit upto about 340 km towards north and upto 215 km towards south. Under this wide extent of landfall point forecasts, MME was able to predict near actual landfall point (Gopalpur) consistently (Table-10).

Table-10. Landfall Point and Landfall time error of MME forecasts for cyclone PHAILIN

Forecast based on	Forecast Lead Time (hr)	Forecasted landfall Point	Landfall Point Forecast error (km)	Landfall Time Error (hr)
00 UTC/08.10.2013	113	GOPALPUR	39	7 hrs Delay
00 UTC/09.10.2013	89	GOPALPUR	0	3 hrs Delay
12 UTC/09.10.2013	77	GOPALPUR	35	3 hrs Delay
00 UTC/10.10.2013	65	GOPALPUR	25	1 hr Delay
12 UTC/10.10.2013	53	GOPALPUR	0	1 hr Delay
00 UTC/11.10.2013	41	GOPALPUR	0	1 hr Delay
12 UTC/11.10.2013	29	GOPALPUR	39	0 hr
00 UTC/12.10.2013	17	GOPALPUR	39	1 hr Delay
12 UTC/12.10.2013	5	GOPALPUR	0	0 hr

Table-11. Landfall point forecast errors (km) of NWP Models at different lead time (hour) for cyclone PHAILIN

Forecast Lead Time (hour) →	5 h	17 h	29 h	41 h	53 h	65 h	77 h	89 h	113 h
UKMO	25	0	24	25	47	69	69	92	-
NCEP GFS	0	0	0	148	61	15	0	25	79
JMA	25	25	0	70	15	161	214	-	-
HWRF	25	94	81	109	166	166	166	342	-
IMD-GFS	70	11	0	25	71	25	15	25	124
WRF-VAR	61	24	0	70	191	-	-	-	-
IMD-MME	0	39	39	0	0	25	35	0	39

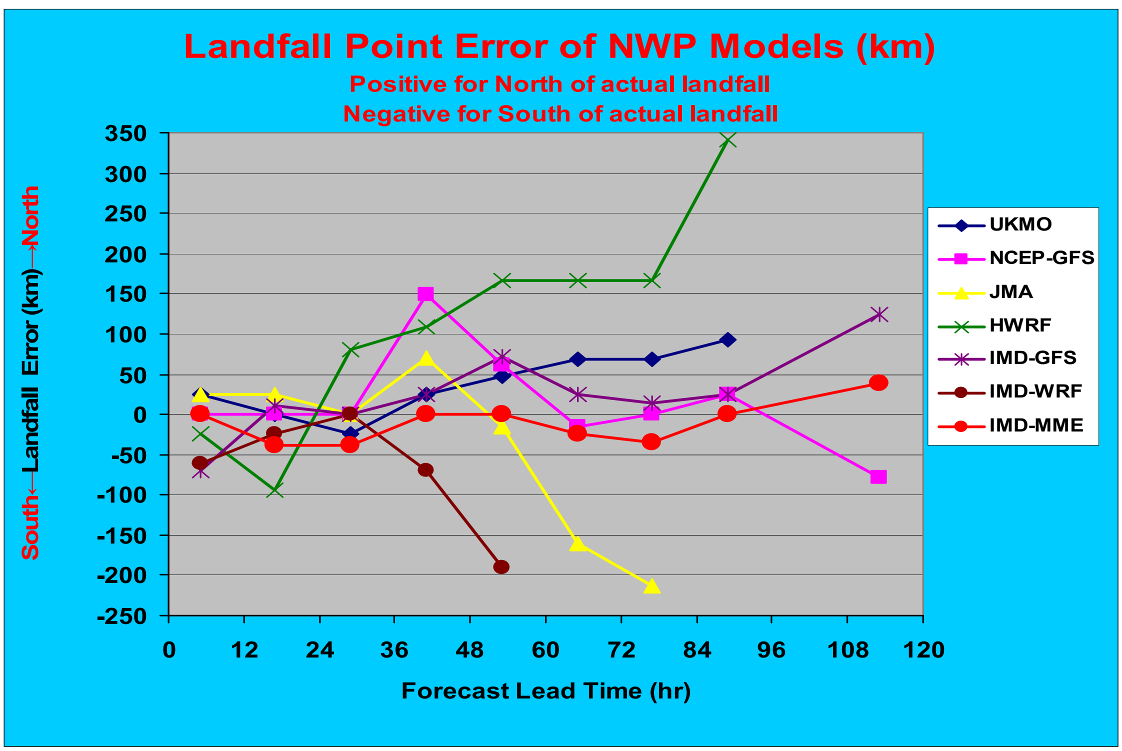


Fig. 16: Landfall point error (hr) of Models for PHAILIN

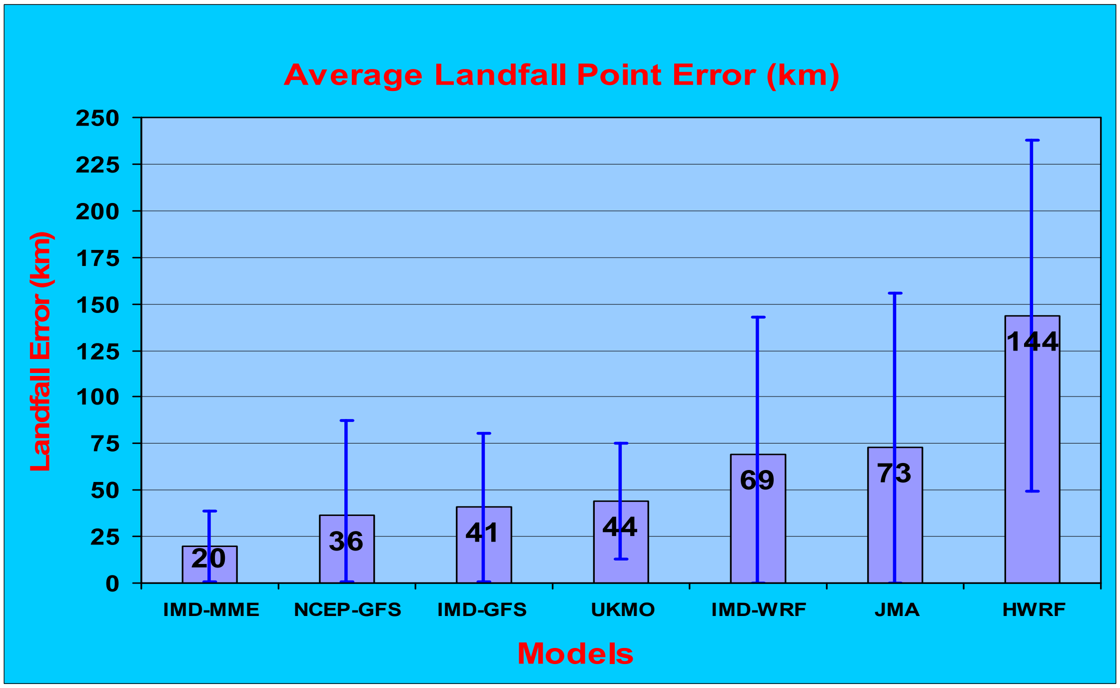


Fig. 17: Average landfall point error (km) of Models (along with range(thick blue line)) for PHAILIN

Average land fall point error (Fig. 17) shows that MME forecast error is least (20 km) compared to other models before 5 h to 113 h of landfall.

Landfall Time Error: Landfall time forecasts errors of NWP model at different forecast lead times (Fig. 18) show that some model predicted earlier than actual landfall time and some predicted delayed than actual landfall time with a maximum limit upto 21 hr delayed and upto 6 hr earlier than actual landfall time. Under this wide extent of landfall time forecasts, MME landfall time error was consistently low (Table-12). Average land fall time error (Fig. 19) shows that MME landfall time forecast error is least (1.9 hr) compared to other models.

Table-12. Landfall time forecast errors (hour) at different lead time (hr) for cyclone PHAILIN

('+' indicates delay landfall, '-' indicates early landfall)

Forecast Lead Time (hour) →	5 h	17 h	29 h	41 h	53 h	65 h	77 h	89 h	113 h
UKMO	0	0	-4	-2	+2	+2	+4	+5	-
NCEP GFS	-2	-4	-4	-6	-1	-3	-4	0	+2
JMA	0	-1	+1	+1	+4	-2	+7	-	-
HWRF	-3	+5	+5	+4	+2	-5	0	+7	-
IMD-GFS	+8	+21	+8	+6	+7	+2	+4	-1	+2
WRF-VAR	-5	+13	+13	+6	+13	-	-	-	-
IMD-MME	0	+1	0	+1	+1	+1	+3	+3	+7

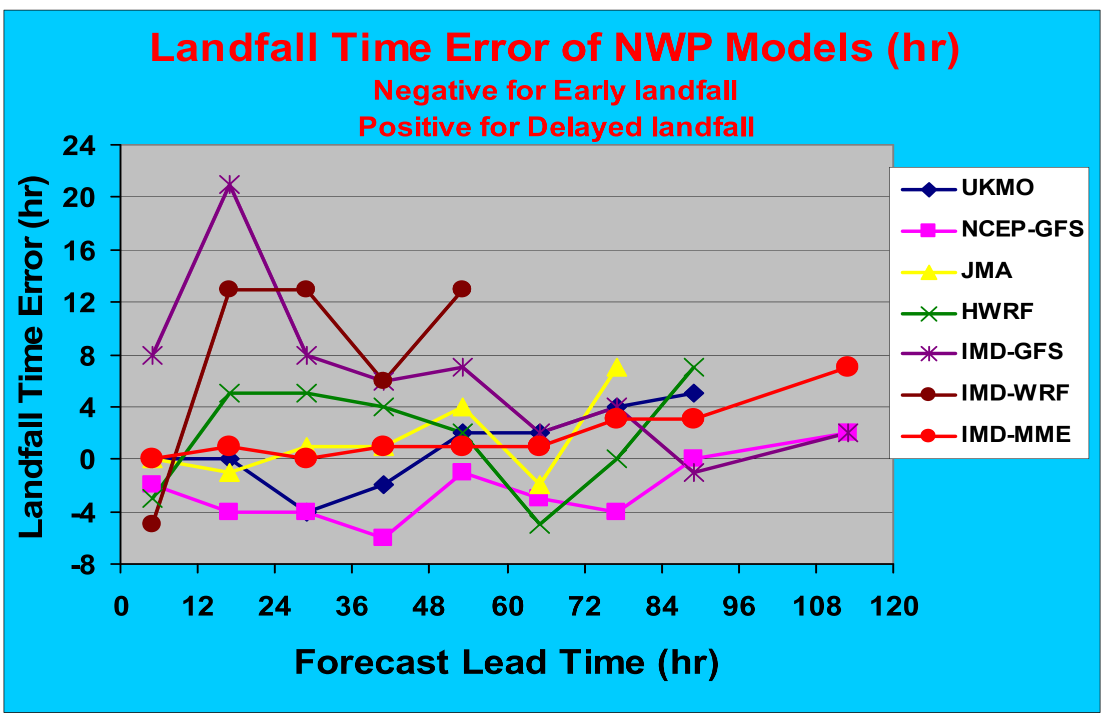


Fig. 18: Landfall time error (km) of models at different lead time (hr) for PHAILIN

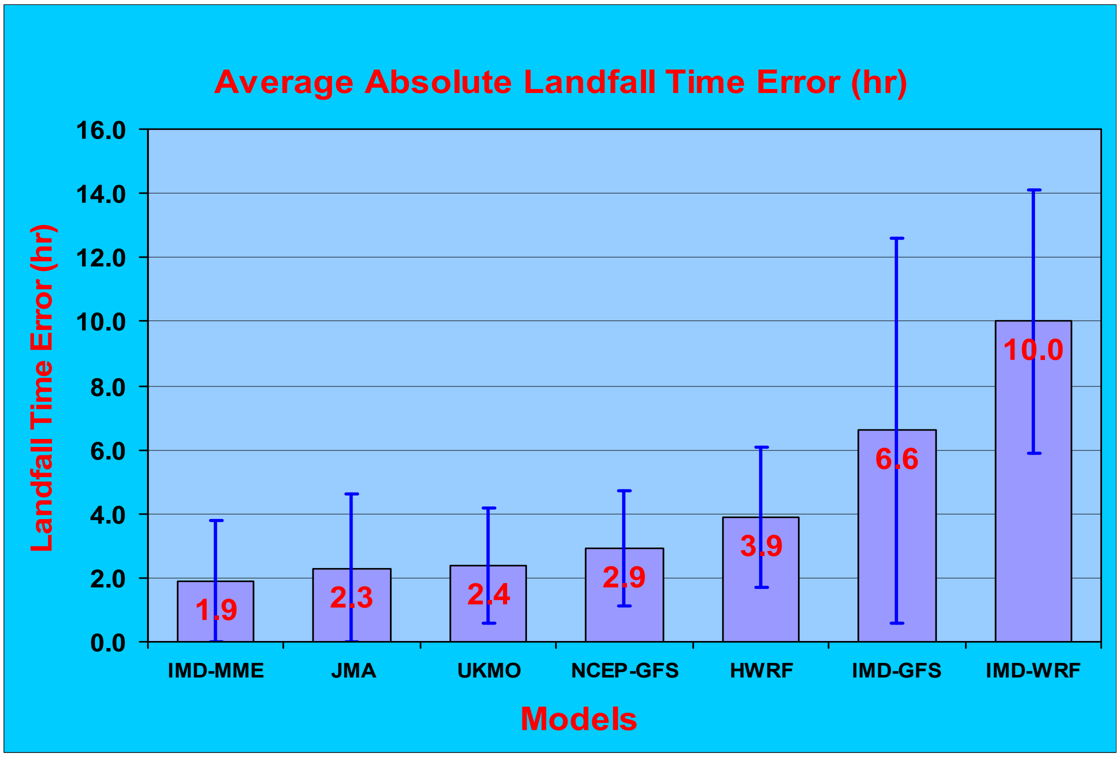


Fig. 19: Average landfall time error (hr) of Models (along with range(thick blue line)) for PHAILIN

6.4 Intensity prediction

Intensity prediction (at stages of 12-h intervals) by statistical-dynamical model SCIP and dynamical model HWRF are shown in Fig. 20 and Fig. 21 respectively. Both the SCIP and HWRF model was able to predict the very severe stage of the PHAILIN at all stages of forecast. But none of the two models could predict the non-intensification phase of the PHAILIN from 0300 UTC of 11 October to 1200 UTC of 12 October 2013 during which the cyclone maintained constant intensity of 115 kt. The SCIP model continued to predict intensification and HWRF model continued to predict weakening during this stagnation phase of the very severe cyclone.

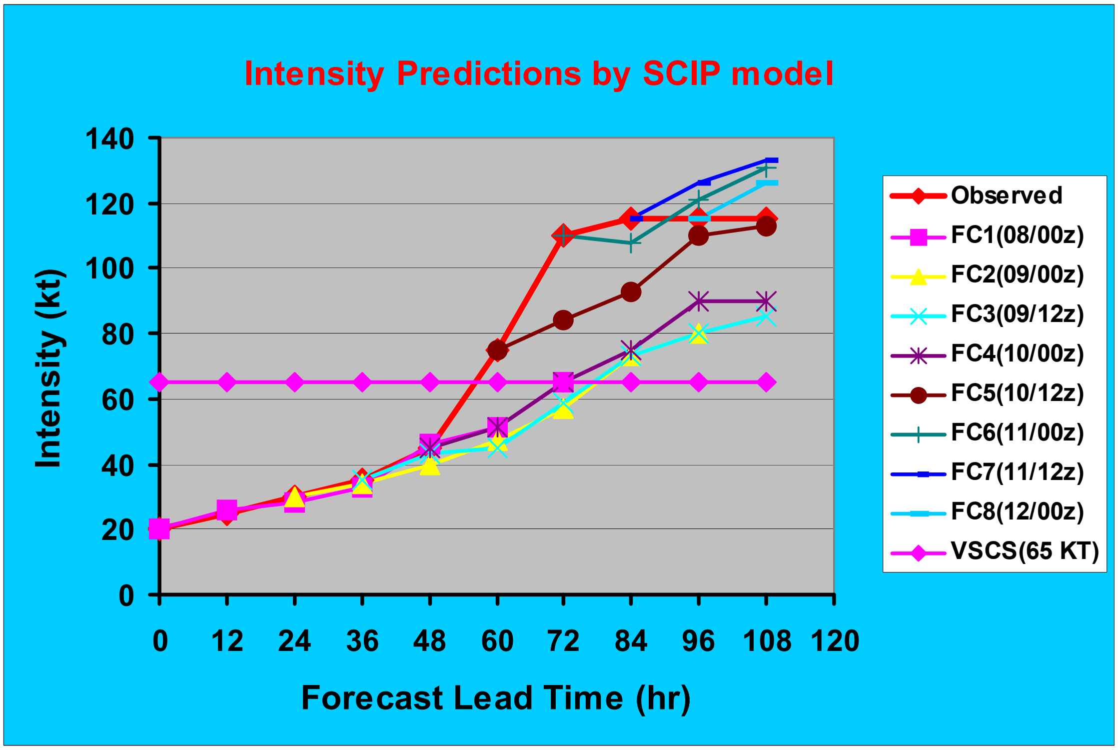


Fig. 20. Intensity forecasts of SCIP model for PHAILIN

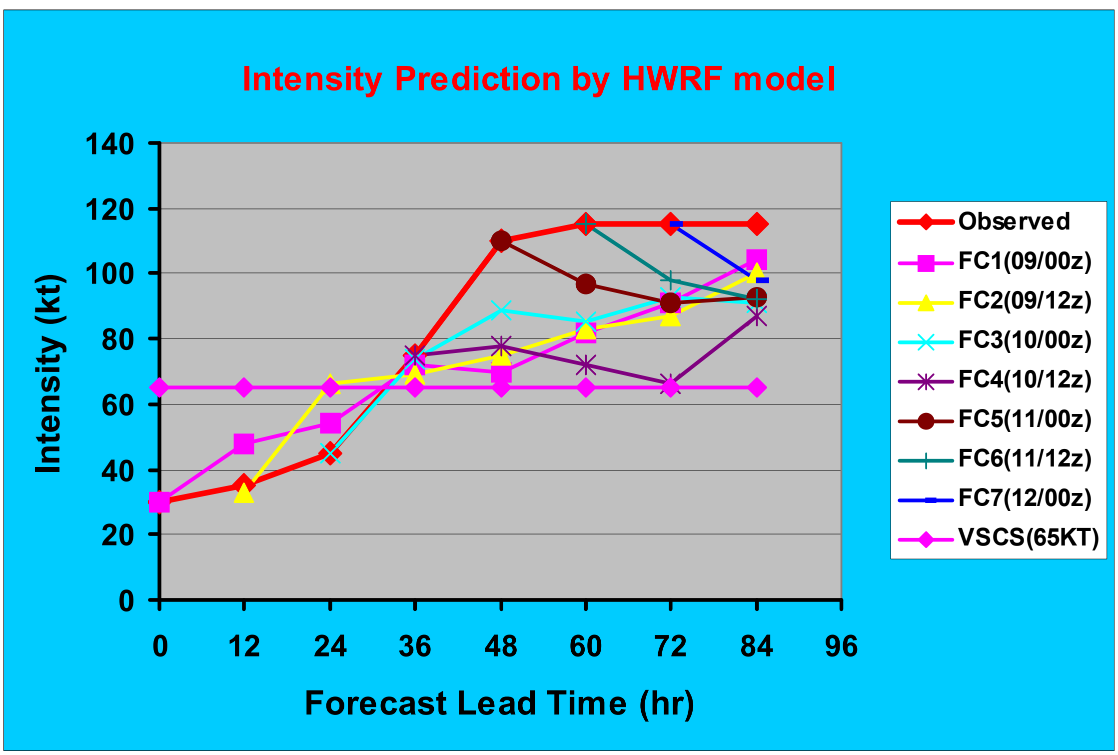


Fig. 21. Intensity forecasts of HWRF model for PHAILIN

Average absolute error (AEE) and Root mean square error (RMSE) of SCIP and HWRF forecast error for cyclone PHAILIN is presented in the following Table-13 and Table-14. Intensity forecasts by SCIP, and HWRF shows that Statistical-dynamical model forecast (SCIP) was superior to HWRF up to 48 hour, HWRF was better at 60 h and 72 h forecasts. AAE of SCIP was 31 kt at 60 hr and 37 kt at 72 hr. AEE of HWRF was 28 kt, 19 kt and 11 kt at 60 hr, 72 hr and 84 hr respectively.

Table-13 Average absolute errors for cyclone PHAILIN (Number of forecasts verified is given in t he parentheses)

(Intensity forecasts prior to landfall (1200 UTC of 12.10.2013) are considered)

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120hr
IMD-SCIP	10.4(8)	18.3(7)	23.7(6)	24.6(5)	31.5(4)	36.7(3)	-	-	-	-
IMD-HWRF	17.0(6)	21.0(5)	27.8(5)	30.5(4)	28.3(3)	19.5(2)	11.0(1)	-	-	-
IMD-OFFICIAL	9.1	14.9	17.4	18.7	17.7	11.1	19.7	10.5	1.8	5.4

Table-14 Root Mean Square (RMSE) errors for cyclone PHAILIN (Number of forecasts verified is given in the parentheses)

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120hr
IMD-SCIP	13.9(8)	23.3(7)	29.6(6)	32.3(5)	32.4(4)	37.2(3)	-	-	-	-
IMD-HWRF	19.0(6)	24.2(5)	31.7(5)	31.2(4)	28.6(3)	20.0(2)	14.9(1)	-	-	-
IMD-OFFICIAL	12.8	21.0	22.2	22.9	20.5	13.9	31.2	16.5	2.2	5.4

Landfall intensity predicted by **SCIP** model in 2-3 days before landfall (from initial cyclonic storm stage at 1200 UTC of 09 October 2013) shows that the model could predict the landfall intensity of very severe cyclonic storm with a reasonable success (Fig. 22).

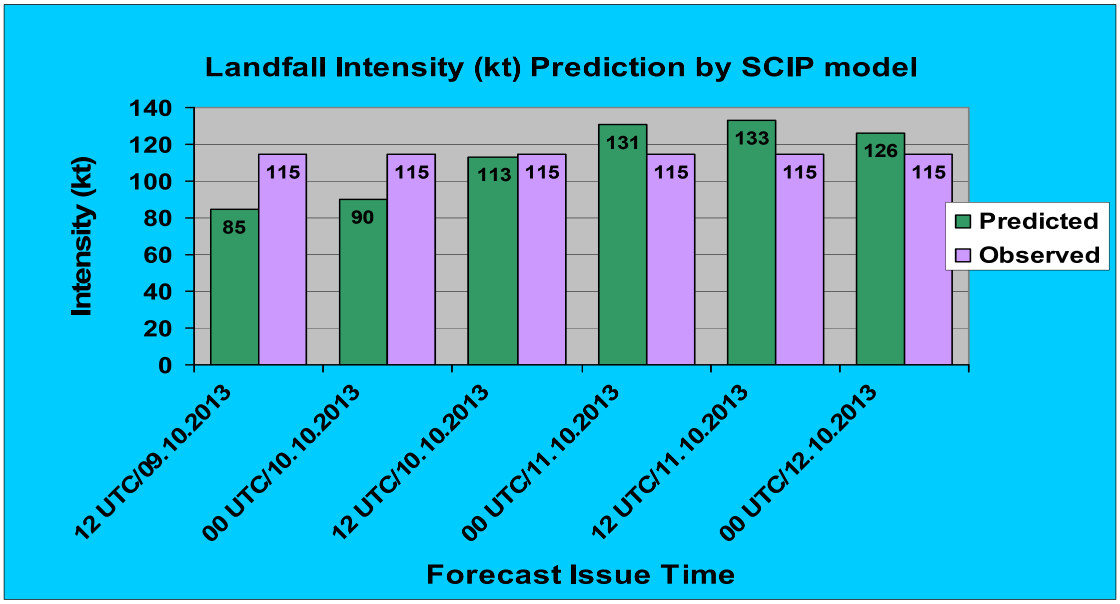


Fig. 22: Landfall Intensity (kt) prediction by SCIP Model for PHAILIN

6.5. Probability of Rapid intensification (by RI-Index)

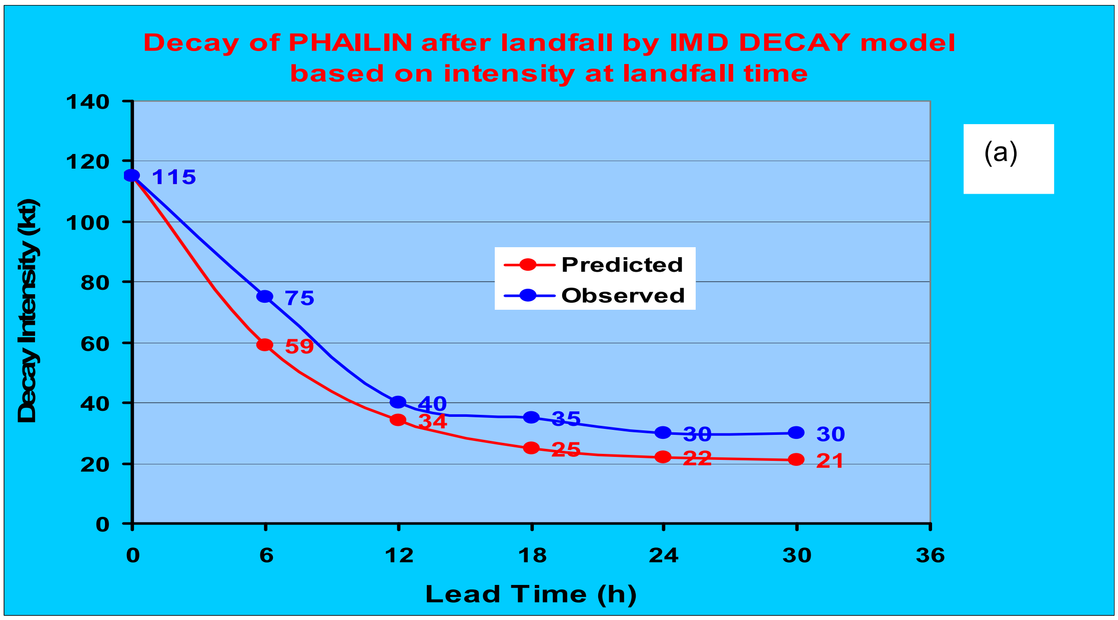
Rapid intensification (RI) is defined as: Increase of intensity by 30 kts or more during subsequent 24 hour.

Table-15 Probability of Rapid intensification for cyclone PHAILIN

Forecast based on	Probability of RI predicted	Chances of occurrence predicted	Intensity changes (kt) in 24h	Occurrence
00 UTC/08.10.2013	9.4 %	VERY LOW	5	NO
00 UTC/09.10.2013	9.4 %	VERY LOW	15	NO
12 UTC/09.10.2013	9.4 %	VERY LOW	40	YES
00 UTC/10.10.2013	72.7 %	HIGH	65	YES
12 UTC/10.10.2013	72.7 %	HIGH	40	YES
00 UTC/11.10.2013	72.7 %	HIGH	5	NO
12 UTC/11.10.2013	32.0 %	MODERATE	0	NO
Inference: RI-Index was able to predict **OCCURENCE** as well as **NON-OCCURENCE** of Rapid Intensification of cyclone PHAILIN during its lifetime except forecast for 12 UTC of 09.10.2013 and 00 UTC of 11.10.2013.				

6.6. Decay after landfall

Decay (after landfall) prediction curve (6-hourly up to 30 hr) (Fig. 23(a-b)) shows slightly first decay compared to observed decay. Decay model correctly predicted the decaying nature of the PHAILIN after landfall.



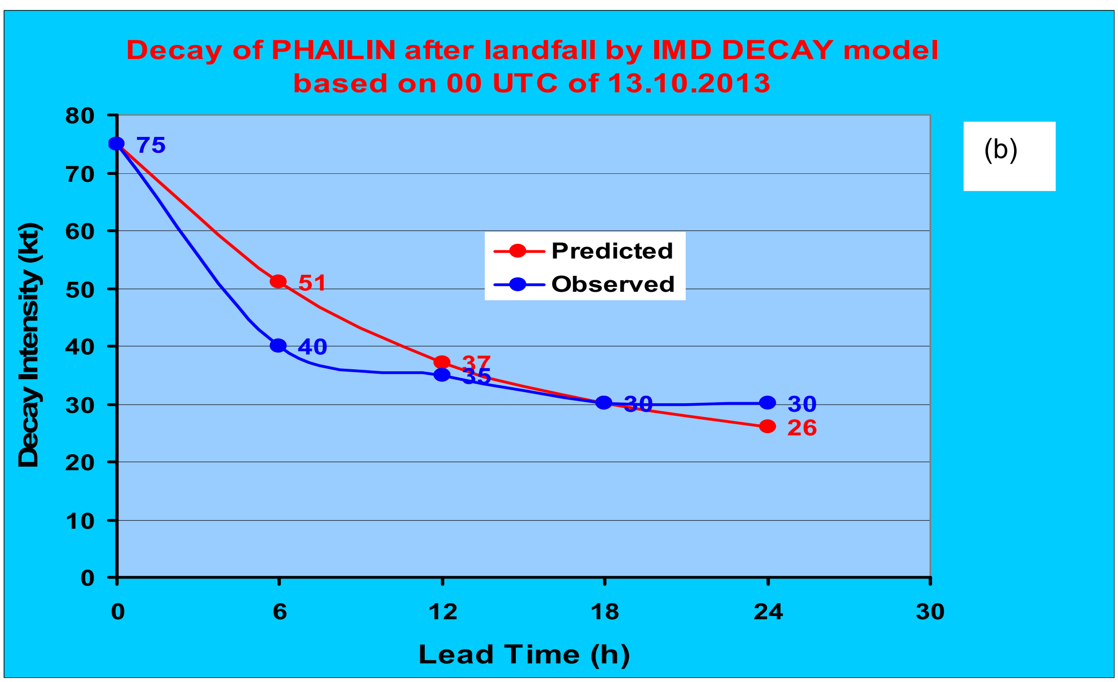
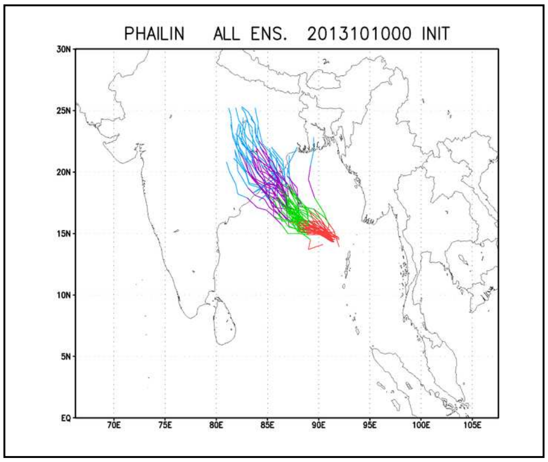
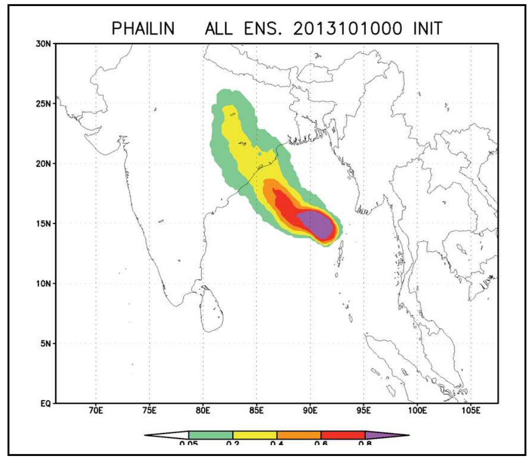


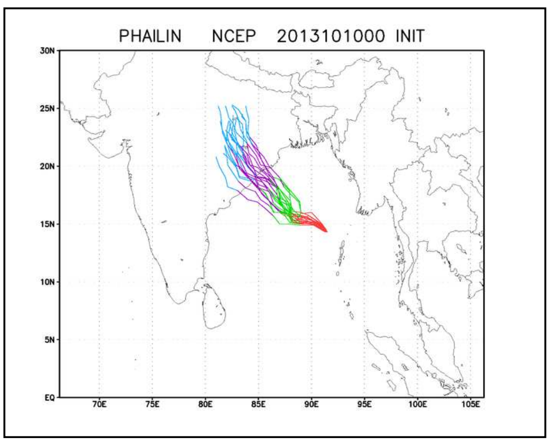
Fig. 23. Decay after landfall for PHAILIN

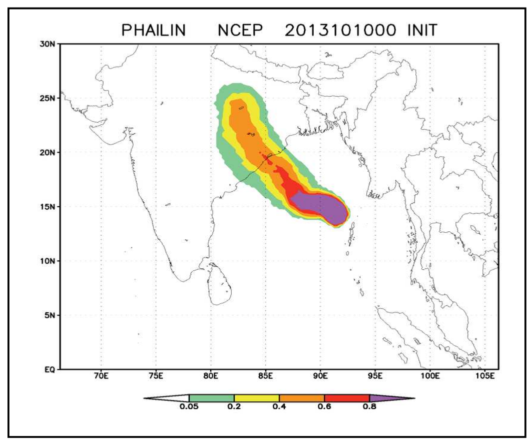
6.7. Ensemble track and Strike Probability forecast for cyclone PHAILIN

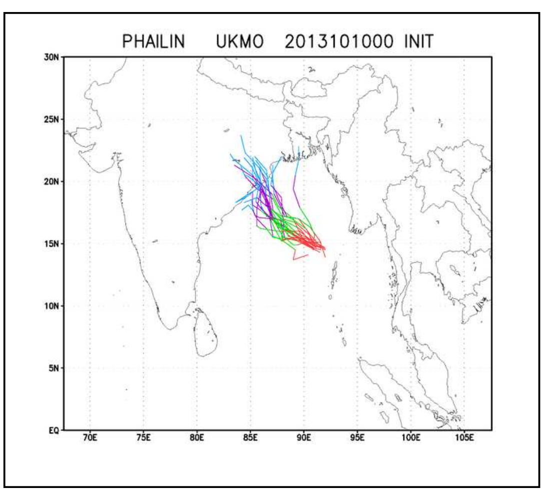
a. Based on 0000 UTC 10.10.2013

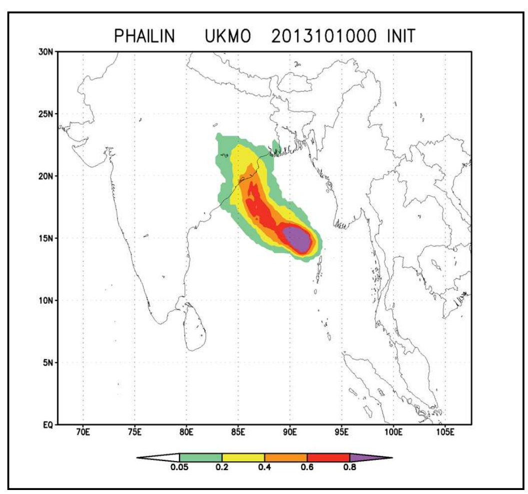












b. Based on 1200 UTC 10.10.2013

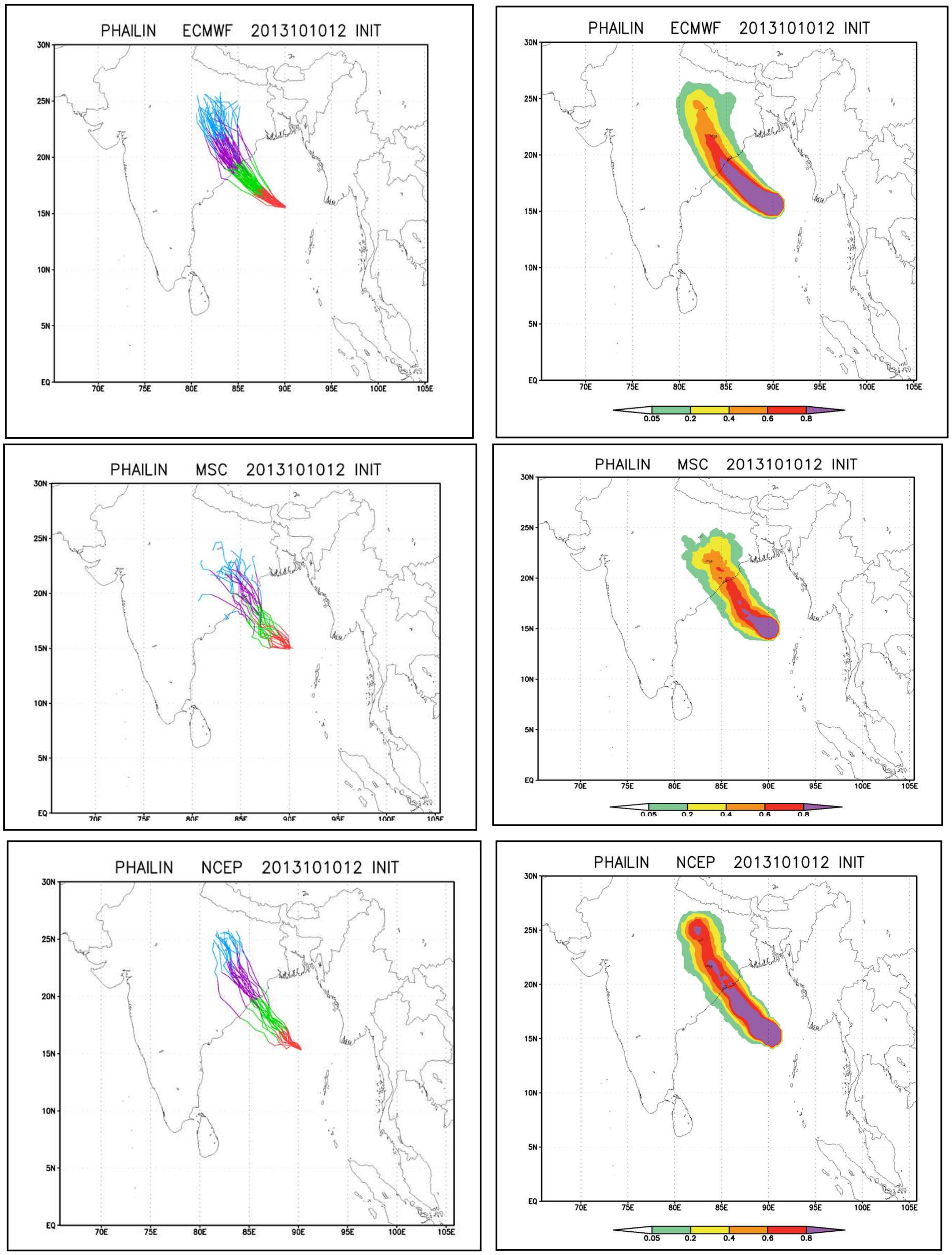


Fig. 21 Ensemble track and Strike Probability forecast for PHAILIN

Ensemble track and strike probability forecast based on 00 UTC 10.10.2013 and 12 UTC 10.10.2013 shows that ECMWF, UKMO, MSC and NCEP all predicted towards Odisha coast.

7. 'DEEP DEPRESSION' over the Arabian Sea (8-11) November 2013

The low pressure system that formed over the south Arabian Sea intensified into depression at 0600 UTC of 8 November 2013 near latitude 8.0^{o} N and longitude 56.5^{o} E. It moved westwards and intensified into a deep depression at 0000 UTC of 9 November 2013. The system further moved westward and crossed Somalia coast as Deep Depression near 8.2°N/50.0^{o}E between 2300 UTC of 10-11-2013 and 0000 UTC of 11-11-2013. The observed track of the Deep Depression is shown in Fig. 22.

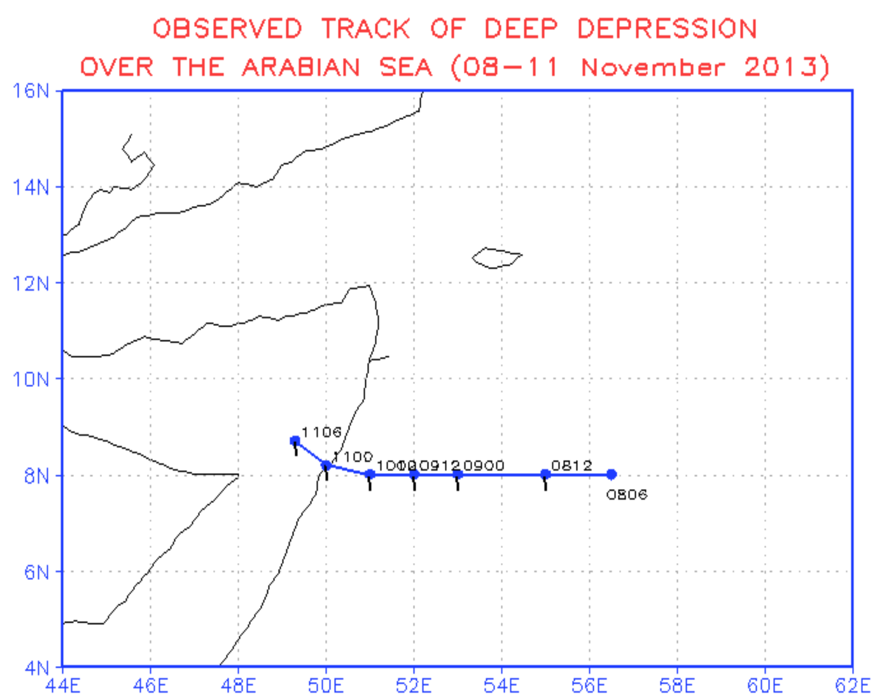
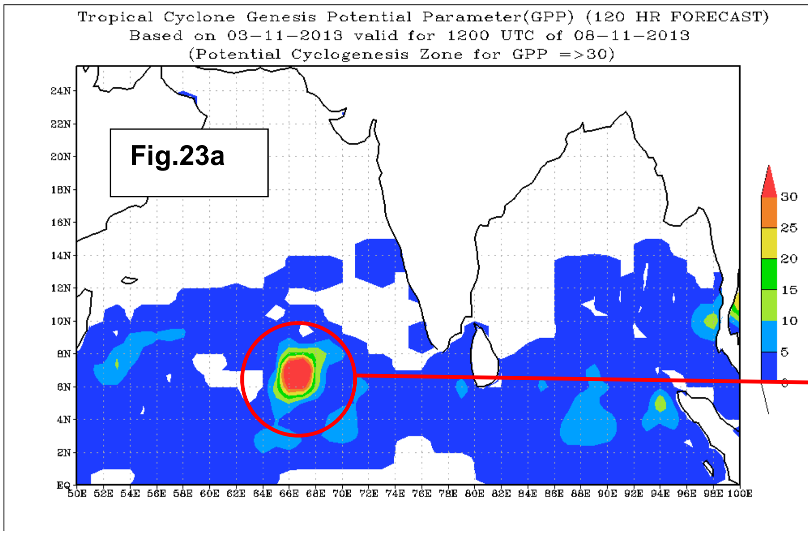


Fig. 22 Observed track of the Deep Depression

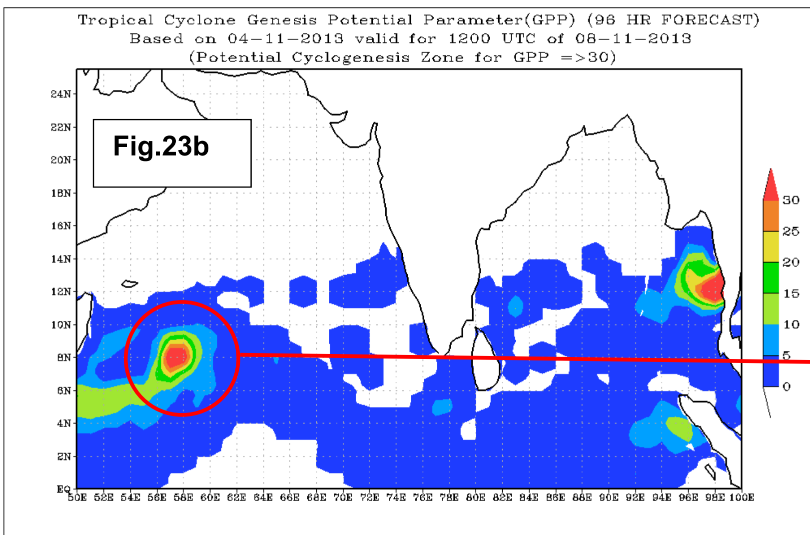
7.1. Grid point analysis and forecast of GPP

Objective: Grid point analysis and forecast of GPP is used to identify potential zone of cyclogenesis.

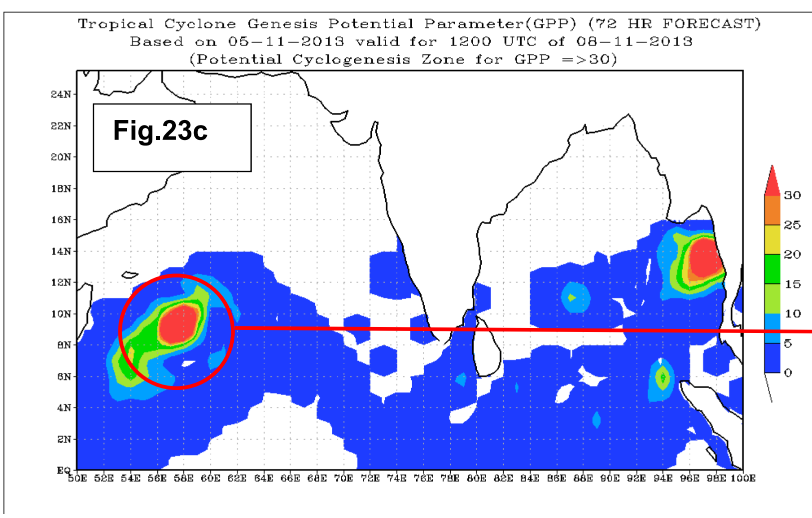
Figure 23(a-f) below shows the predicted zone of formation of cyclogenesis.



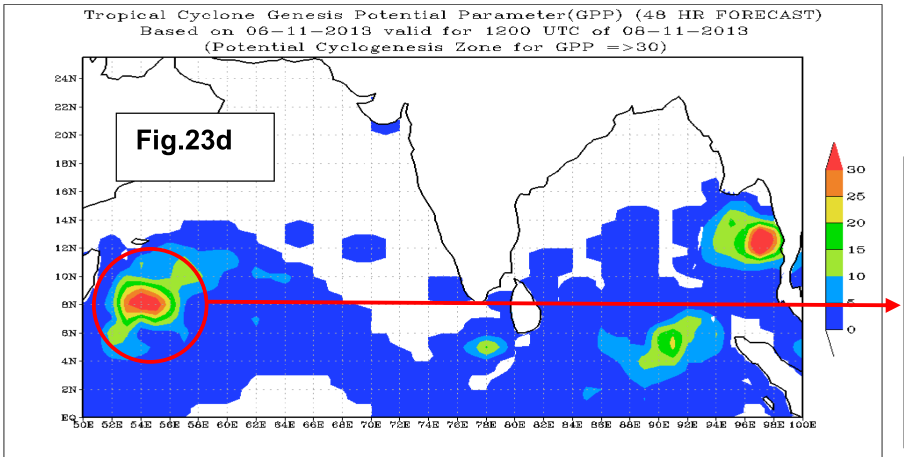
120 hour forecast of GPP valid for 12 UTC 08 October 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



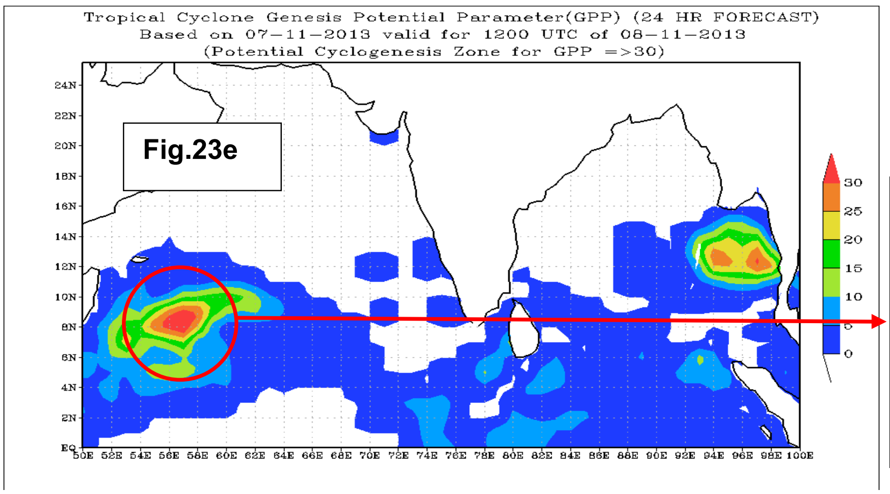
96 hour forecast of GPP valid for 12 UTC 08 October 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



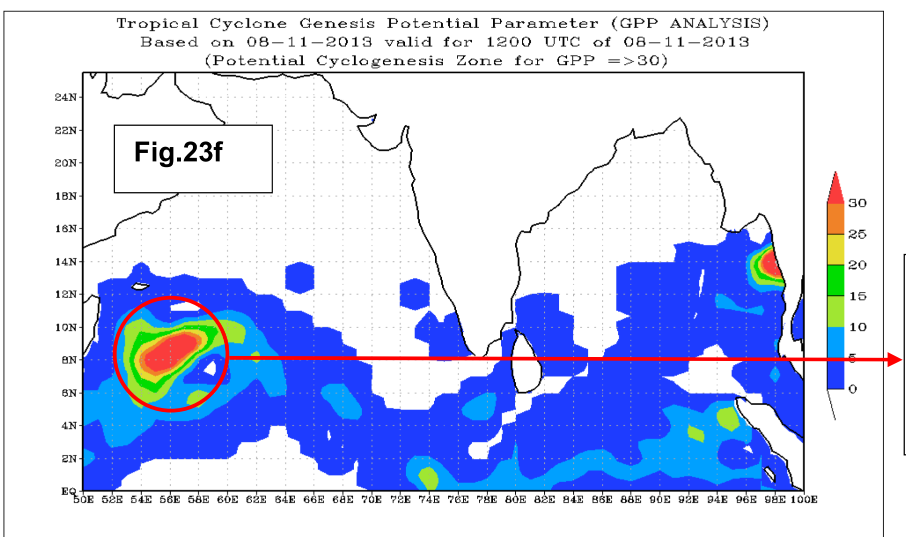
72 hour forecast of GPP valid for 12 UTC 08 October 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



48 hour forecast of GPP valid for 12 UTC 08 October 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



24 hour forecast of GPP valid for 12 UTC 08 October 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



Analysis of GPP for 12 UTC 08 October 2013 indicated the cyclogenesis zone, where Depression formed on that day.

