NWP report on Very Severe Cyclonic Storm 'PHAILIN' over the Bay of Bengal (October 8-14, 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
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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 effort to translate research to operation, and to meet the need 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 very severe cyclonic storm of the Bay of Bengal of October 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/forecast as first guess and boundary conditions. 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^ox80^o and inner domain 6^ox6^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 PHAILIN, 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. Performance of the CPS is presented in section 6.

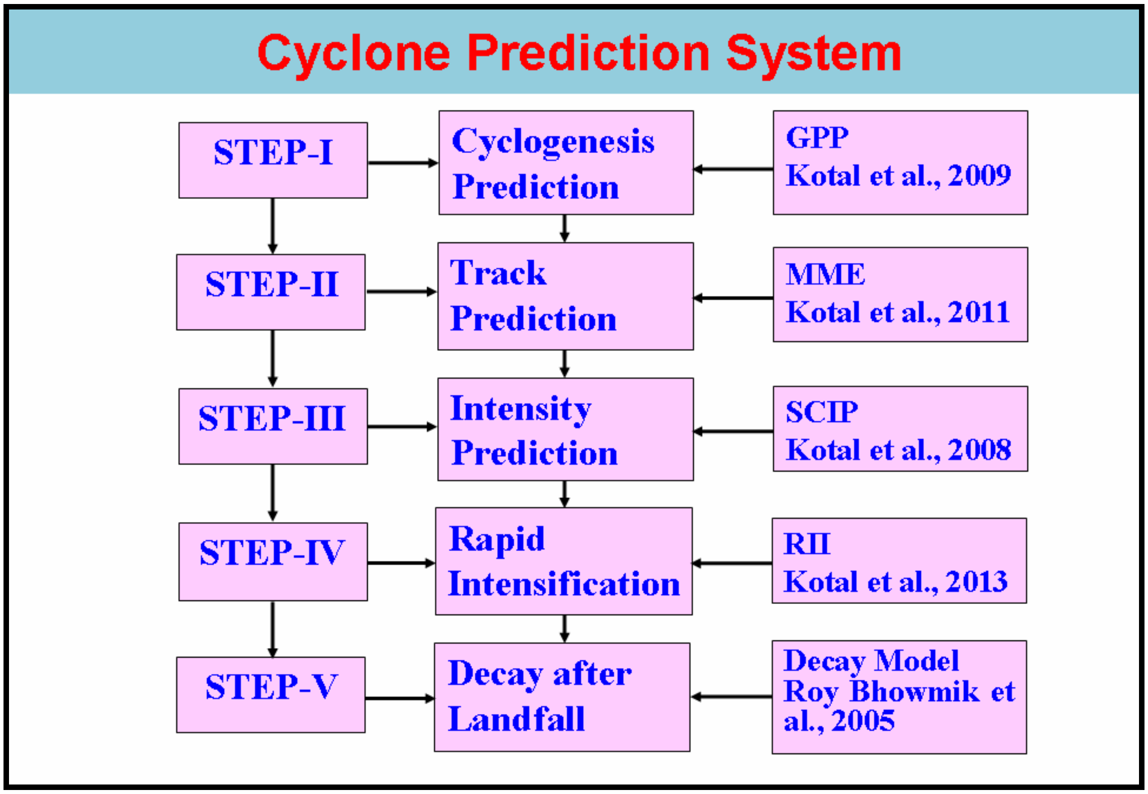

Fig. 1 Flow Diagram of Cyclone Prediction System (CPS)

4. 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^{o} N and longitude 96.0^{o} 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.