Figure 23(a-f): Predicted zone of cyclogenesis for Deep Depression

Inference: Grid point analysis and forecasts of GPP (Fig.23(a-f)) shows that it was able to predict the formation and location of the system before 120 hours of its formation.

(Product available at http://www.imd.gov.in/section/nhac/dynamic/Analysis1.htm)

7.2. Area average analysis of GPP

Objective: Since all low pressure systems do not intensify into cyclones, it is important to identify the potential of intensification (into cyclone) of a low pressure system at the early stages of development.

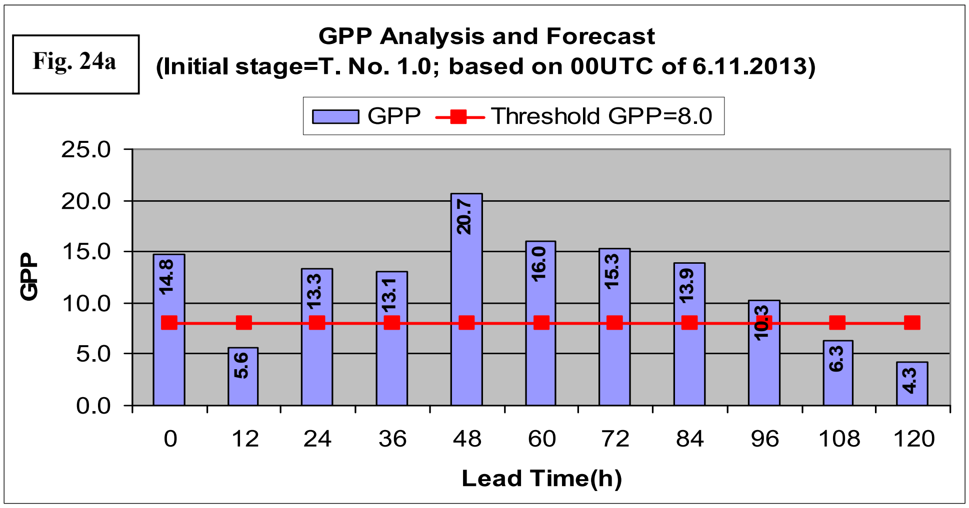


Fig 24a: Analysis and forecasts of GPP shows that GPP ≥ 8.0 (Threshold) at very early stage of development (T.No.-1.0) indicated its potential to intensify into a cyclone and weakening in the later phase.

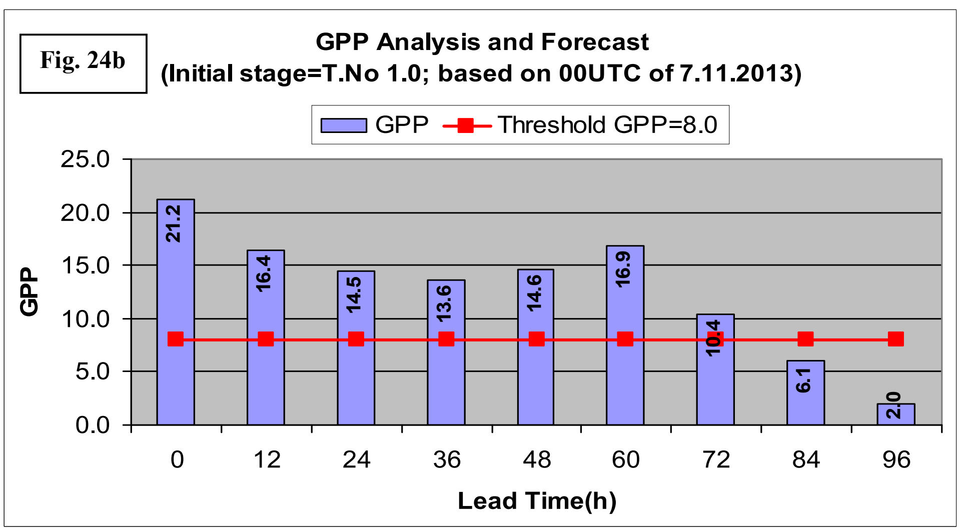


Fig 24b: Analysis and forecasts of GPP shows that GPP ≥ 8.0 (Threshold) at very early stage of development (T.No. 1.0) indicated its potential to intensify into a cyclone and weakening in the later phase.

Fig. 24(a-b) Area average analysis of GPP for Deep Depression

(Product available at http://www.imd.gov.in/section/nhac/dynamic/gpp.pdf)

Analysis and forecasts of GPP (Fig.24(a-b)) shows that GPP ≥ 8.0 (threshold value for intensification into cyclone) indicated its potential to intensify into a cyclone at early stages of development (T.No. 1.0) and weakening in the later phase.

7.3 Track prediction

The average track forecast errors (DPE, CTE, ATE) of NWP models along with the consensus forecast by Multi-model ensemble (MME) forecast are presented in the Table 16, Table 17 and Table 18 respectively. The landfall point error (km) and landfall time (hour) is presented in Table-19 and Table-20 respectively. The MME forecasts track based on different initial conditions along with the observed track is depicted in Fig 25.

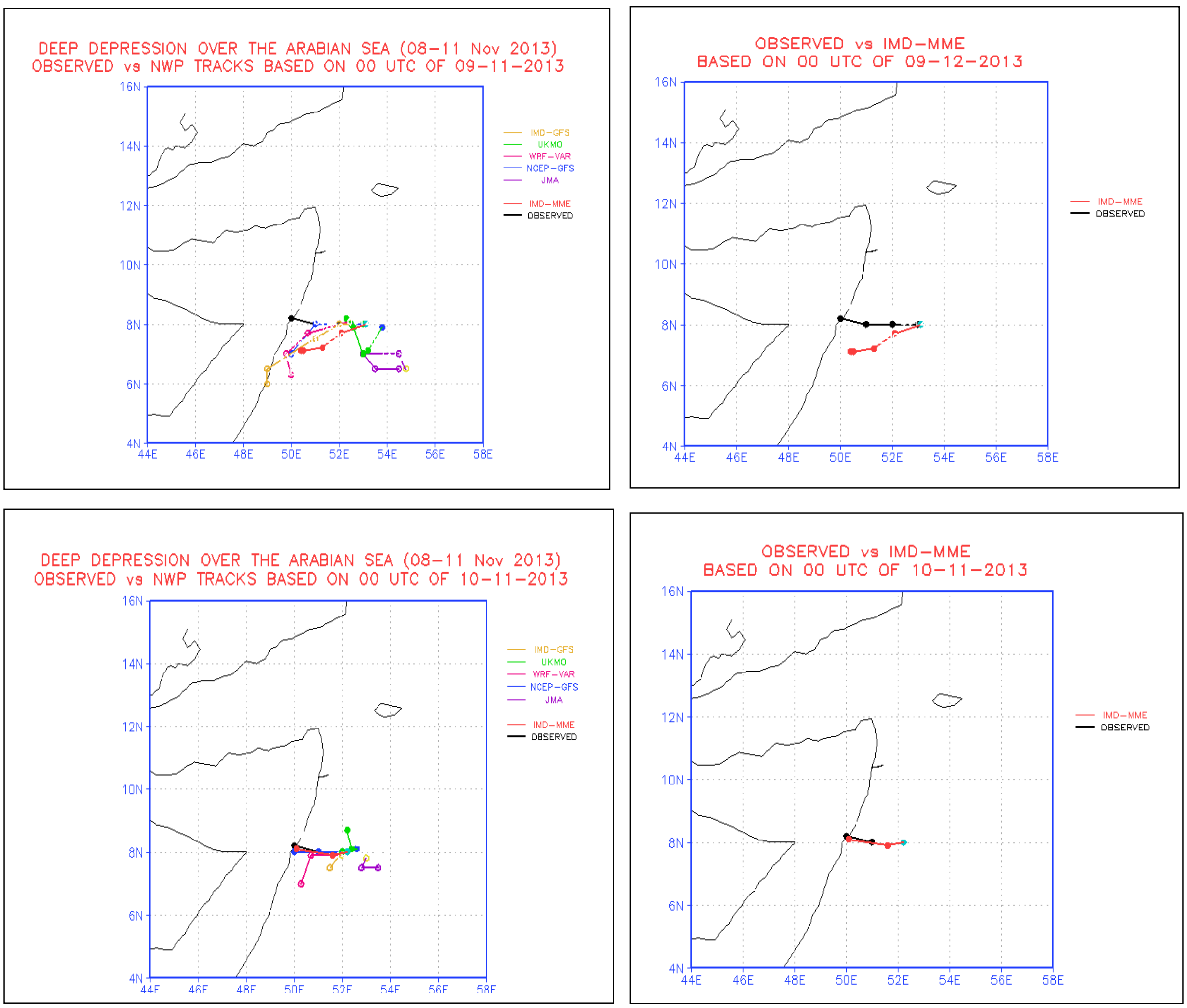


Fig. 25. MME forecasts track based on different initial conditions for Deep Depression

Direct position Error (DPE): Average track forecast error (direct position error (DPE)) was highest for JMA (about 250 km at 12 h to 530 km at 48 h)(Fig. 26). Average DPE was lowest for MME (about 50 km at 12 h to 130 km at 48 h. The DPE of all models are shown in Fig. 27.

Table-16. Average track forecast errors (DPE) in km (Number of forecasts verified)

Lead time →	12 hr	24 hr	36 hr	48 hr
IMD-GFS	39(2)	119(2)	276(1)	268(1)
IMD-WRF	91(2)	155(2)	219(1)	211(1)
JMA	251(2)	320(2)	322(1)	531(1)
NCEP-GFS	55(2)	89(2)	156(1)	133(1)
UKMO	160(2)	247(2)	176(1)	253(1)
IMD-MME	51(2)	55(2)	114(1)	130(1)

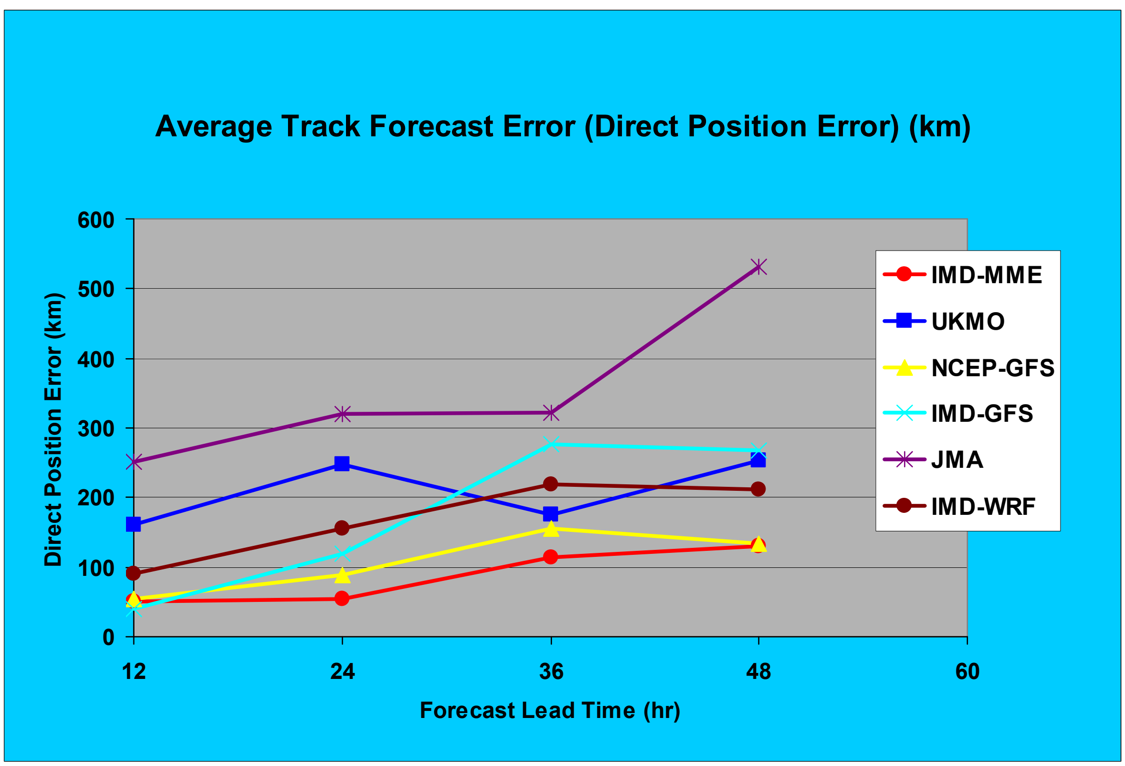


Fig. 26: Average track forecast errors (DPE) of NWP models for Deep Depression

Cross Track Error (CTE): Average cross track error (CTE) of all models is shown in Fig. 27. The CTE was lowest for IMD-GFS and MME at 24h (50 km) and for 36h (10km) and 48h (15km) UKMO was lowest.

Table-17. Average cross track error (CTE) in km for Deep Depression

Lead time →	12 hr	24 hr	36 hr	48 hr
IMD-GFS	39	49	166	251
IMD-WRF	34	117	189	211
JMA	158	56	167	154
NCEP-GFS	1	66	111	133
UKMO	127	107	11	17
IMD-MME	50	49	100	119

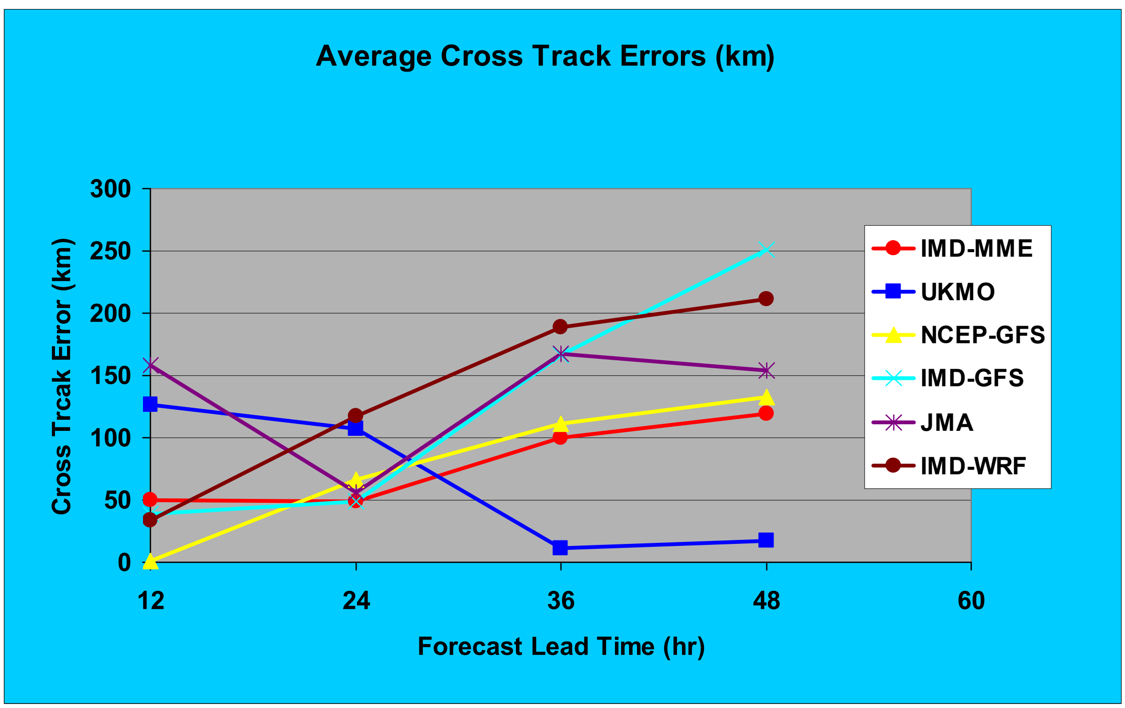


Fig. 27: Average cross track errors (CTE) of NWP models for Deep Depression

Along Track Error (ATE): Average along track error (ATE) for Deep Depression was lowest for MME (about 6 km at 12 h to 50 km at 48 h) (Table-18). The ATE of all models is shown in Fig. 28.

Table-18. Average along track error (ATE) in km for Deep Depression

Lead time →	12 hr	24 hr	36 hr	48 hr
IMD-GFS	0	89	221	95
IMD-WRF	72	96	111	13
JMA	138	307	276	508
NCEP-GFS	55	57	111	8
UKMO	66	223	176	252
IMD-MME	6	23	55	52

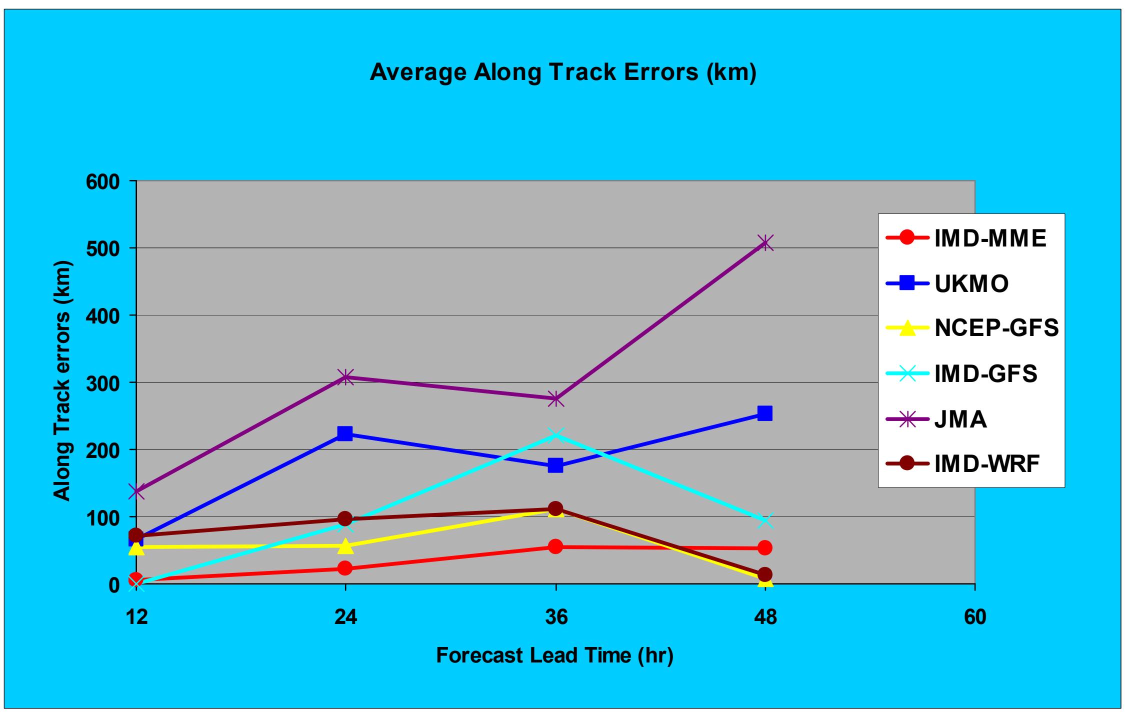


Fig. 28: Average along track errors (ATE) of NWP models for Deep Depression

Track Forecast Error of MME: The DPE, ATE and CTE of consensus forecast of NWP models (MME) is shown in Fig 29, Fig 30 and Fig 31 respectively.

The average DPE of MME was about 50 km at 12 h to 130 km at 48 h (Fig. 29).

The average ATE of MME was about 6 km at 12 h to 52 km at 48 h (Fig. 30).

The average CTE of MME was about 50 km at 12 h to 120 km at 48 h (Fig. 31).

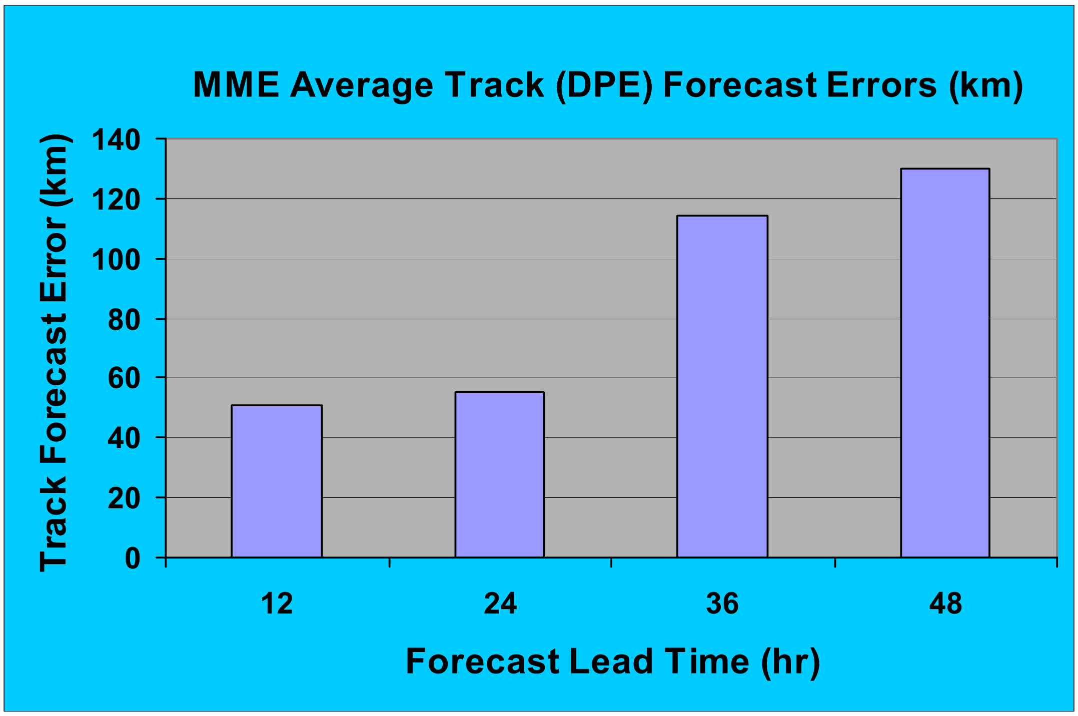


Fig. 29: Average direct track error (DPE) of MME for Deep Depression

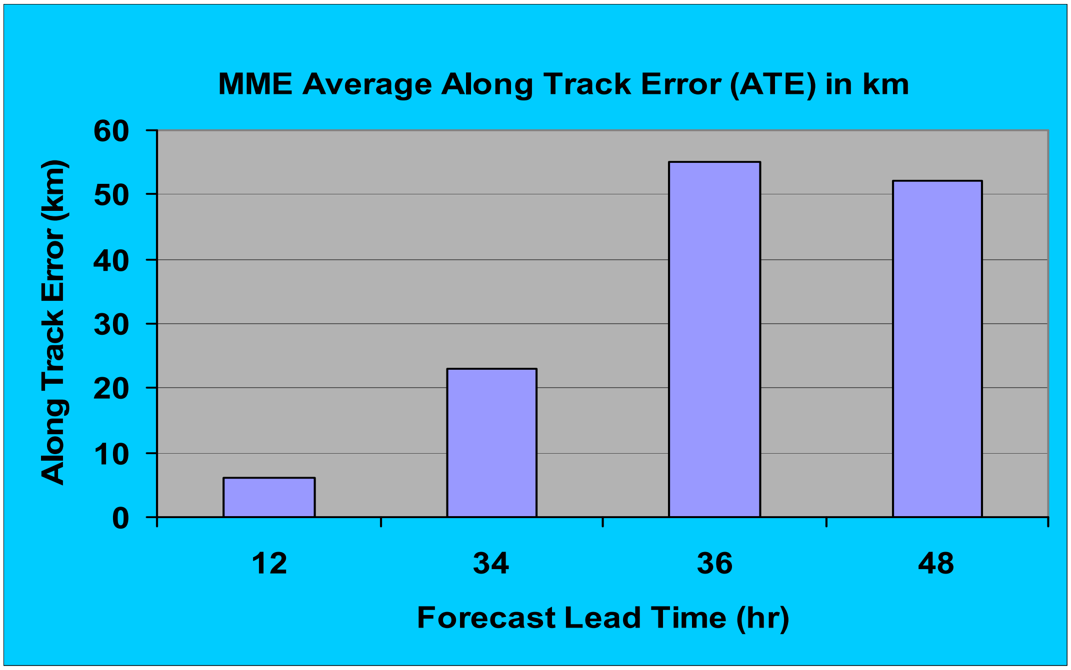


Fig. 30: Average along track error (ATE) of MME for Deep Depression

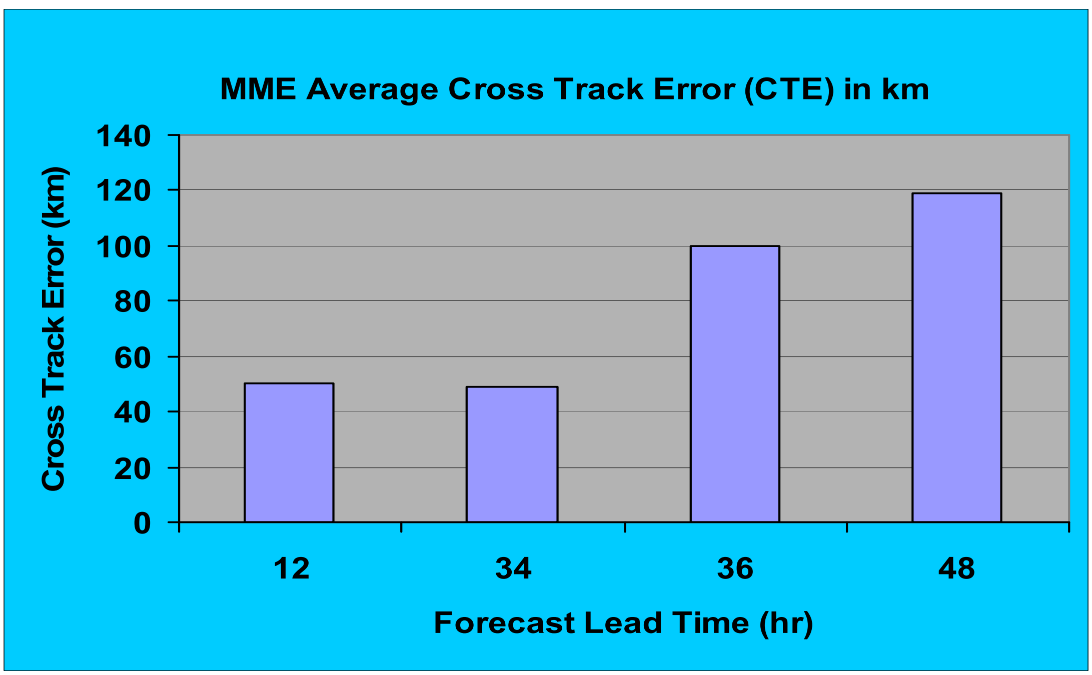


Fig. 31: Average cross track error (CTE) of MME for Deep Depression

Table-19. Landfall point forecast errors (km) of NWP Models at different lead time (hour) for Deep Depression; Landfall time forecast errors (hr) ('+' for North, '-' for South, LF = landfall)

Forecast Lead Time (hour) →	24 h	48 h
UKMO	No LF	No LF
NCEP GFS	-22	-179
JMA	No LF	No LF
IMD-GFS	-278	-219
WRF-VAR	No LF	No LF
IMD-MME	-16	-160

Table-20. Landfall time forecast errors (hour) at different lead time (hr) for Deep Depression ('+' indicates delay landfall, '-' indicates early landfall)

Forecast Lead Time (hour) →	24 h	48 h
UKMO	No LF	No LF
NCEP GFS	00:00	03:00
JMA	No LF	No LF
IMD-GFS	+12:00	-12:00
WRF-VAR	No LF	No LF
IMD-MME	00:00	+07:00

7.4. Intensity prediction

Average absolute error (AEE) and Root mean square error (RMSE) of SCIP forecast error is presented in the following Table-21. AAE of SCIP was 3 kt at 12 hr and 12 kt at 48 hr. The Table shows that the SCIP model was able to predict the intensity.

Table-21 Average absolute errors for Deep Depression (Number of forecasts verified)

(Intensity forecasts prior to landfall are considered)

Lead time →	**12 hr**	**24 hr**	**36 hr**	**48 hr**
AAE	3.0(2)	2.5(2)	7.0(1)	12.0(1)
RMSE	3.6(2)	2.9(2)	7.0(1)	12.0(1)

7.5. Probability of Rapid intensification (by RI-Index)

Rapid intensification (RI) is defined as: Increase of intensity by 30 kts or more during subsequent 24 hour.

Table-22 Probability of Rapid intensification for Deep Depression

Forecast based on	**Probability of RI predicted**	**Chances of occurrence predicted**	**Intensity changes (kt) in 24h**	**Occurrence**
00 UTC/09.11.2013	5.2 %	VERY LOW	0	NO
00 UTC/10.11.2013	2.6 %	VERY LOW	0	NO
Inference: RI-Index was able to predict **NON-OCCURENCE** of Rapid Intensification of the DEEP DEPRESSION during its lifetime.				

8. ‘DEPRESSION’ over the Bay of Bengal (13-17) November 2013

The low pressure system that formed over south Bay of Bengal intensified into depression at 0000 UTC of 13 November 2013 near latitude 11.5° N and longitude 86.5° E. It moved westwards till 0000 UTC of 14 November 2013 and then southwestward till 1200 UTC of 15 November 2013. Thereafter the system moved west northwest direction and crossed Tamil Nadu coast near Nagapattinam (near lat. 11.0°N and long. 79.9° E) between 0700 and 0800 UTC of 16 November 2013 as Depression. The observed track of the DEPRESSION is shown in Fig. 32.

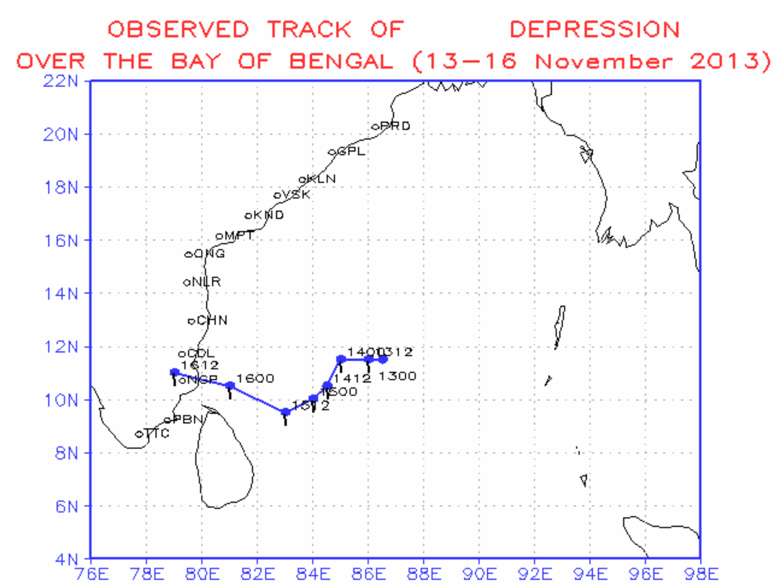
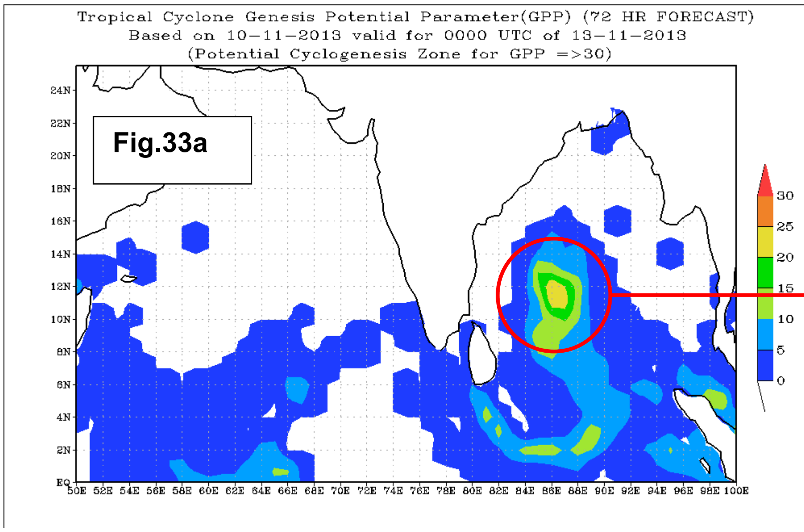


Fig. 32 Observed track of the Depression

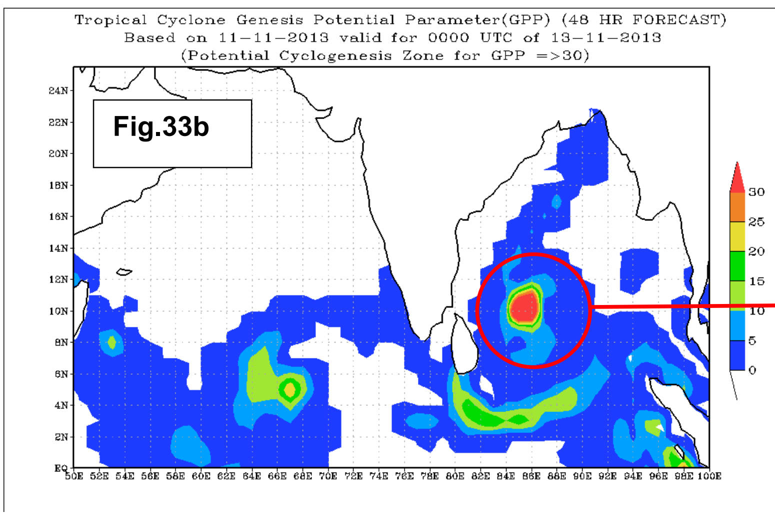
8.1. Grid point analysis and forecast of GPP

Objective: Grid point analysis and forecast of GPP is used to identify potential zone of cyclogenesis.

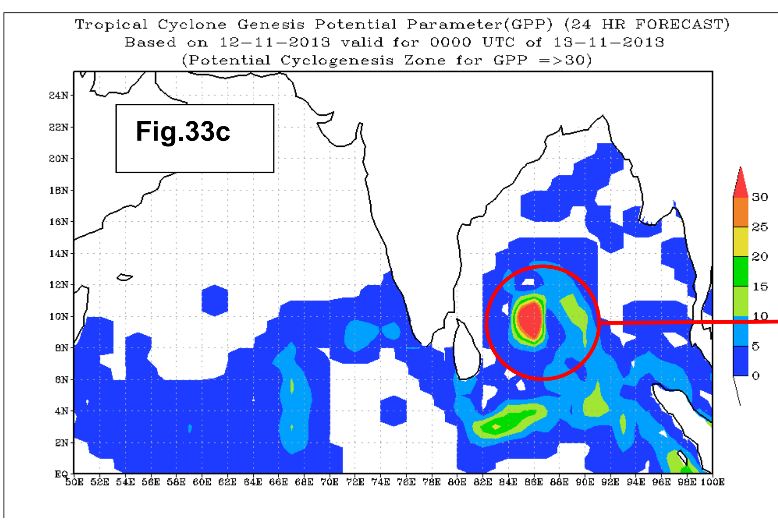
Figure 33(a-h) below shows the predicted zone of formation of cyclogenesis.



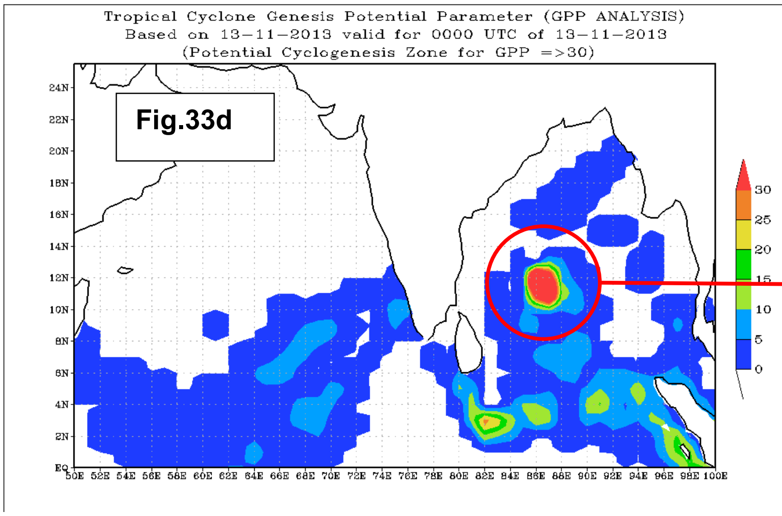
72 hour forecast of GPP valid for 00 UTC 13 November 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



48 hour forecast of GPP valid for 00 UTC 13 November 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



24 hour forecast of GPP valid for 00 UTC 13 November 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



Analysis of GPP on 00 UTC 23 November 2013 indicates the zone of cyclogenesis.

Figure 33(a-d): Predicted zone of cyclogenesis for Depression.

Inference: Grid point analysis and forecasts of GPP (Fig.33(a-d)) shows that it was able to predict the formation and location of the system before 72 hours of its formation.

(Product available athttp://www.imd.gov.in/section/nhac/dynamic/Analysis1.htm)

8.2. Area average analysis of GPP

Objective: Since all low pressure systems do not intensify into cyclones, it is important to identify the potential of intensification (into cyclone) of a low pressure system at the early stages of development.

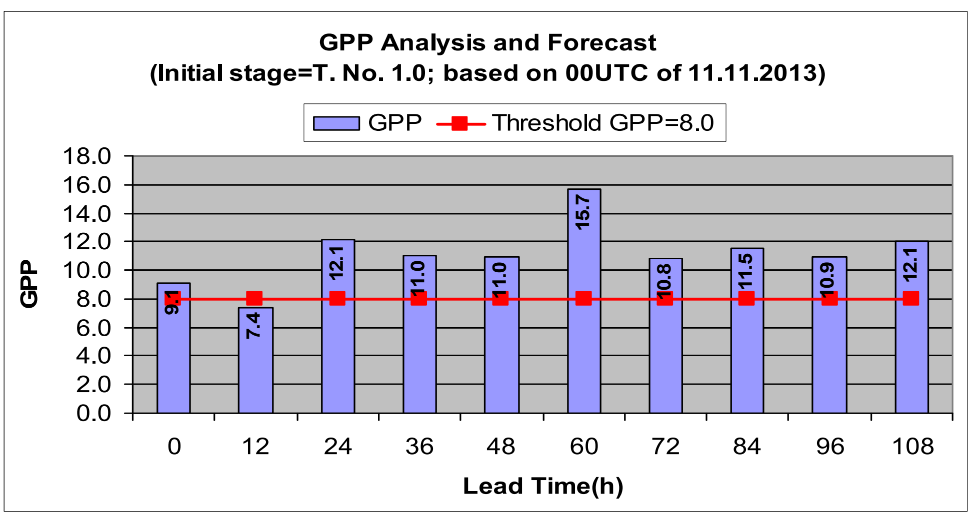


Fig 34a: Analysis and forecasts of GPP shows that GPP ≥ 8.0 (Threshold) at very early stage of development (**T.No.-1.0**) indicated its potentential to intensify into a cyclone except at 12 h.

Fig.34a

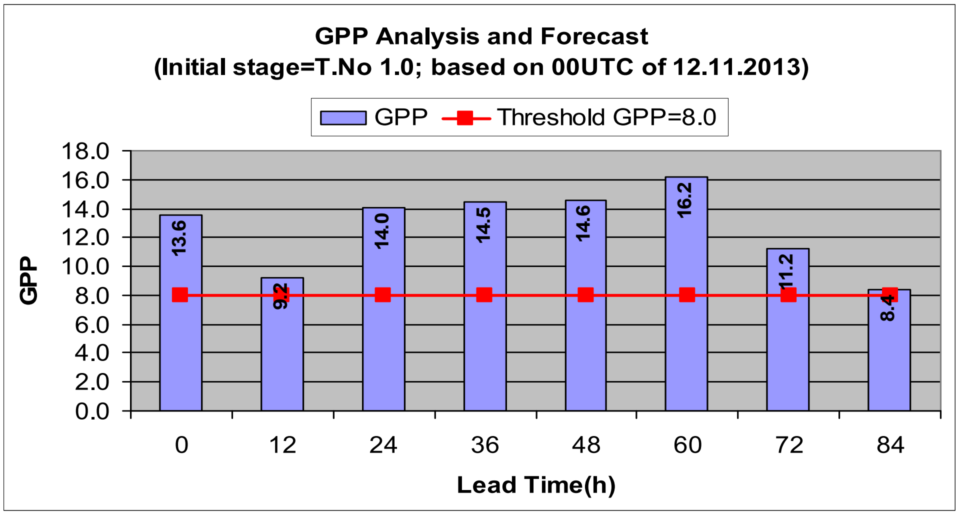


Fig 34b: Analysis and forecasts of GPP shows that GPP ≥ 8.0 (Threshold) at very early stage of development (**T.No. 1.0**) indicated its potential to intensify into a cyclone.

Fig. 34b

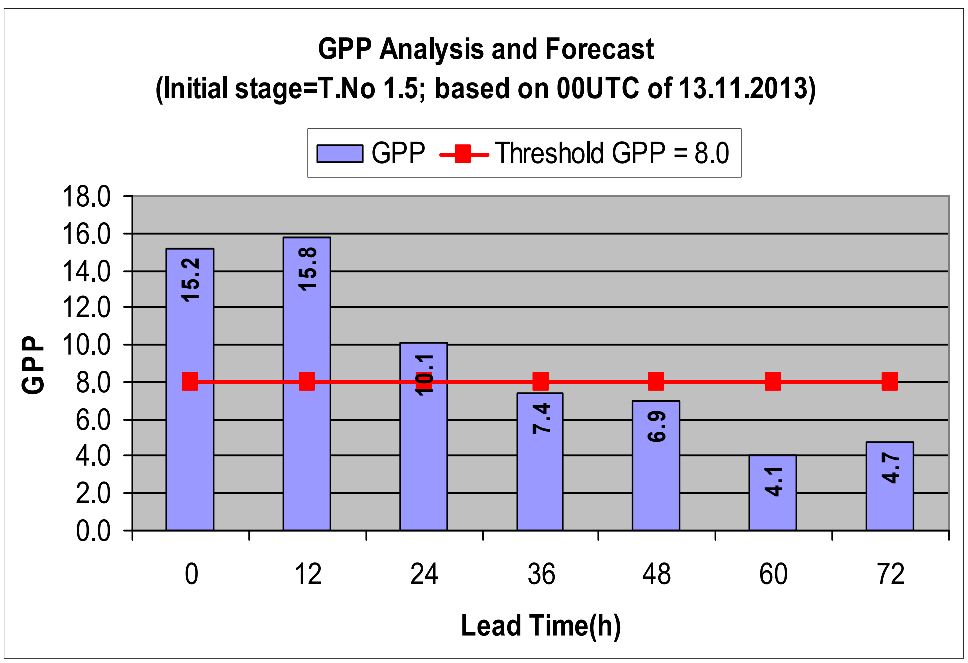


Fig 34c: Analysis and forecasts of GPP shows that GPP ≥ 8.0 (Threshold) at early stage of development (**T.No. 1.5, & up to 24h**) indicated its potential to intensify into a cyclone. 36h to 72h forecasts indicated non-intensification of the system.

Fig. 34c

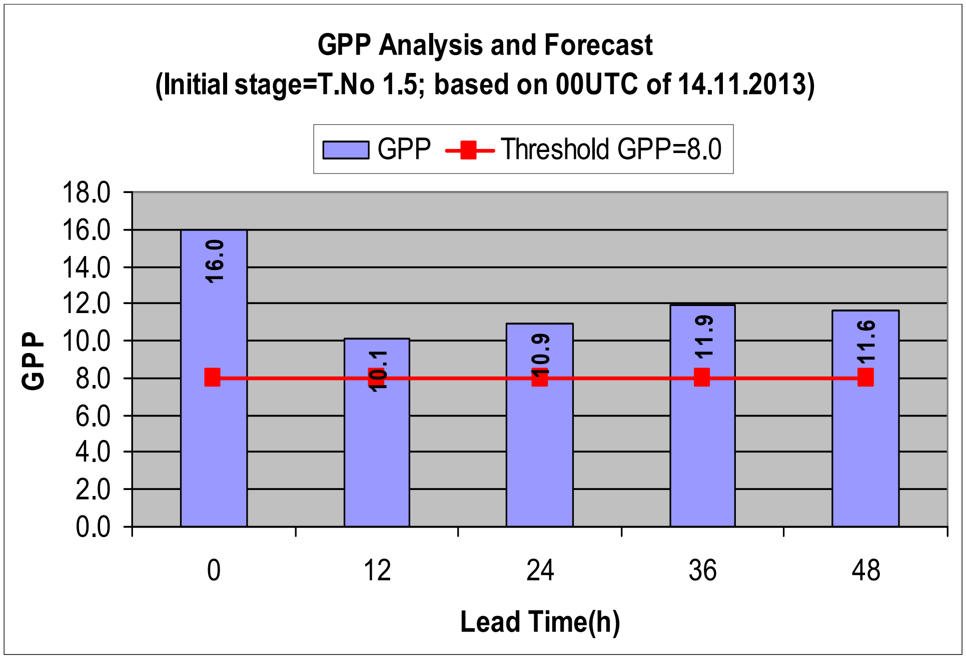


Fig 34d: Analysis and forecasts of GPP shows that GPP ≥ 8.0 (Threshold) at early stage of development (**T.No. 1.5**) indicated its potential to intensify into a cyclone.

Fig. 34d

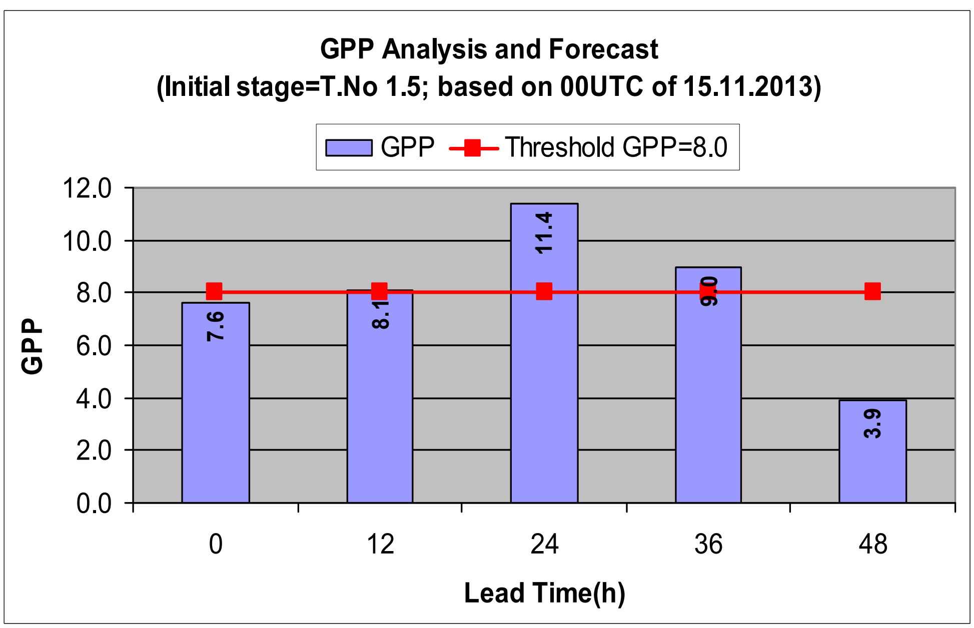


Fig 34e: Analysis and forecasts of GPP at early stage of development (**T.No. 1.5**) indicated its potential to intensify into a marginal cyclone.