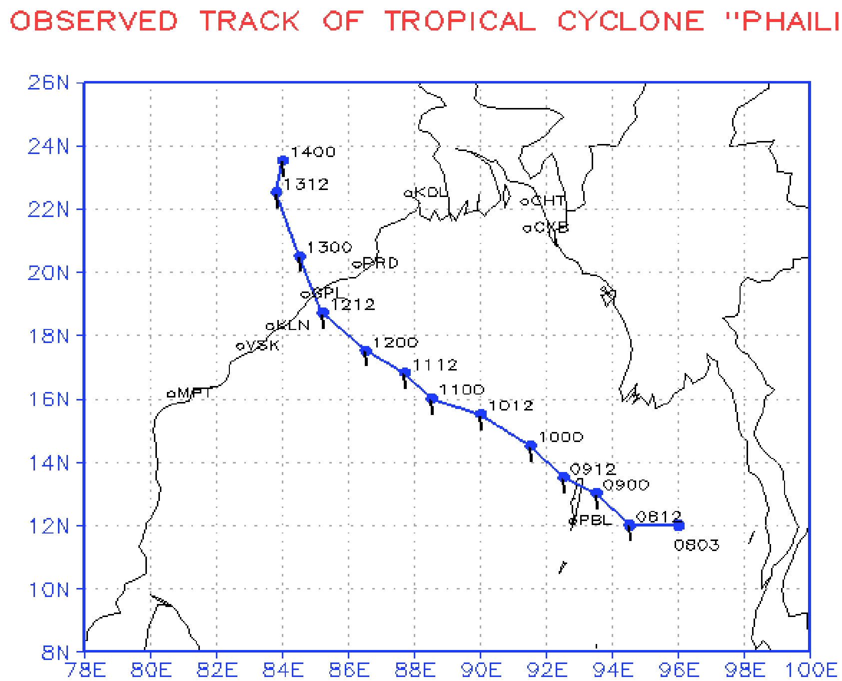

Fig. 2 Observed track of the cyclone PHAILIN

5. <u>NWP bulletins (based on CPS) issued for cyclone 'PHAILIN" over the Bay of Bengal during (7-13) October 2013</u>

5.1. <u>NWP BULLETIN No.-1:</u>

<u>BASED ON 0000 UTC of 07 October 2013:</u> Gensis Potential Parameter (GPP).

<u>GPP</u>: Analysis and forecasts of Genesis Potential Parameter (GPP) based on 0000 UTC of 07 October 2013 (Fig. 3) indicate that the low pressure system over the north Andaman Sea has enough potential (GPP $\geq$ 8.0) to intensify into a Tropical Cyclone.

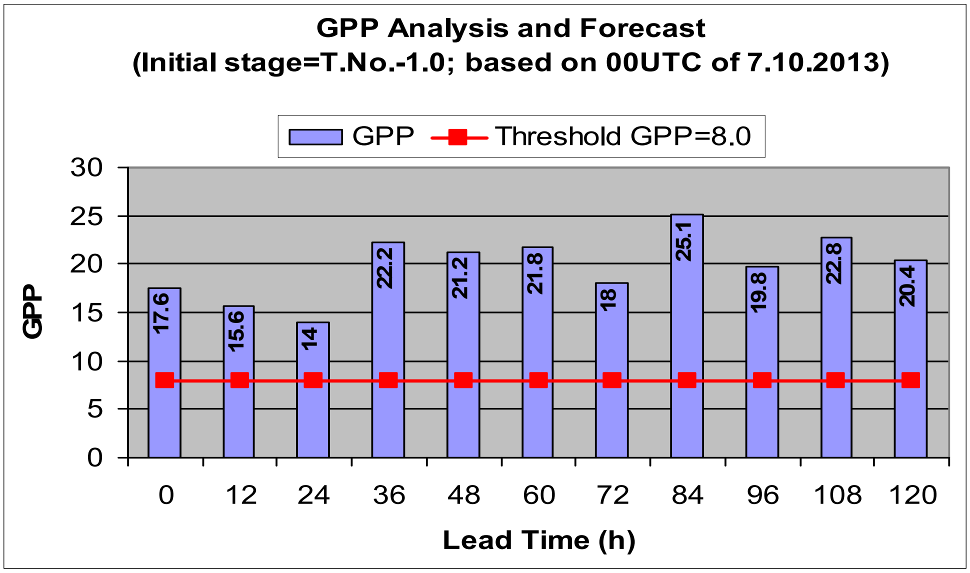

Fig. 3 Analysis and forecasts of Genesis Potential Parameter (GPP) based on 0000 UTC of 07 October 2013

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5.2. <u>NWP BULLETIN No.-2:</u>

<u>BASED ON 0000 UTC of 08 October 2013:</u> Gensis Potential Parameter, MME track and Intensity prediction.

<u>GPP</u>: Analysis and forecasts of Genesis Potential Parameter (GPP) based on 0000 UTC of 08 October 2013 (Fig. 4) indicate that the Depression over the north Andaman Sea has enough potential (GPP ≥ 8.0) to intensify into a Tropical Cyclone.

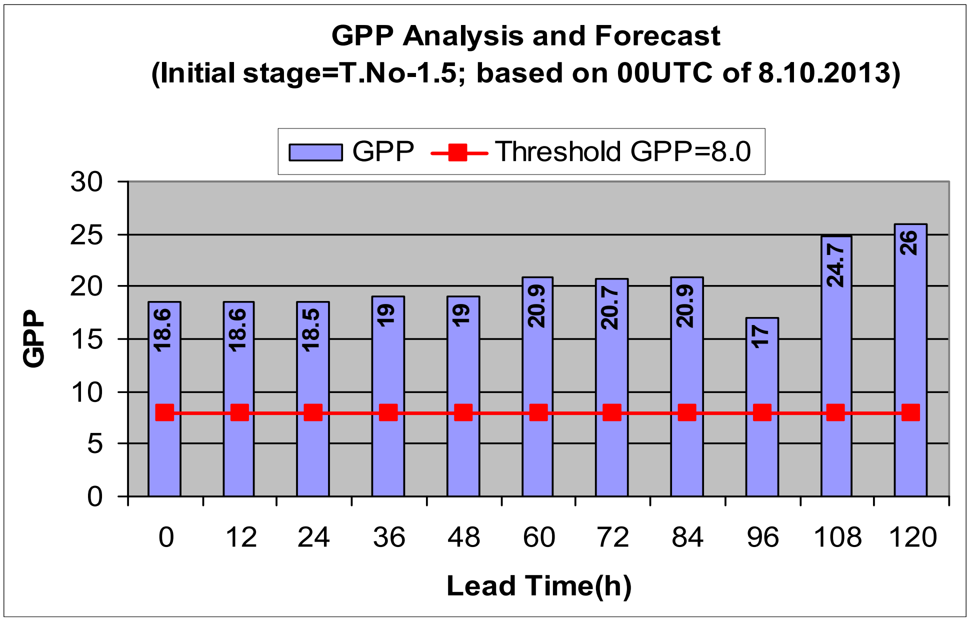

Fig. 4 Analysis and forecasts of Genesis Potential Parameter (GPP) based on 0000 UTC of 08 October 2013

MME TRACK: MME track forecast based on 0000 UTC of 08 October 2013 (Fig. 5) shows **landfall near Gopalpur, at about 0000 UTC of 13 October 2013.**

SCIP Intensity: The 12-hourly Intensity prediction by SCIP model shows that the Depression over Andaman Sea would intensify into a

(i) Cyclonic storm at 0000 UTC of 09 October 2013,

(ii) Severe Cyclonic storm at 1200 UTC of 10 October 2013,

(iii) Very Severe Cyclonic storm at 0000 UTC of 11 October 2013.

Probability of Rapid Intensification (RI): Probability of Rapid Intensification (Intensity increase by 30 kts or more in next 24 hr) = **9.4 %** ; **Inference:** RI Probability in next 24 hr (00 UTC of 08 October to 00 UTC of 09 October 2013) is **VERY LOW**.