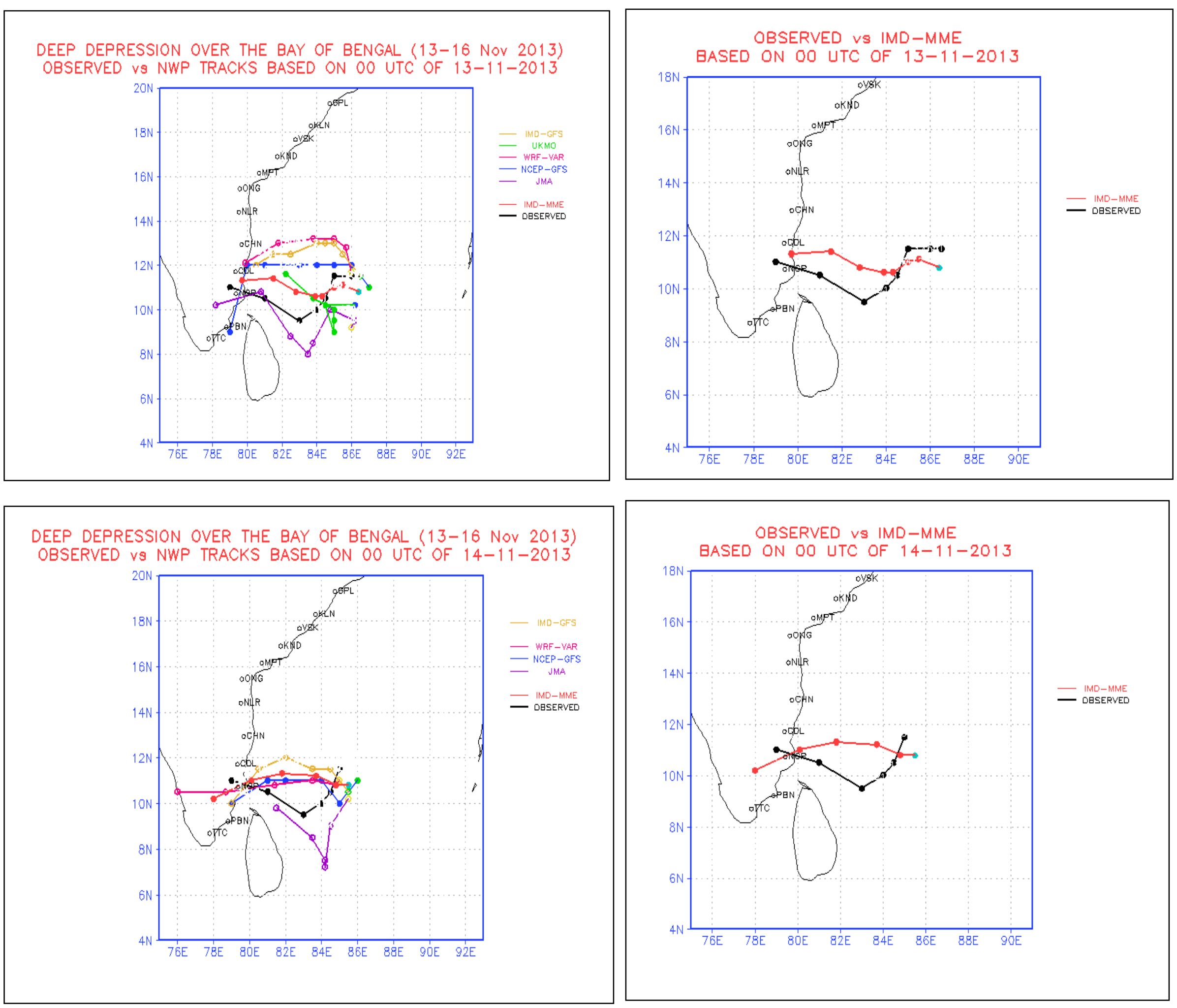
Fig. 34e

Fig. 34(a-e) Area average analysis of GPP for Depression

Inference: Analysis and forecasts of GPP (Fig.34(a-e)) shows that GPP ≥ 8.0 (threshold value for intensification into cyclone) indicated its potential to intensify into a cyclone at early stages of development (T.No. 1.0, 1.5). 36h to 72h forecasts based on 00 UTC of 13.11.2013 indicated non-intensification of the system and analysis and forecasts of based on 00 UTC of 13.11.2013 and 15.11.2013 indicated its potential to intensify into a marginal cyclone.

8.3 Track prediction

The average track forecast errors (DPE, CTE, ATE) of NWP models along with the consensus forecast by Multi-model ensemble (MME) forecast are presented in the Table 23, Table 24 and Table 25 respectively. The landfall point error (km) and landfall time (hour) is presented in Table-26 and Table-27 respectively. The MME forecasts track based on different initial conditions along with the observed track is depicted in Fig 35.



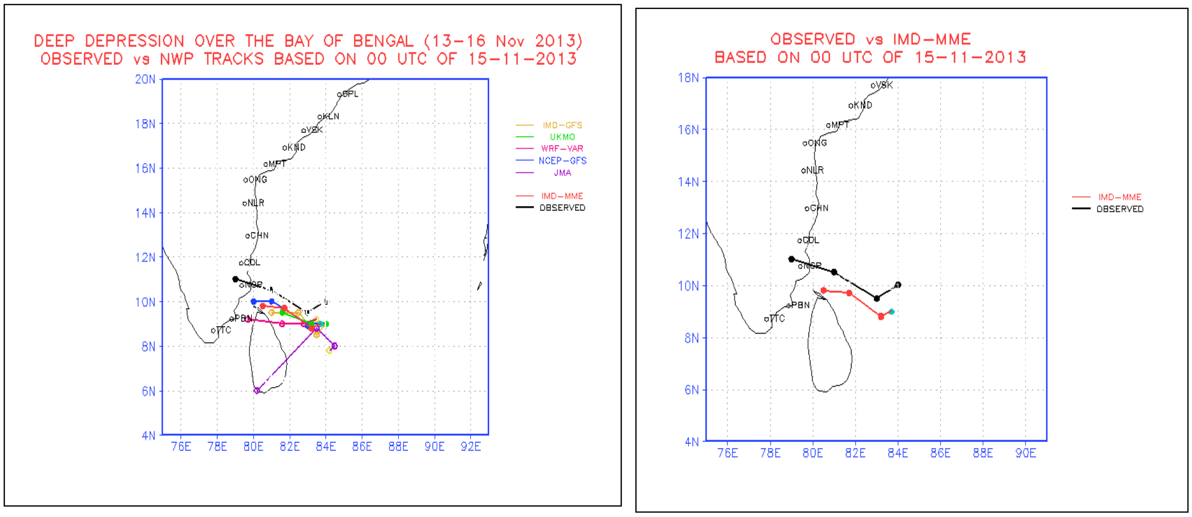


Fig. 35. MME forecasts track based on different initial conditions for Depression

Direct position Error (DPE): Average track forecast error (direct position error (DPE)) of MME was lowest at all forecast hours except at 24h and 72h. The DPE for MME was about 65 km at 12 h to 85 km at 84 h (Table-23) with highest at 36h (160km). The DPE of all models are shown in Fig. 36.

Table-23. Average track forecast errors (DPE) in km for Depression (Number of forecasts verified)

Lead time →	**12 hr**	**24 hr**	**36 hr**	**48 hr**	**60 hr**	**72 hr**	**84 hr**
IMD-GFS	120(3)	180(3)	284(3)	229(2)	224(2)	229(1)	198(1)
IMD-WRF	85(3)	164(3)	250(3)	331(2)	389(2)		
JMA	208(3)	271(3)	355(3)	291(2)	200(2)	40(1)	125(1)
NCEP-GFS	63(3)	74(3)	177(3)	152(2)	232(2)	199(1)	222(1)
UKMO	139(2)	203(2)	175(1)	123(1)	226(1)	306(1)	355(1)
IMD-MME	66(3)	103(3)	158(3)	90(2)	143(2)	114(1)	83(1)

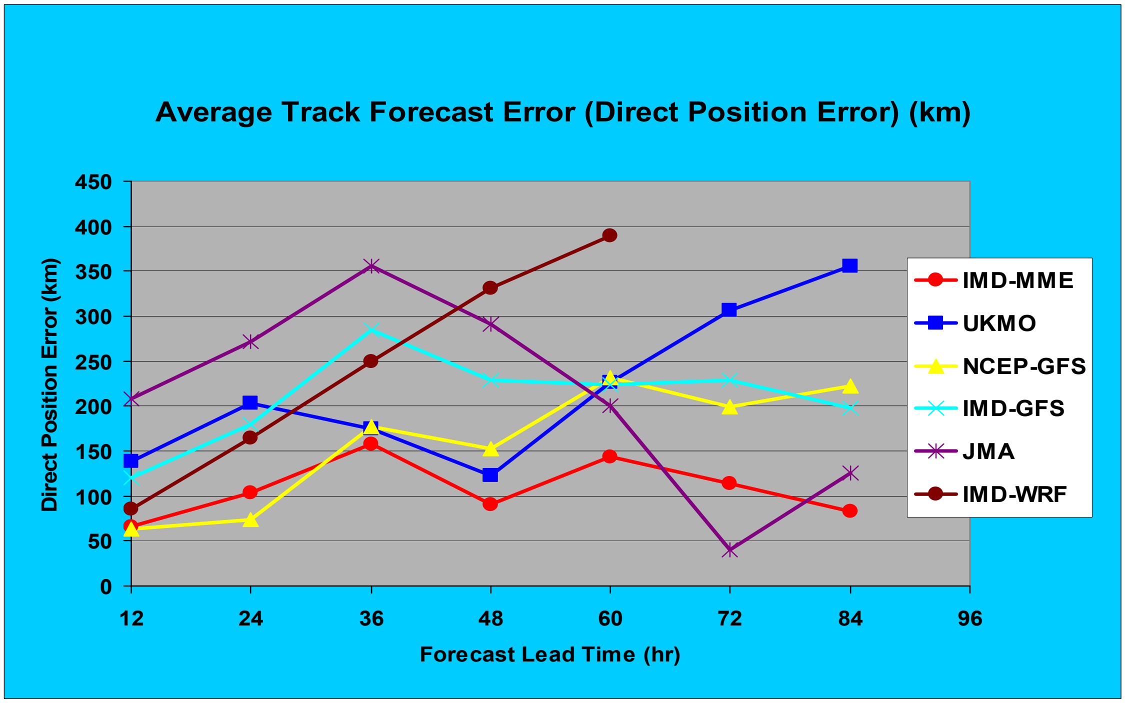


Fig. 36: Average track forecast errors (DPE) of NWP models for Depression

Cross Track Error (CTE): Average cross track error (CTE) was lowest for MME up to 48 h (45 km to 115 km) and comparable to UKMO and JMA at 60h, 72h and 84h (105 km to 25 km) (Table-24). The CTE of all models are shown in Fig. 37.

Table-24. Average cross track error (CTE) in km for Depression

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr
IMD-GFS	95	129	213	203	213	208	98
IMD-WRF	66	150	236	237	222	-	-
JMA	173	165	311	222	98	37	81
NCEP-GFS	60	57	152	150	230	185	222
UKMO	102	188	173	105	63	57	40
IMD-MME	46	77	117	71	107	88	27

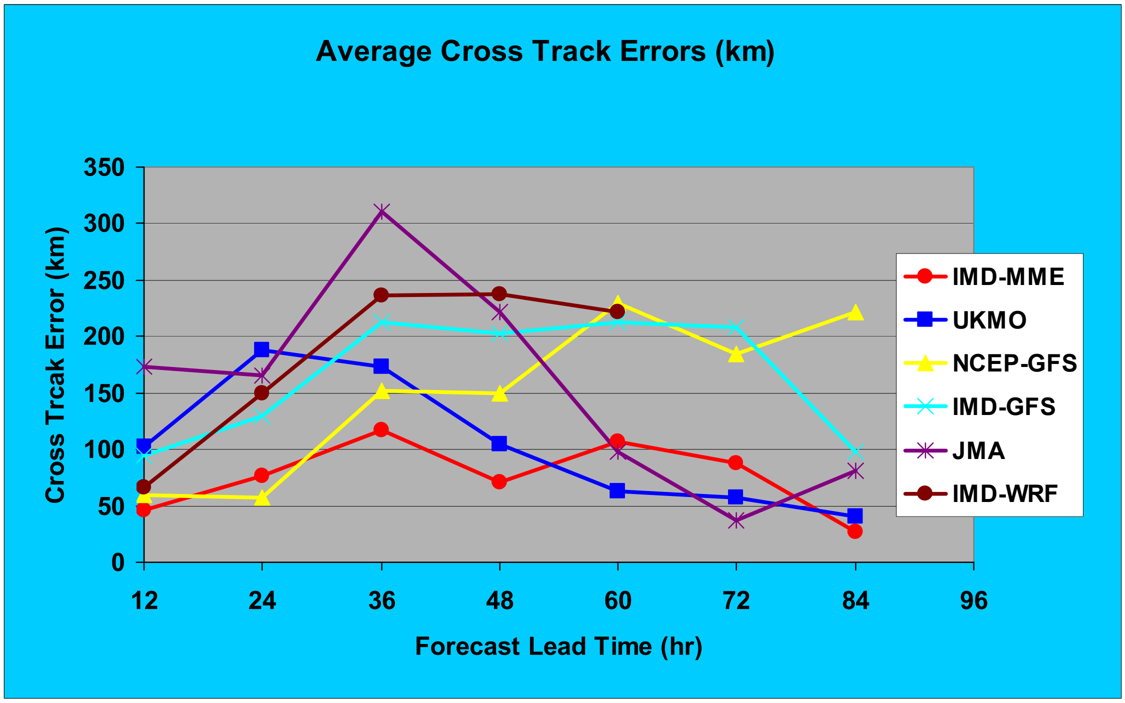


Fig. 37: Average cross track errors (CTE) of NWP models for Depression

Along Track Error (ATE): Average along track error (ATE) was lowest for NCEP-GFS and MME was comparable to NCEP-GFS and below 100km at all forecast hours (Table-25). The ATE of all models is shown in Fig. 38.

Table-25. Average along track error (ATE) in km for Depression

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr
IMD-GFS	52	97	166	100	66	96	172
IMD-WRF	40	52	67	135	237		
JMA	81	191	158	187	173	15	94
NCEP-GFS	17	34	67	19	28	75	18
UKMO	85	42	27	64	217	301	353
IMD-MME	38	61	84	53	86	73	79

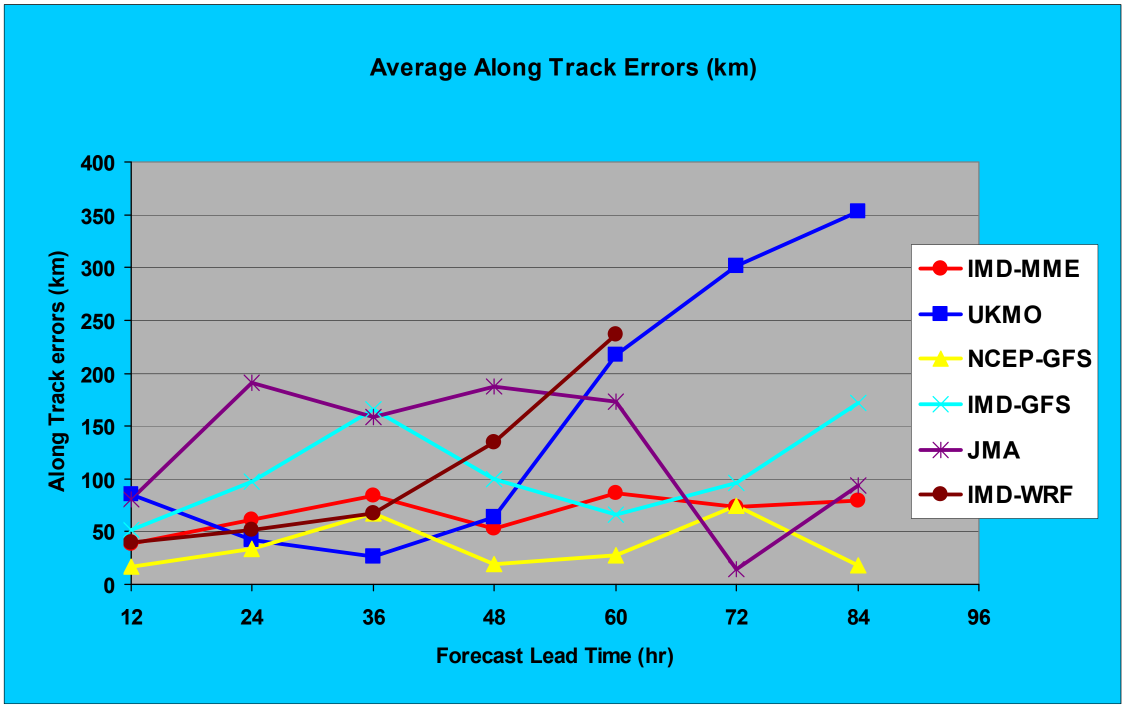


Fig. 38: Average along track errors (ATE) of NWP models for Depression

Track Forecast Error of MME: The DPE, ATE and CTE of consensus forecast of NWP models (MME) are shown in Fig 39, Fig 40 and Fig 41 respectively.

The average DPE of MME was about 65 km at 12 h to 85 km at 84 h with highest 160 km at 36h (Fig. 39).

The average ATE of MME was about 40 km at 12 h to 80 km at 84 h with highest 85 km at 36h (Fig. 40).

The average CTE of MME was about 45 km at 12 h to 25 km at 84 h with highest 115 km at 36h (Fig. 41).

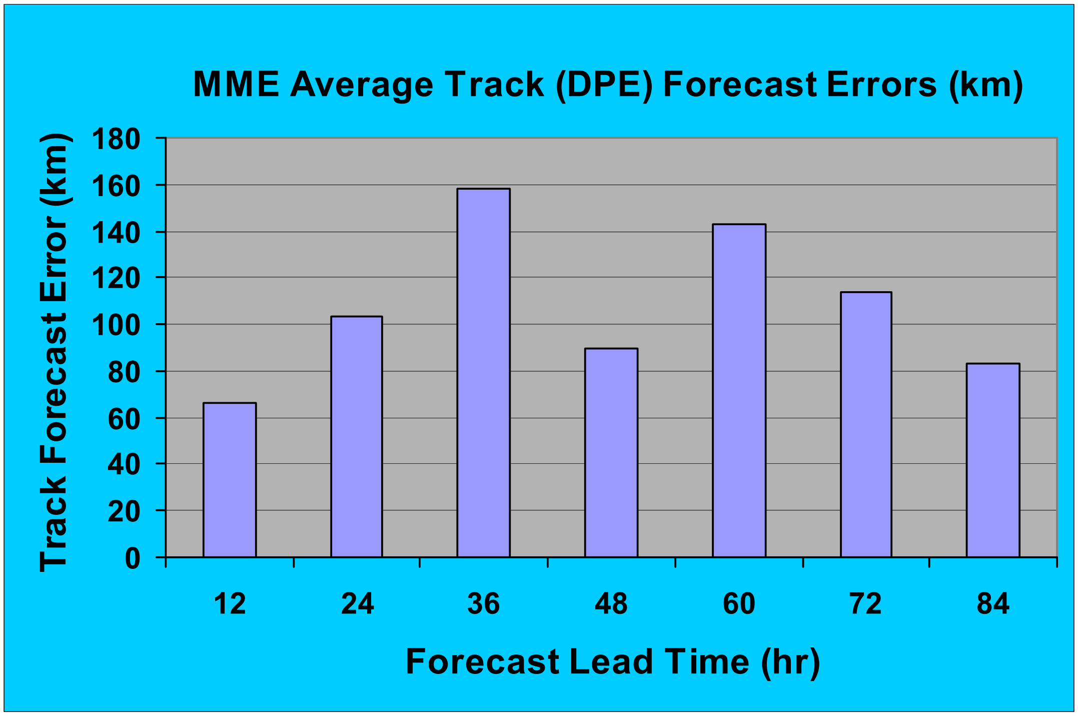


Fig. 39: Average direct track error (DPE) of MME for Depression

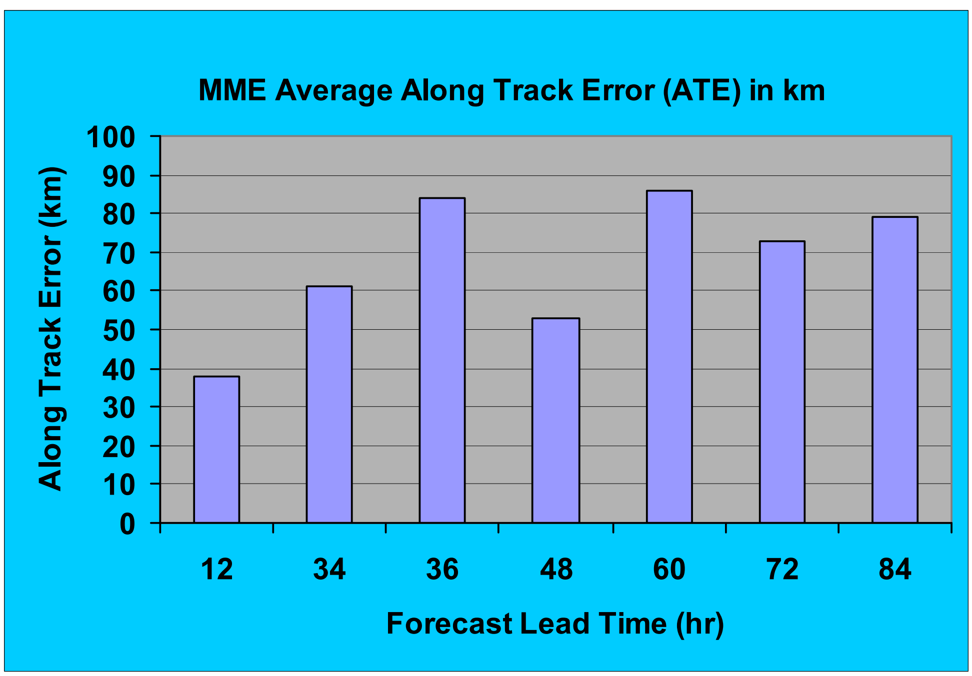


Fig. 40: Average along track error (ATE) of MME for Depression

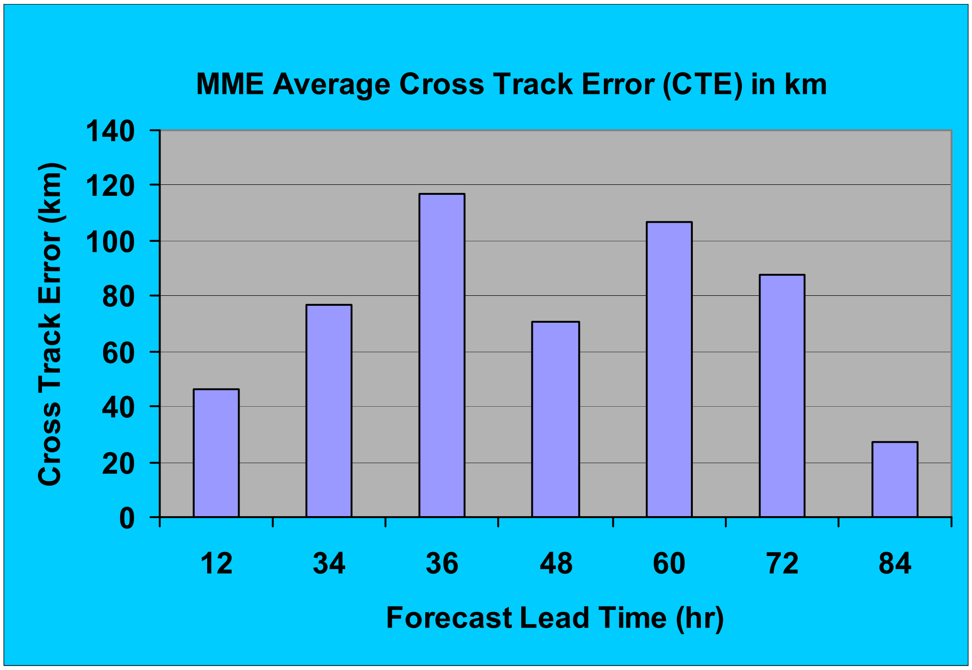


Fig. 41: Average cross track error (CTE) of MME for Depression

Table-26. Landfall point forecast errors (km) of NWP Models at different lead time (hour) for Depression; ('+' indicates north of landfall point, '-' indicates south of landfall point)

Forecast Lead Time (hour) →	**31 h**	**55 h**	**79 h**	**103 h**
UKMO	No LF	***	No LF	No LF
NCEP GFS	-148	-55	+112	+148
JMA	No LF	No LF	-45	No LF
IMD-GFS	No LF	-15	No LF	+25
WRF-VAR	-233	-45	+112	No LF
IMD-MME	-148	00	+40	00

Table-27. Landfall time forecast errors (hour) at different lead time (hr) for Depression

('+' indicates delay landfall, '-' indicates early landfall)

Forecast Lead Time (hour) →	31 h	55 h	79 h	103 h
UKMO	No LF	***	No LF	No LF
NCEP GFS	+7:00	0:00	-7:00	-7:00
JMA	No LF	No LF	-0200	No LF
IMD-GFS	No LF	-2:00	No LF	-4:00
WRF-VAR	+11:00	-12:00	-19:00	No LF
IMD-MME	+11:00	-06:00	+5:00	-04:00

8.4 Intensity prediction

Average absolute error (AEE) and Root mean square error (RMSE) of SCIP forecast error is presented in the following Table-28. The AAE of SCIP was 2 kt at 12 hr and 1 kt at 72 hr with maximum error 4.5 kt at 48h. The RMSE was 2.6 kt at 12 hr and 1 kt at 72 hr with maximum error 5.1 kt at 48h.

Table-28 Average absolute errors (AAE) and Root Mean square error (RMSE) of SCIP model for Depression (Number of forecasts verified is given in the parentheses)

(Intensity forecasts prior to landfall are considered)

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
SCIP (AAE)	2.0(3)	4.0(3)	3.0(3)	4.5(2)	0.0(2)	1.0(1)
SCIP (RMSE)	2.6	4.7	4.2	5.1	0.0	1.0

8.5. Probability of Rapid intensification (by RI-Index)

Rapid intensification (RI) is defined as: Increase of intensity by 30 kts or more during subsequent 24 hour.

Table-29 Probability of Rapid intensification for Depression

Forecast based on	Probability of RI predicted	Chances of occurrence predicted	Intensity changes (kt) in 24h	Occurrence
00 UTC/13.11.2013	0 %	NIL	0	NO
00 UTC/14.11.2013	2.6 %	VERY LOW	0	NO
00 UTC/15.11.2013	5.2 %	VERY LOW	0	NO
Inference: RI-Index was able to predict **NON-OCCURENCE** of Rapid Intensification of the Depression during its lifetime.				

9. Severe Cyclonic storm 'HELEN' (19-23) November 2013

A low pressure system that formed over west central Bay of Bengal intensified into depression at 0000 UTC of 19 November 2013 near latitude 14.5^{o} N and longitude 86.5^{o} E. It moved west north-westwards and intensified into a deep depression at 1500 UTC of 19 November 2013 and further intensified into a cyclonic storm (T.No. 2.5), HELEN at 0300 UTC of 20 November 2013. The cyclonic storm continued to move in west north-westerly direction and intensified to T.No. 3.0 at 1200 UTC of 20 November 2013 and subsequently intensified into severe cyclonic storm (T. No. 3.5) at 0000 UTC of 21 November 2013. Moving west north-westward direction the system crossed Andhra Pradesh coast close to south of Machilliptnam near 16.1^{0}N/81.2^{0}E between 0800-0900UTC. After landfall the system weakened to Depression at 1800 UTC of 22 November 2013 and into a well marked low pressure area over coastal Andhra Pradesh and neighbourhood. The observed track of the cyclone HELEN is shown in Fig. 42.

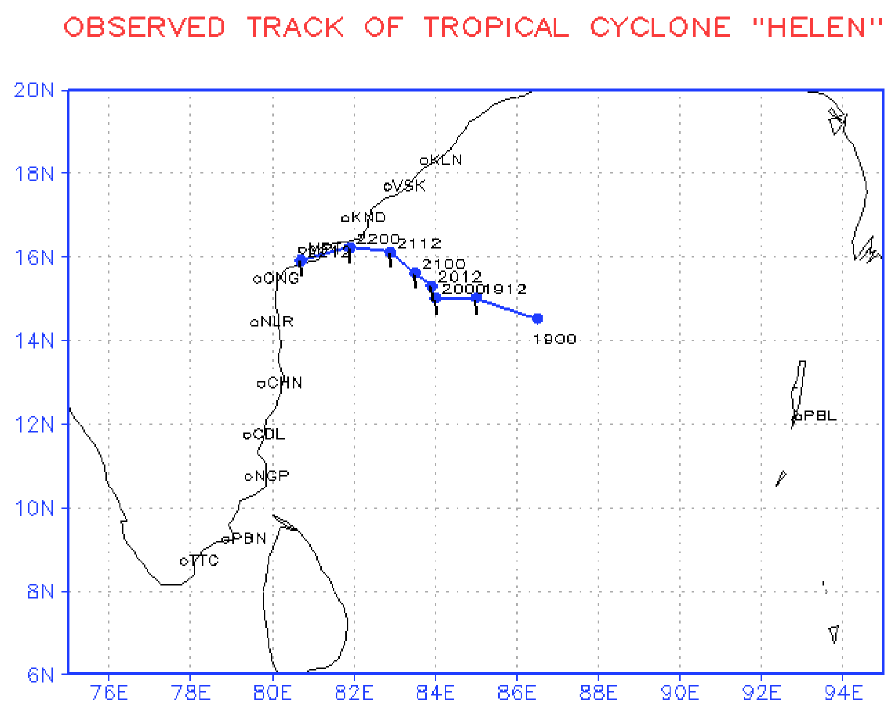
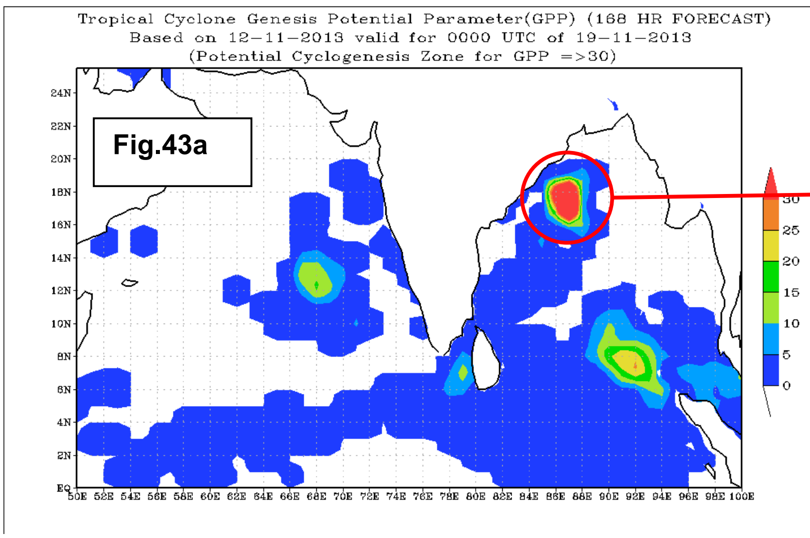


Fig. 42 Observed track of the cyclone HELEN

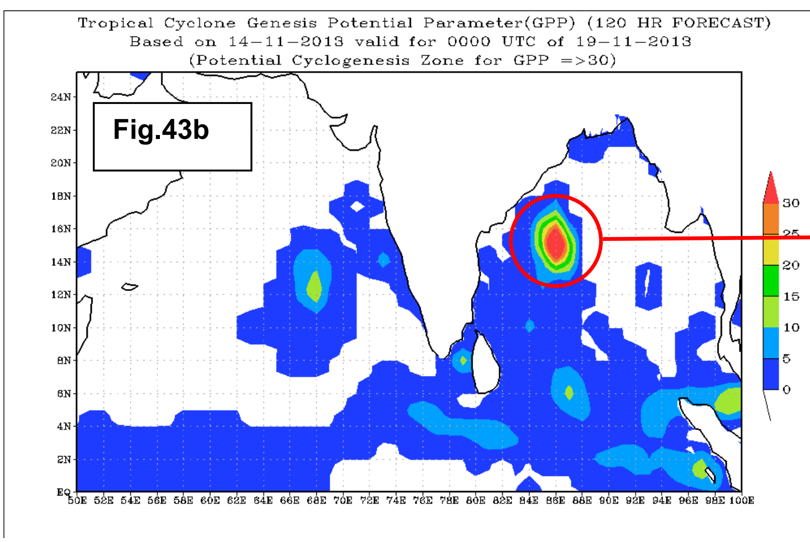
9.1. Grid point analysis and forecast of GPP

Objective: Grid point analysis and forecast of GPP is used to identify potential zone of cyclogenesis.

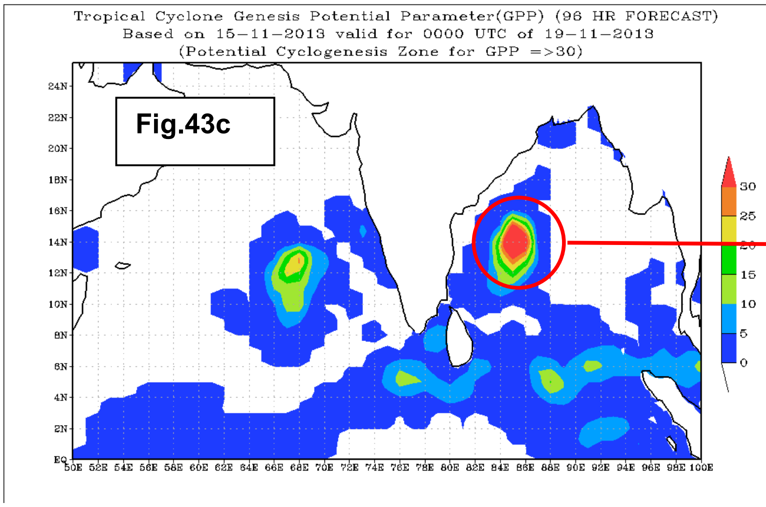
Figure 43(a-g) below shows the predicted zone of formation of cyclogenesis.



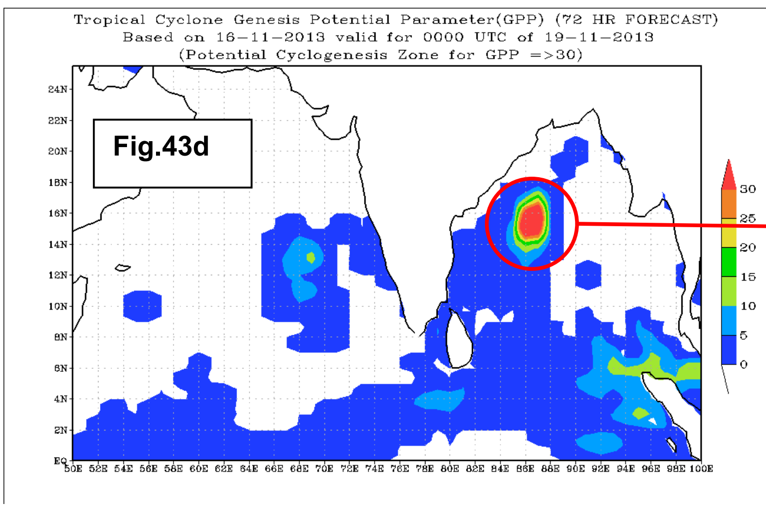
168 hour forecast of GPP valid for 00 UTC 19 November 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



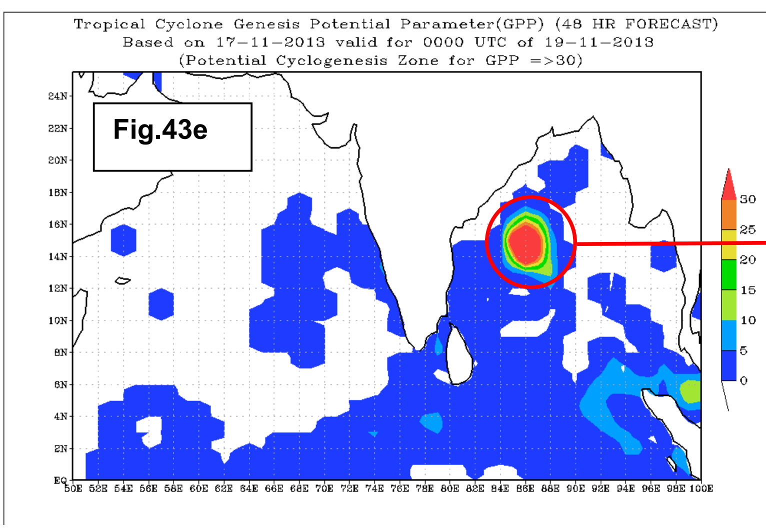
120 hour forecast of GPP valid for 00 UTC 19 November 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



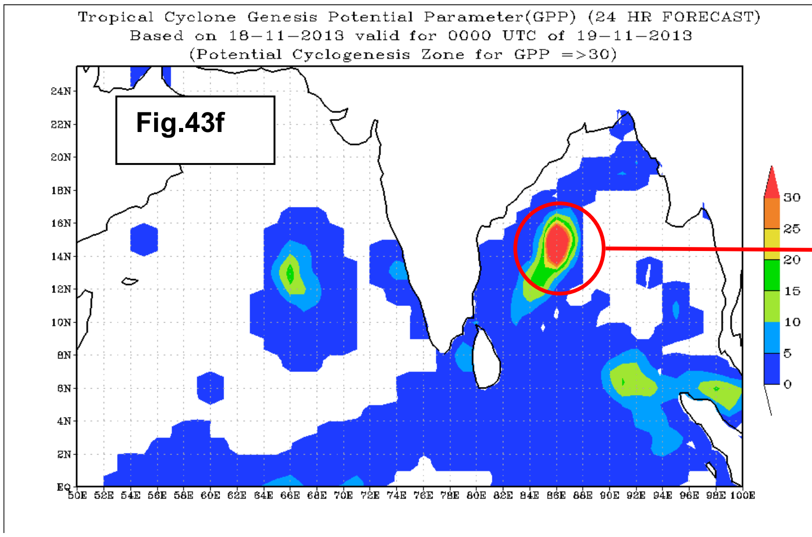
96 hour forecast of GPP valid for 00 UTC 19 November indicated the potential cyclogenesis zone, where Depression formed on that day.



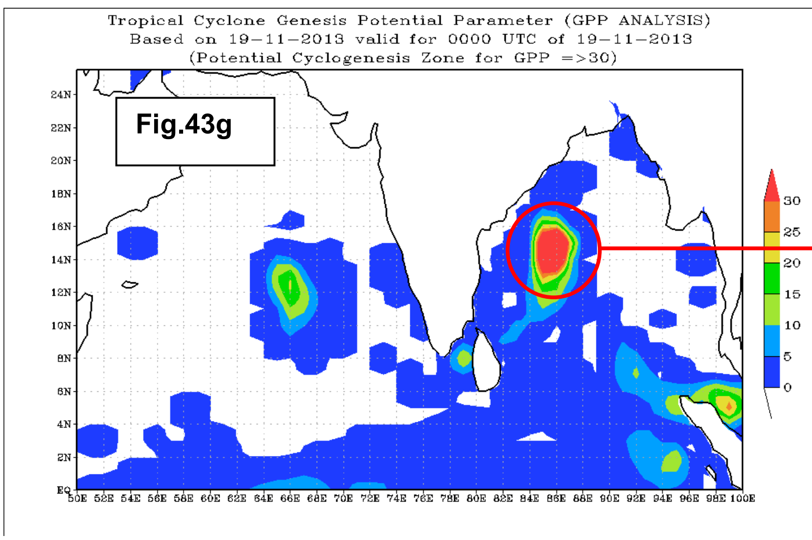
72 hour forecast of GPP valid for 00 UTC 19 November 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



48 hour forecast of GPP valid for 00 UTC 19 November 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



24 hour forecast of GPP valid for 00 UTC 19 November 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



Analysis of GPP on 00 UTC 19 November 2013 indicates the zone of cyclogenesis.

Figure 43(a-g): Predicted zone of cyclogenesis for HELEN.

Inference: Grid point analysis and forecasts of GPP (Fig.43(a-g)) shows that it was able to predict the formation and location of the system before 168 hours of its formation.

(Product available athttp://www.imd.gov.in/section/nhac/dynamic/Analysis1.htm)

9.2. Area average analysis of GPP

Objective: Since all low pressure systems do not intensify into cyclones, it is important to identify the potential of intensification (into cyclone) of a low pressure system at the early stages of development.

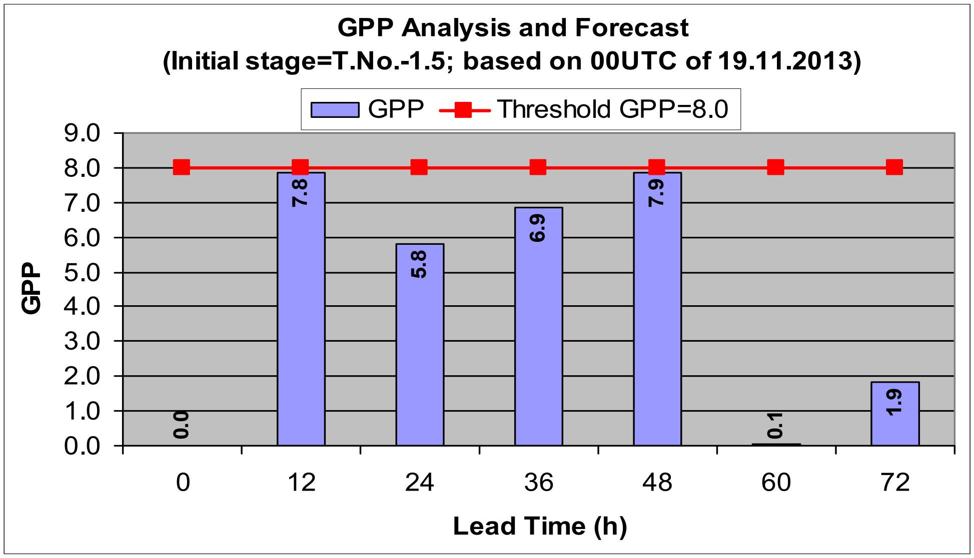


Fig 44a: Analysis and forecasts of GPP shows that GPP < 8.0 (Threshold) at very early stage of development (**T.No.-1.5**) indicated no potential to intensify into a cyclone.

Fig.44a

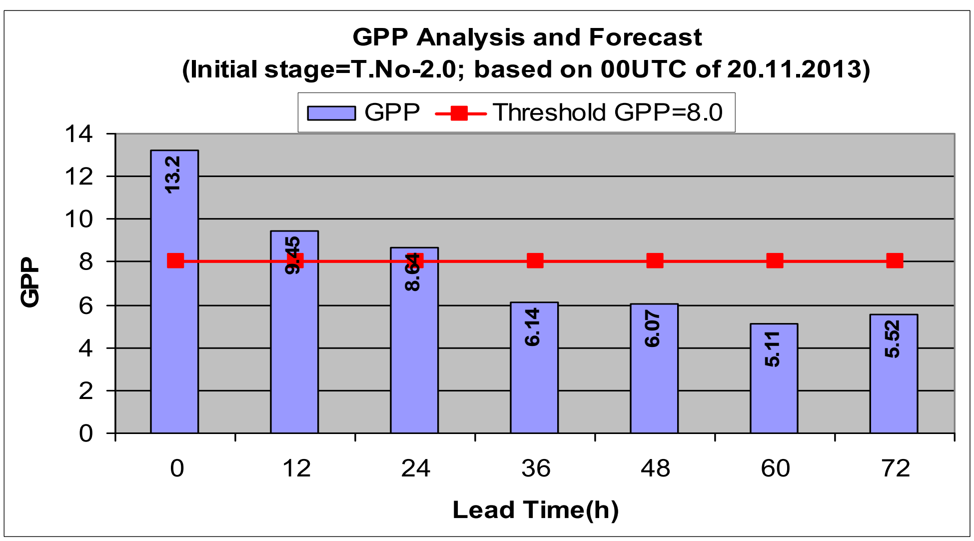


Fig 44b: Analysis and forecasts of GPP shows that GPP ≥ 8.0 (Threshold) at very early stage of development (**T.No. 2.0**) indicated its potentential to intensify into a cyclone.

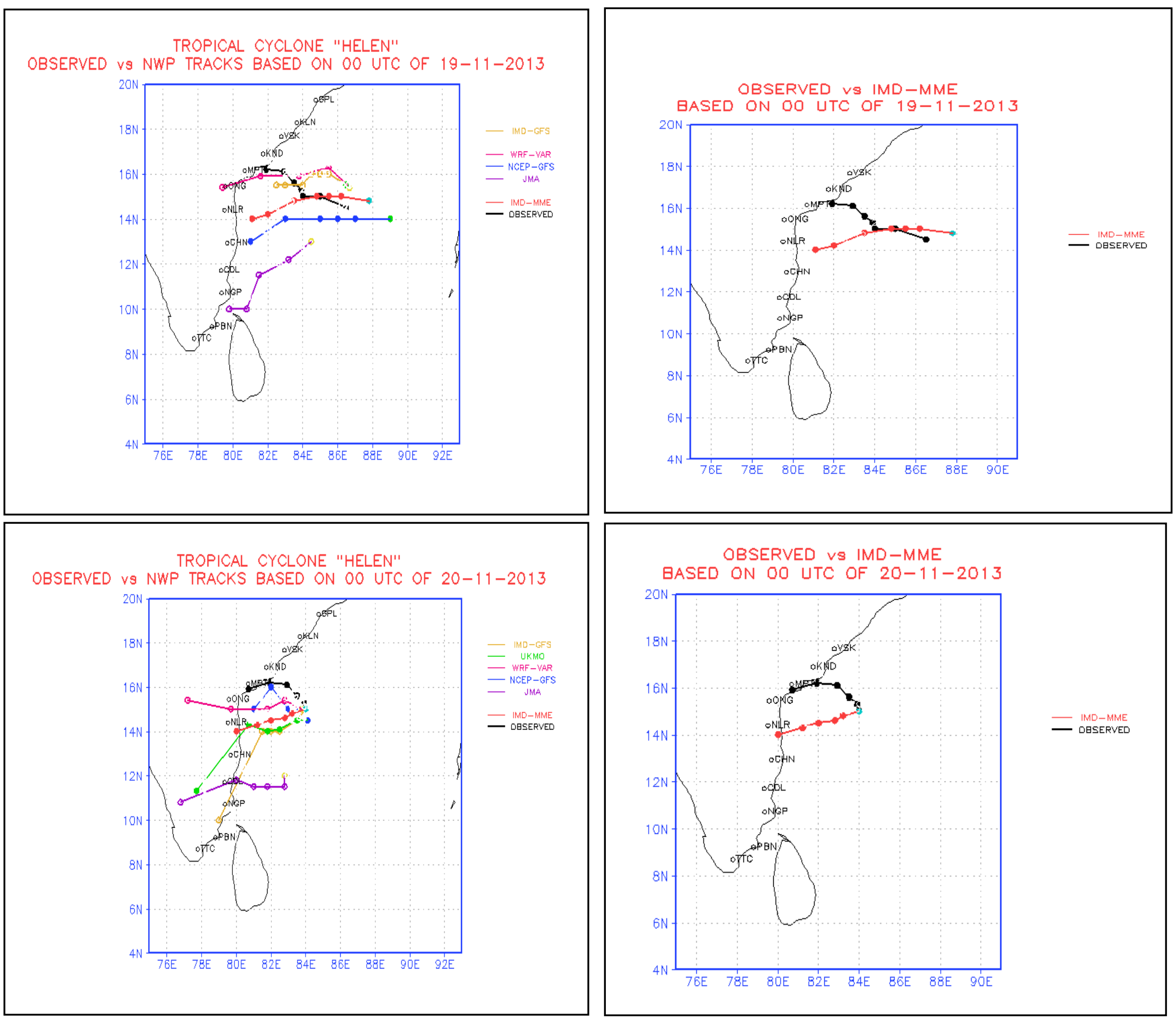
Fig. 44b

Fig. 44(a-b) Area average analysis of GPP for HELEN.

Inference: Analysis and forecasts of GPP based on 00 UTC of 19 November 2013 indicated no potential to intensify into a cyclone (GPP < 8.0 at stage T. No. 1.5 (Fig 44a)) but updated forecast based on 00 UTC of 20 November 2013 (Fig 44b) shows that GPP ≥ 8.0 (threshold value for intensification into cyclone) indicated its potential to intensify into a cyclone at stage T.No. 2.0.

9.3. Track prediction

The average track forecast errors (DPE, CTE, ATE) of NWP models along with the consensus forecast by Multi-model ensemble (MME) forecast are presented in the Table 30, Table 31 and Table 32 respectively. The landfall point error (km) and landfall time (hour) is presented in Table-33 and Table-34 respectively. The MME forecasts track based on different initial conditions along with the observed track is depicted in Fig 45. The figure shows that from the day1 (00 UTC 19 November to 00 UTC 21 November 2013).