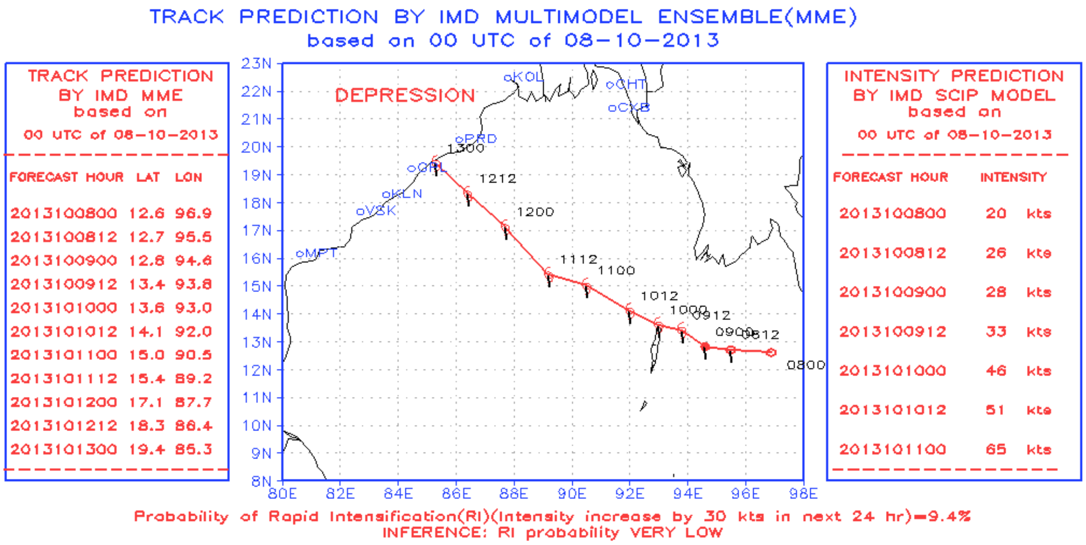

Fig. 5 MME track forecast based on 0000 UTC of 08 October 2013 along with Intensity (SCIP) and Rapid intensification (RI) forecast.

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5.3. <u>NWP BULLETIN No.-3:</u>

<u>BASED ON 0000 UTC of 09 October 2013:</u> Gensis Potential Parameter, MME track and Intensity prediction.

<u>GPP</u>: Analysis and forecasts of Genesis Potential Parameter (GPP) based on 0000 UTC of 09 October 2013 (Fig. 6) indicate that the Deep-Depression over the Andaman Sea has enough potential to intensify into a Tropical Cyclone.

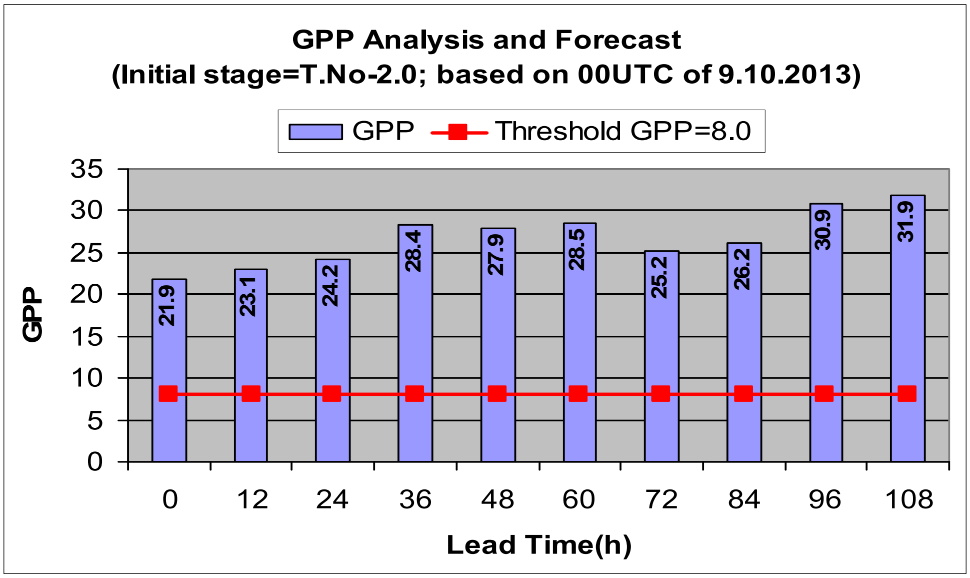

Fig. 6 Analysis and forecasts of Genesis Potential Parameter (GPP) based on 0000 UTC of 09 October 2013

MME TRACK: MME track forecast based on 0000 UTC of 09 October 2013 (Fig. 7) shows **landfall near Gopalpur, at around 2000 UTC of 12 October 2013.**

SCIP Intensity: The 12-hourly Intensity prediction by SCIP model shows that the Deep Depression over Andaman Sea would intensify into a

(i) Cyclonic storm at 1200 UTC of 09 October 2013,

(ii) Severe Cyclonic storm at 0000 UTC of 11 October 2013,

(iii) Very Severe Cyclonic storm at 1200 UTC of 11 October 2013.

Probability of Rapid Intensification (RI): Probability of Rapid Intensification (Intensity increase by 30 kts or more in next 24 hr) = **9.4 %** ; **Inference:** RI Probability in next 24 hr (00 UTC of 08 October to 00 UTC of 09 October 2013) is **VERY LOW.**

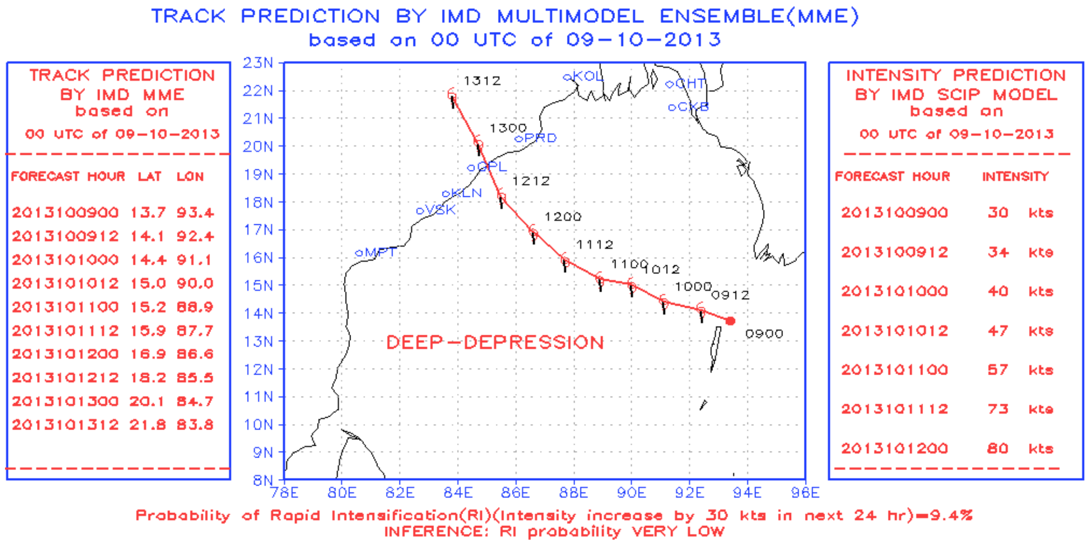

Fig. 7 MME track forecast based on 0000 UTC of 09 October 2013 along with Intensity (SCIP) and Rapid intensification (RI) forecast.

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5.4. <u>NWP BULLETIN No.-4:</u>

<u>BASED ON 1200 UTC of 09 October 2013:</u> MME track and Intensity prediction.

<u>MME TRACK</u>: MME track forecast based on 1200 UTC of 09 October 2013 (Fig.8) shows **<u>landfall near Gopalpur, at around 2000 UTC of 12 October 2013.</u>**

<u>SCIP Intensity</u>: The 12-hourly Intensity prediction by SCIP model based on 1200 UTC of 09 October 2013 shows that the cyclone PHAILIN would intensify into a

(i) Severe Cyclonic storm at 0000 UTC of 11 October 2013,

(ii) Very Severe Cyclonic storm at 1200 UTC of 11 October 2013.

<u>Probability of Rapid Intensification (RI)</u>: Probability of Rapid Intensification (Intensity increase by 30 kts or more in next 24 hr) = **9.4 %** ; **Inference:** RI Probability in next 24 hr (00 UTC of 08 October to 00 UTC of 09 October 2013) is **<u>VERY LOW</u>.**

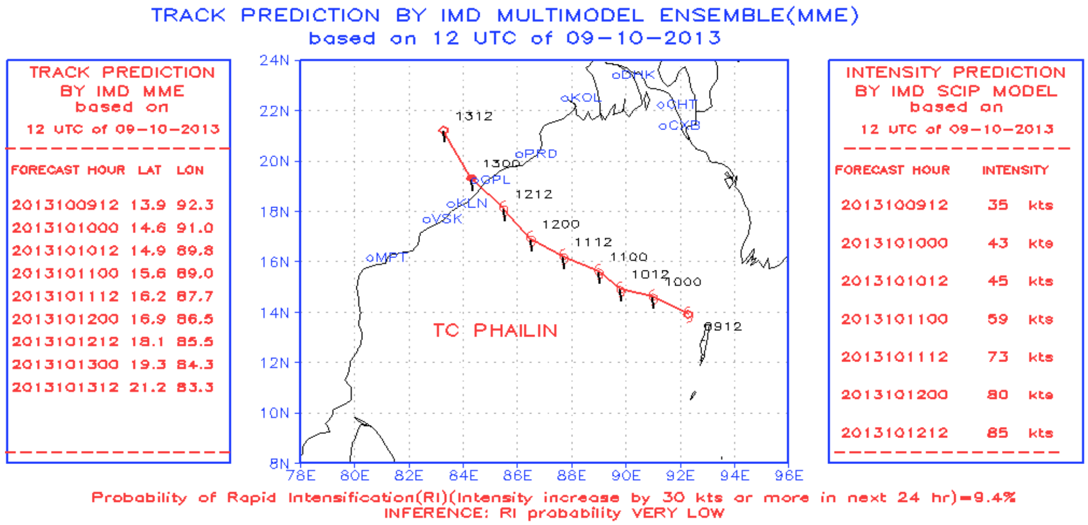

Fig. 8 MME track forecast based on 1200 UTC of 09 October 2013 along with Intensity (SCIP) and Rapid intensification (RI) forecast.