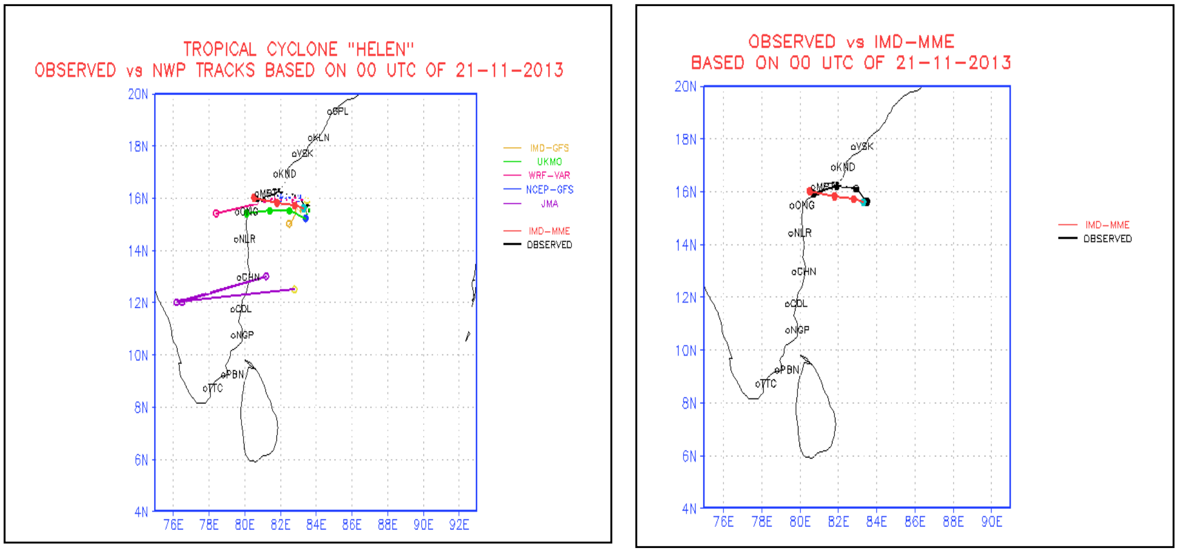


Fig. 45. MME forecasts track based on different initial conditions for HELEN

Direct position Error (DPE): Average track forecast error (direct position error (DPE)) was highest for JMA (about 570 km at 12 h to 705 km at 60 h). Average DPE was lowest for HWRF (about 45 km at 12 h to 180 km at 60 h). The DPE for MME was about 80 km at 12 h to 260 km at 72 h (Table-30). The DPE of all models are shown in Fig. 46.

Table-30. Average track forecast errors (DPE) in km for HELEN (Number of forecasts verified)

Lead time →	**12 hr**	**24 hr**	**36 hr**	**48 hr**	**60 hr**	**72 hr**
IMD-GFS	135(4)	170(3)	177(2)	151(2)	374(2)	101(1)
IMD-WRF	82(4)	114(3)	290(3)	475(2)	-	-
JMA	571(4)	443(3)	618(3)	635(2)	706(1)	-
NCEP-GFS	121(4)	117(3)	142(2)	105(2)	253(2)	368(1)
UKMO	75(3)	146(2)	173(2)	247(1)	605(1)	-
IMD-MME	78(4)	114(3)	109(3)	156(2)	228(2)	259(1)
IMD-HWRF	46(4)	111(4)	128(3)	122(2)	178(1)	-
IMD-OFFICIAL	47(11)	98(9)	166(7)	236(5)	317(3)	-

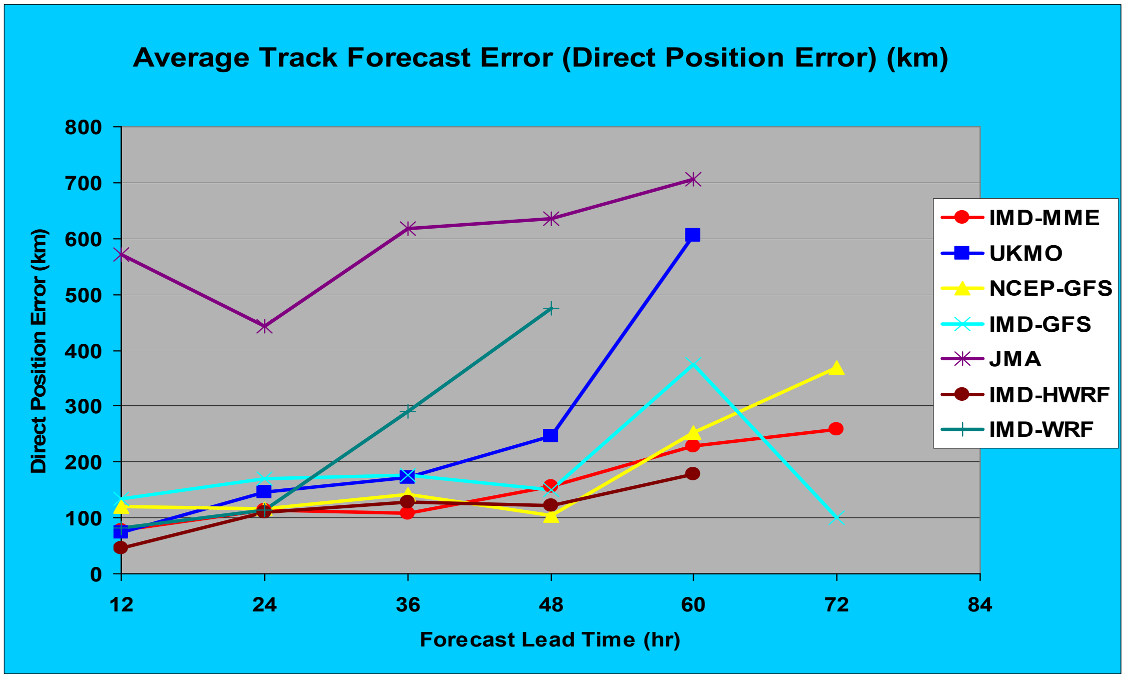


Fig. 46: Average track forecast errors (DPE) of NWP models for HELEN

Cross Track Error (CTE): Average cross track error (CTE) was highest for JMA (about 430 km at 12 h to 655 km at 60 h). Average CTE was lowest for HWRF (about 30 km at 12 h to 160 km at 60 h). MME forecast error was about 55 km at 12 h to 260 km at 72 h (Table-31). The CTE of all models are shown in Fig. 47.

Table-31. Average cross track error (CTE) in km for HELEN

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
IMD-GFS	85	142	163	120	369	50
IMD-WRF	76	107	139	248	-	-
JMA	428	407	547	624	656	-
NCEP-GFS	54	55	89	100	243	367
UKMO	62	140	155	247	578	-
IMD-MME	54	69	68	152	228	259
IMD-HWRF	27	70	78	95	161	-

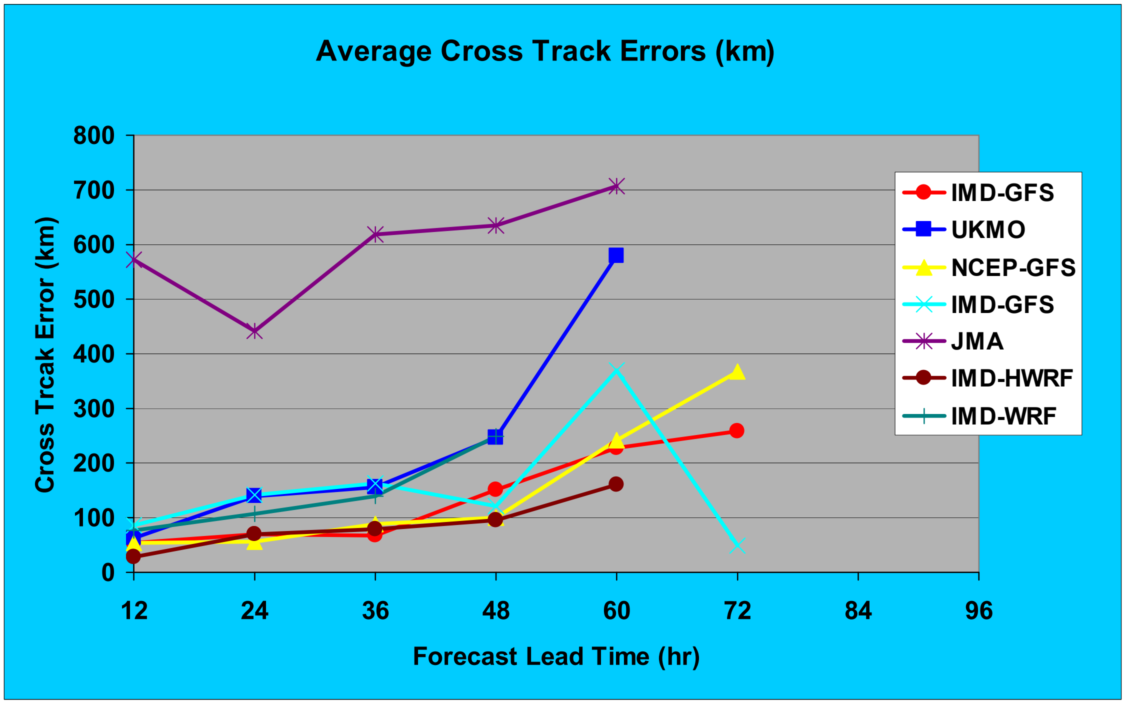


Fig. 47: Average cross track errors (CTE) of NWP models for HELEN

Along Track Error (ATE): Average along track error (ATE) was highest for JMA (about 315 km at 12 h to 260 km at 60 h). ATE was lowest for UKMO (35 km at 12h to 72 km at 36h and 5 km at 48h) and MME (46km at 12h, 36km at 48h with maximum 68km at 24h) up to 48 h and for 60h and 72h forecast, ATE of MME was lowest (less than 10 km) (Table-32). The ATE of all models is shown in Fig. 48.

Table-32. Average along track error (ATE) in km for HELEN

Lead time →	**12 hr**	**24 hr**	**36 hr**	**48 hr**	**60 hr**	**72 hr**
IMD-GFS	91	87	69	70	21	87
IMD-WRF	21	41	216	399	-	-
JMA	315	162	260	116	261	-
NCEP-GFS	89	90	108	16	52	32
UKMO	35	42	72	5	180	-
IMD-MME	46	68	62	36	9	4
IMD-HWRF	29	83	94	75	76	-

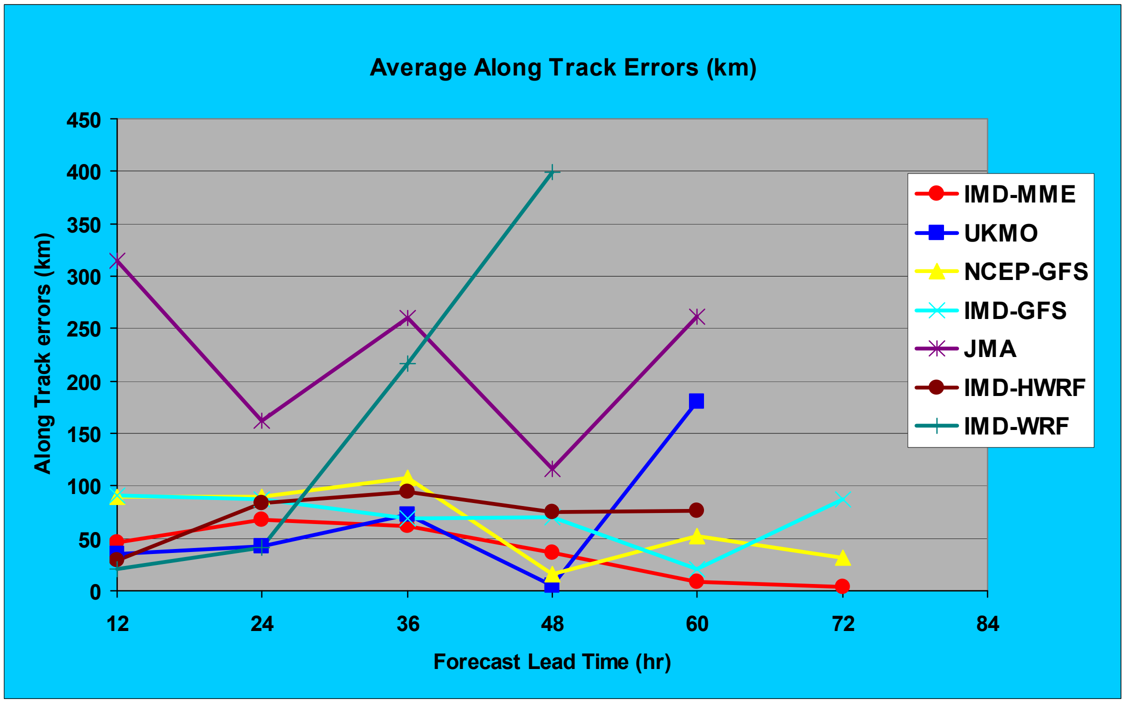


Fig. 48: Average along track errors (ATE) of NWP models for HELEN

Track Forecast Error of MME: The DPE, ATE and CTE of consensus forecast of NWP models (MME) are shown in Fig 49, Fig 50 and Fig 51 respectively.

The average DPE of MME was about 78 km at 12 h to 260 km at 72h (Fig. 49).

The average ATE of MME was about 45 km at 12 h to 5 km at 72h (Fig. 50).

The average CTE of MME was about 5 km at 12 h to 260 km at 72 h (Fig. 51).

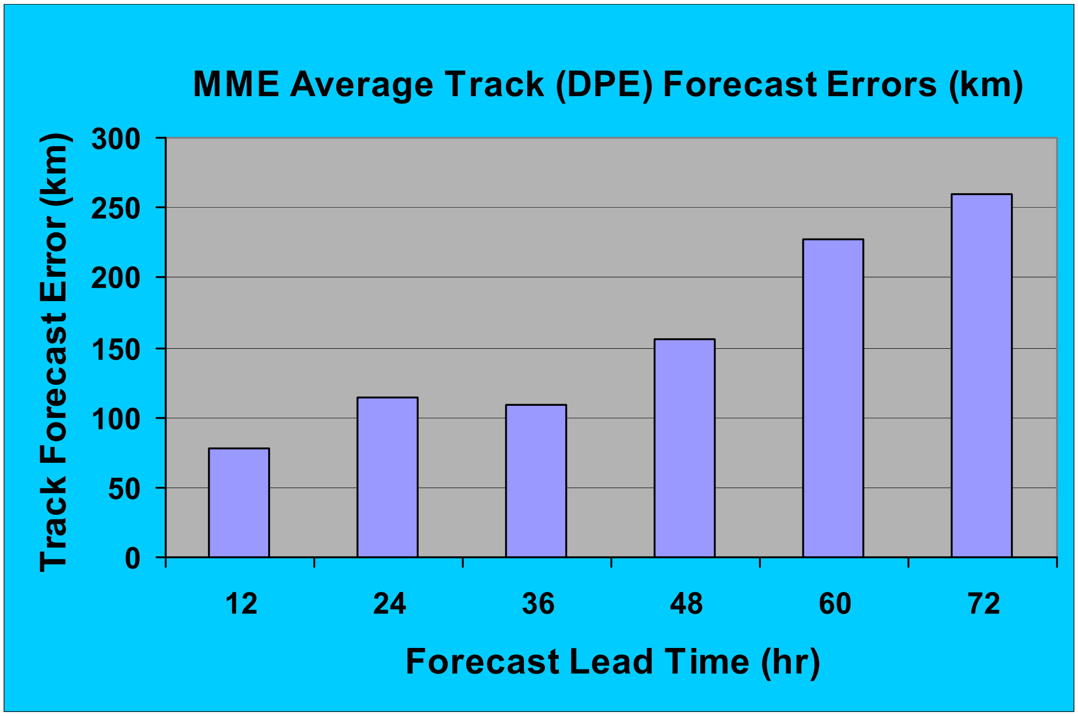


Fig. 49: Average direct track error (DPE) of MME for HELEN

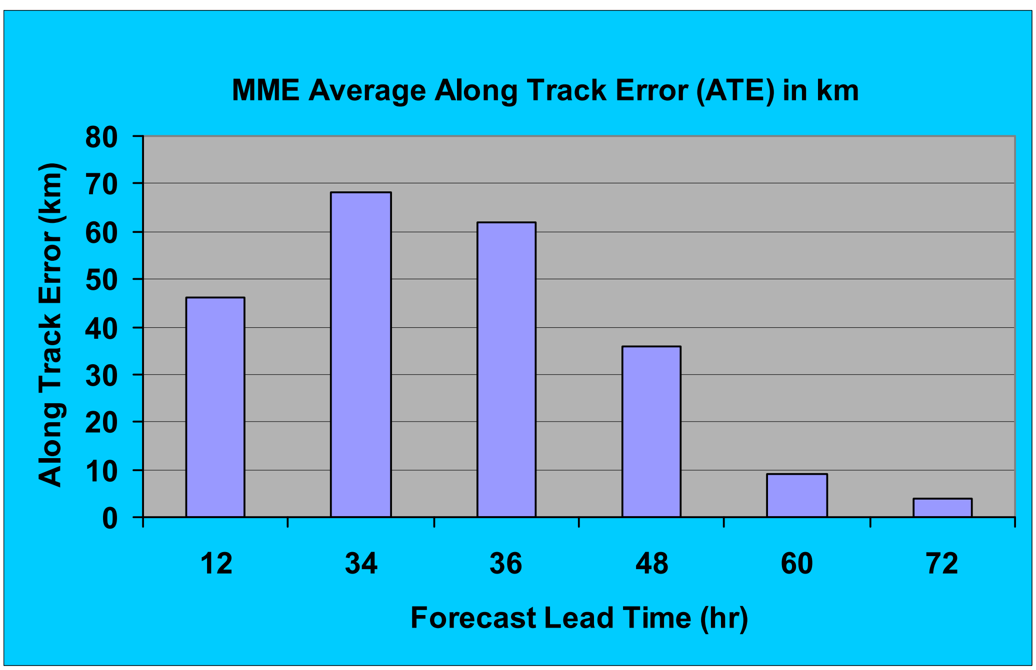


Fig. 50: Average along track error (ATE) of MME for HELEN

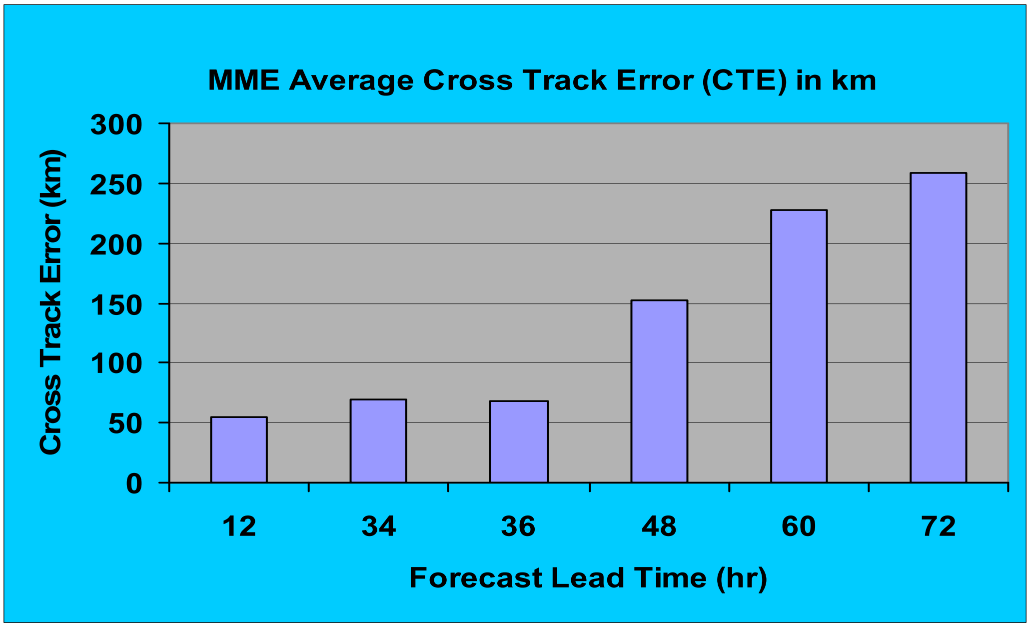


Fig. 51: Average cross track error (CTE) of MME for HELEN

Landfall Point Error: Landfall point forecasts errors of NWP model at different forecast lead times show that some model predicted north of actual landfall point and some predicted south of actual landfall point with a maximum limit up to about 126 km (HWRF) towards north and up to 568 km (IMD-GFS) towards south (Table-33). MME landfall point error was ranged from near landfall point (before 8h of landfall) to 250 km (before 56h of landfall) south of actual landfall point.

Table-33. Landfall point forecast errors (km) of NWP Models at different lead time (hour) for HELEN ('+' indicated north of actual landfall; '-' indicates south of actual landfall point)

Forecast Lead Time (hour) →	08.5 h	32.5 h	56.5 h	80.5 h
UKMO	00	-141	-277	***
NCEP GFS	-170	No LF	-170	No LF
JMA	-257	***	-501	No LF
HWRF	***	+126	+141	***
IMD-GFS	No LF	No LF	-568	No LF
WRF-VAR	00	-49	-170	-121
IMD-MME	00	-24	-252	No LF

Landfall Time Error: Landfall time forecasts errors of NWP model at different forecast lead times show that some model predicted earlier than actual landfall time and some predicted delayed than actual landfall time with a maximum limit up to 22 hr delayed (IMD-WRF) and up to 15 hr earlier (NCEP-GFS) than actual landfall time. Under this wide extent of landfall time forecasts, MME landfall time error (±1.5 h) was consistently low (Table-34).

Table-34. Landfall time forecast errors (hour) at different lead time (hr) for HELEN

('+' indicates delay landfall, '-' indicates early landfall)

Forecast Lead Time (hour) →	08.5 h	32.5 h	56.5 h	80.5 h
UKMO	-1.5	+3.5	-6.5	***
NCEP GFS	+2.5	No LF	+15.5	No LF
JMA	-5.5	***	-7.5	No LF
HWRF	***	+1.5	-3.5	***
IMD-GFS	No LF	No LF	+0.5	No LF
WRF-VAR	-0.5	-3.5	-22.5	-36.5
IMD-MME	-1.5	+1.5	+1.5	No LF

9.4 Intensity prediction

Intensity prediction (at stages of 12-h intervals) by statistical-dynamical model SCIP and dynamical model HWRF are shown in Fig. 52 and Fig. 53 respectively. The figure shows that the SCIP model underestimated and HWRF model over estimated the intensity at all forecasts.

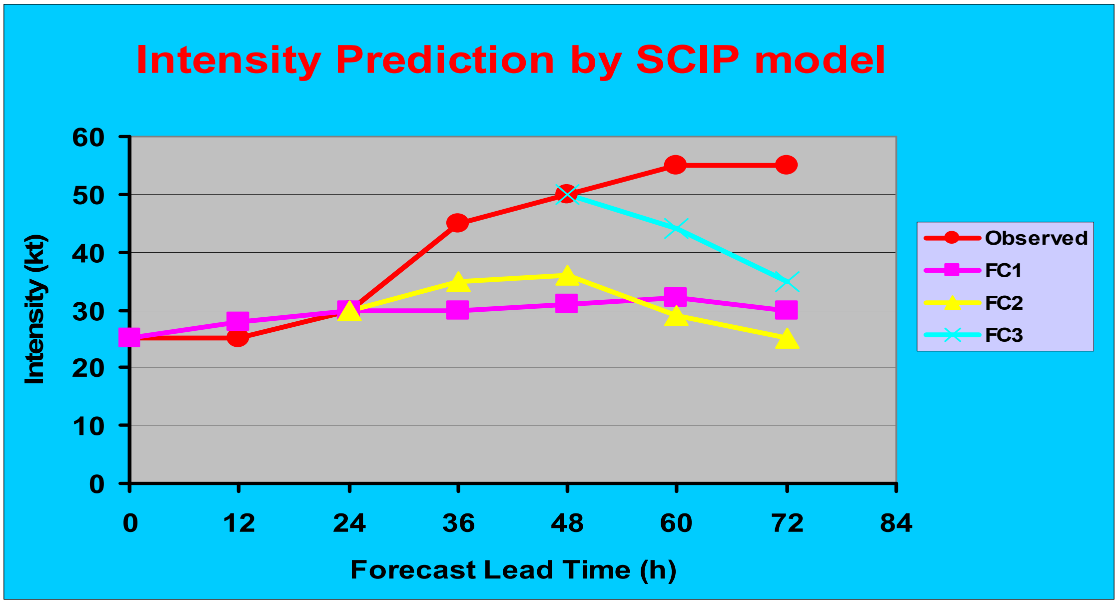


Fig. 52. Intensity forecasts of SCIP model for HELEN

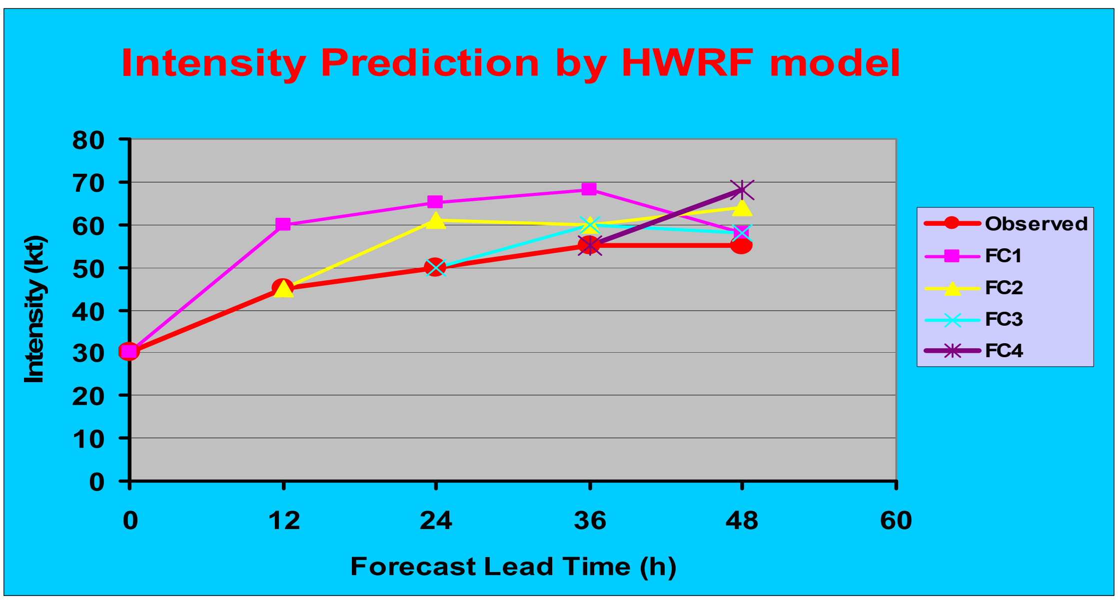


Fig. 53. Intensity forecasts of HWRF model for HELEN

Average absolute error (AEE) and Root mean square error (RMSE) of SCIP and HWRF forecast error of HELEN is presented in the following Table-35 and Table-36. The AAE of SCIP was ranged from 8 kt at 12 hr and 25 kt at 72 hr and the AEE of HWRF was ranged from 7.9 kt at 12 h to 6 kt at 48 h.

Table-35 Average absolute errors for HELEN (Number of forecasts verified)

(Intensity forecasts prior to landfall (1200 UTC of 12.10.2013) are considered)

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr
IMD-SCIP	8.0(3)	11.3(3)	20.5(2)	24.5(2)	14.0(2)	25.0(1)	-
IMD-HWRF	5.3(4)	11.0(4)	7.0(3)	6.0(2)	-	-	-
IMD-OFFICIAL	2.8(11)	4.0(9)	9.5(7)	12.8(5)	12.6(3)	-	-

Table-36 Root Mean Square (RMSE) errors for HELEN (Number of forecasts verified)

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr
IMD-SCIP	8.8(3)	14.1(3)	21.2(2)	25.1(2)	16.6(2)	25.0(1)	-
IMD-HWRF	7.9(4)	11.6(4)	8.2(3)	6.7(3)	-	-	-
IMD-OFFICIAL	3.9(11)	9.0(9)	14.0(7)	15.0(5)	16.8(3)	-	-

9.5. Probability of Rapid intensification (by RI-Index)

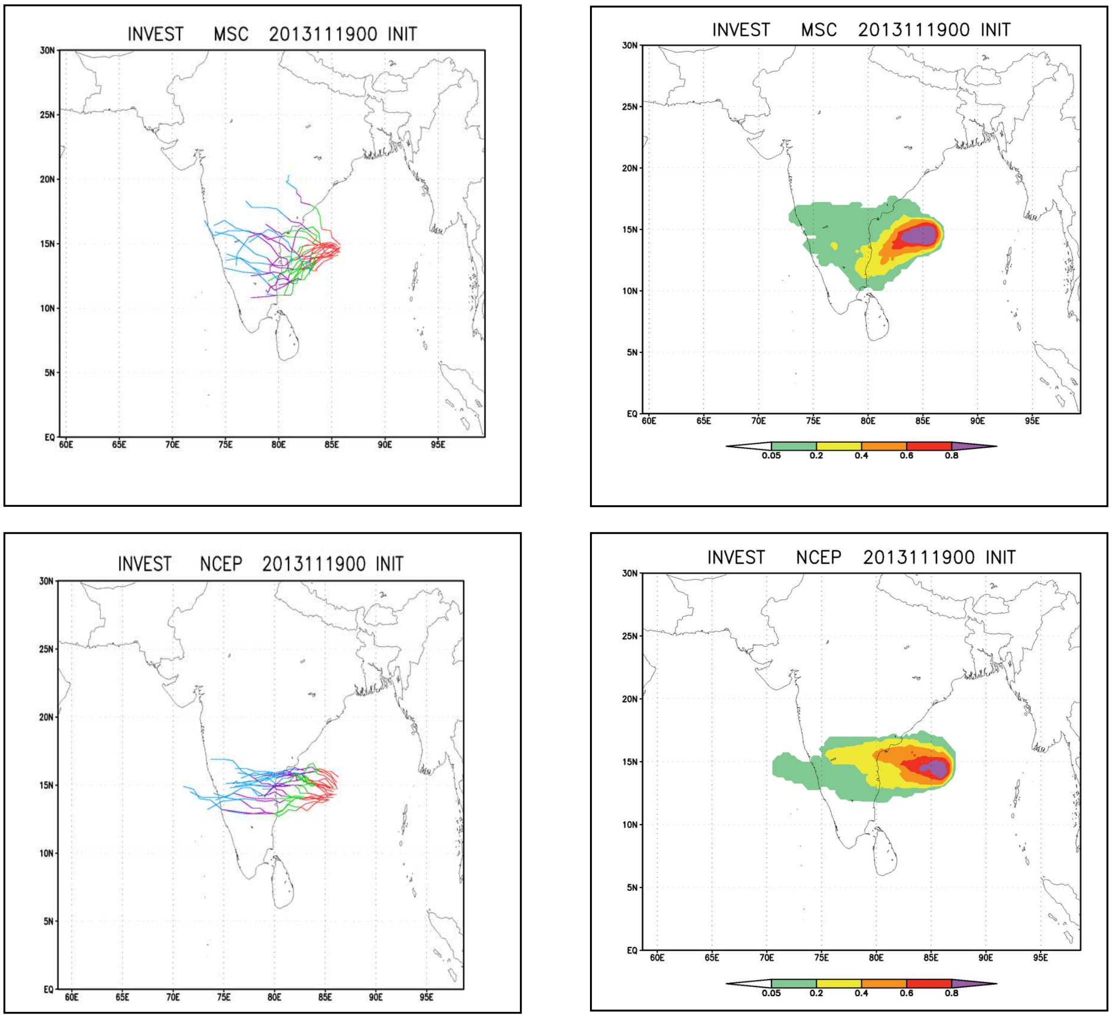
Rapid intensification (RI) is defined as: Increase of intensity by 30 kts or more during subsequent 24 hour.

Table-37 Probability of Rapid intensification for HELEN

Forecast based on	Probability of RI predicted	Chances of occurrence predicted	Intensity changes (kt) in 24h	Occurrence
00 UTC/19.12.2013	5.2 %	VERY LOW	5	NO
00 UTC/20.12.2013	9.4 %	VERY LOW	20	NO
00 UTC/21.10.2013	9.4 %	VERY LOW	5	NO
Inference: RI-Index was able to predict **NON-OCCURENCE** of Rapid Intensification of cyclone HELEN during its lifetime.				

9.6. Ensemble track and Strike Probability forecast for HELEN

a. Based on 0000 UTC 19.11.2013



b. Based on 0000 UTC 20.11.2013

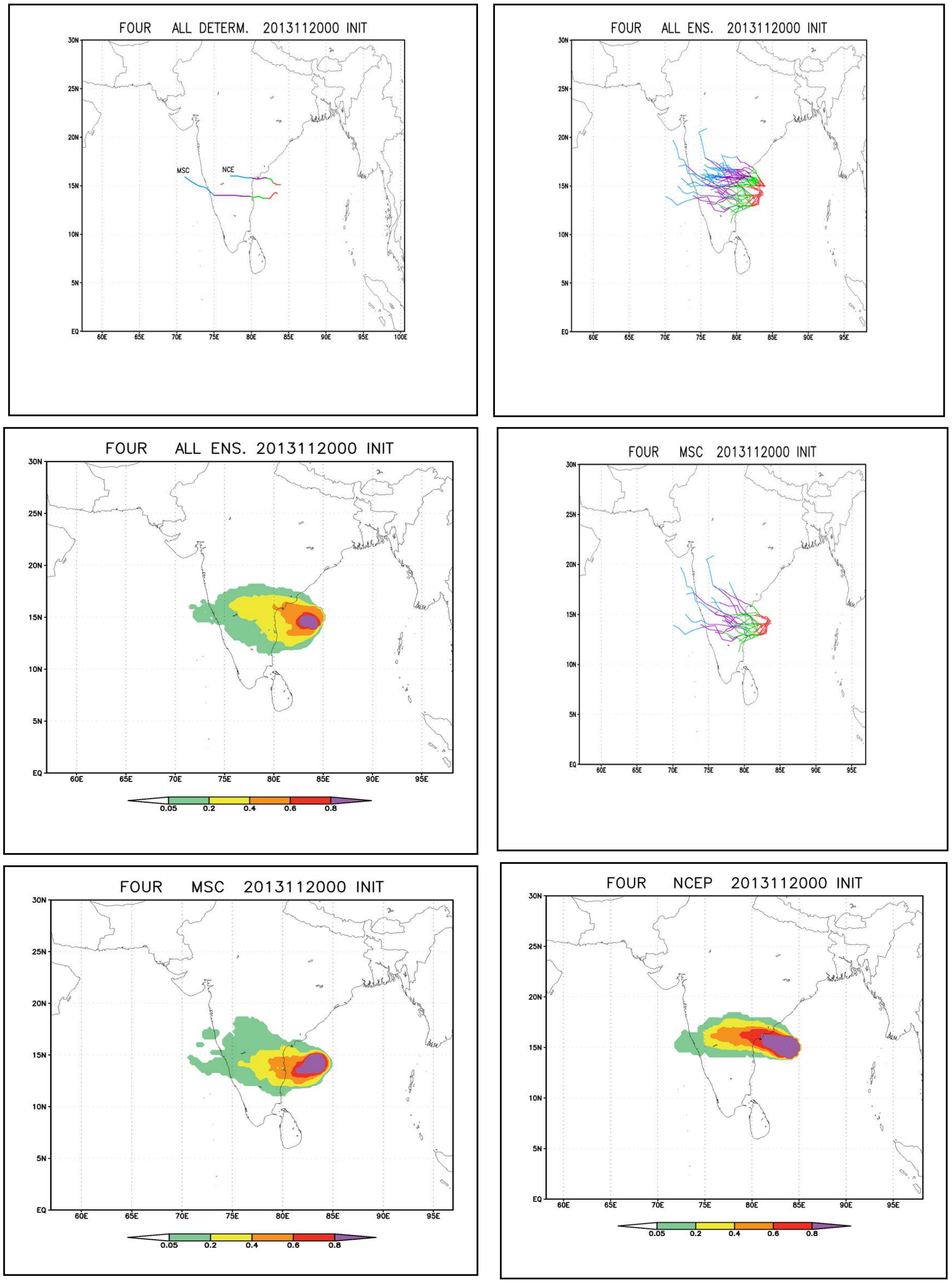


Fig. 54 Ensemble track and Strike Probability forecasts for HELEN

Ensemble track and strike probability forecasts based on 00 UTC 19.11.2013 and 00 UTC 20.11.2013 shows that ALL, MSC and NCEP all predicted towards Andhra Pradesh coast.

10. Very Severe Cyclonic Storm 'LEHAR' (23-28) November 2013

A low pressure system that formed over the south Andaman Sea intensified into depression at 1200 UTC of 23 November 2013 near latitude 8.5° N and longitude 96.5° E. The system moved northwestwards and intensified into a deep depression at 1800 UTC of same day and further intensified into a cyclonic storm (T.No. 2.5), LEHAR at 0000 UTC of 24 November 2013. The cyclonic storm continued to move in northwesterly direction and intensified into severe cyclonic storm (T.No. 3.5) at 0000 UTC of 25 November 2013. Thereafter the system moved west northwestward direction and further intensified into very severe cyclonic storm (T. No. 4.0) at 2100 UTC of 25 November 2013. Moving west northwestward direction the system weakened to severe cyclonic storm at 1200 UTC of 27 November 2013, to cyclonic storm at 1800 UTC on the same day. The system further weakened to Deep Depression at 0000 UTC 28 November 2013 and crossed Andhra Pradesh close to north of Machilipatnam near 15.9^{0}N/81.1^{0} E around 0830 UTC as Deep Depression and subsequently Weakened into a well marked low pressure area over coastal Andhra Pradesh and adjoining Telengana. The observed track of the cyclone LEHAR is shown in Fig. 55.

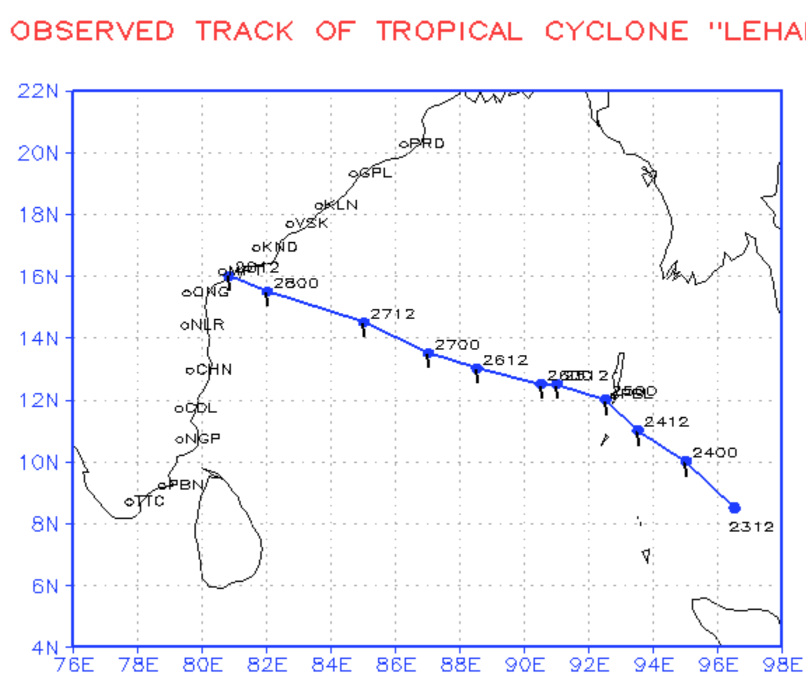
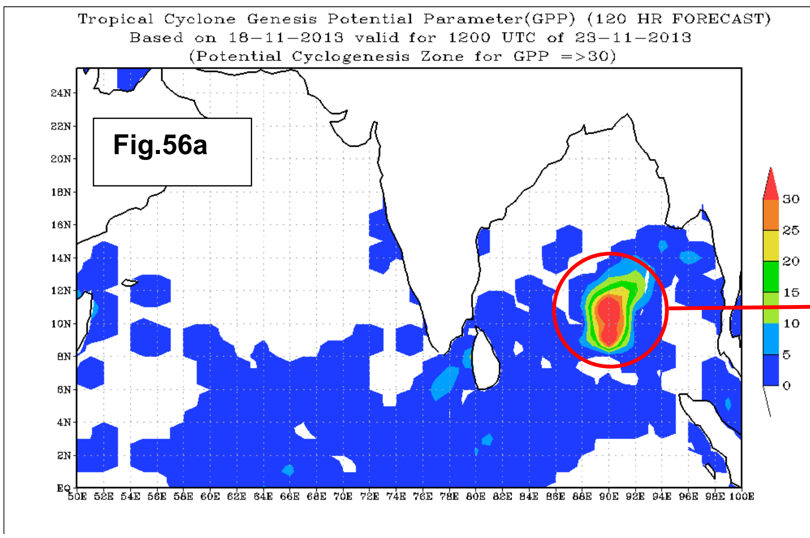


Fig. 55 Observed track of the cyclone LEHAR

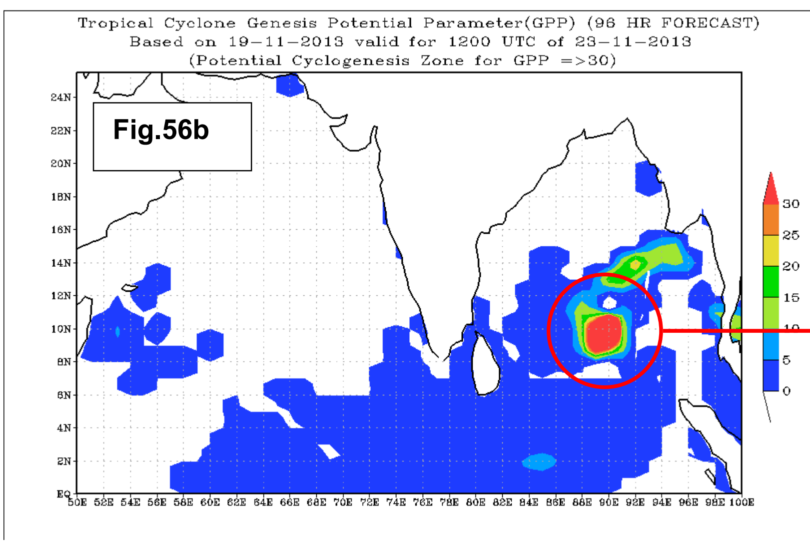
10.1. Grid point analysis and forecast of GPP

Objective: Grid point analysis and forecast of GPP is used to identify potential zone of cyclogenesis.

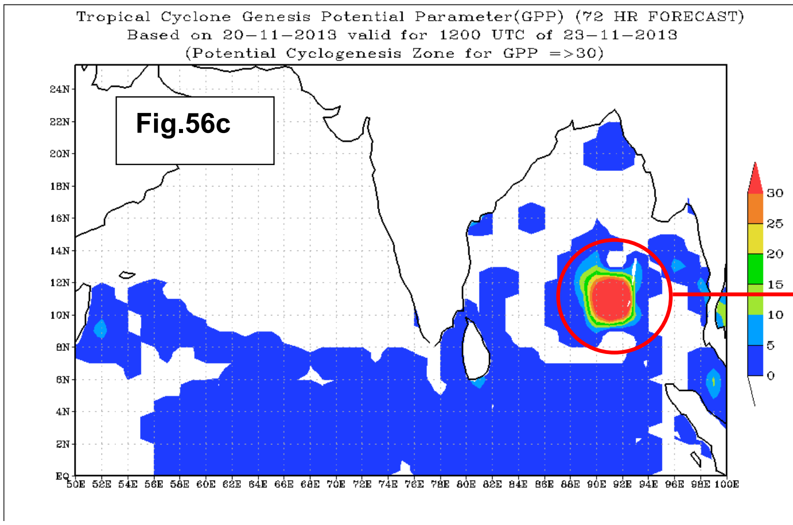
Figure 56(a-f) below shows the predicted zone of formation of cyclogenesis.



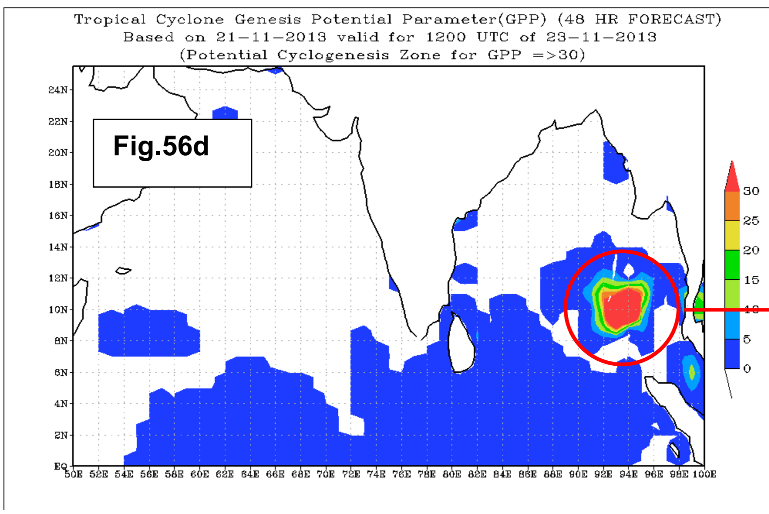
120 hour forecast of GPP valid for 12 UTC 23 November 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



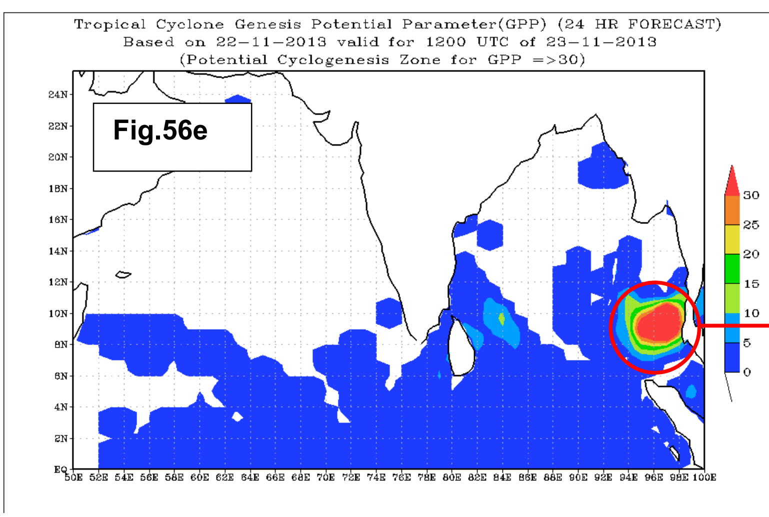
96 hour forecast of GPP valid for 12 UTC 23 November 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



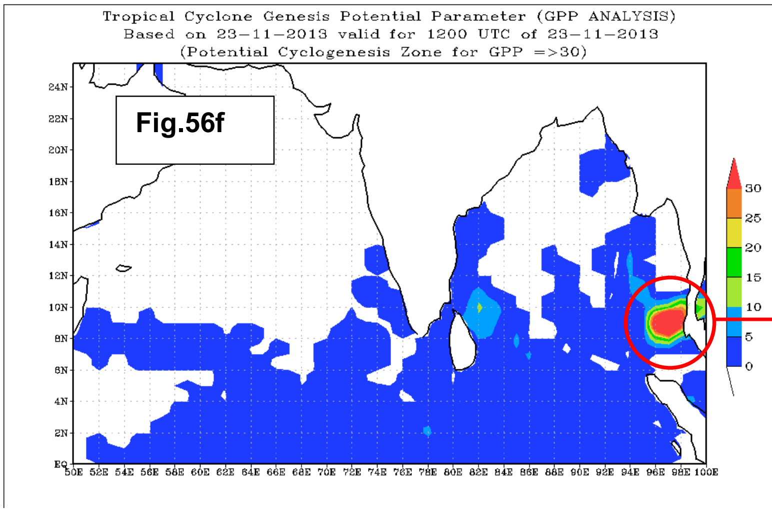
72 hour forecast of GPP valid for 12 UTC 23 November indicated the potential cyclogenesis zone, where Depression formed on that day.



96 hour forecast of GPP valid for 12 UTC 23 November 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



72 hour forecast of GPP valid for 12 UTC 23 November 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



Analysis of GPP on 00 UTC 07 October 2013 indicates the zone of cyclogenesis.

Figure 56(a-f): Predicted zone of cyclogenesis for LEHAR.

Inference: Grid point analysis and forecasts of GPP (Fig.56(a-f)) shows that it was able to predict the formation and location of the system before 120 hours of its formation.

(Product available at http://www.imd.gov.in/section/nhac/dynamic/Analysis1.htm)

10.2. Area average analysis of GPP

Objective: Since all low pressure systems do not intensify into cyclones, it is important to identify the potential of intensification (into cyclone) of a low pressure system at the early stages of development.

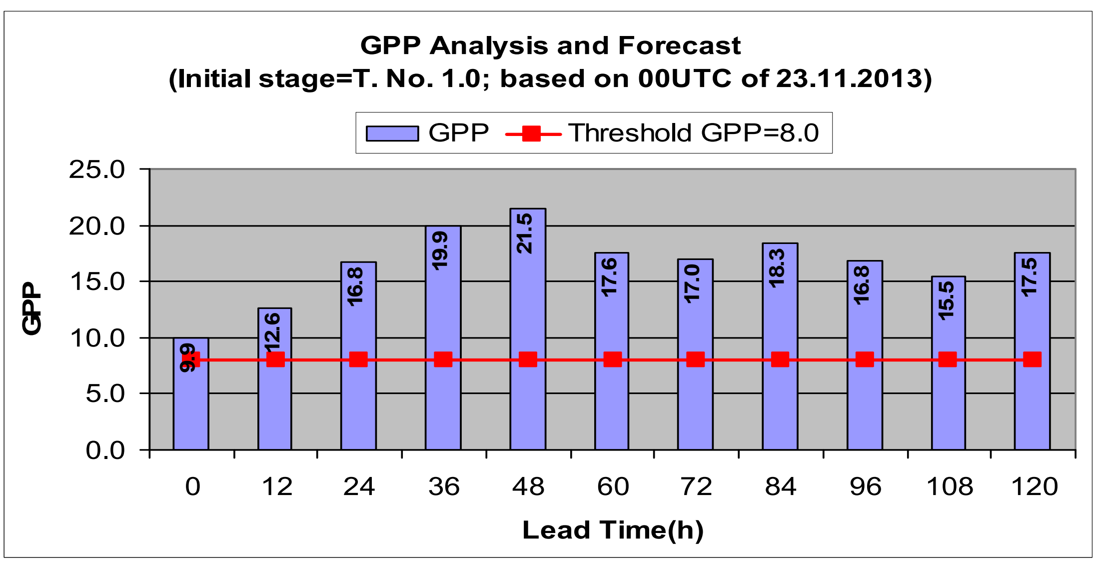


Fig. 57a

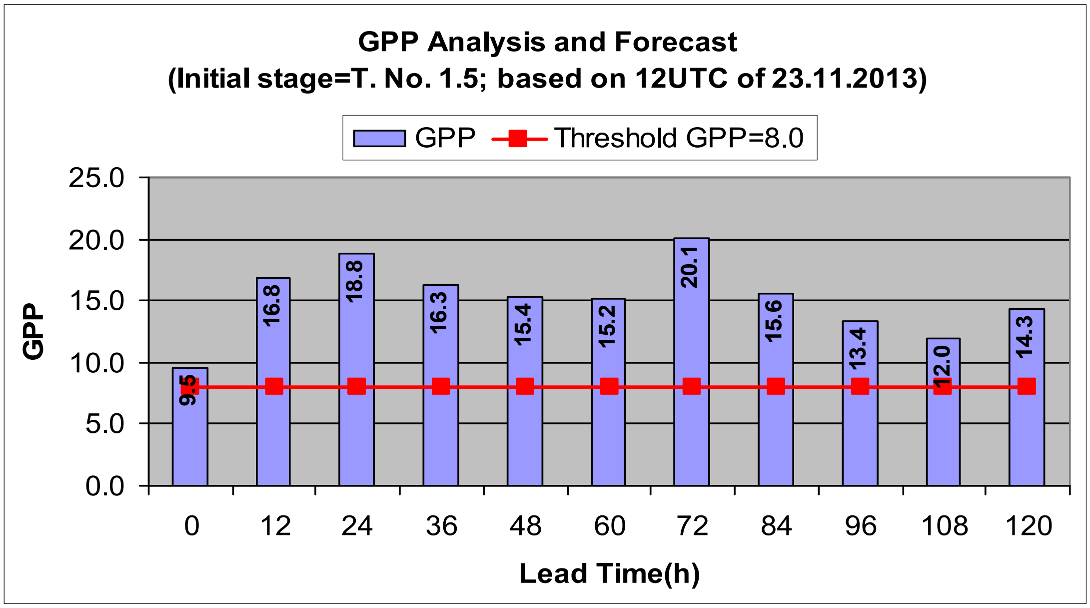


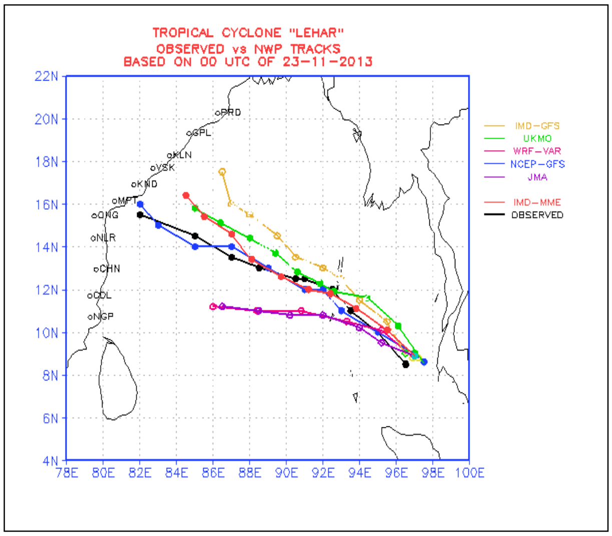
Fig. 57b

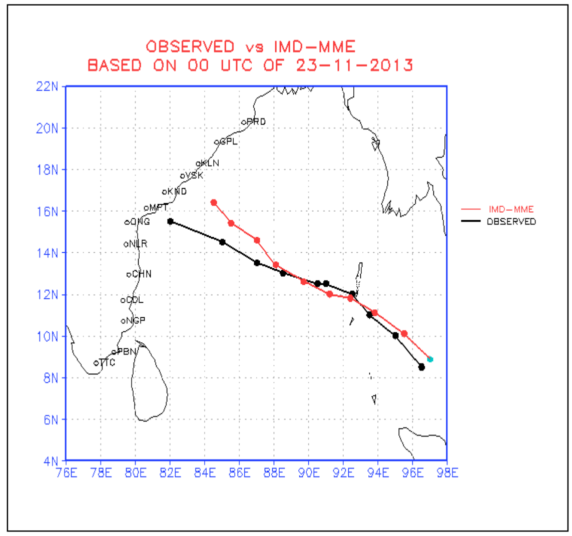
Fig. 57 (a-b) Area average analysis of GPP for LEHAR

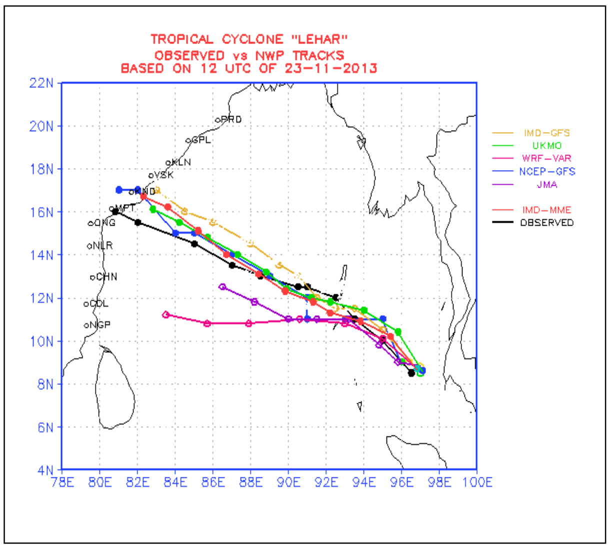
Inference: Analysis and forecasts of GPP (Fig.57(a-b)) shows that GPP $\geq$ 8.0 (threshold value for intensification into cyclone) indicated its potentential to intensify into a cyclone at early stages of development (T.No. 1.0, 1.5).

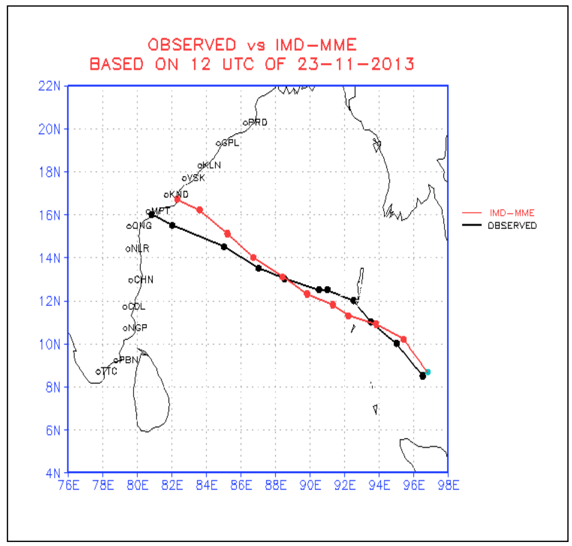
10.3. Track prediction

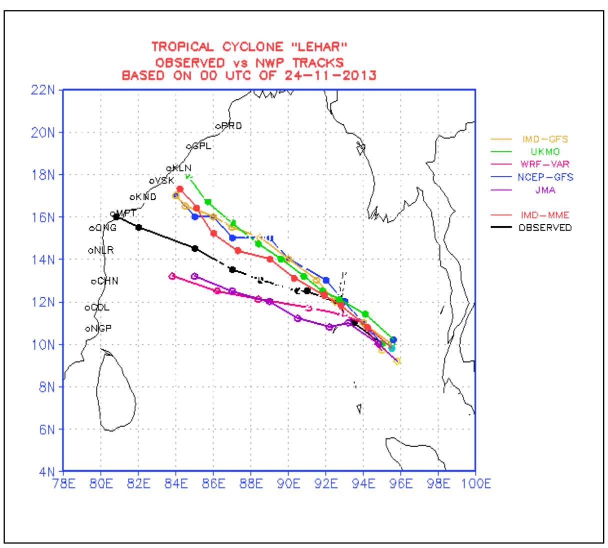
The average track forecast errors (DPE, CTE, ATE) of NWP models along with the consensus forecast by Multi-model ensemble (MME) forecast are presented in the Table 38, Table 39 and Table 40 respectively. The landfall point error (km) and landfall time (hour) is presented in Table-41 and Table-42 respectively. The MME forecasts track based on different initial conditions along with the observed track is depicted in Fig 58.

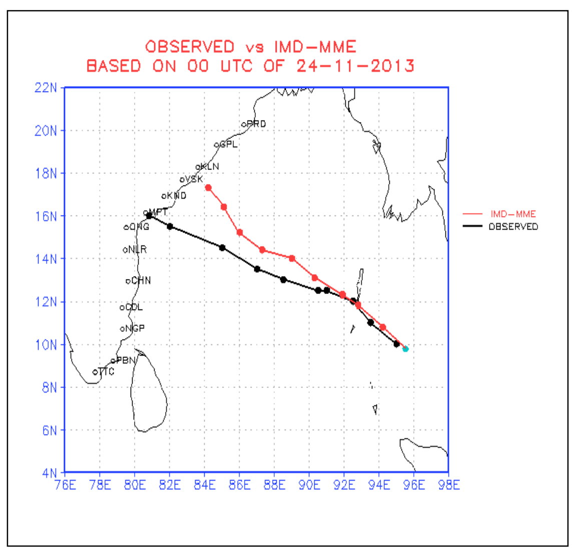

TROPICAL CYCLONE "LEHAR"
OBSERVED vs NWP TRACKS
BASED ON 00 UTC OF 23-11-2013
IMD-GFS
UKMO
WRF-VAR
NCEP-GFS
JMA
IMD-MME
OBSERVED

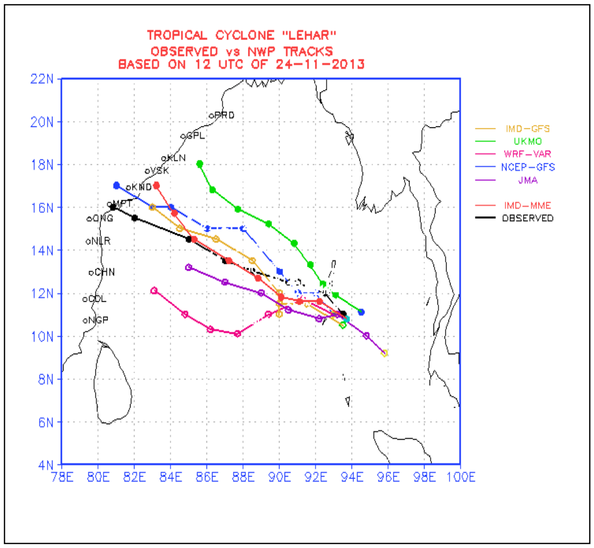

OBSERVED vs IMD-MME
BASED ON 00 UTC OF 23-11-2013
IMD-MME
OBSERVED

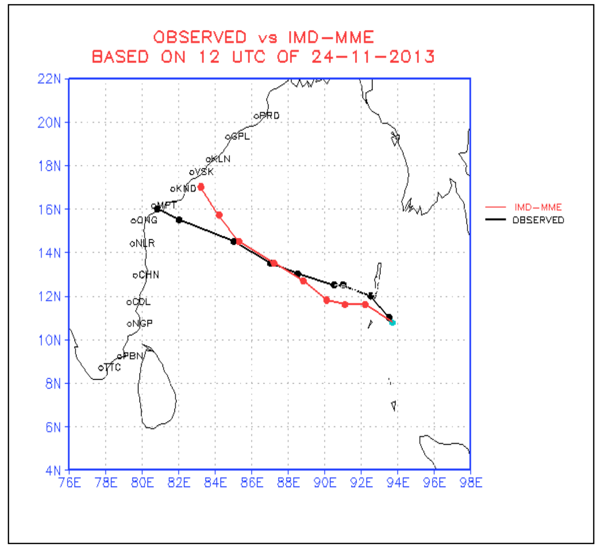

TROPICAL CYCLONE "LEHAR"
OBSERVED vs NWP TRACKS
BASED ON 12 UTC OF 23-11-2013
IMD-GFS
UKMO
WRF-VAR
NCEP-GFS
JMA
IMD-MME
OBSERVED

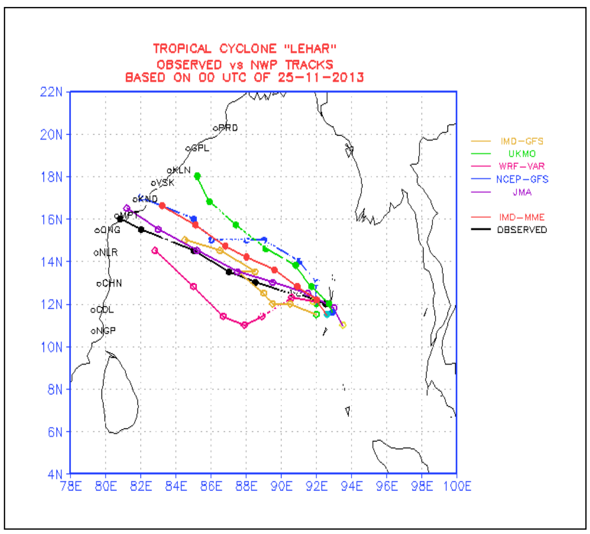

OBSERVED vs IMD-MME
BASED ON 12 UTC OF 23-11-2013
IMD-MME
OBSERVED

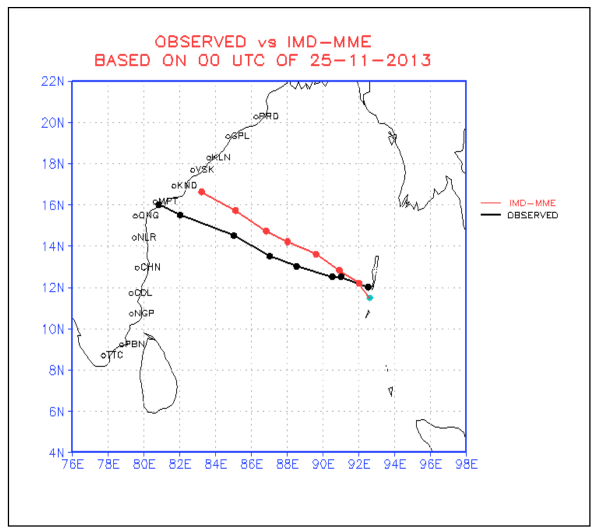

TROPICAL CYCLONE "LEHAR"
OBSERVED vs NWP TRACKS
BASED ON 00 UTC OF 24-11-2013
IMD-GFS
UKMO
WRF-VAR
NCEP-GFS
JMA
IMD-MME
OBSERVED

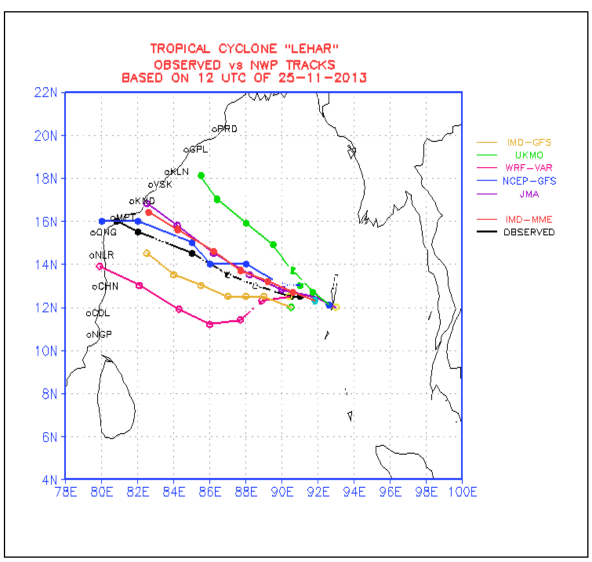

OBSERVED vs IMD-MME
BASED ON 00 UTC OF 24-11-2013
IMD-MME
OBSERVED

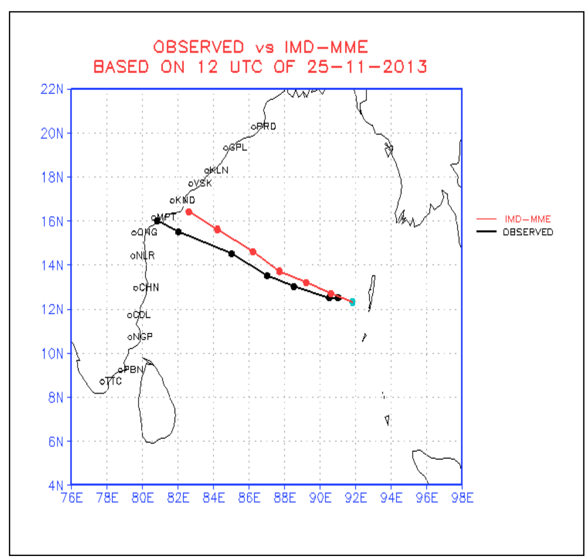

TROPICAL CYCLONE "LEHAR"
OBSERVED vs NWP TRACKS
BASED ON 12 UTC OF 24-11-2013
IMD-GFS
UKMO
WRF-VAR
NCEP-GFS
JMA
IMD-MME
OBSERVED
22N 20N 18N 16N 14N 12N 10N 8N 6N 4N
78E 80E 82E 84E 86E 88E 90E 92E 94E 96E 98E 100E

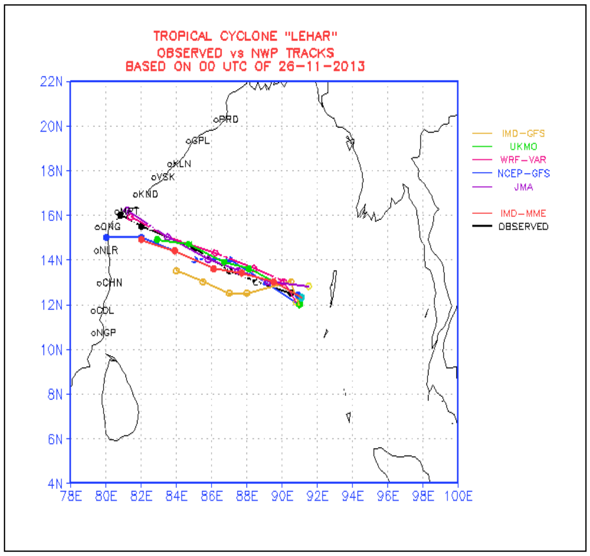

OBSERVED vs IMD-MME
BASED ON 12 UTC OF 24-11-2013
IMD-MME
OBSERVED
22N 20N 18N 16N 14N 12N 10N 8N 6N 4N
76E 78E 80E 82E 84E 86E 88E 90E 92E 94E 96E 98E

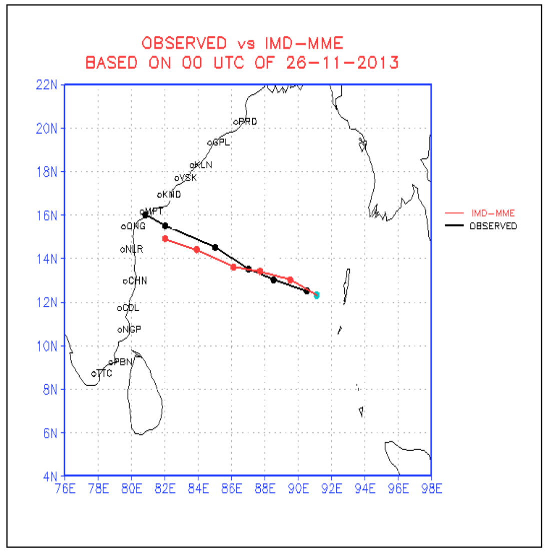

TROPICAL CYCLONE "LEHAR"
OBSERVED vs NWP TRACKS
BASED ON 00 UTC OF 25-11-2013
IMD-GFS
UKMO
WRF-VAR
NCEP-GFS
JMA
IMD-MME
OBSERVED
22N 20N 18N 16N 14N 12N 10N 8N 6N 4N
78E 80E 82E 84E 86E 88E 90E 92E 94E 96E 98E 100E

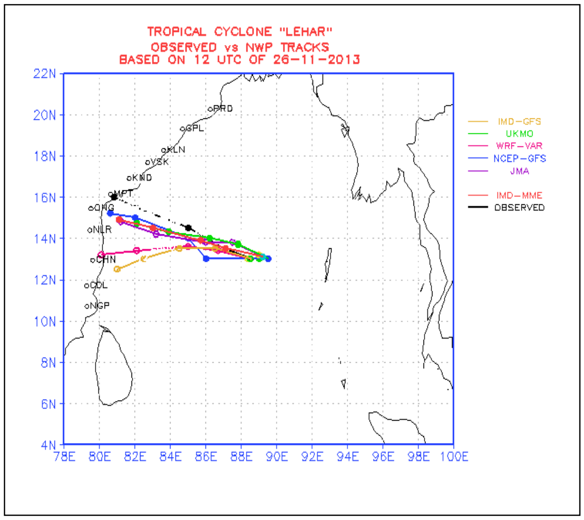

OBSERVED vs IMD-MME
BASED ON 00 UTC OF 25-11-2013
IMD-MME
OBSERVED
22N 20N 18N 16N 14N 12N 10N 8N 6N 4N
76E 78E 80E 82E 84E 86E 88E 90E 92E 94E 96E 98E

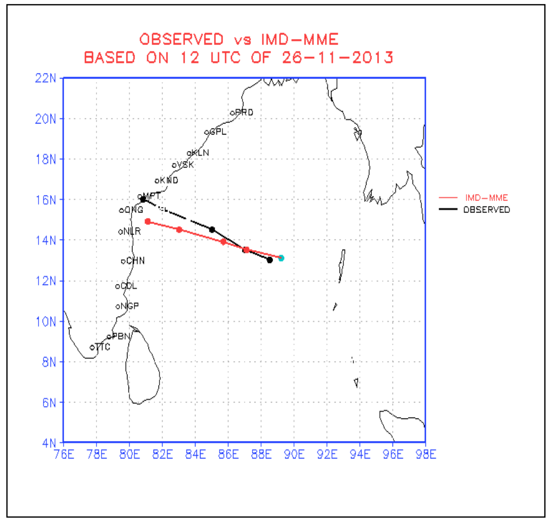

TROPICAL CYCLONE "LEHAR"
OBSERVED vs NWP TRACKS
BASED ON 12 UTC OF 25-11-2013
IMD-GFS
UKMO
WRF-VAR
NCEP-GFS
JMA
IMD-MME
OBSERVED
22N 20N 18N 16N 14N 12N 10N 8N 6N 4N
78E 80E 82E 84E 86E 88E 90E 92E 94E 96E 98E 100E

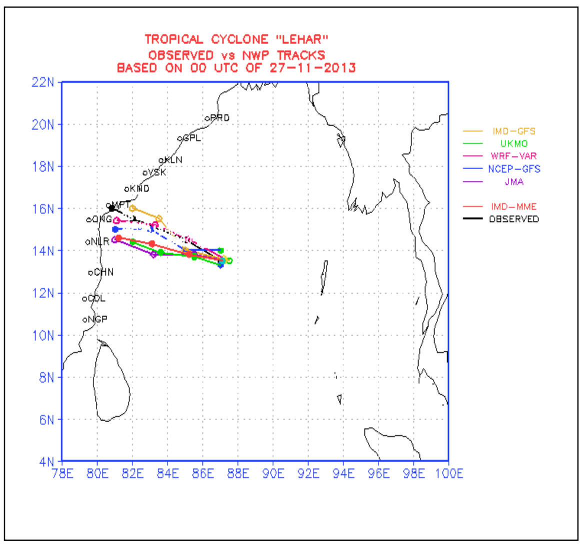

OBSERVED vs IMD-MME
BASED ON 12 UTC OF 25-11-2013
IMD-MME
OBSERVED
22N 20N 18N 16N 14N 12N 10N 8N 6N 4N
76E 78E 80E 82E 84E 86E 88E 90E 92E 94E 96E 98E

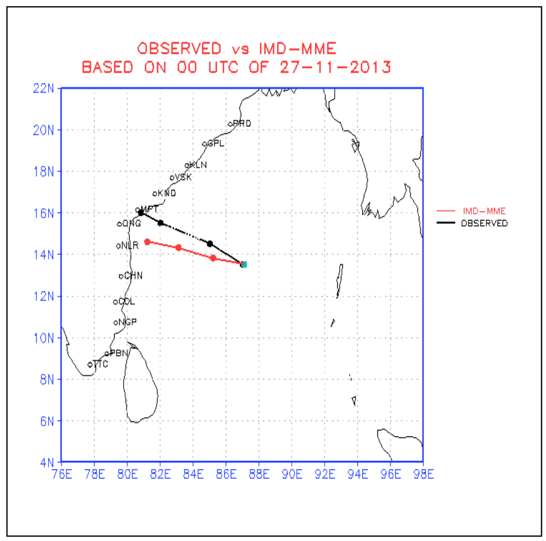

TROPICAL CYCLONE "LEHAR"
OBSERVED vs NWP TRACKS
BASED ON 00 UTC OF 26-11-2013
IMD-GFS
UKMO
WRF-VAR
NCEP-GFS
JMA
IMD-MME
OBSERVED

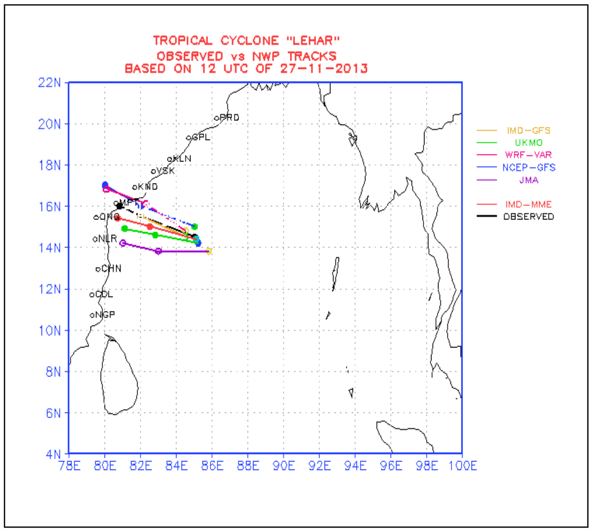

OBSERVED vs IMD-MME
BASED ON 00 UTC OF 26-11-2013
IMD-MME
OBSERVED


TROPICAL CYCLONE "LEHAR"
OBSERVED vs NWP TRACKS
BASED ON 12 UTC OF 26-11-2013
IMD-GFS
UKMO
WRF-VAR
NCEP-GFS
JMA
IMD-MME
OBSERVED


OBSERVED vs IMD-MME
BASED ON 12 UTC OF 26-11-2013
IMD-MME
OBSERVED


TROPICAL CYCLONE "LEHAR"
OBSERVED vs NWP TRACKS
BASED ON 00 UTC OF 27-11-2013
IMD-GFS
UKMO
WRF-VAR
NCEP-GFS
JMA
IMD-MME
OBSERVED


OBSERVED vs IMD-MME
BASED ON 00 UTC OF 27-11-2013
IMD-MME
OBSERVED



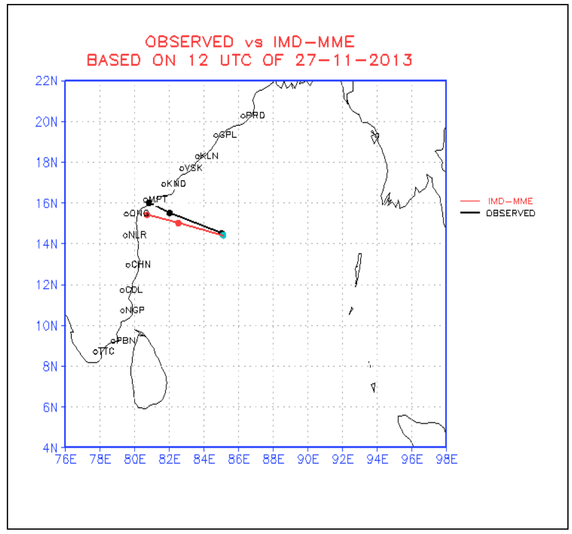


Fig. 58. MME forecasts track based on different initial conditions for LEHAR

Direct position Error (DPE): Average track forecast error (direct position error (DPE)) was highest for WRF (about 80 km at 12 h to 360 km at 72 h) up to 72 h, for forecast hours 84 h to 96h UKMO forecast error was highest (about 290 km at 84 h to 300 km at 96 h) and for forecast hours 108h and 120h HWRF forecast error was highest (about 325 km at 108 h to 425 km at 120 h). Average DPE was lowest for MME up to 84 h (about 65 km at 12 h to 150 km at 84 h), (Table-38). The DPE of all models are shown in Fig. 59.

Table-38. Average track forecast errors (DPE) in km for LEHAR

Lead time →	**12 hr**	**24 hr**	**36 hr**	**48 hr**	**60 hr**	**72 hr**	**84 hr**	**96 hr**	**108 hr**	**120 hr**
IMD-GFS	85(10)	103(9)	144(9)	202(8)	244(7)	226(6)	247(5)	231(4)	301(3)	394(2)
IMD-WRF	78(10)	132(10)	193(9)	281(8)	291(7)	361(6)	-	-	-	-
JMA	138(10)	151(10)	144(9)	136(8)	130(7)	152(6)	151(5)	-	-	-
NCEP-GFS	78(10)	84(10)	114(9)	114(8)	139(7)	191(6)	191(5)	196(4)	249(3)	84(2)
UKMO	111(10)	138(10)	182(9)	196(8)	240(7)	266(6)	288(5)	301(4)	288(3)	268(2)
IMD-MME	67(10)	79(10)	110(9)	107(8)	127(7)	128(6)	152(5)	204(4)	230(3)	232(2)
IMD-HWRF	77 (9)	129 (9)	141 (8)	144 (7)	113 (7)	173 (6)	194 (5)	255 (4)	323 (3)	424 (2)
IMD-OFFICIAL	57(18)	92(16)	111(14)	133(12)	141(10)	140(8)	134(6)	143(4)	169(2)	-

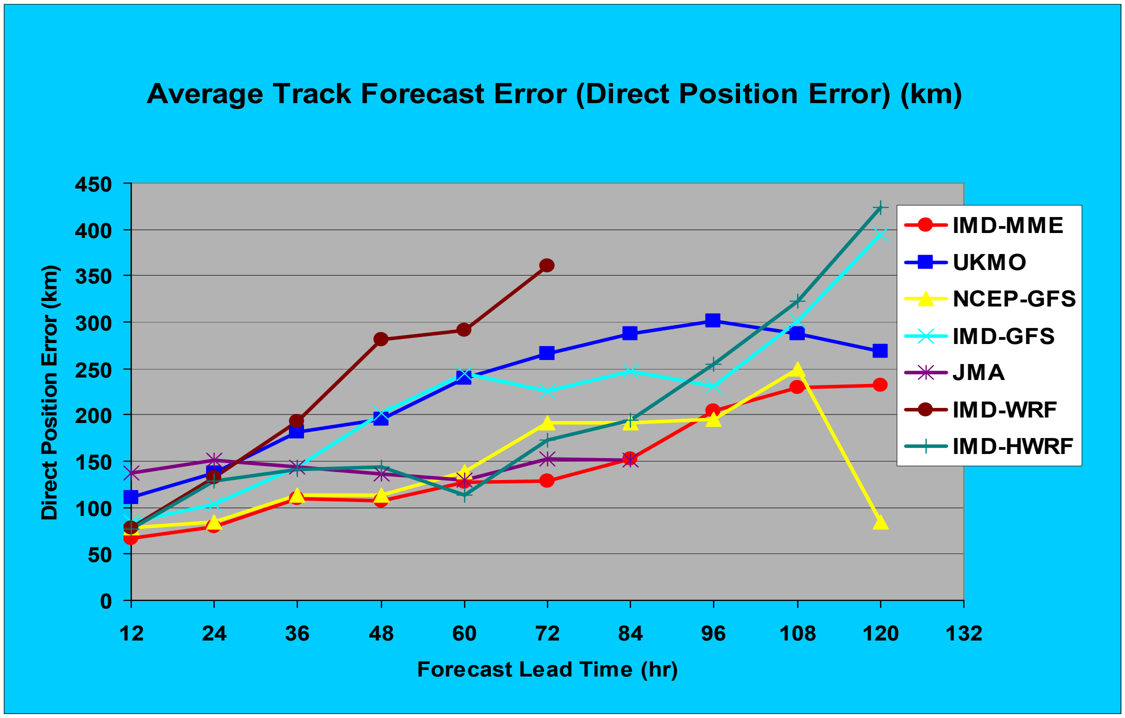


Fig. 59: Average track forecast errors (DPE) of NWP models for LEHAR

Cross Track Error (CTE): Average cross track error (CTE) was highest for WRF (about 40 km at 12 h to 275 km at 72 h). Average CTE was lowest for MME for all forecast hours (about 35 km at 12 h to 170 km at 120 h) except for forecast hours from 96 h to 120 h where NCEP-GFS forecast errors are found to be lowest (Table-39). The CTE of all models are shown in Fig. 60.

Table-39. Average cross track error (CTE) in km for LEHAR

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
IMD-GFS	44	75	104	113	103	101	121	170	213	301
IMD-WRF	41	92	168	241	242	274	-	-	-	-
JMA	41	52	61	75	93	122	123	-	-	-
NCEP-GFS	57	58	90	97	100	85	100	84	143	80
UKMO	54	70	96	108	150	192	209	216	193	132
IMD-MME	35	41	68	54	66	64	83	148	175	170
IMD-HWRF	50	112	94	96	82	130	159	193	209	245

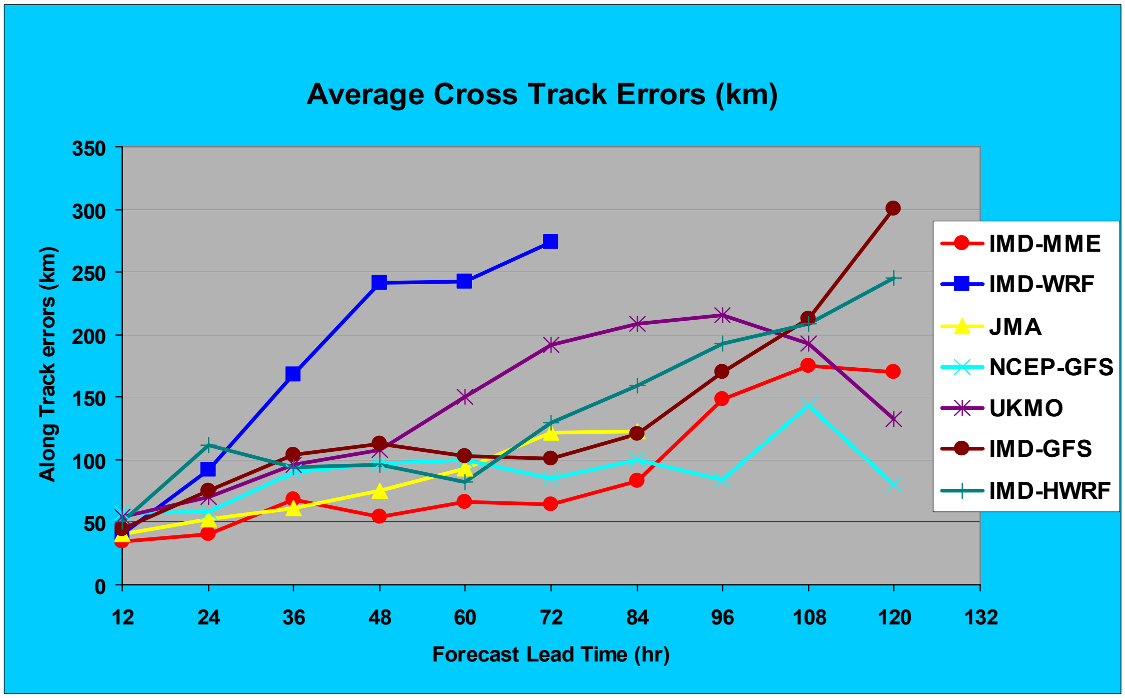


Fig. 60 Average cross track errors (CTE) of NWP models for LEHAR

Along Track Error (ATE): Average along track error (ATE) was highest for UKMO (about 80 km at 12 h to 205 km at 96 h) up to 96 h and for forecast hours 108h (220km) and 120h (345km) HWRF forecast hours were highest. Average ATE was lowest for MME for all forecast hours (about 45 km at 12 h to 155 km at 120 h) except for forecast hours from 120 h where NCEP-GFS forecast errors are found to be lowest (Table-40). The ATE of all models is shown in Fig. 61.

Table-40. Average along track error (ATE) in km for LEHAR

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
IMD-GFS	60	55	81	146	202	181	154	119	203	254
IMD-WRF	55	78	71	99	145	207	-	-	-	-
JMA	120	133	125	100	75	77	60	-	-	-
NCEP-GFS	48	47	50	55	78	160	132	158	187	25
UKMO	82	109	139	147	174	178	189	203	207	233
IMD-MME	46	61	77	88	98	102	123	134	135	157
IMD-HWRF	52	56	83	92	61	104	93	147	220	345

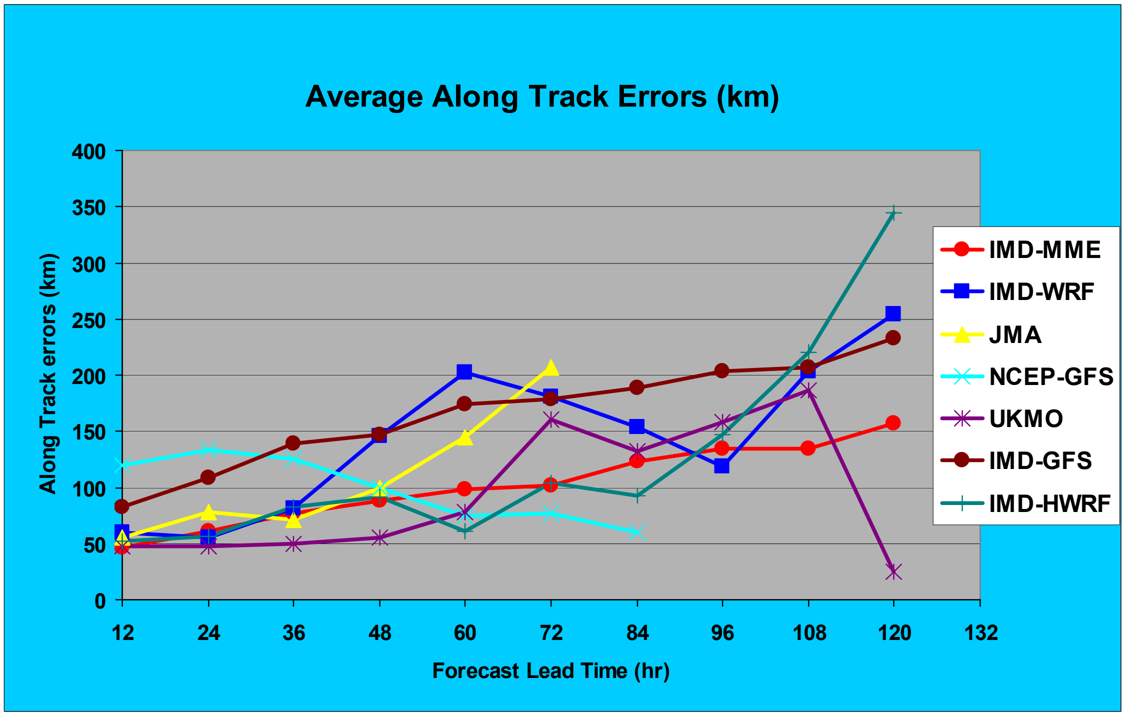


Fig. 61 Average along track errors (ATE) of NWP models for LEHAR

Track Forecast Error of MME: The DPE, ATE and CTE of consensus forecast of NWP models (MME) are shown in Fig 62, Fig 63 and Fig 64 respectively.

The average DPE of MME was about 65 km at 12 h to 230 km at 120 h (Fig. 62).

The average ATE of MME was about 45 km at 12 h to 155 km at 120 h (Fig. 63).

The average CTE of MME was about 35 km at 12 h to 170 km at 120 h (Fig. 64).

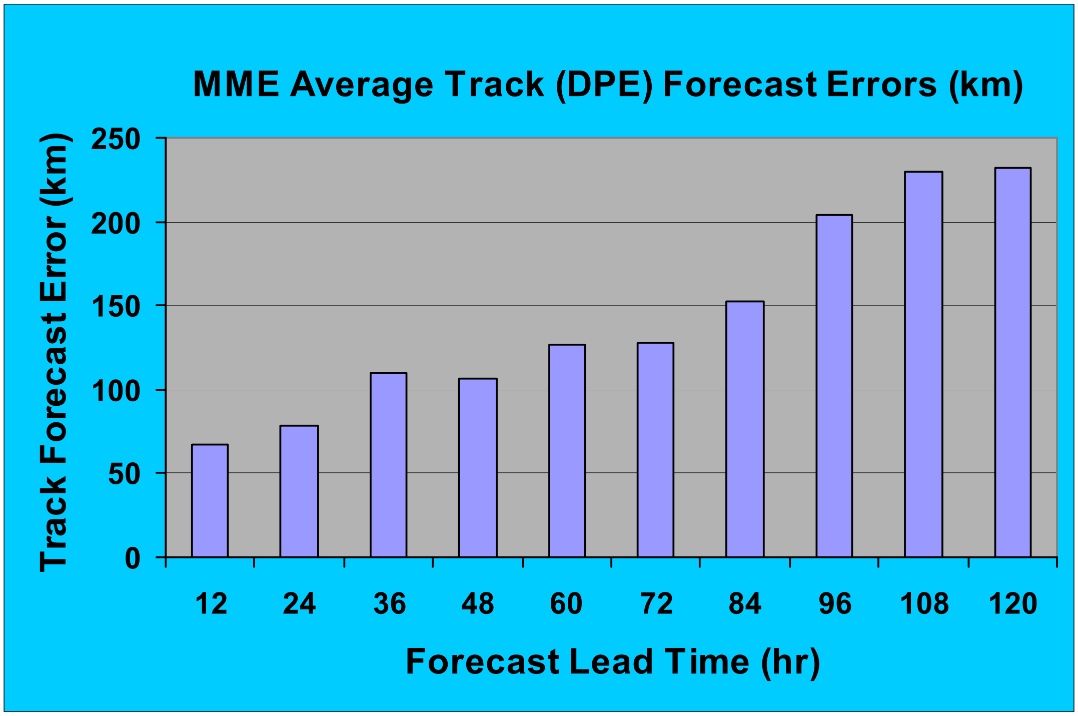


Fig. 62: Average direct track error (DPE) of MME for LEHAR

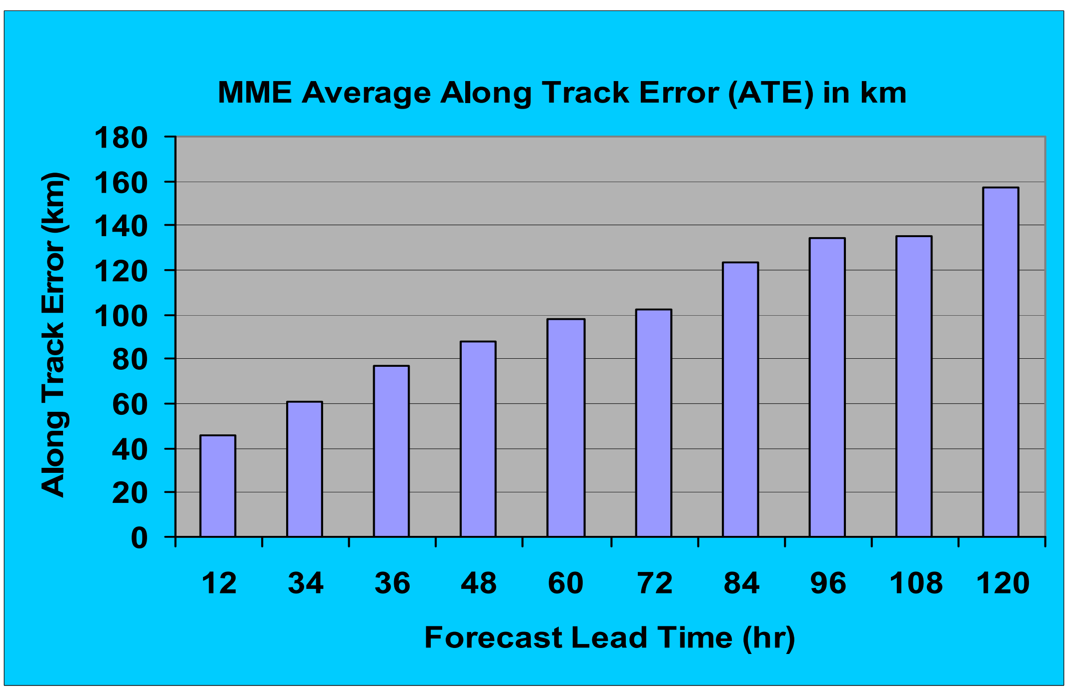


Fig. 63: Average along track error (ATE) of MME for LEHAR

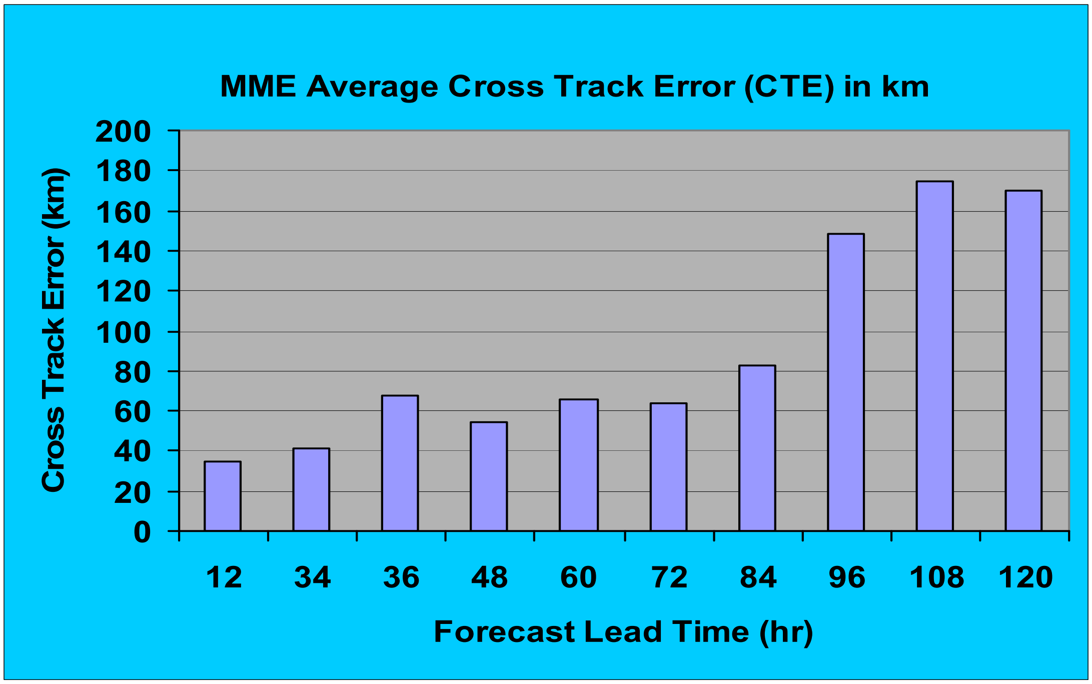


Fig. 64: Average cross track error (CTE) of MME for LEHAR

Landfall Point Error: Landfall point forecasts errors of NWP model at different forecast lead times (Table-41) show that some model predicted north of actual landfall point and some predicted south of actual landfall point with a maximum limit upto about 552 km towards north and up to 487 km towards south. Under this wide extent of landfall point forecasts, MME was able to predict landfall point with reasonable success.