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5.5. <u>NWP BULLETIN No.-5:</u>

<u>BASED ON 0000 UTC of 10 October 2013:</u> MME track and Intensity prediction and Probability of Rapid Intensification

<u>MME TRACK</u>: MME track forecast based on 0000 UTC of 10 October 2013 (Fig. 9) shows **<u>landfall near Gopalpur, at about 1800 UTC of 12 October 2013.</u>**

<u>SCIP Intensity</u>: The 12-hourly Intensity prediction by SCIP model based on 0000 UTC of 10 October 2013 (Fig. 9) shows that the cyclone PHAILIN would intensify into a

(i) Severe Cyclonic storm at 1200 UTC of 10 October 2013,

(ii) Very Severe Cyclonic storm at 0000 UTC of 11 October 2013.

(iii) Landfall Intensity = 90 kts

<u>Probability of Rapid Intensification (RI):</u> Probability of Rapid Intensification (Intensity increase by 30 kts or more in next 24 hr) = **73 %** ; **Inference:** RI Probability in next 24 hr is **<u>HIGH.</u>**

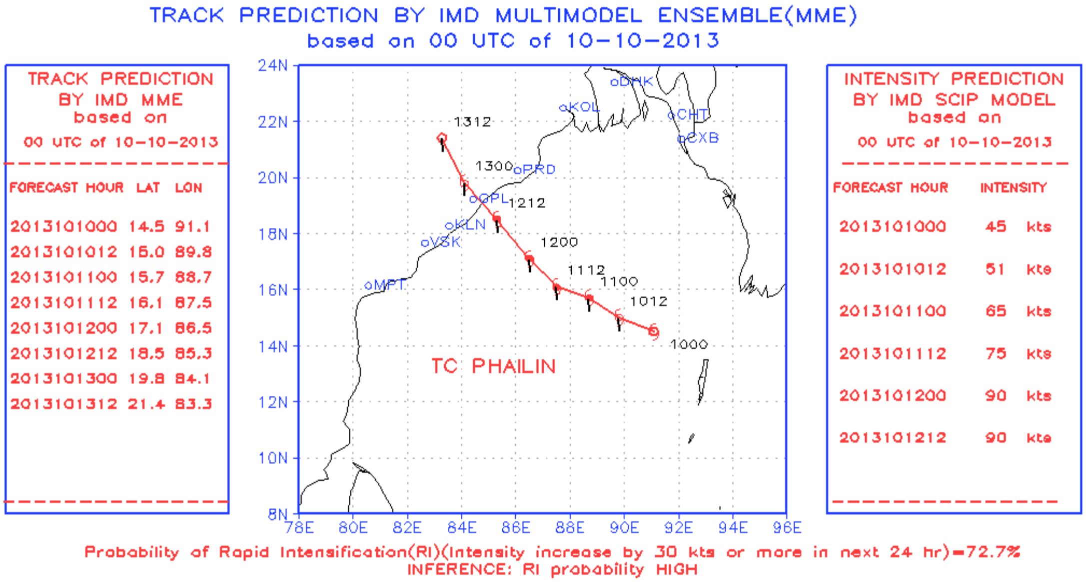

Fig. 9 MME track forecast based on 0000 UTC of 10 October 2013 along with Intensity (SCIP) and Rapid intensification (RI) forecast.