Table-41. Landfall point forecast errors (km) of NWP Models at different lead time (hour) for LEHAR ('+' indicates North; '-'indicates South of landfall point; No LF indicates no landfall)

Forecast Lead Time (hour) →	20.5 h	32.5 h	44.5 h	56.5 h	68.5 h	80.5 h	92.5 h	104.5 h	116.5 h
UKMO	-139	No LF	No LF	No LF	No LF	**+552**	No LF	+445	No LF
NCEP GFS	+35	-135	-132	-141	+11	+154	+102	No LF	+147
JMA	-163	-155	-141	+25	+147	+82	No LF	No LF	No LF
HWRF	+93	-106	**-487**	+11	+141	+117	+147	+208	No LF
IMD-GFS	No LF	No LF	-385	No LF	+102	+102	No LF	No LF	No LF
WRF-VAR	+82	No LF	-78	+16	-247	No LF	No LF	No LF	No LF
IMD-MME	-121	-162	-141	+53	+147	+169	+232	+323	+156

Landfall Time Error: Landfall time forecasts errors of NWP model at different forecast lead times (Table-42) show that some model predicted earlier than actual landfall time and some predicted delayed than actual landfall time with a maximum limit up to 15 hr delayed and up to 9 hr earlier than actual landfall time.

Table-42. Landfall time forecast errors (hour) at different lead time (hr) for LEHAR

('+' indicates delay landfall, '-' indicates early landfall)

Forecast Lead Time (hour) →	20.5 h	32.5 h	44.5 h	56.5 h	68.5 h	80.5 h	92.5 h	104.5 h	116.5 h
UKMO	+11.5	No LF	No LF	No LF	No LF	**+15.5**	No LF	+10.5	No LF
NCEP GFS	-5.5	+8.5	+14.5	+3.5	-2.5	+1.5	-2.5	No LF	**-9.5**
JMA	+8.5	+9.5	+12.5	+3.5	+3.5	+1.5	No LF	No LF	No LF
HWRF	+0.5	+7.5	**+9.5**	+4.5	-7.5	-2.5	-7.5	-0.5	No LF
IMD-GFS	No LF	No LF	**+15.5**	No LF	No LF	+3.5	+15.5	No LF	No LF
WRF-VAR	-5.5	No LF	+3.5	+4.5	+2.5	No LF	No LF	No LF	No LF
IMD-MME	+8.5	+6.5	+6.5	+12.5	+4.5	+7.5	+8.5	**+15.5**	+3.0

10.4. Intensity prediction

Intensity prediction (at stages of 12-h intervals) by statistical-dynamical model SCIP and dynamical model HWRF are shown in Fig. 65 and Fig. 66 respectively. Both the SCIP and HWRF model was able to predict the very severe stage of the LEHAR. None of the two models could predict the decay phase over the Sea initially but updated forecast able to predict the decay phase in the later stage.

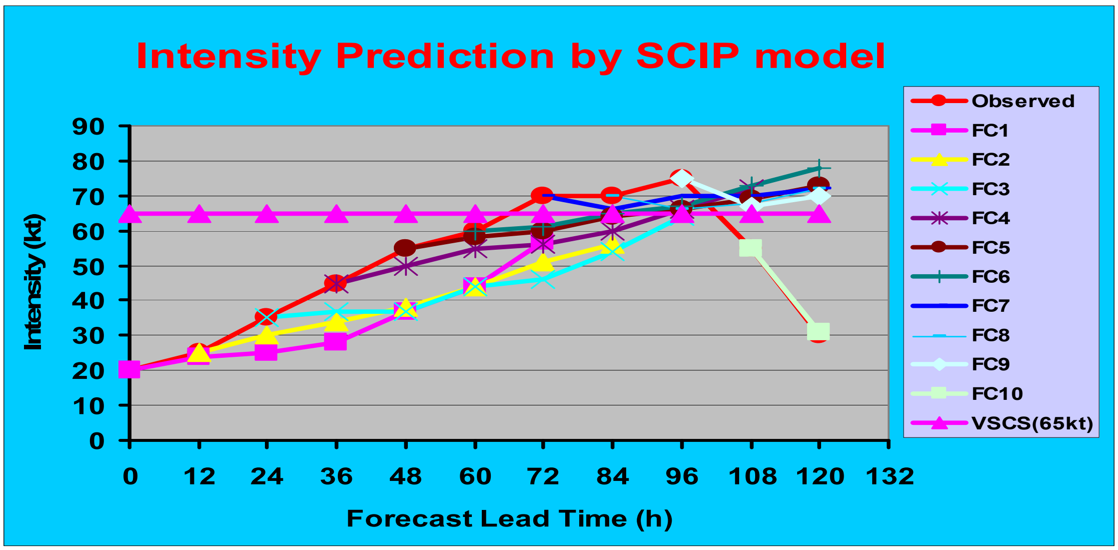


Fig. 65. Intensity forecasts of SCIP model for LEHAR

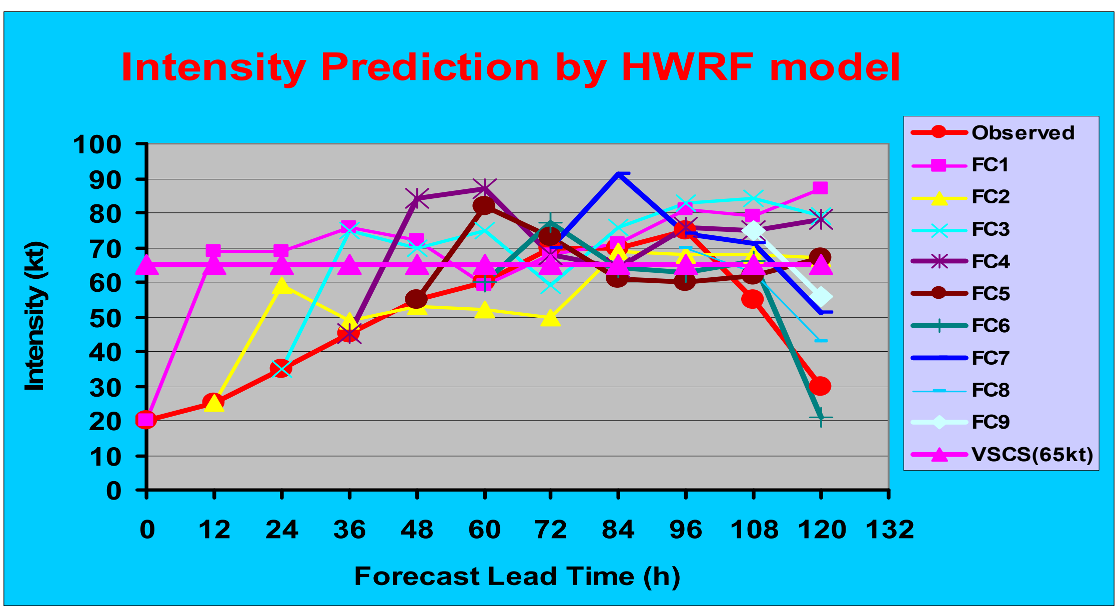


Fig. 66. Intensity forecasts of HWRF model for LEHAR

Average absolute error (AEE) and Root mean square error (RMSE) of SCIP and HWRF forecast error of LEHAR is presented in the following Table-43 and Table-44.

Table-43 Average absolute errors for LEHAR (Number of forecasts verified)

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
IMD-SCIP	5.6 (10)	13.0 (9)	16.9 (8)	19.6 (7)	20.3 (6)	19.6 (5)	-	-	-	-
IMD-HWRF	23.4(9)	12.9(8)	12.4(7)	12.7(7)	7.3(6)	13.6(5)	21.3(4)	22.7(3)	30.5(2)	57(1)
IMD-OFFICIAL	10.2	18.4	25.5	29.2	32.4	41	47	48.5	34.5	-

Table-44 Root Mean Square (RMSE) errors for LEHAR (Number of forecasts verified)

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
IMD-SCIP	6.6 (10)	16.6 (9)	19.7 (8)	22.1 (7)	24.0 (6)	22.9 (5)	-	-	-	-
IMD-HWRF	25.7(9)	17.1(8)	15.5(7)	13.6(7)	9.7(6)	19.2(5)	28.3(4)	29.5(3)	31.2(2)	57(1)
IMD-OFFICIAL	13.4	24.5	33.1	38	39.3	47.3	49.6	54.3	36.9	-

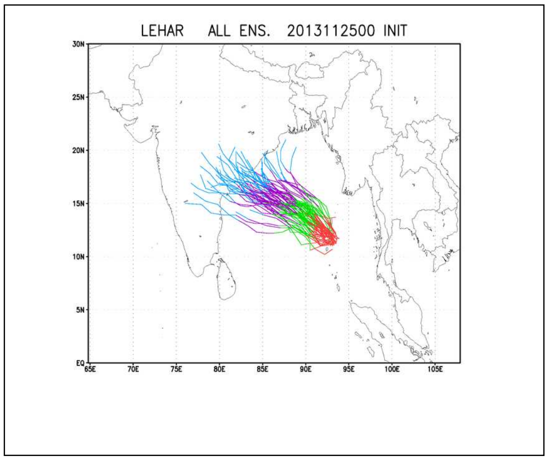
10.5. Probability of Rapid intensification (by RI-Index)

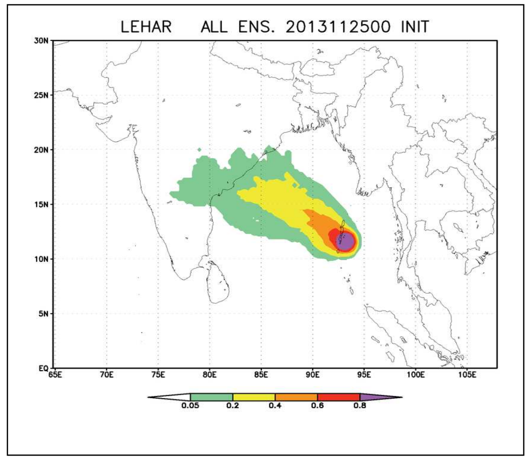
Table-45 Probability of Rapid intensification (Increase of intensity by 30 kts or more in 24h) for LEHAR

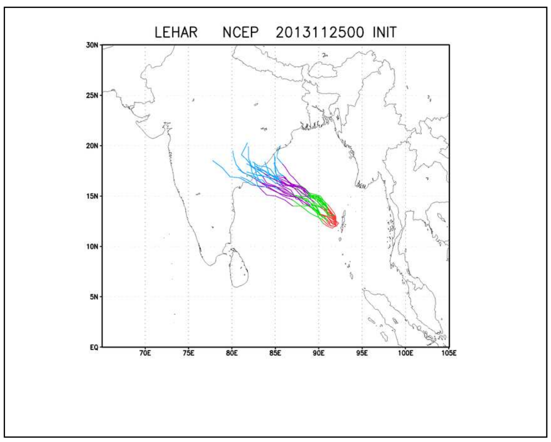
Forecast based on	**Probability of RI predicted**	**Chances of occurrence predicted**	**Intensity changes (kt) in 24h**	**Occurrence**
00 UTC/23.11.2013	5.2 %	VERY LOW	5	NO
12 UTC/23.11.2013	5.2 %	VERY LOW	20	NO
00 UTC/24.11.2013	22.0 %	LOW	20	NO
12 UTC/24.11.2013	22.0 %	LOW	15	NO
00UTC/25.11.2013	32.0 %	MODERATE	15	NO
12 UTC/25.11.2013	9.4 %	VERY LOW	10	NO
00 UTC/26.11.2013	9.4%	VERY LOW	5	NO
12 UTC/26.11.2013	5.2%	VERY LOW	-15	NO
00 UTC/27.11.2013	9.4%	VERY LOW	-45	NO
12 UTC/27.11.2013	0.0%	NIL	-30	NO
Inference: RI-Index was able to predict **NON-OCCURENCE** of Rapid Intensification of cyclone LEHAR during its lifetime.				

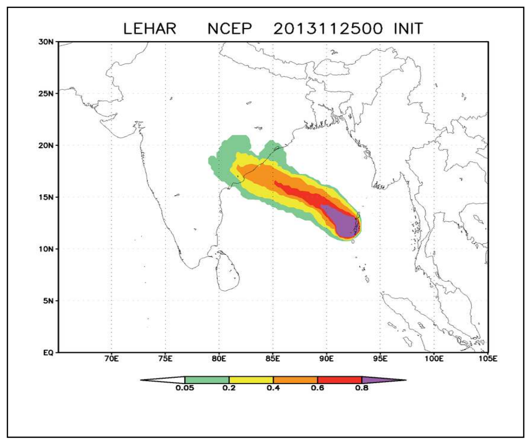
10.6. Ensemble track and Strike Probability forecast for LEHAR

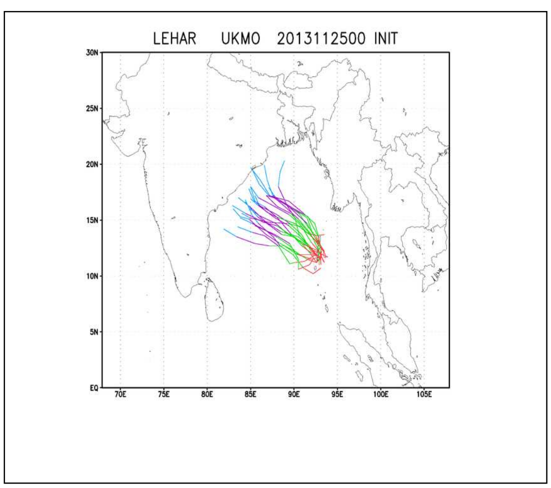
a. Based on 0000 UTC 25.11.2013

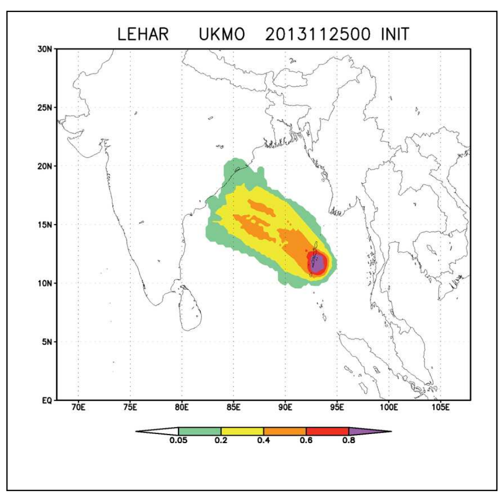




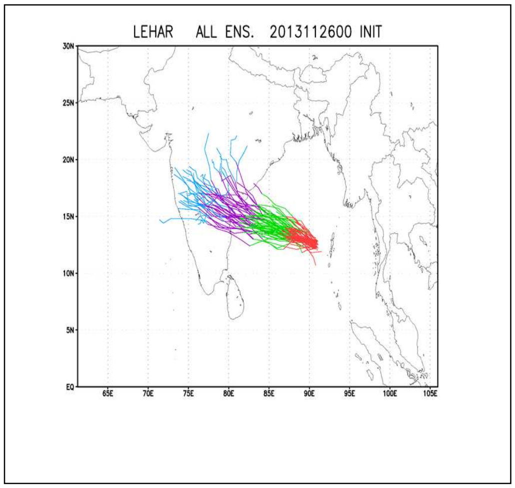


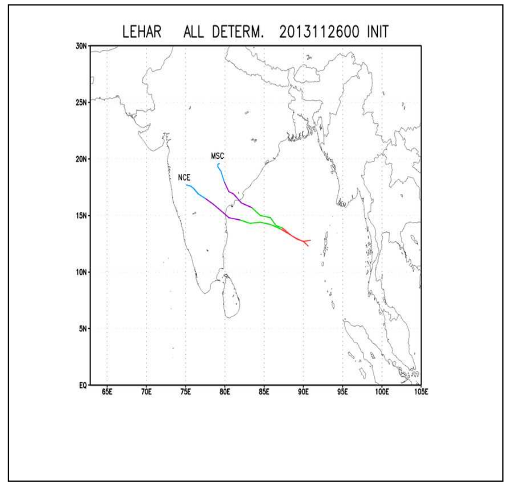


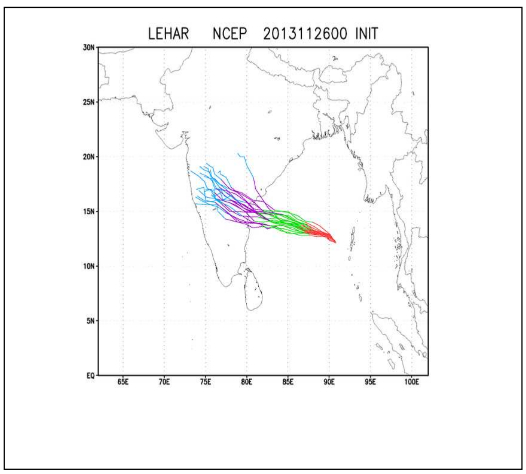


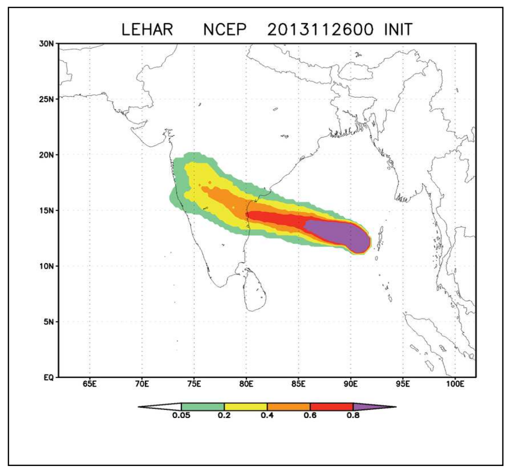


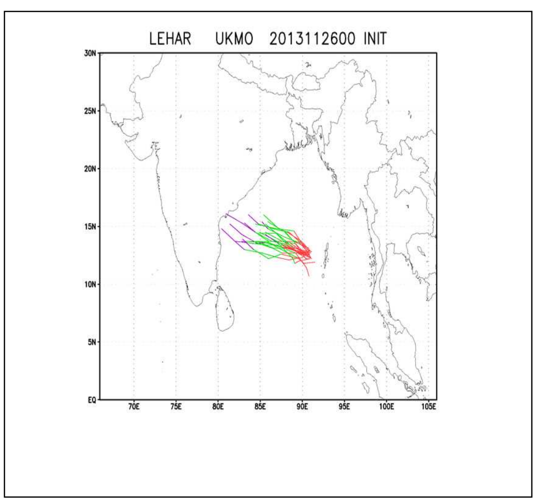
b. Based on 0000 UTC 26.11.2013

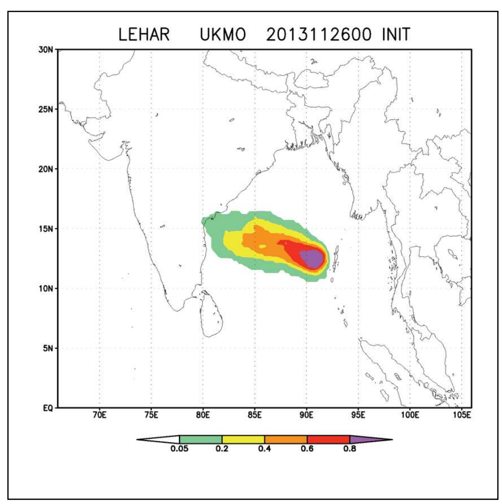












c. Based on 0000 UTC 27.11.2013

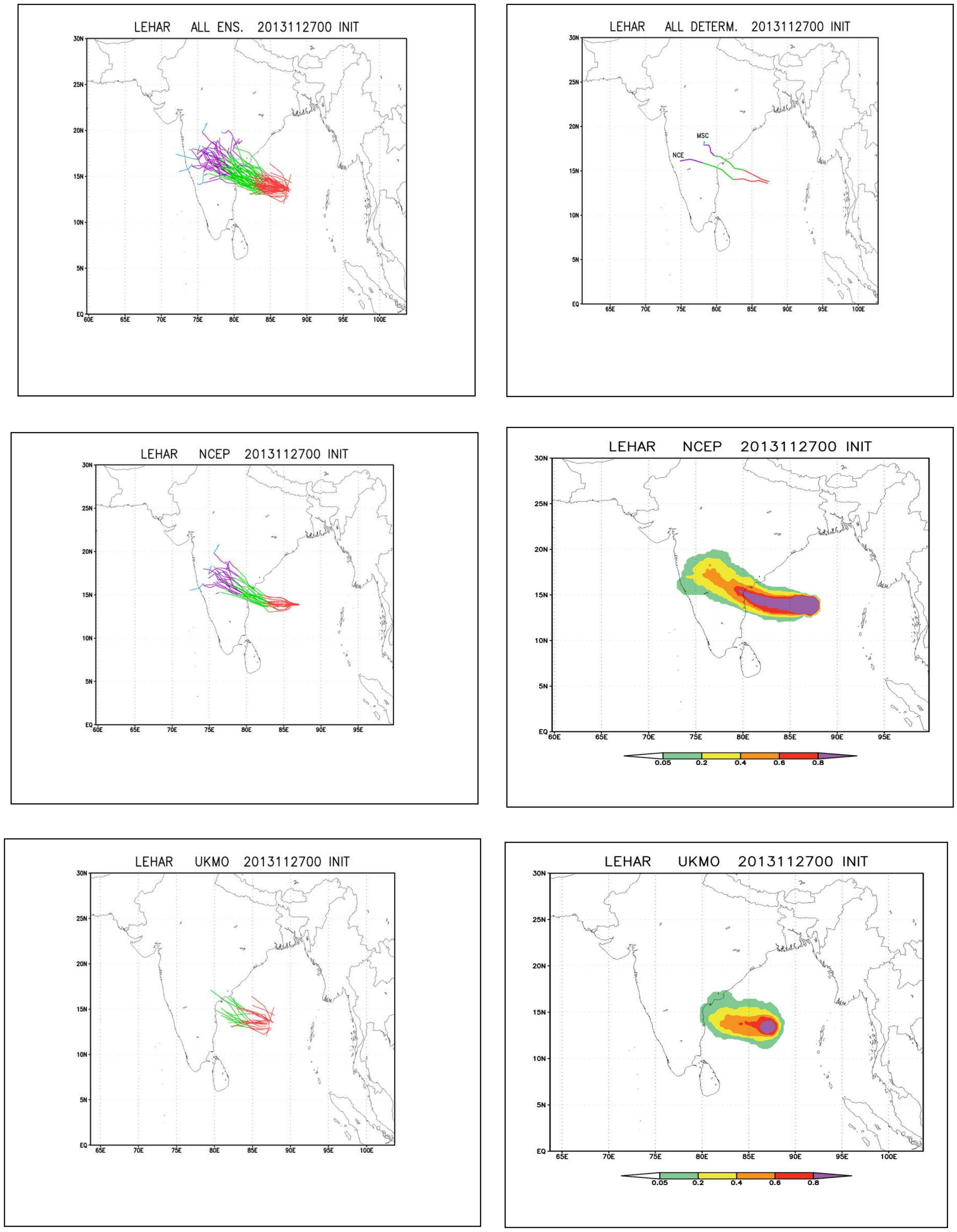


Fig. 67 Ensemble track and strike probability forecasts for LEHAR

Ensemble track and strike probability forecasts (Fig. 67) based on 00 UTC 25.11.2013, 26.11.2013 and 27.11.2013 shows that ALL, NCEP and UKMO all predicted towards Andhra Pradesh coast.

11. Very Severe Cyclonic storm ‘MADI’ (6-13) December 2013

A low pressure system that formed over southwest Bay of Bengal on 2 December 2013 intensified into depression at 0300 UTC of 6 December 2013 near latitude 10.0^{o} N and longitude 84.0^{o} E. It moved north north-eastwards and intensified into a deep depression at 1800 UTC of same day. The system intensified into a cyclonic storm (T.No. 2.5), MADI at 0000 UTC of 7 December 2013 and into a severe cyclonic storm at 0900 UTC of the same day. The cyclonic storm continued to move in north north-eastward direction and intensified into very severe cyclonic storm at 0600 UTC of 8 December 2013. Moving north north-eastward direction the system weakened to severe cyclonic storm at 1200 UTC of 9 December 2013. Moving further north north-eastward direction the system changed its course of movement towards southwest direction from 0900 UTC of 10 December 2013 and weakened to cyclonic storm at 2100 UTC of same day. Moving further southwest direction the system weakened to Deep Depression at 0300 UTC of 11 December and into Depression at 1800 UTC of same day and crossed the Tamil Nadu coast near Nagapattinam at around 1200 UTC of 12 December as Depression. The observed track of the cyclone MADI is shown in Fig. 68.

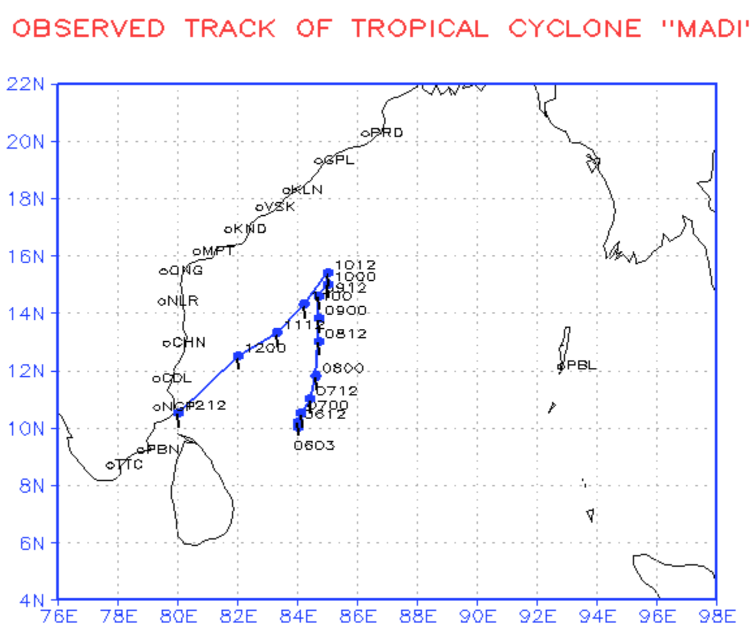
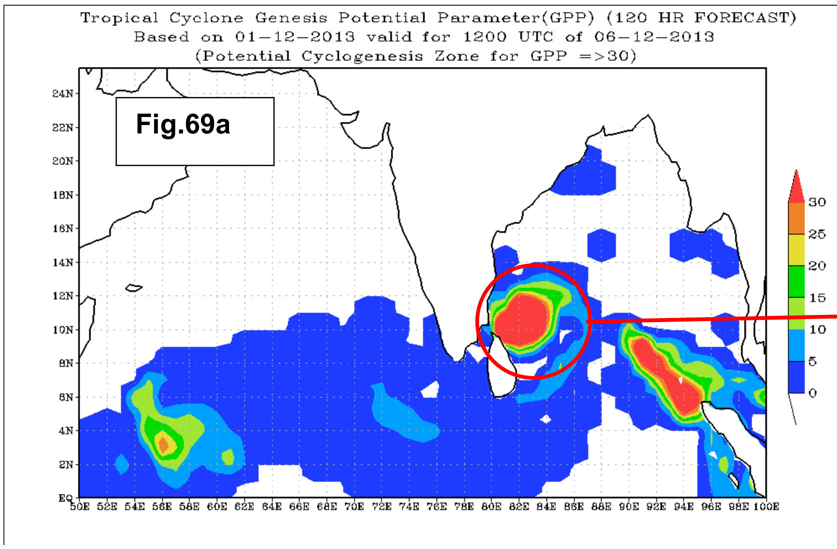


Fig. 68 Observed track of the cyclone MADI

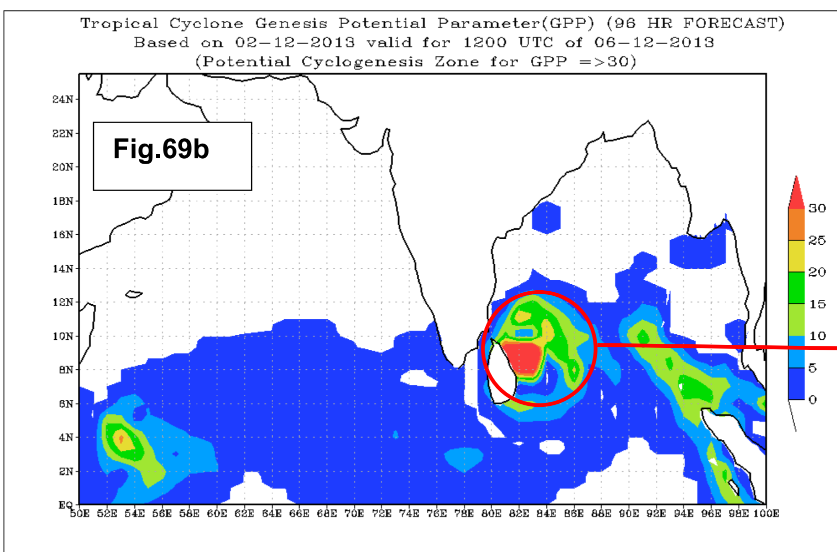
11.1. Grid point analysis and forecast of GPP

Objective: Grid point analysis and forecast of GPP is used to identify potential zone of cyclogenesis.

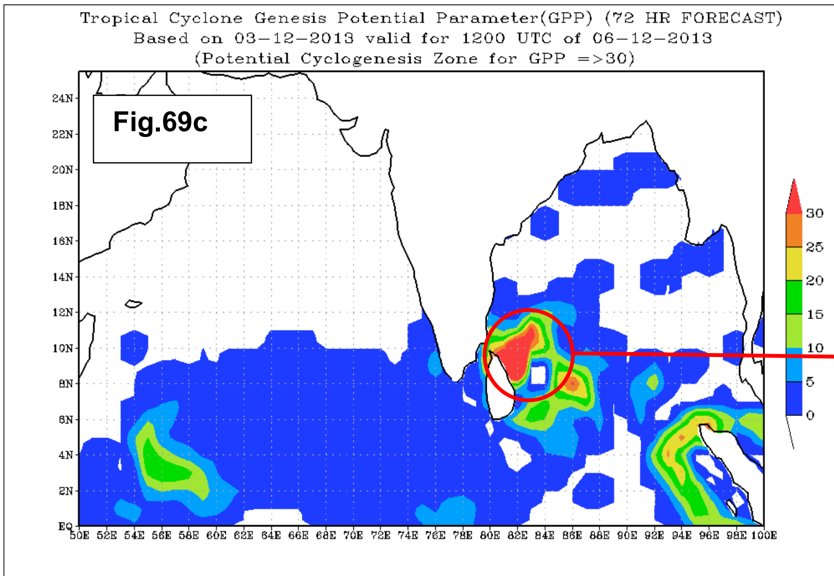
Figure 69(a-f) below shows the predicted zone of formation of cyclogenesis.



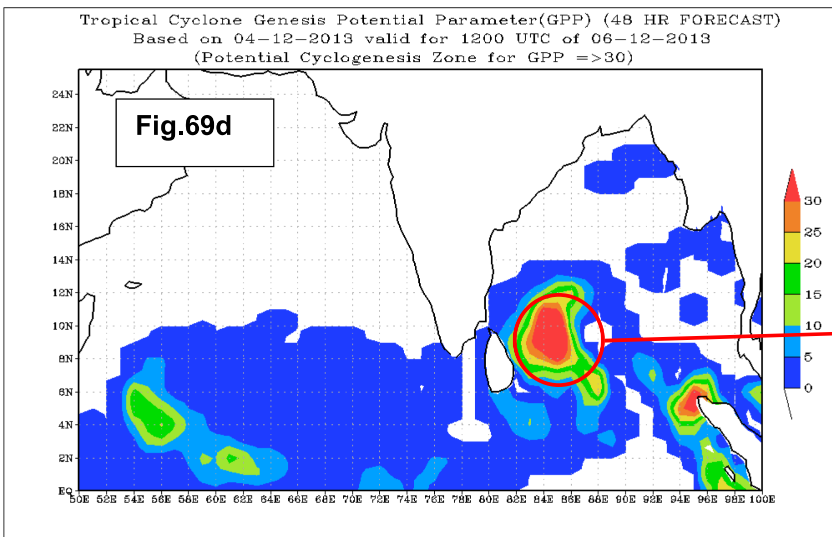
120 hour forecast of GPP valid for 12 UTC 06 October 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



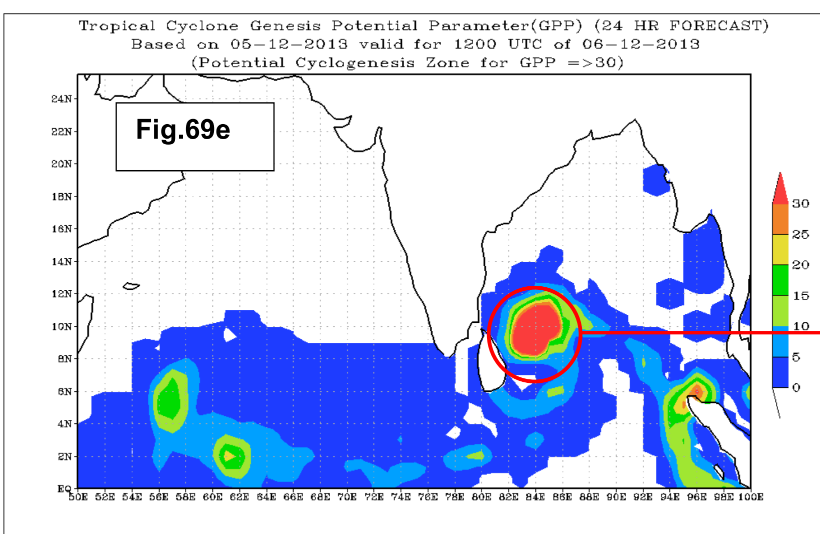
96 hour forecast of GPP valid for 12 UTC 06 October 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



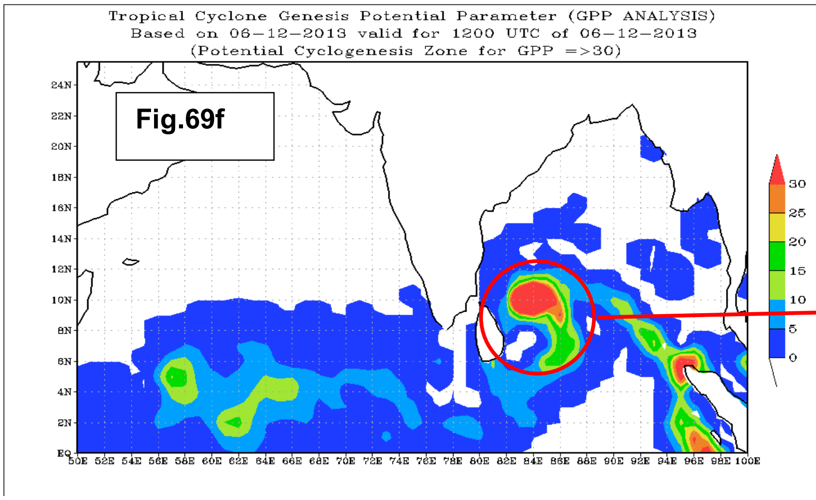
72 hour forecast of GPP valid for 12 UTC 06 October 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



48 hour forecast of GPP valid for 12 UTC 06 October 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



24 hour forecast of GPP valid for 12 UTC 06 October 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



Analysis of GPP on 12 UTC 06 December 2013 indicates the zone of cyclogenesis (Depression).

Figure 69(a-f): Predicted zone of cyclogenesis for MADI.

Inference: Grid point analysis and forecasts of GPP (Fig.69(a-f)) shows that it was able to predict the formation and location of the system before 120 hours of its formation.

11.2. Area average analysis of GPP

Objective: Since all low pressure systems do not intensify into cyclones, it is important to identify the potential of intensification (into cyclone) of a low pressure system at the early stages of development.

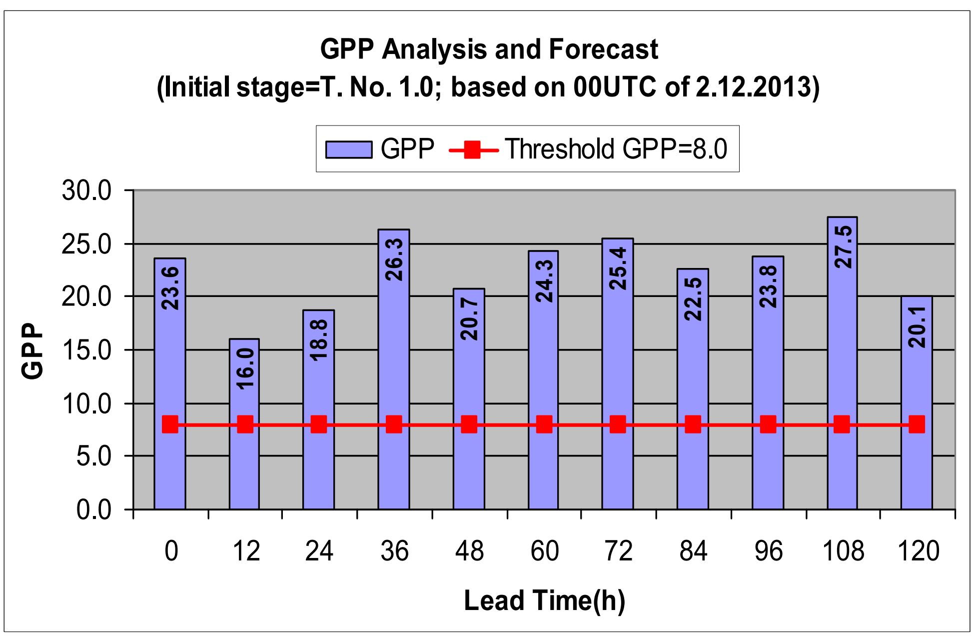


Fig 70a: Analysis and forecasts of GPP shows that GPP ≥ 8.0 (Threshold) at very early stage of development (**T.No.-1.0**) indicated its potentential to intensify into a cyclone.

Fig.70a

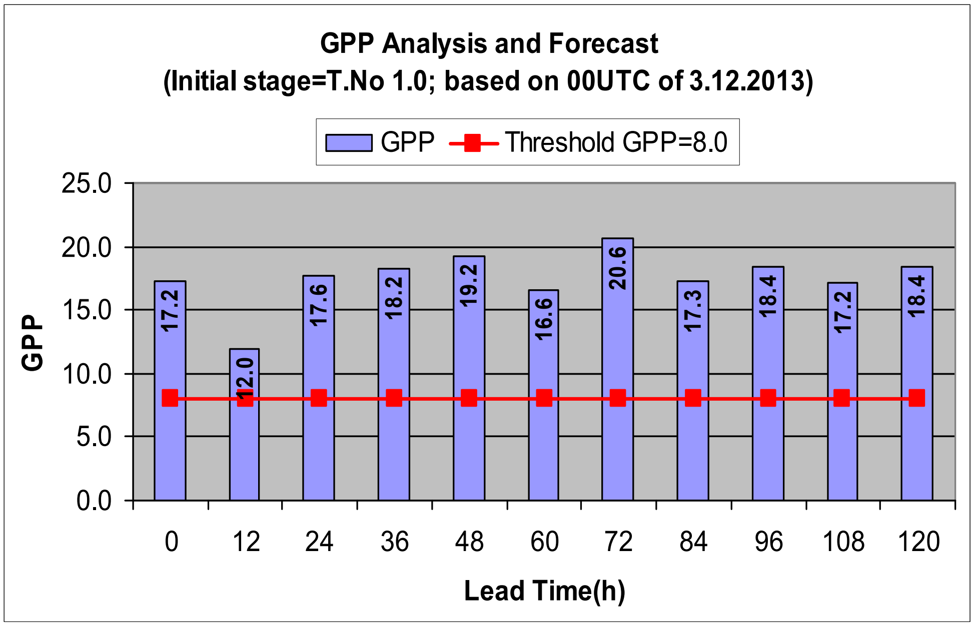


Fig 70b: Analysis and forecasts of GPP shows that GPP ≥ 8.0 (Threshold) at very early stage of development (**T.No. 1.0**) indicated its potentential to intensify into a cyclone.

Fig. 70b

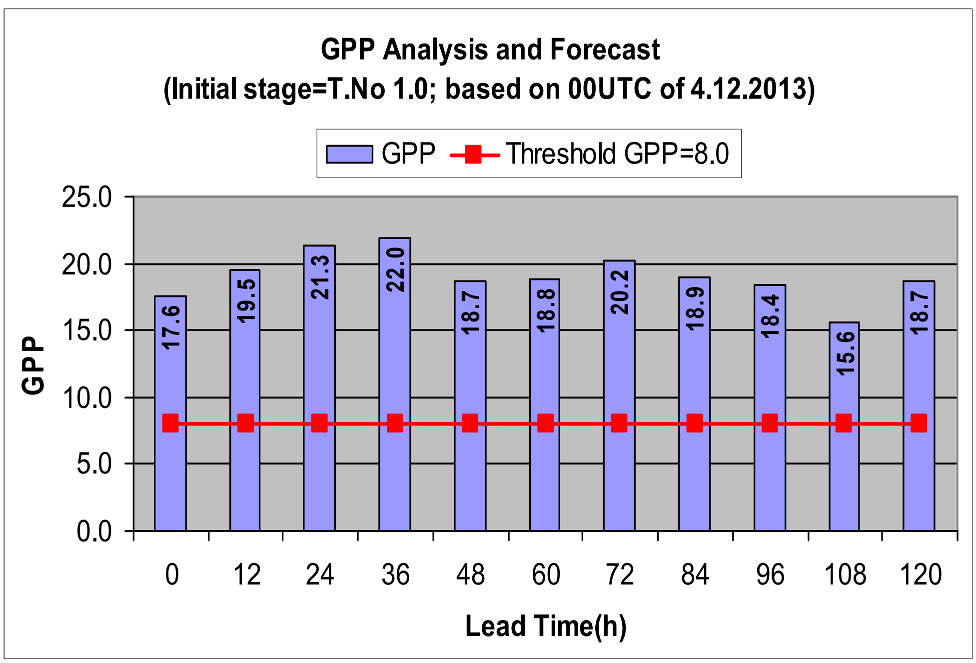


Fig 70c: Analysis and forecasts of GPP shows that GPP ≥ 8.0 (Threshold) at very early stage of development (**T.No. 1.0**) indicated its potentential to intensify into a cyclone.

Fig. 70c

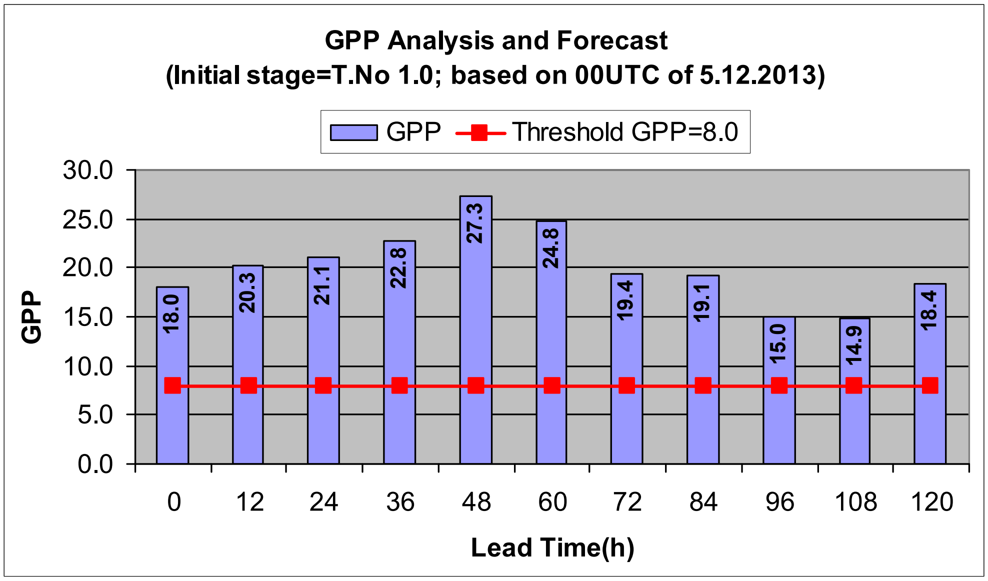


Fig 70d: Analysis and forecasts of GPP shows that GPP ≥ 8.0 (Threshold) at very early stage of development (**T.No. 1.0**) indicated its potential to intensify into a cyclone.

Fig. 70d

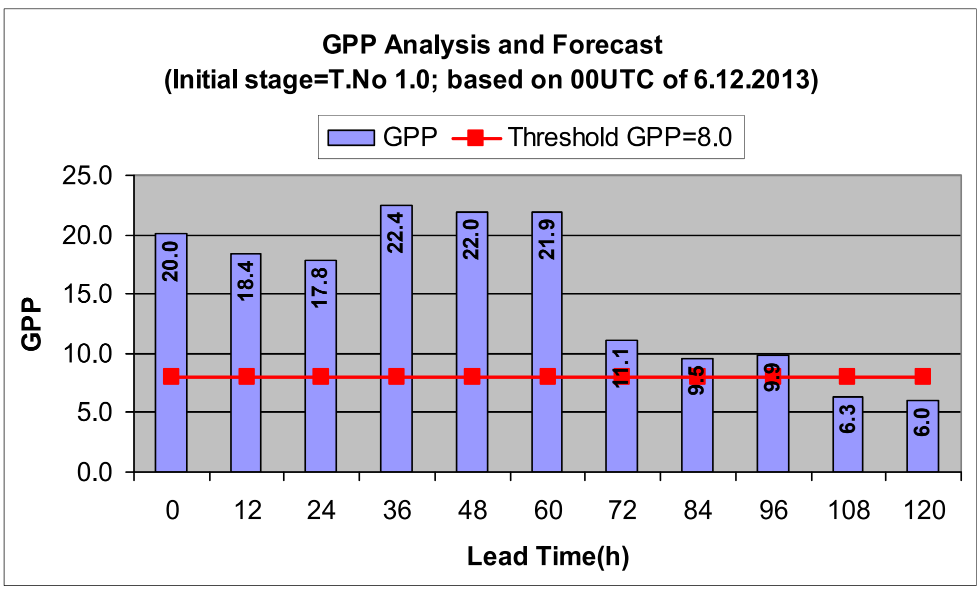


Fig 70e: Analysis and forecasts of GPP shows that GPP ≥ 8.0 (Threshold) at very early stage of development (**T.No. 1.0**) indicated its potential to intensify into a cyclone.

Fig. 70e

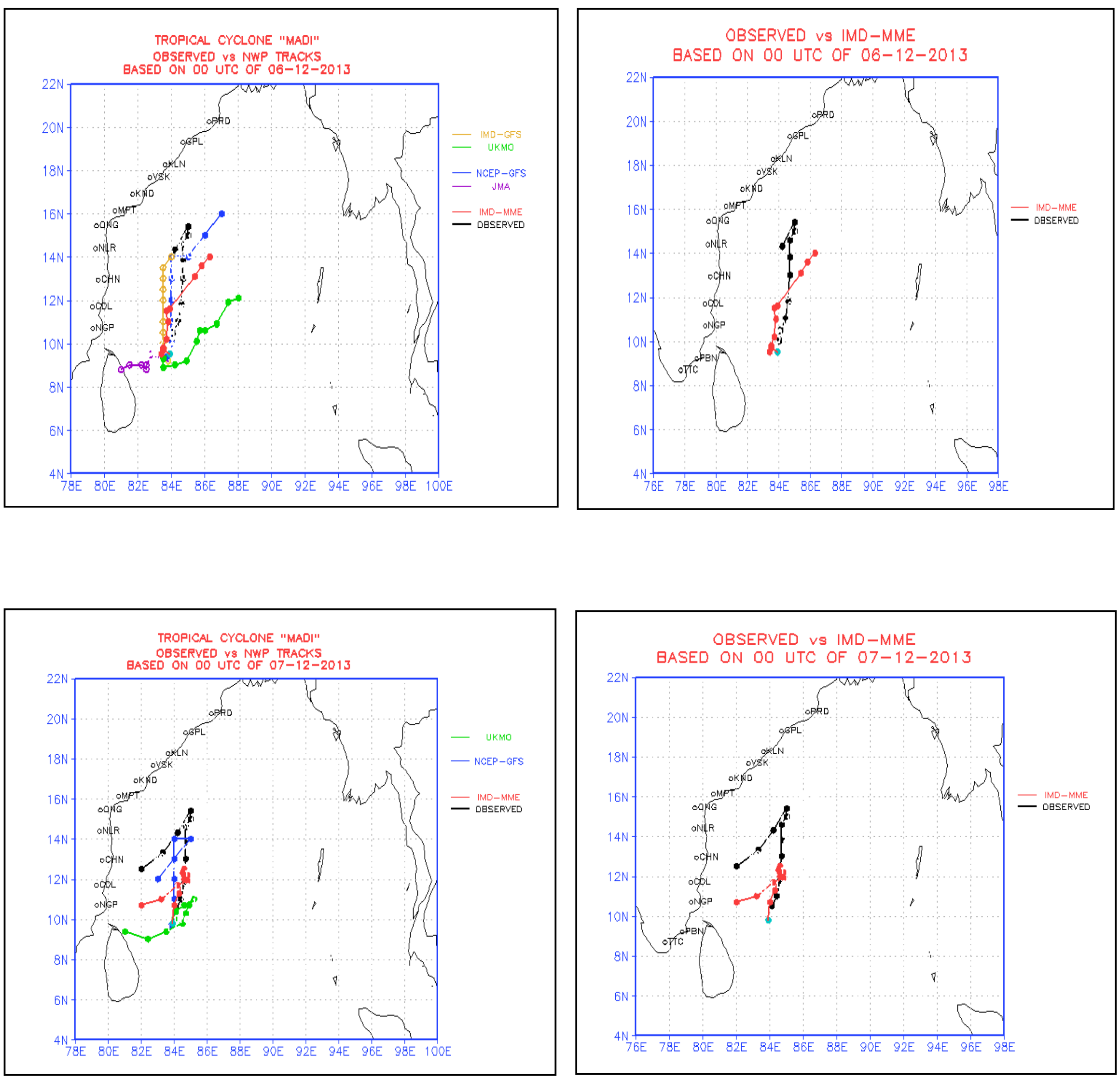
Fig. 70(a-e) Area average analysis of GPP for MADI

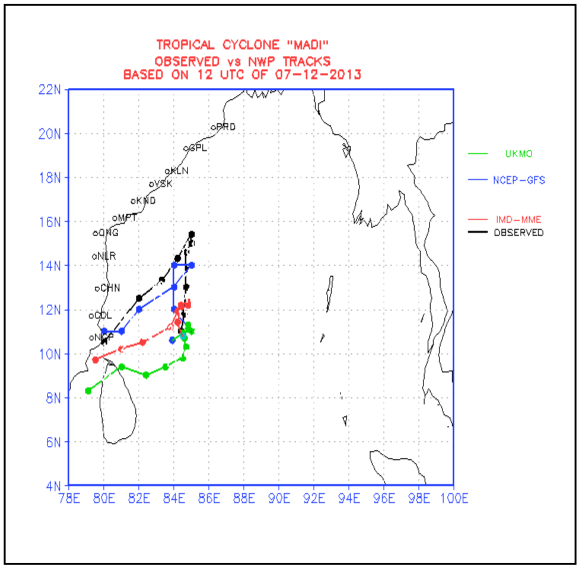
(Product available at http://www.imd.gov.in/section/nhac/dynamic/gpp.pdf)

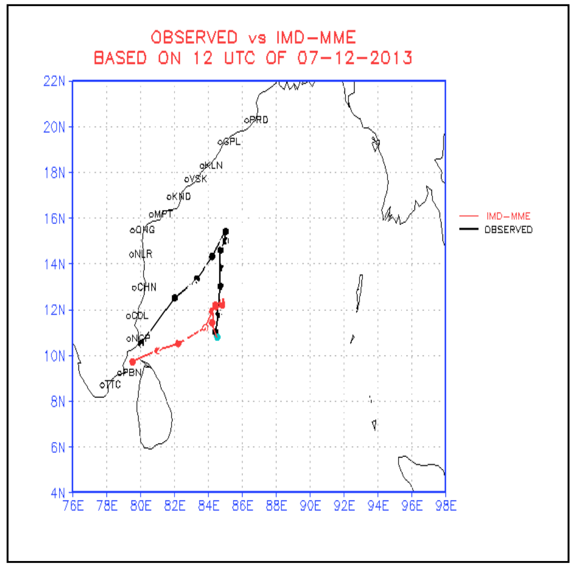
Inference: Analysis and forecasts of GPP (Fig.70(a-e)) shows that GPP ≥ 8.0 (threshold value for intensification into cyclone) indicated its potential to intensify into a cyclone at early stages of development (T.No. 1.0).

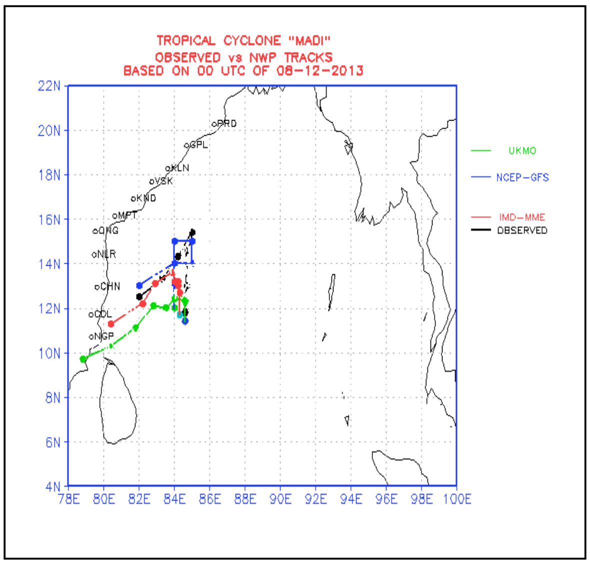
11.3. Track prediction

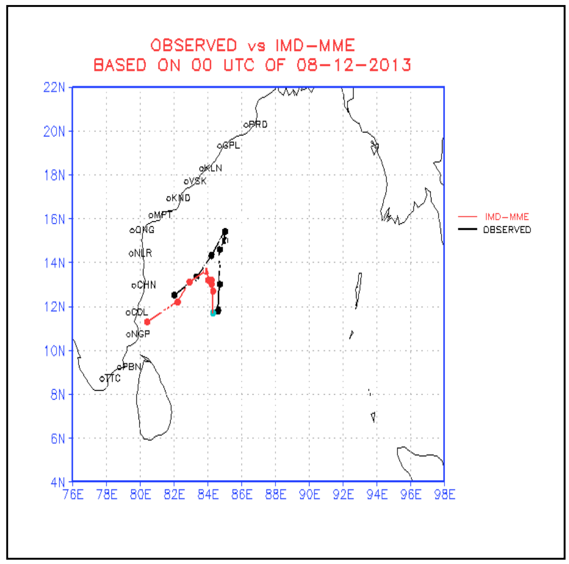
The average track forecast errors (DPE, CTE, ATE) of NWP models along with the consensus forecast by Multi-model ensemble (MME) forecast are presented in the Table 46, Table 47 and Table 48 respectively. The MME forecasts track based on different initial conditions along with the observed track is depicted in Fig 71. The figure shows that from the day1 (00 UTC 6 December to 00 UTC 11 December 2013), MME was able to predict correctly initially north northeastward movement then southwestward direction towards Tamil Nadu coast.

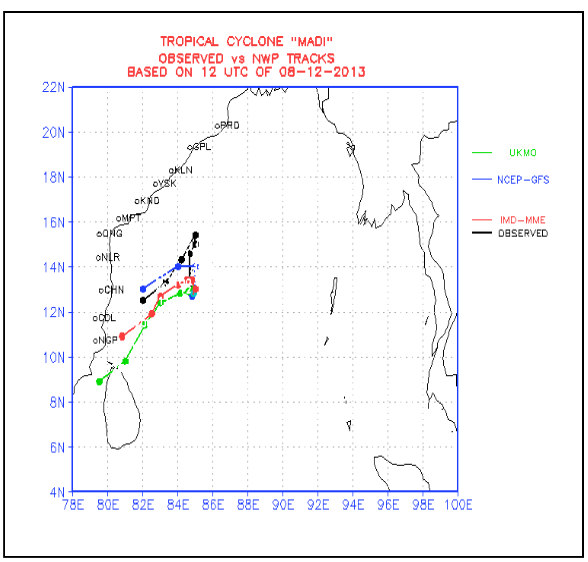


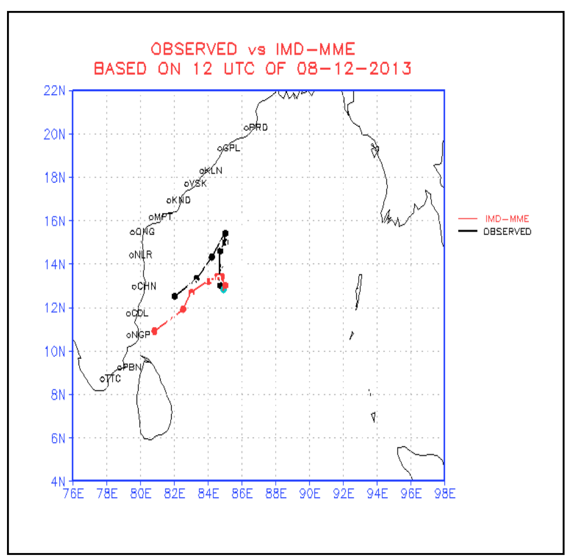

TROPICAL CYCLONE "MADI"
OBSERVED vs NWP TRACKS
BASED ON 12 UTC OF 07-12-2013
UKMO
NCEP-GFS
IMD-MME
OBSERVED

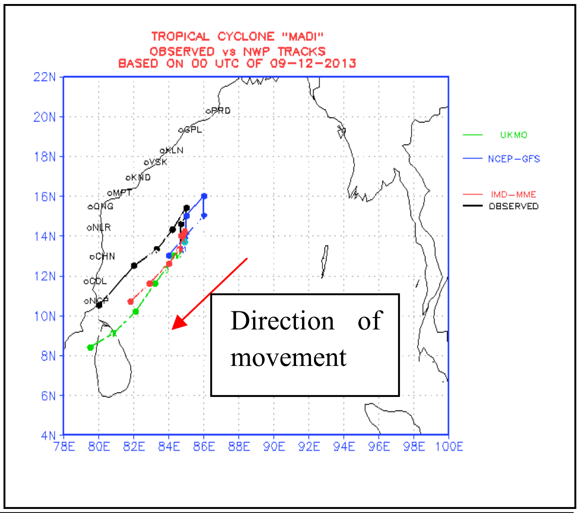

OBSERVED vs IMD-MME
BASED ON 12 UTC OF 07-12-2013
IMD-MME
OBSERVED

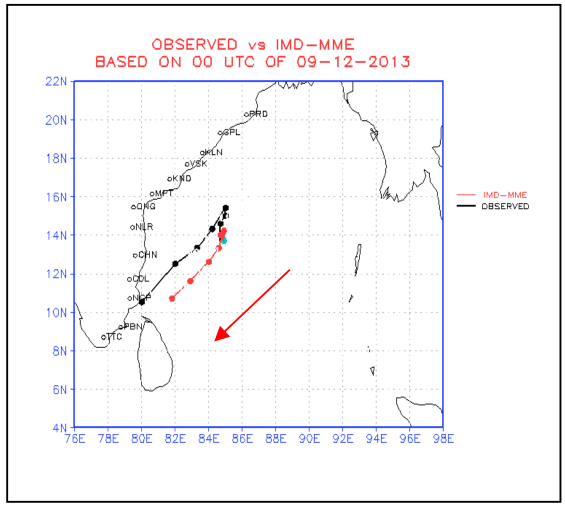

TROPICAL CYCLONE "MADI"
OBSERVED vs NWP TRACKS
BASED ON 00 UTC OF 08-12-2013
UKMO
NCEP-GFS
IMD-MME
OBSERVED

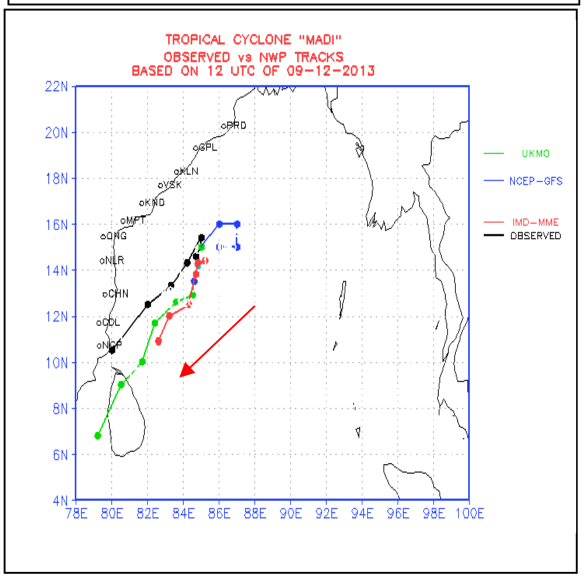

OBSERVED vs IMD-MME
BASED ON 00 UTC OF 08-12-2013
IMD-MME
OBSERVED

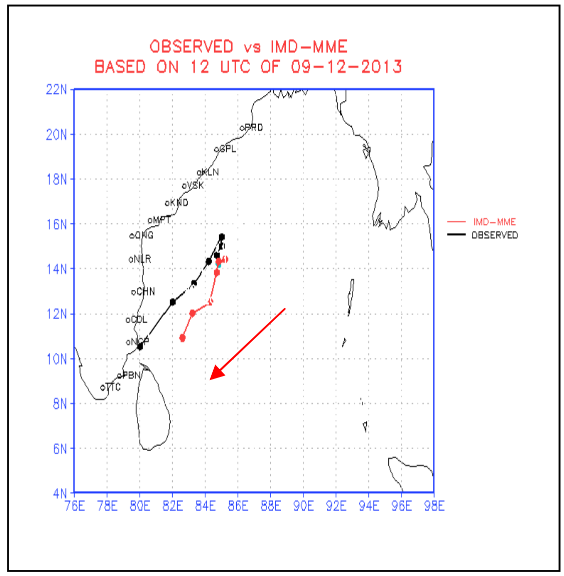

TROPICAL CYCLONE "MADI"
OBSERVED vs NWP TRACKS
BASED ON 12 UTC OF 08-12-2013
UKMO
NCEP-GFS
IMD-MME
OBSERVED

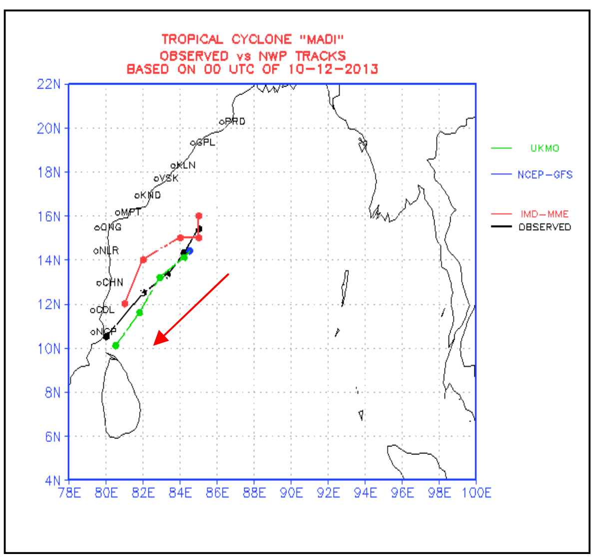

OBSERVED vs IMD-MME
BASED ON 12 UTC OF 08-12-2013
IMD-MME
OBSERVED

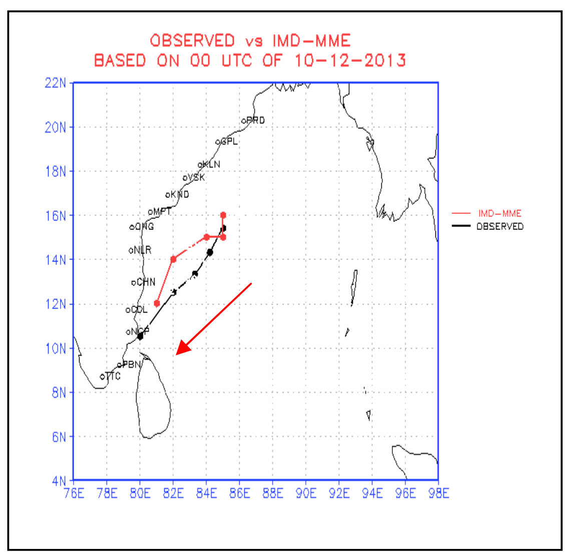

TROPICAL CYCLONE "MADI"
OBSERVED vs NWP TRACKS
BASED ON 00 UTC OF 09-12-2013
UKMO
NCEP-GFS
IMD-MME
OBSERVED
Direction of movement


OBSERVED vs IMD-MME
BASED ON 00 UTC OF 09-12-2013
IMD-MME
OBSERVED


TROPICAL CYCLONE "MADI"
OBSERVED vs NWP TRACKS
BASED ON 12 UTC OF 09-12-2013
UKMO
NCEP-GFS
IMD-MME
OBSERVED


OBSERVED vs IMD-MME
BASED ON 12 UTC OF 09-12-2013
IMD-MME
OBSERVED


TROPICAL CYCLONE "MADI"
OBSERVED vs NWP TRACKS
BASED ON 00 UTC OF 10-12-2013
UKMO
NCEP-GFS
IMD-MME
OBSERVED


OBSERVED vs IMD-MME
BASED ON 00 UTC OF 10-12-2013
IMD-MME
OBSERVED

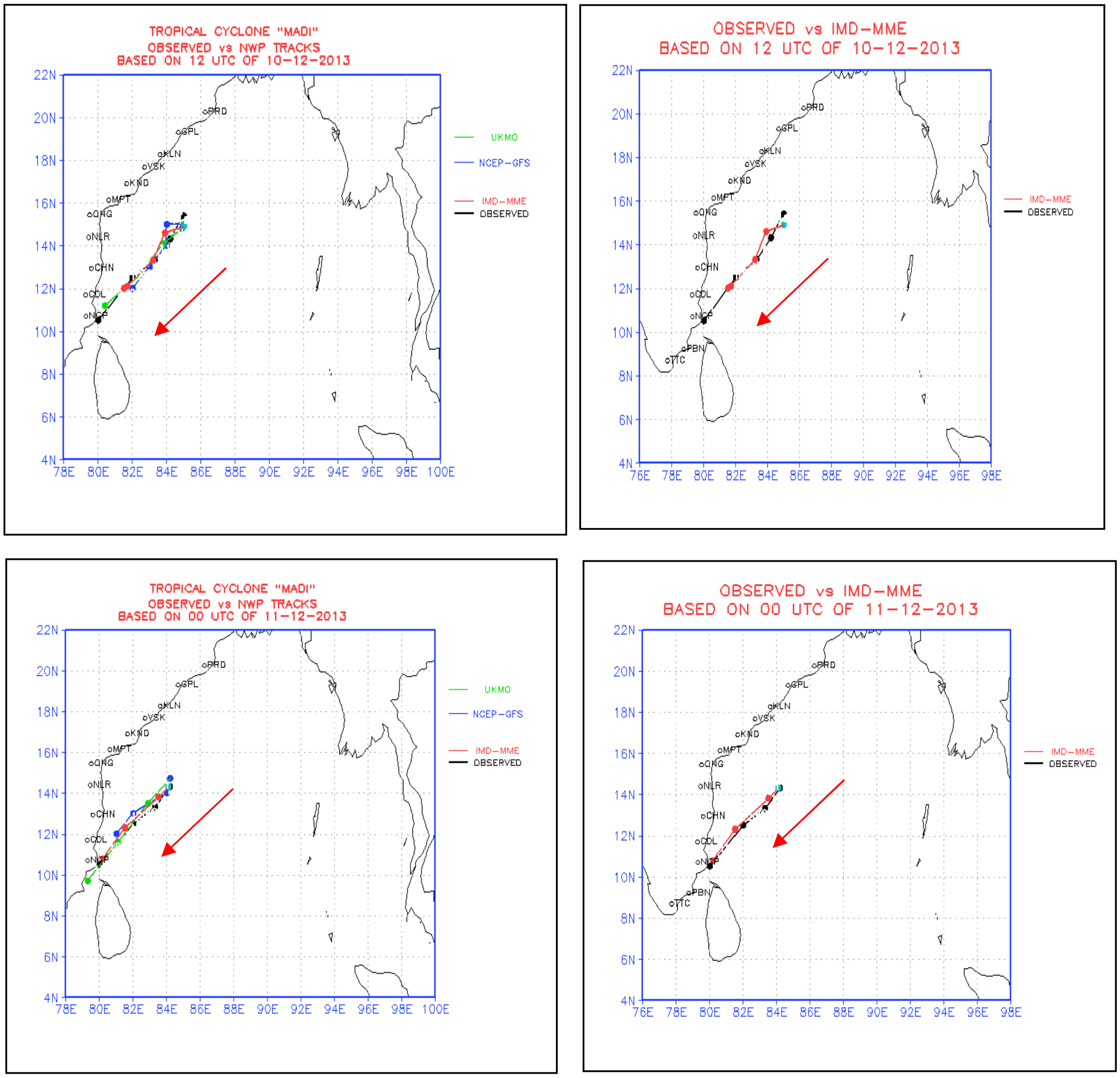


Fig. 71. MME forecasts track based on different initial conditions for MADI

Direct position Error (DPE): Average track forecast error (direct position error (DPE)) was highest for JMA (about 155 km at 12 h to 760 km at 84 h) for one forecast only and UKMO (about 115 km at 12 h to 500 km at 96 h and 370 at 120 h). Average DPE was lowest for NCEP-GFS (about 75 km at 12 h to 250 km at 72 h and 175 at 120h), IMD-GFS (about 60 km at 12 h to 230 km at 84 h and 40 at 120h for one forecast only), and for MME (about 65 km at 12 h to 280 km at 84 h and 180 at 120 h)(Table-46). The DPE of all models are shown in Fig. 72.

.

Table-46. Average track forecast errors (DPE) in km (Number of forecasts verified) of MADI

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
IMD-GFS	59(1)	86(1)	113(1)	149(1)	171(1)	194(1)	220(1)	232(1)	189(1)	40(1)
JMA	153(1)	242(1)	321(1)	405(1)	521(1)	637(1)	760(1)	-	-	-
NCEP-GFS	77(10)	76(10)	145(10)	175(9)	179(8)	250(7)	176(6)	131(5)	149(4)	177(3)
UKMO	114(10)	190(10)	256(10)	356(8)	416(7)	463(7)	471(6)	499(4)	439(3)	368(3)
IMD-MME	65(10)	95(10)	133(10)	197(9)	214(8)	255(7)	278(6)	264(4)	250(3)	178(3)
IMD-OFFICIAL	49(21)	89(19)	115(17)	150(17)	196(15)	231(13)	272(11)	313(9)	438(7)	463(4)

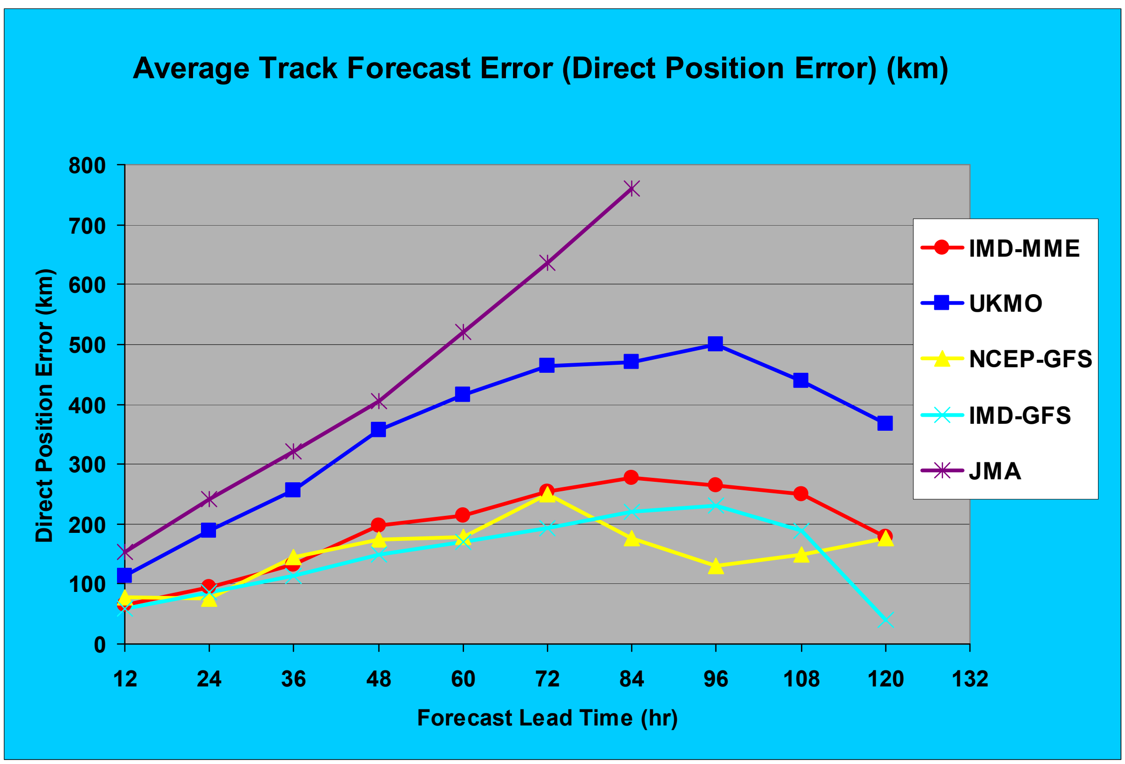


Fig. 72: Average track forecast errors (DPE) of NWP models for MADI

Cross Track Error (CTE): Average cross track error (CTE) was highest for JMA (about 130 km at 12 h to 305 km at 84 h) and UKMO (about 35 km at 12 h to 325 km at 120 h).

Average CTE was lowest for IMD-GFS (for one forecast only), NCEP-GFS and MME (about 40 km at 12 h to 125 km at 120 h) (Table-47). The CTE of all models are shown in Fig. 73.

Table-47. Average cross track error (CTE) in km for MADI

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
IMD-GFS	55	54	71	86	102	102	102	127	78	20
JMA	132	140	105	115	168	251	307	-	-	-
NCEP-GFS	44	39	53	79	46	50	49	106	126	127
UKMO	37	24	59	134	184	220	221	254	300	326
IMD-MME	36	27	46	77	104	139	144	147	161	96

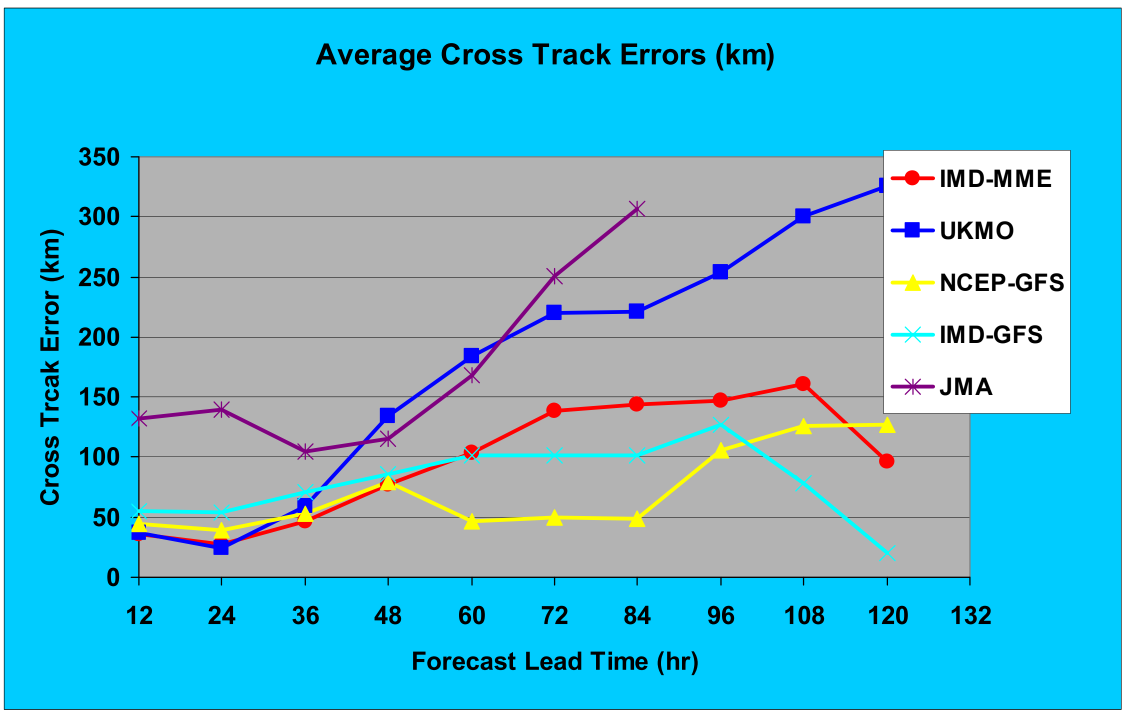


Fig. 73: Average cross track errors (CTE) of NWP models for MADI

Along Track Error (ATE): Average along track error (ATE) was highest for JMA (about 80 km at 12 h to 695 km at 84 h). ATE was lowest for IMD-GFS (one forecast only), NCEP-GFS, MME (about 45 km at 12 h to 140 km at 120 h). The ATE for MME was highest at 96h about 200 km (Table-48). The ATE of all models is shown in Fig. 74.

Table-48. Average along track error (ATE) in km for MADI

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
IMD-GFS	22	67	88	122	137	165	195	194	172	34
JMA	78	197	303	388	494	586	695	-	-	-
NCEP-GFS	46	51	125	135	164	229	149	63	58	109
UKMO	103	188	247	315	352	368	359	401	286	170
IMD-MME	46	85	114	156	152	165	192	198	154	141

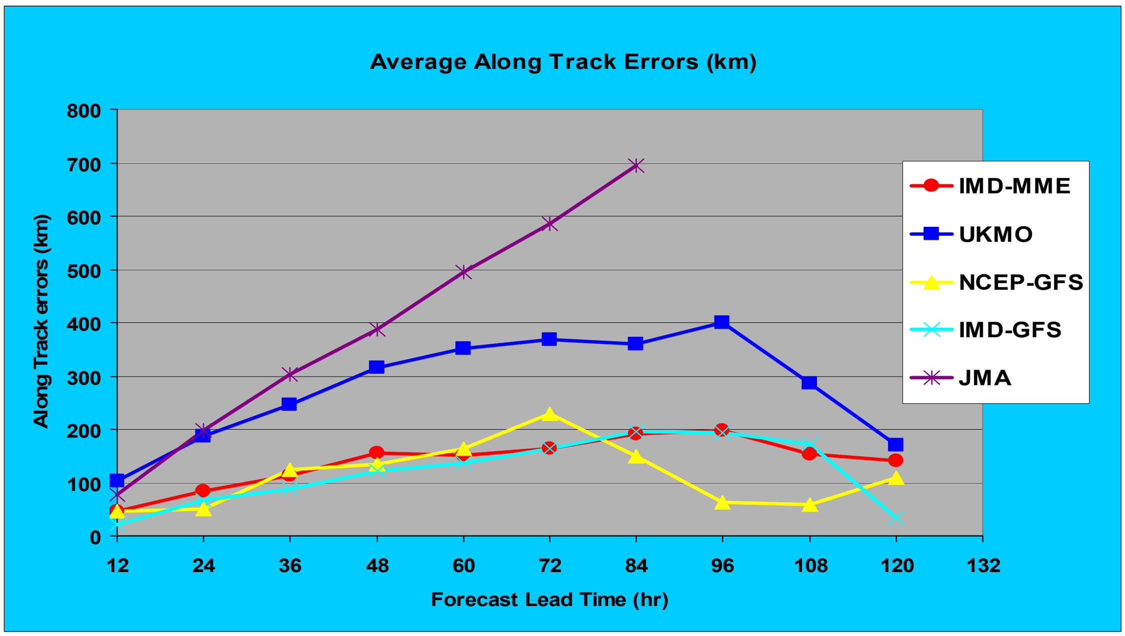


Fig. 74: Average along track errors (ATE) of NWP models for MADI

Track Forecast Error of MME: The DPE, ATE and CTE of consensus forecast of NWP models (MME) are shown in Fig 75, Fig 76 and Fig 77 respectively.

The average DPE of MME was about 65 km at 12 h to 280 km at 84h and 180 km at 120 h (Fig. 75).

The average ATE of MME was about 45 km at 12 h to 200 km at 96h and 140 km at 120 h (Fig. 76).

The average CTE of MME was about 35 km at 12 h to 145 km at 84h and 95 km at 120 h (Fig. 77).

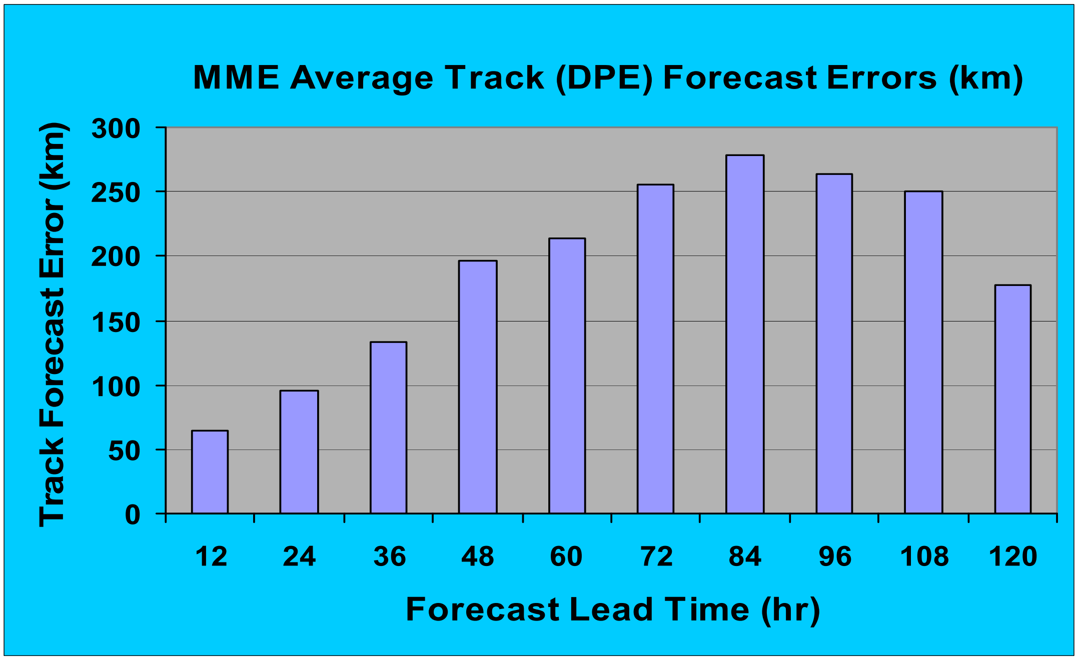


Fig. 75: Average direct track error (DPE) of MME for MADI

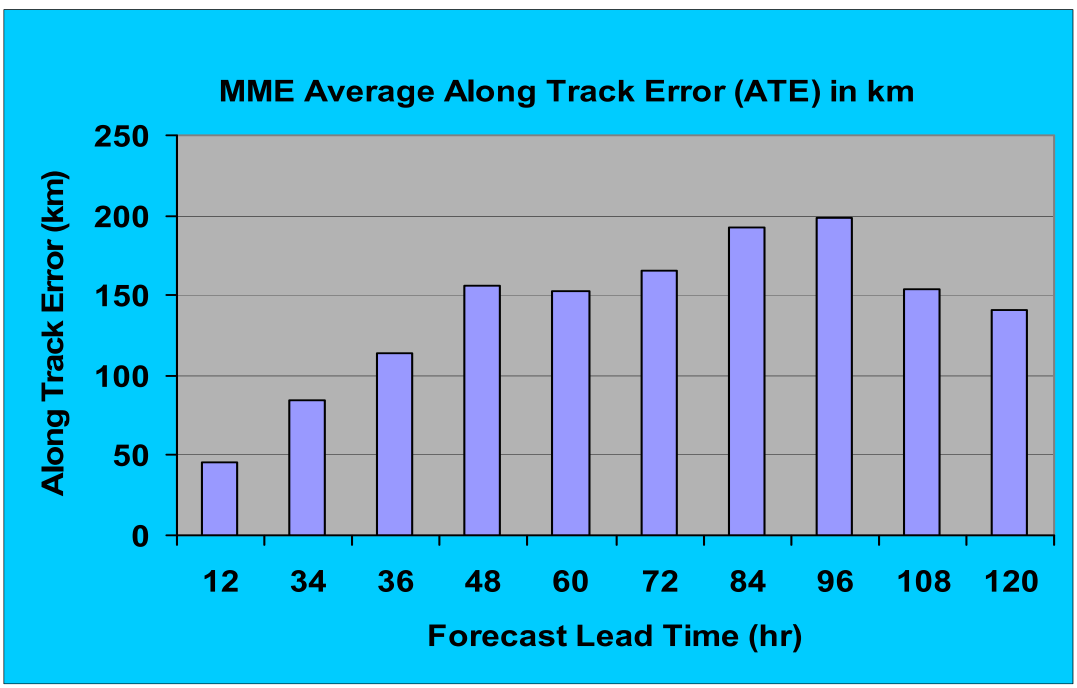


Fig. 76: Average along track error (ATE) of MME for MADI

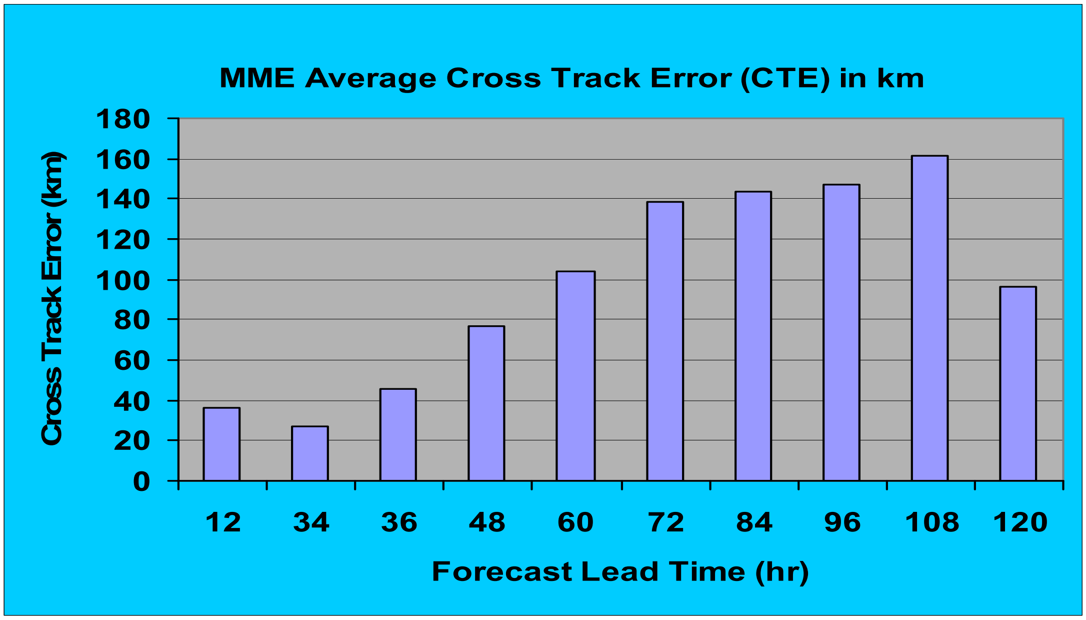


Fig. 77: Average cross track error (CTE) of MME for MADI

11.4. Intensity prediction

Intensity prediction (at stages of 12-h intervals) by statistical-dynamical model SCIP using different initial conditions is shown in Fig. 78. The model was able to predict the intensification in the initial stage and decay over Sea after attaining the very severe stage (VSCS) in the later stage.

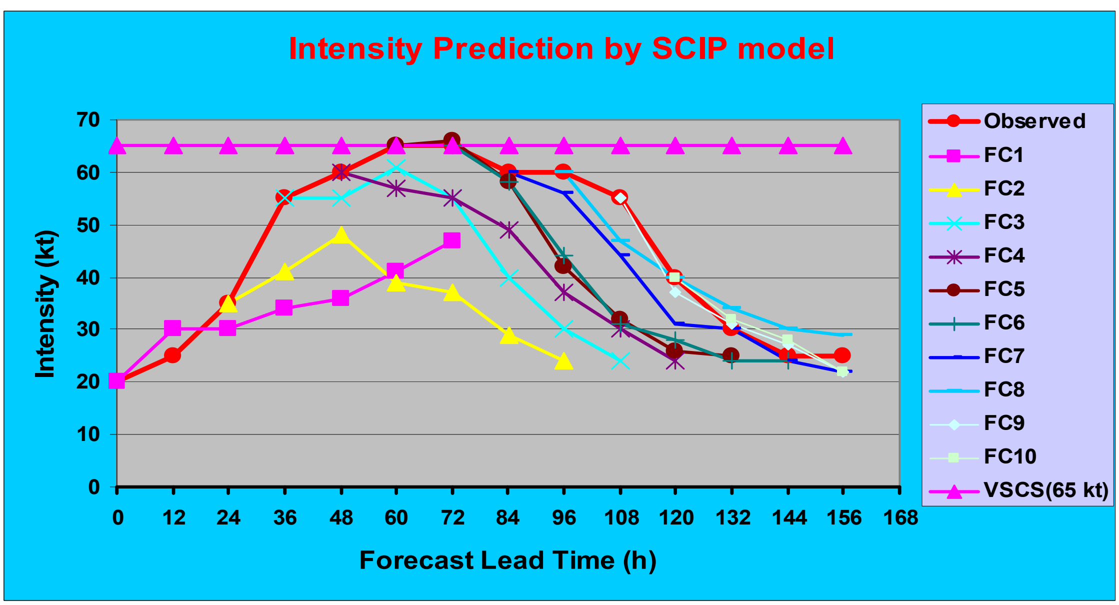


Fig. 78. Intensity forecasts of SCIP model for MADI

Average absolute error (AEE) and Root mean square error (RMSE) of SCIP forecast error is presented in the following Table-49(a-b). AAE of SCIP was 5.2 kts at 12h and 15.7 kt at 72h and RMSE varies from 6.4 kt at 12h to 20.3 kt at 72 h.

Table-49a Average absolute errors (AAE) of SCIP (Number of forecasts verified is given in the parentheses) for cyclone MADI

Lead time →	**12 hr**	**24 hr**	**36 hr**	**48 hr**	**60 hr**	**72 hr**	**84 hr**	**96 hr**	**108 hr**	**120 hr**
IMD-SCIP	5.2(10)	6.4(10)	12.8(10)	15.3(9)	16.9(8)	15.7(7)	-	-	-	-
IMD-OFFICIAL	5.0(23)	6.6(21)	8.8(19)	8.7(17)	7.5(15)	7.3(13)	9.0(11)	11.3(9)	14.8(7)	14.2(5)

Table-49b Root Mean Square (RMSR) of SCIP (Number of forecasts verified is given in the parentheses) for cyclone MADI

Lead time →	**12 hr**	**24 hr**	**36 hr**	**48 hr**	**60 hr**	**72 hr**	**84 hr**	**96 hr**	**108 hr**	**120 hr**
IMD-SCIP	6.4(10)	8.2(10)	15.3(10)	18.2(9)	20.3(8)	20.3(7)	-	-	-	-
IMD-OFFICIAL	6.5(23)	8.1(21)	10.6(19)	9.9(17)	8.9(15)	9.8(13)	11.8(11)	13.0(9)	15.2(7)	14.4(5)

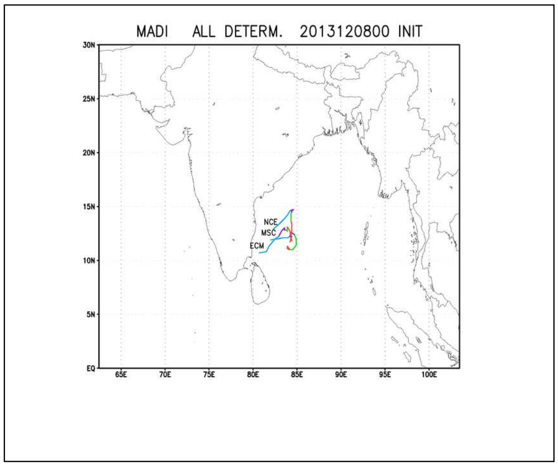
11.5. Probability of Rapid intensification (by RI-Index)

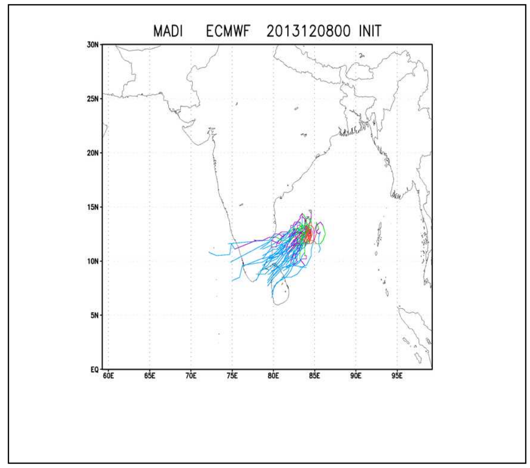
Table-50 Probability of Rapid intensification (Increase of intensity by 30 kts or more in 24 h) for MADI

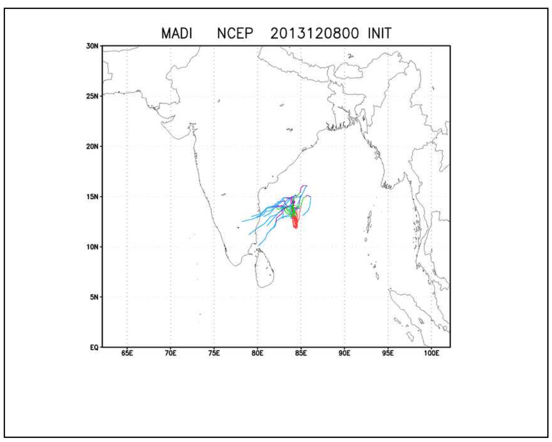
Forecast based on	**Probability of RI predicted**	**Chances of occurrence predicted**	**Intensity changes (kt) in 24h**	**Occurrence**
00 UTC/06.12.2013	5.2 %	VERY LOW	10	NO
00 UTC/07.12.2013	22.0 %	LOW	25	NO
12 UTC/07.12.2013	5.2 %	VERY LOW	10	NO
00 UTC/08.12.2013	22.0 %	LOW	5	NO
12 UTC/08.12.2013	9.4 %	VERY LOW	-5	NO
00 UTC/09.12.2013	9.4 %	VERY LOW	-5	NO
12 UTC/09.12.2013	22.0 %	LOW	-5	NO
00 UTC/10.12.2013	9.4 %	VERY LOW	-20	NO
12 UTC/10.12.2013	0 %	NIL	-25	NO
00 UTC/11.12.2013	0 %	NIL	-15	NO
Inference: RI-Index was able to predict **NON-OCCURENCE** of Rapid Intensification of cyclone MADI during its lifetime by all ten forecasts issued.				

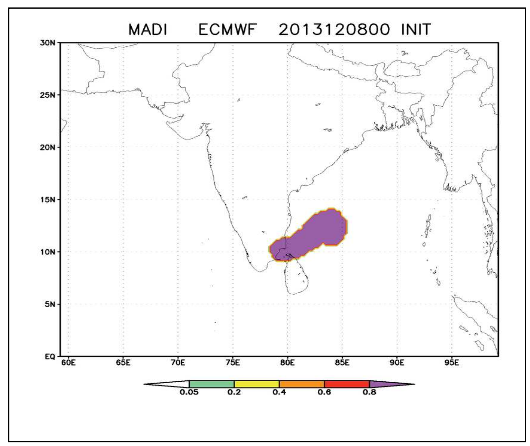
11.6. Ensemble track and Strike Probability forecasts for MADI

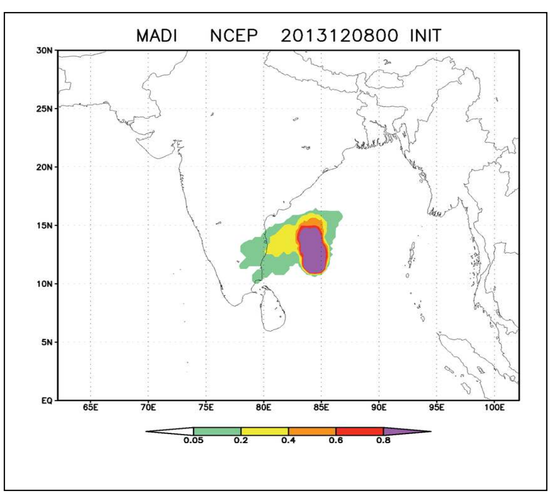
a. Based on 0000 UTC 08.12.2013

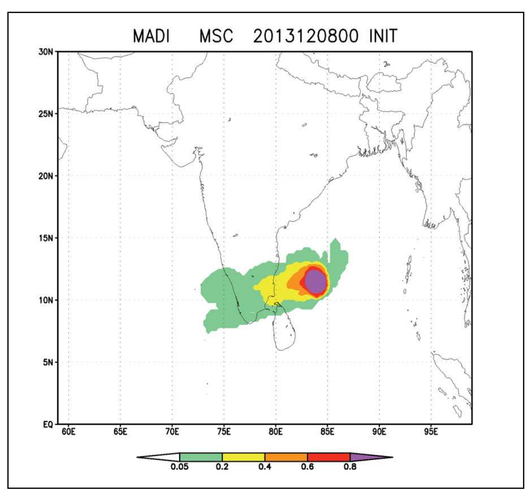




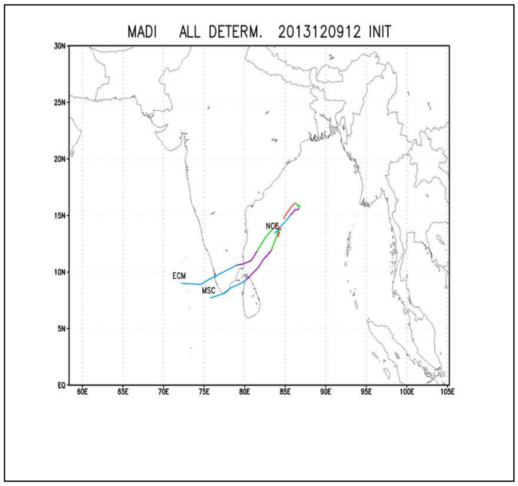


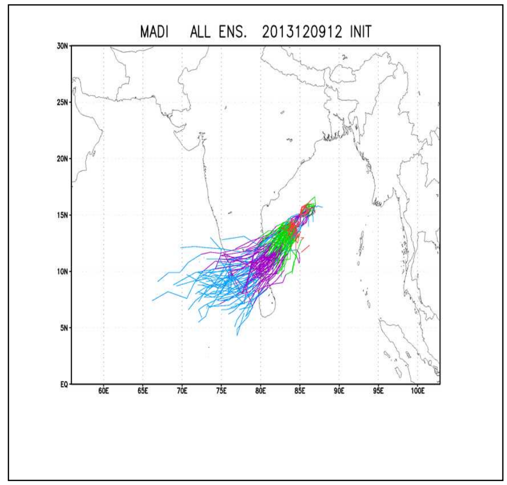


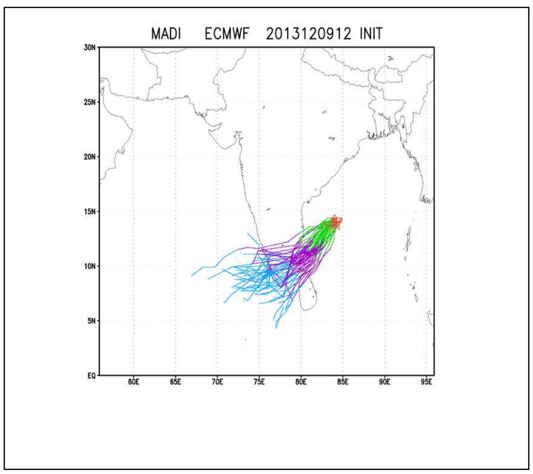


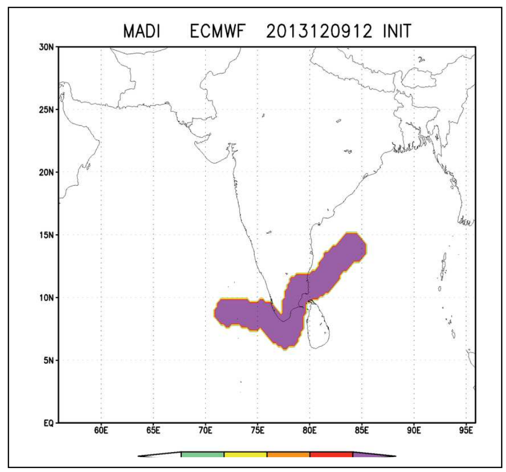


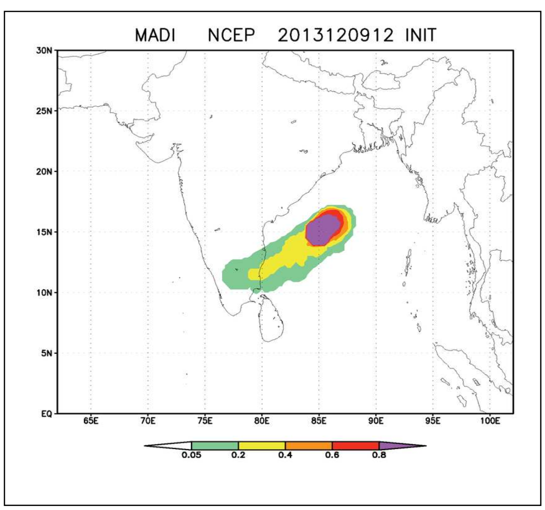
b. Based on 1200 UTC 09.12.2013

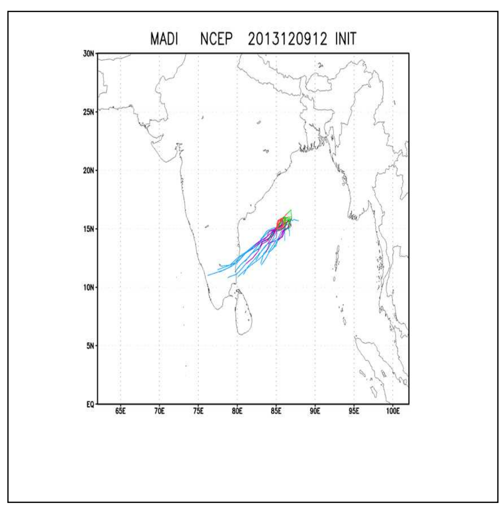












c. Based on 0000 UTC 10.12.2013

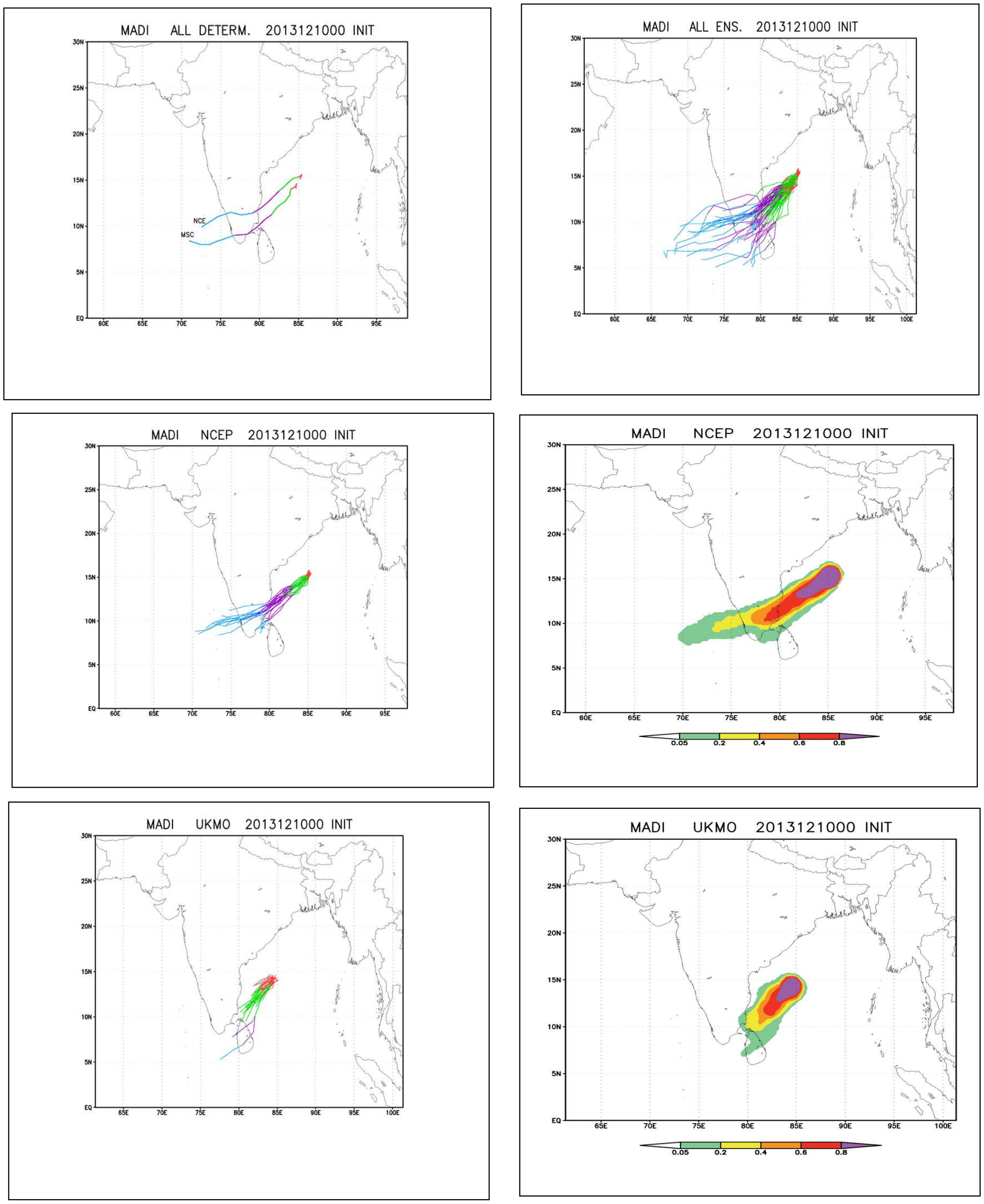


Fig. 79 Ensemble track and strike probability forecasts for MADI

Ensemble track and strike probability forecast (Fig. 79) based on 00 UTC of 8.12.2013, 12 UTC of 9.12.2013 and 00 UTC of 10.12.2013 shows that UKMO, ECMWF, and NCEP all was able to predict north northeastward movement initially and southwestwards thereafter towards Tamil Nadu coast.

12. Mean forecast errors for Cyclonic Storms during 2013

12.1. POD and FAR of Cyclogenesis by Genesis Potential Parameter (GPP)

Probability of detection (POD) and false alarm ratio (FAR) of Cyclogenesis by Genesis Potential Parameter (GPP) (Fig 80) shows that POD was 63% and FAR was 37% during 2013. Fig 81 shows that POD was 73% and FAR was 27% during 2008-2013.

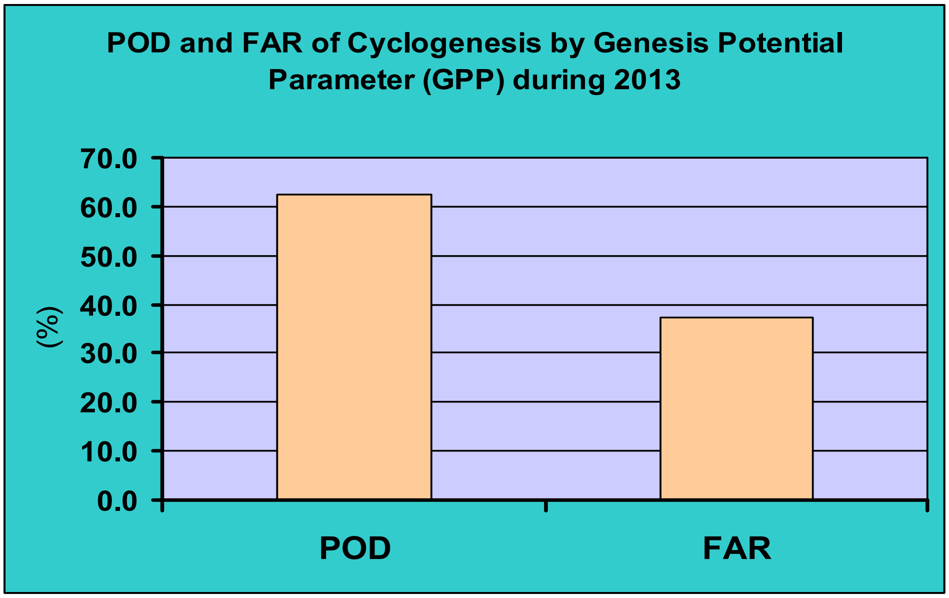


Fig. 80 POD and FAR of Cyclogenesis by Genesis Potential Parameter (GPP) during 2013

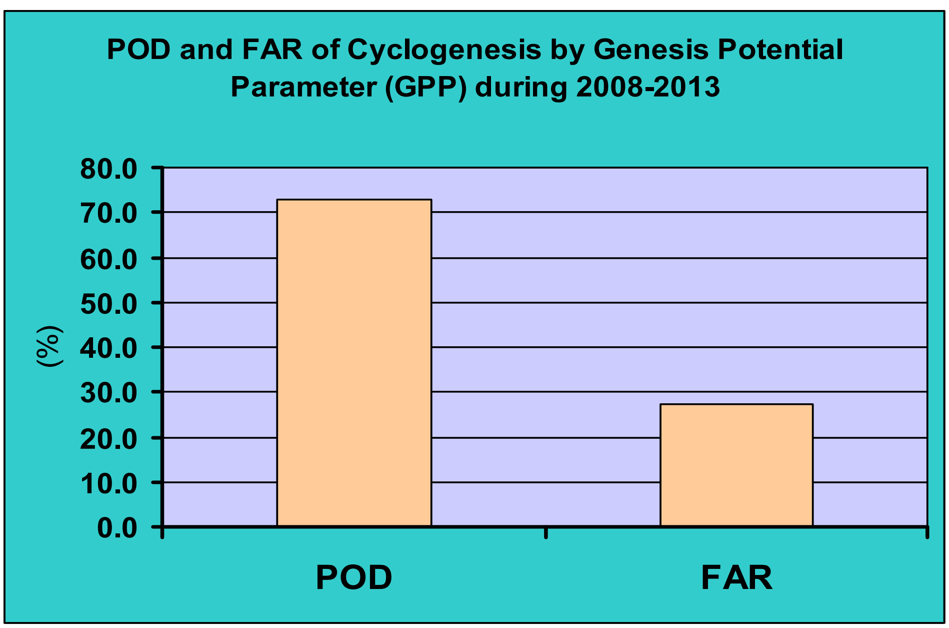


Fig. 81 POD and FAR of Cyclogenesis by Genesis Potential Parameter (GPP) during 2008-2013

12.2. Mean track forecast error (km) (Direct position error (DPE))-2013

The annual average track forecast errors (DPE) of various models for the year 2013 are shown in Table 51a (Fig. 82). The 24 hr track forecast errors is less than 100 km for NCEP and MME, 48 hr track forecast errors is less than 150 km for NCEP and MME, 72hr track forecast errors is less than 200 km for NCEP, ECMWF and MME, 96hr track forecast errors is less than 200 km for NCEP, ECMWF and 210 km for MME, 120hr track forecast errors is less than 200 km for NCEP and MME. Forecast verification carried out for the systems and corresponding models is shown in Table-51b.

Table-51a: Mean track forecast error (DPE) (km) during 2013 (Number of forecast verified)

FORECAST HOUR→	12H	24H	36H	48H	60H	72H	84H	96H	108H	120H
IMD-GFS	90(36)	119(34)	173(31)	200(26)	253(22)	213(17)	272(14)	254(10)	252(7)	277(5)
IMD-WRF	90(36)	153(34)	225(31)	288(26)	345(20)	340(15)	-	-	-	-
JMA	178(37)	184(35)	220(32)	217(27)	213(22)	210(17)	281(15)	-	-	-
NCEP GFS	82(46)	79(44)	128(40)	131(35)	166(30)	189(24)	220(24)	159(15)	193(11)	186(8)
UKMO	101(36)	144(35)	173(32)	209(27)	275(22)	306(19)	322(16)	337(11)	320(8)	309(6)
ECMWF	105(8)	149(7)	202(6)	153(5)	199(5)	173(4)	224(4)	104(3)	255(3)	233(2)
IMD-QLM	163(7)	230(6)	292(5)	252(4)	289(4)	238(3)	-	-	-	-
IMD-HWRF	65(32)	139(30)	195(27)	227(23)	258(20)	316(16)	354(13)	401(10)	447(7)	510(4)
IMD-MME	68(46)	90(44)	121(41)	132(35)	164(30)	175(24)	204(20)	210(14)	231(11)	187(8)
IMD-OFFICIAL	64(94)	109(84)	135(72)	157(65)	175(55)	195(44)	205(34)	251(26)	305(18)	296(11)

Table-51b: Forecast verification carried out for the systems and corresponding models

MODEL	Forecast verified for the cyclonic systems over the North Indian Ocean during 2013
IMD-GFS	MAHASEN, PHAILIN, DD-Arabian Sea, D-Bay of Bengal, HELEN, LEHAR, MADI(one forecast only)
IMD-WRF	MAHASEN, PHAILIN, DD-Arabian Sea, D-Bay of Bengal, HELEN, LEHAR
JMA	MAHASEN, PHAILIN, DD-Arabian Sea, D-Bay of Bengal, HELEN, LEHAR, MADI
NCEP GFS	MAHASEN, PHAILIN, DD-Arabian Sea, D-Bay of Bengal, HELEN, LEHAR, MADI
UKMO	MAHASEN, PHAILIN, DD-Arabian Sea, D-Bay of Bengal, HELEN, LEHAR, MADI
ECMWF	MAHASEN
IMD-QLM	MAHASEN
IMD-HWRF	MAHASEN, PHAILIN, HELEN, LEHAR
IMD-MME	MAHASEN, PHAILIN, DD-Arabian Sea, D-Bay of Bengal, HELEN, LEHAR, MADI

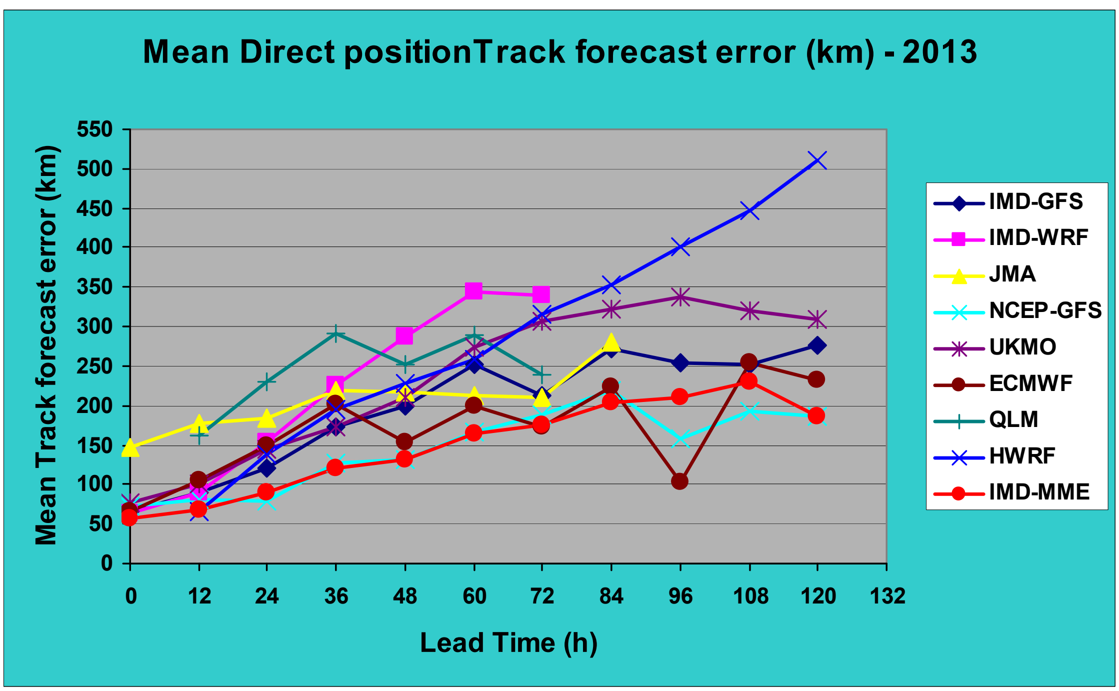


Fig. 82 Mean direct position track (DPE) forecast error (km) – 2013

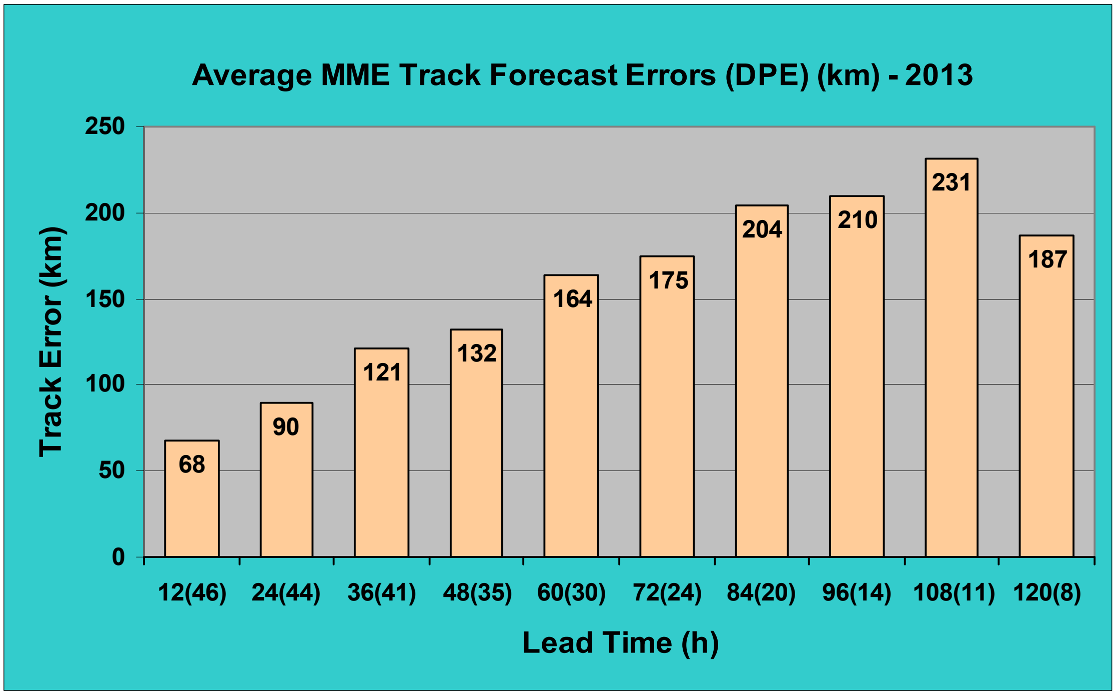


Fig. 83 Average MME track forecast error (DPE) (km) during 2013

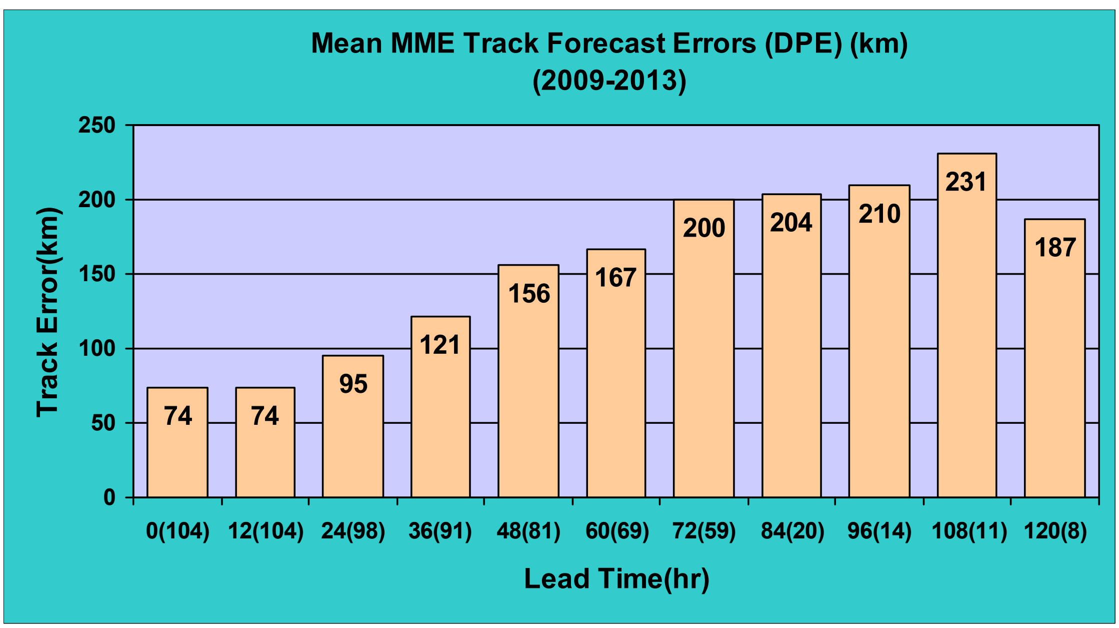


Fig. 84 Average MME track forecast error (DPE) (km) during 2009-2013*

* 84h to 120h track forecast errors of MME shown in **Fig 84** above is for 2013 only as MME track forecast lead time has been extended from 72h to 120h in 2013.

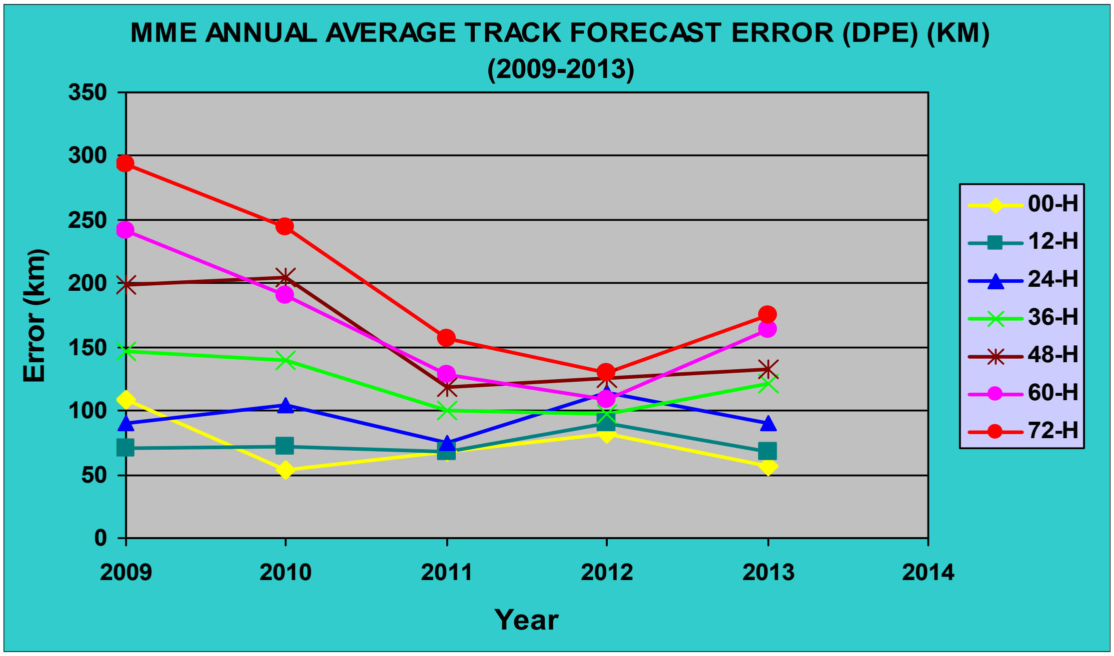


Fig. 85 Yearly average MME track forecast error (km) during 2009-2013

Fig. 85 shows that improvement of forecast errors from 2009 to 2011 and forecast error was ranged from about 50 km to 150 km for 12h to 72h during past three hours from 2011 to 2013.

12.3. Mean track forecast error (km) (Along track error (ATE))-2013

Table-52: Mean along track forecast error (ATE) (km) during 2013

HR→	12h	24h	36h	48h	60h	72h	84h	96h	108h	120h
IMD-GFS	53	76	123	143	159	140	157	97	135	132
IMD-WRF	50	94	141	166	201	169	***	***	***	***
JMA	105	124	133	120	126	131	189	***	***	***
NCEP	49	46	79	68	105	129	87	74	87	84
UKMO	72	114	141	169	213	241	249	264	231	198
ECMWF	53	98	135	51	101	69	156	64	211	199
QLM	61	153	192	114	175	75	***	***	***	***
HWRF	46	67	110	100	107	89	87	101	147	242
IMD-MME	39	65	88	90	100	107	145	120	150	126

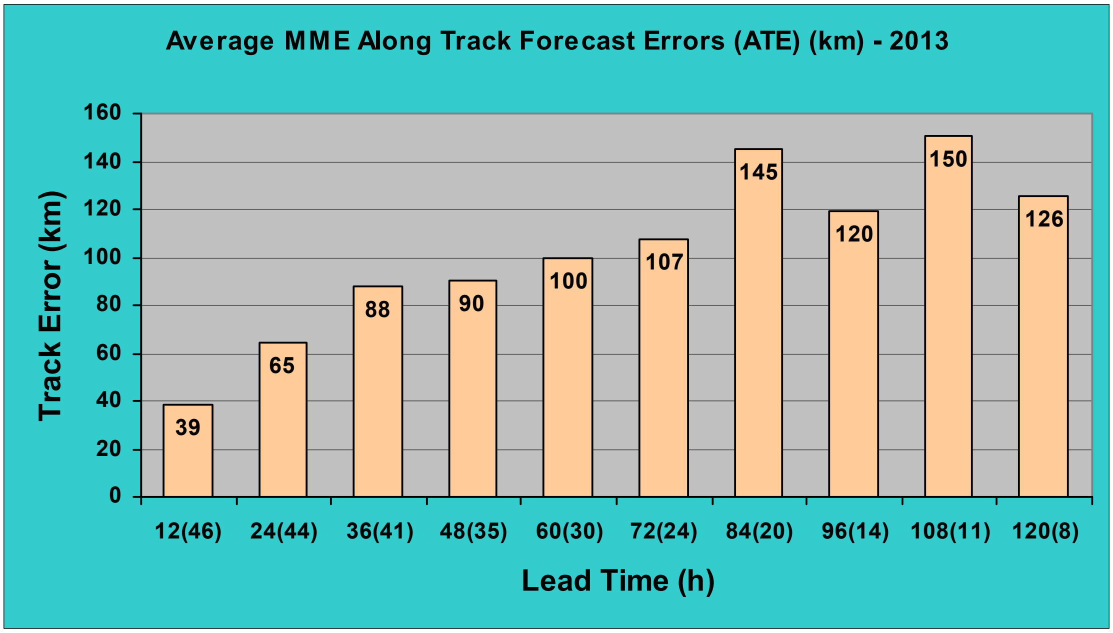


Fig. 86 Mean (absolute) MME Along track forecast error (ATE))-2013

12.4. Mean track forecast error (km) (Cross track error (CTE))-2013

Table-53: Mean cross track forecast error (CTE) (km) during 2013

HR→	12h	24h	36h	48h	60h	72h	84h	96h	108h	120h
IMD-GFS	57	76	97	111	144	127	154	210	192	227
IMD-WRF	60	101	141	205	253	270	***	***	***	***
JMA	117	107	152	151	140	134	150	***	***	***
NCEP	51	53	83	93	100	95	165	119	154	158
UKMO	55	60	72	93	141	154	155	180	197	212
ECMWF	74	81	125	130	142	154	138	81	99	99
QLM	133	157	191	200	141	205	***	***	***	***
HWRF	44	74	80	102	114	145	165	179	209	216
IMD-MME	46	47	65	75	95	103	106	149	141	121

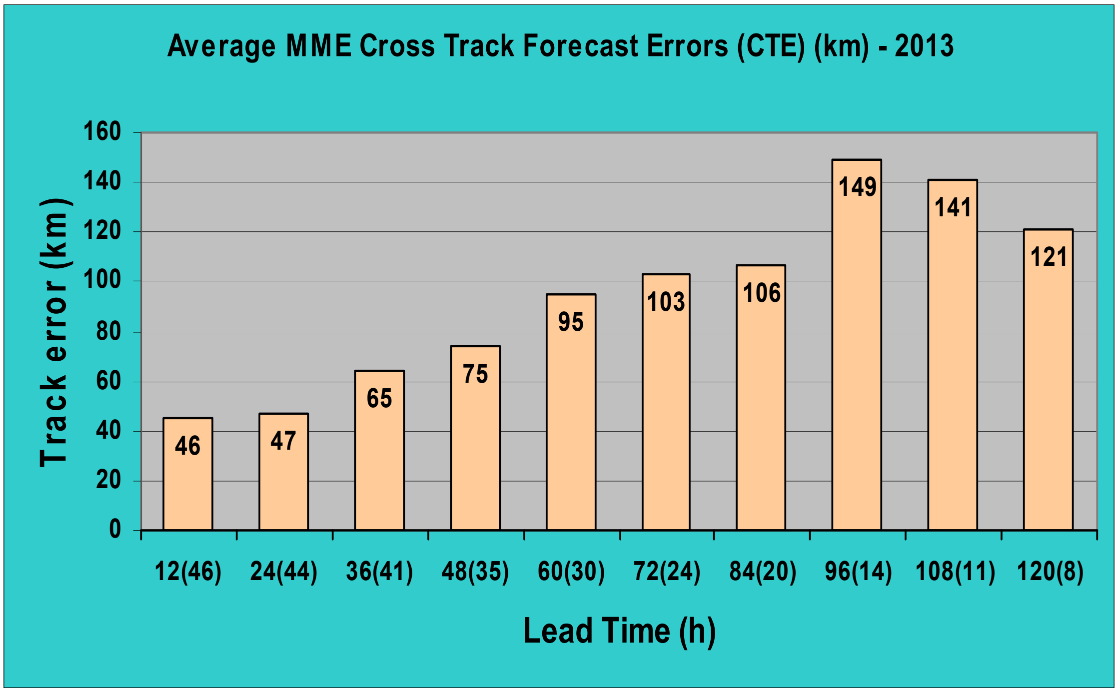


Fig. 87 Mean (absolute) MME Cross track forecast error (CTE))-2013

12.5 Mean Intensity forecast error (kt)

I. SCIP model

The annual average intensity forecast errors of SCIP model are shown in Table 54 (Fig. 88) for SCIP model. The error is 10 kts at 24hr, 17 kts at 48hr and 20 kts at 72hr for all the systems during 2013 (MAHASEN, PHAILIN, DEEP DEPRESSION over Arabian Sea, DEPRESSION over Bay of Bengal, HELEN, LEHAR and MADI).

Table-54: Mean intensity forecast error (kt) of SCIP during 2013

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
AAE	5.9	9.9	15.0	17.3	17.7	19.8
RMSE	7.3	12.8	17.6	19.9	20.5	22.0
Number of forecasts verified	49	46	41	35	29	24

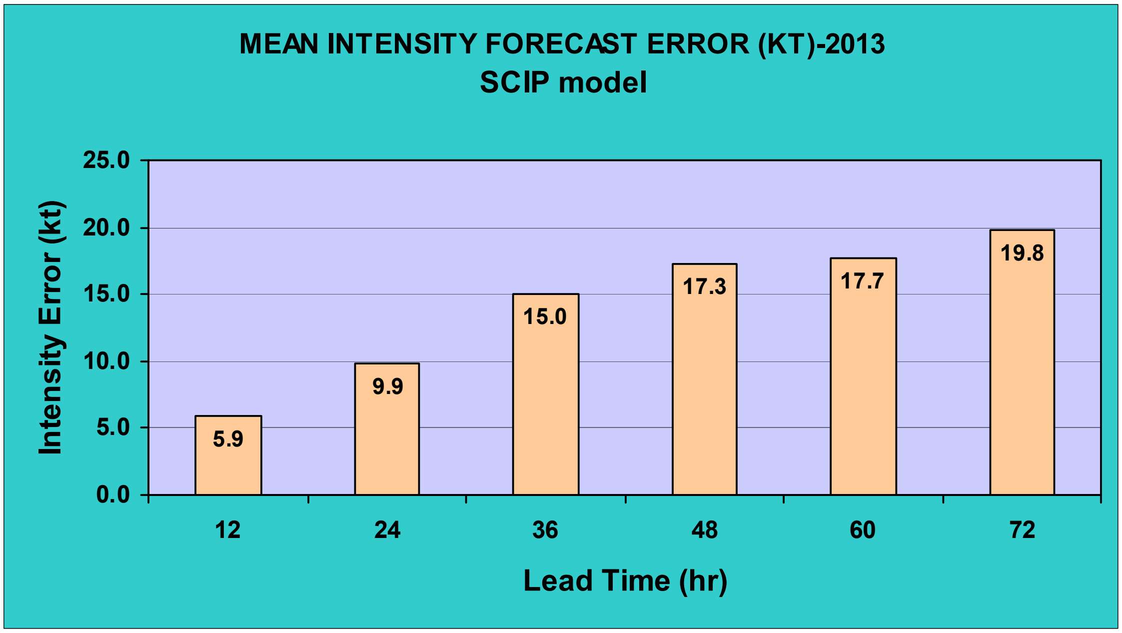


Fig. 88 Average SCIP intensity forecast error (kt) during 2013

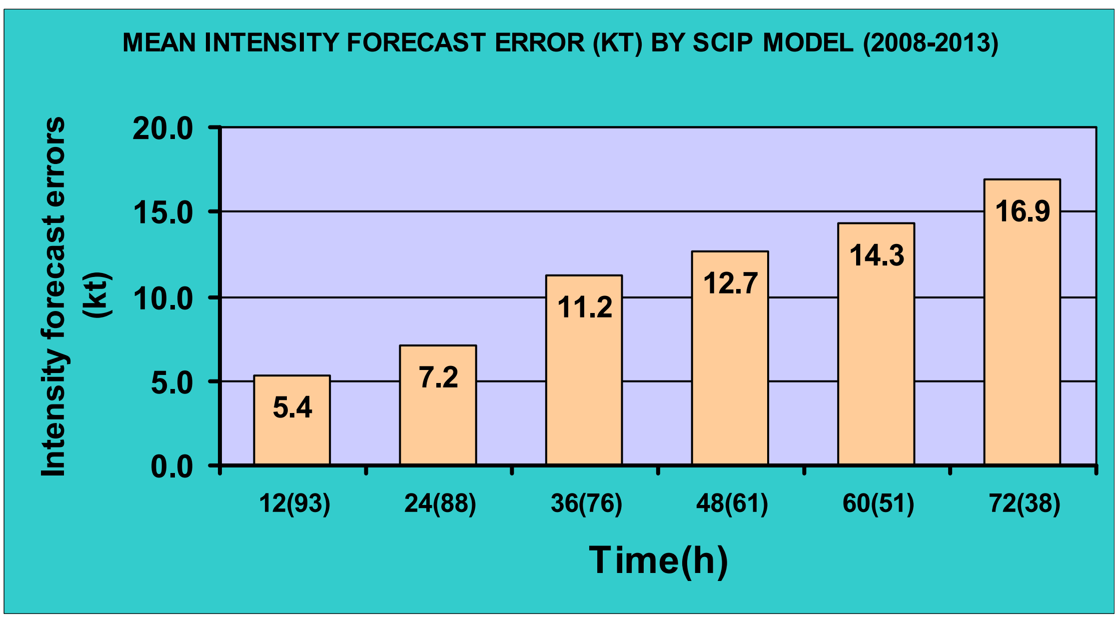


Fig. 89 Average SCIP intensity forecast error (kt) during 2008-2013

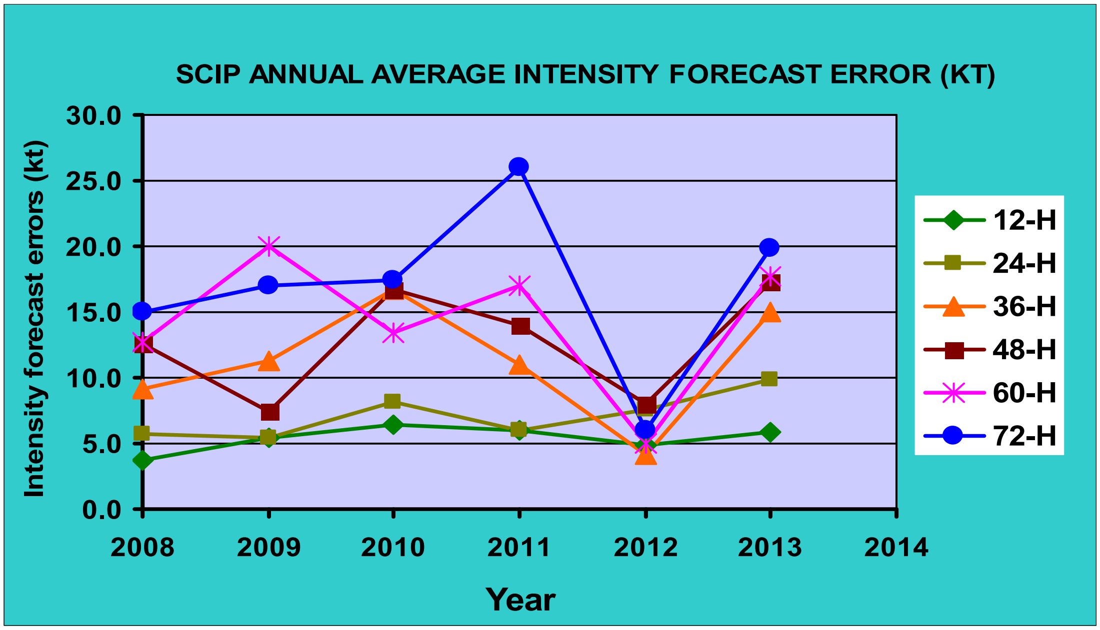


Fig. 90 Yearly average SCIP intensity forecast error (kt) during 2008-2013

Fig. 90 shows that during the period 2008-2013 the intensity error of SCIP model was less than 10 kts for 24h forecast around 15 kts up to 60h forecast and less than 20 kts for 72h forecast and forecast errors at all forecast hours was lowest in 2012.

II. HWRF model

The annual average intensity forecast errors for 2013 are shown in Table 55 for HWRF model. The error is 16 kts at 24hr, 11 kts at 48hr and 18 kts at 72hr and 96 hr and 43 kts at 120hr for the cyclones MAHASEN, PHAILIN, HELEN and LEHAR during 2013.

Table-55 Mean intensity forecast error (kts) of HWRF during 2013

Lead time →	**12 hr**	**24 hr**	**36 hr**	**48 hr**	**60 hr**	**72 hr**	**84h**	**96h**	**108h**	**120h**
AAE	21.9	16.1	9.8	11.1	13.3	18.3	25.4	18.3	26.3	43.0
RMSE	23.1	17.4	11.4	11.9	15.1	20.8	26.4	18.5	26.5	43.0
Number of forecasts verified	23	21	18	16	12	10	8	6	4	2

Table-56 Mean intensity forecast error (kts) of IMD OFFICIAL during 2013

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84h	96h	108h	120h
AAE	6.2	10.1	13.5	14.9	15.6	16.2	18.5	16.1	14.1	13.2
RMSE	8.2	13.9	17.2	18.4	18.9	19.5	22,4	19.5	15	14.3
Number of forecasts verified	94	84	72	65	55	44	34	26	18	11

12.6 Mean Decay (after landfall) forecast error (kt) by DECAY model

Yearly average decay (after landfall) forecast errors (kt) at 6h interval up to 24h during 2013 and during 2008-2013 are shown in Fig 91 and Fig. 92 respectively. The figures show that model was able to predict decay after landfall with reasonable success.

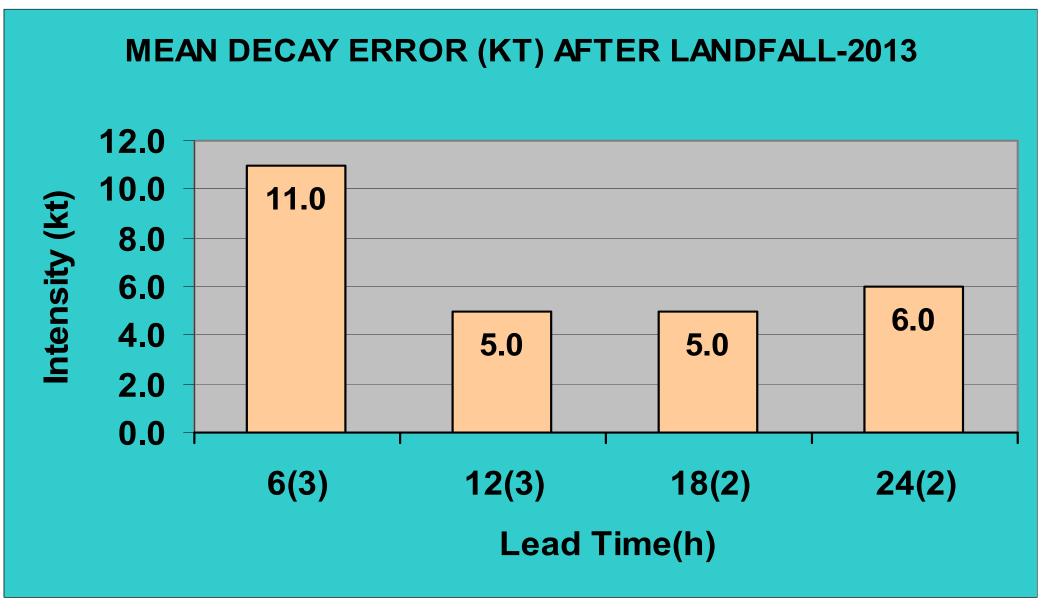


Fig. 91 Yearly average decay (after landfall) forecast error (kt) during 2013

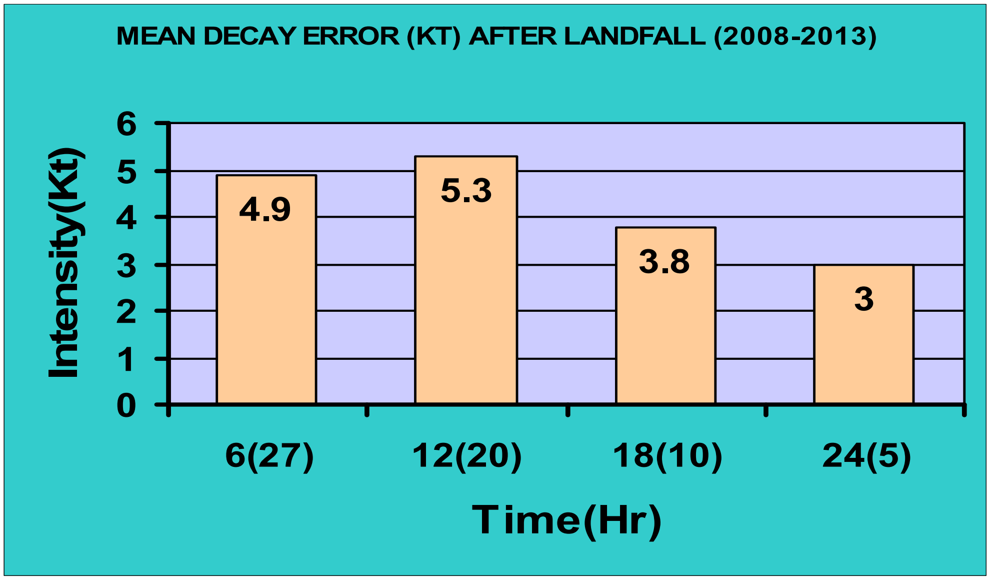


Fig. 92 Yearly average decay (after landfall) forecast error (kt) during 2008-2013

References

Kotal, S.D., Kundu, P.K. and Roy Bhowmik S.K., **2009**. Analysis of Cyclogenesis parameter for developing and non-developing low pressure systems over the Indian Sea. ***Natural hazards*****, 50:**389-402.

Kotal, S.D., Roy Bhowmik, S.K., Kundu, P.K. and Das, A.K., **2008.** A Statistical Cyclone Intensity Prediction (SCIP) Model for Bay of Bengal. ***Journal of Earth System Science*****,** **117**:157-168.

Kotal, S.D. and Roy Bhowmik S.K. **2011**. A Multimodel Ensemble (MME) Technique for Cyclone Track Prediction over the North Indian Sea. ***Geofizika*****, 28(2**): 275-291.

Kotal, S.D., and Roy Bhowmik S.K. **2013**. Large-Scale Characteristics of Rapidly Intensifying Tropical Cyclones over the Bay of Bengal and a Rapid Intensification (RI) Index. ***Mausam,*** **64:13-24.**

Kotal, S.D. and Bhattacharya S.K. **2013**. Tropical Cyclone Genesis Potential Parameter (GPP) and it's application over the North Indian Sea. ***Mausam*****, 64:149-170**.

Roy Bhowmik S.K. and Kotal S.D. **2010**, A dynamical statistical model for prediction of a tropical cyclone, ***Marine Geodesy*****, 33**, 412-425

Roy Bhowmik S.K., Kotal, S.D. and Kalsi S.R, **2005**. An empirical model for predicting decaying rate of tropical cyclone wind speed after landfall over Indian region. ***Journal of Applied Meteorology*** **44**:179-185.

Roy Bhowmik, SK,.2**003**, An evaluation of cyclone genesis parameter over the Bay of Bengal using model analysis, ***Mausam*****, 54**, 351-358

Heming, J., 1**994**: Verification of Tropical Cyclone Forecast Tracks at the UK Met Office. ***NWP Gazette***, **1**, 2–8.

Acknowledgements

Authors are grateful to the Director General of Meteorology for his encouragement, support and for providing all facilities to carry out this job. Authors gratefully acknowledge the support of all colleagues in NWP Division, IMD, New Delhi who are involved in operation of NWP models and Cyclone Warning Division, IMD, New Delhi. Authors are thankful to NCEP, JMA, UKMO and ECMWF and acknowledge the use of their product in this report.

****