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5.6. NWP BULLETIN No.-6:

BASED ON 1200 UTC of 10 October 2013: MME track and Intensity prediction and Probability of Rapid Intensification

MME Track Forecast: MME track forecast based on 1200 UTC of 10 October 2013 (Fig. 10) shows **landfall near Gopalpur(Odisha), at around 1800 UTC of 12 October 2013.**

SCIP Intensity Forecast: The 12-hourly Intensity prediction by SCIP model based on 1200 UTC of 10 October 2013 shows that the cyclone PHAILIN would intensify to:

(i) 85 kts (Very Severe Cyclonic storm) at 0000 UTC of 11 October 2013

(ii) 95 kts (Very Severe Cyclonic Storm) at 1200 UTC of 11 October 2013

(iii) 110 kts (Very Severe Cyclonic Storm) at 0000 UTC of 12 October 2013

(iv) 115 kts (Very Severe Cyclonic Storm) at 1200 UTC of 12 October 2013

(v) **Landfall Intensity = 115 kts (Very Severe Cyclonic Storm)**

<u>Probability of Rapid Intensification (RI)</u>: Probability of Rapid Intensification (Intensity increase by 30 kts or more in next 24 hr) = **73 %** ; **Inference:** RI Probability in next 24 hr (12 UTC of 10 October to 12 UTC of 11 October 2013) is **<u>HIGH</u>.**

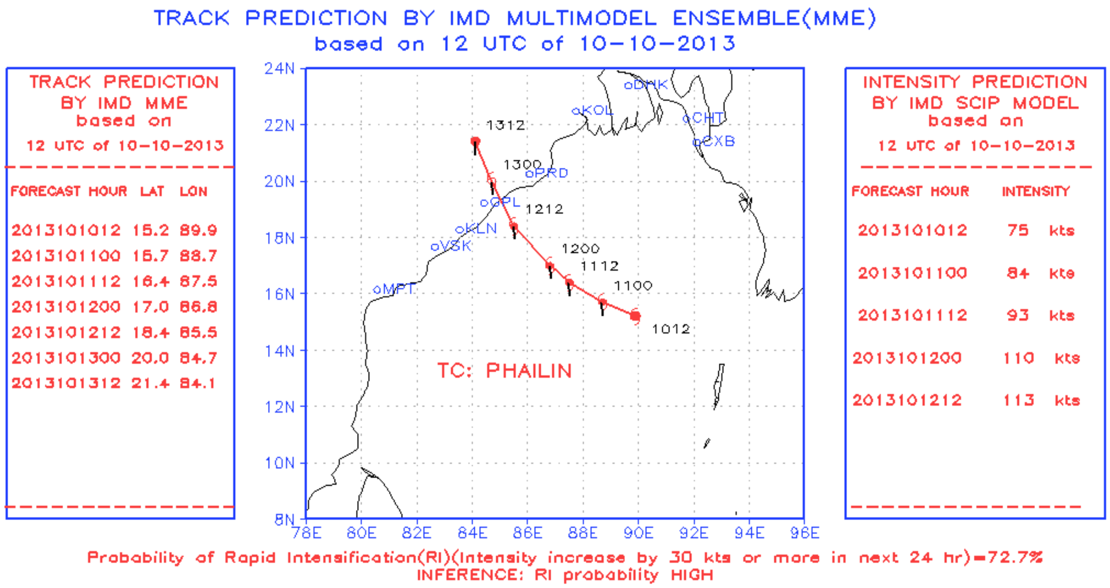

Fig. 10 MME track forecast based on 1200 UTC of 10 October 2013 along with Intensity (SCIP) and Rapid intensification (RI) forecast.

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5.7. <u>NWP BULLETIN No.-7:</u>

<u>BASED ON 0000 UTC of 11 October 2013:</u> MME track and Intensity prediction and Probability of Rapid Intensification

<u>MME Track Forecast</u>: MME track forecast based on 0000 UTC of 11 October 2013 (Fig. 11) shows **<u>landfall near Gopalpur(Odisha), at around 1800 UTC of 12 October 2013.</u>**

<u>SCIP Intensity Forecast</u>: The 12-hourly Intensity prediction by SCIP model based on 0000 UTC of 11 October 2013 shows that the cyclone PHAILIN would intensify to:

(i) 110 kts (Very Severe Cyclonic storm) at 1200 UTC of 11 October 2013

(ii) 120 kts (Super Cyclonic Storm) at 0000 UTC of 12 October 2013

(iii) 130 kts (Super Cyclonic Storm) at 1200 UTC of 12 October 2013

(iv) **<u>Landfall Intensity</u> = 130 kts (Super Cyclonic Storm)**

<u>Probability of Rapid Intensification (RI)</u>: Probability of Rapid Intensification (Intensity increase by 30 kts or more in next 24 hr) = **73 %** ; **Inference:** RI Probability in next 24 hr (00 UTC of 11 October to 00 UTC of 12 October 2013) is **<u>HIGH</u>.**

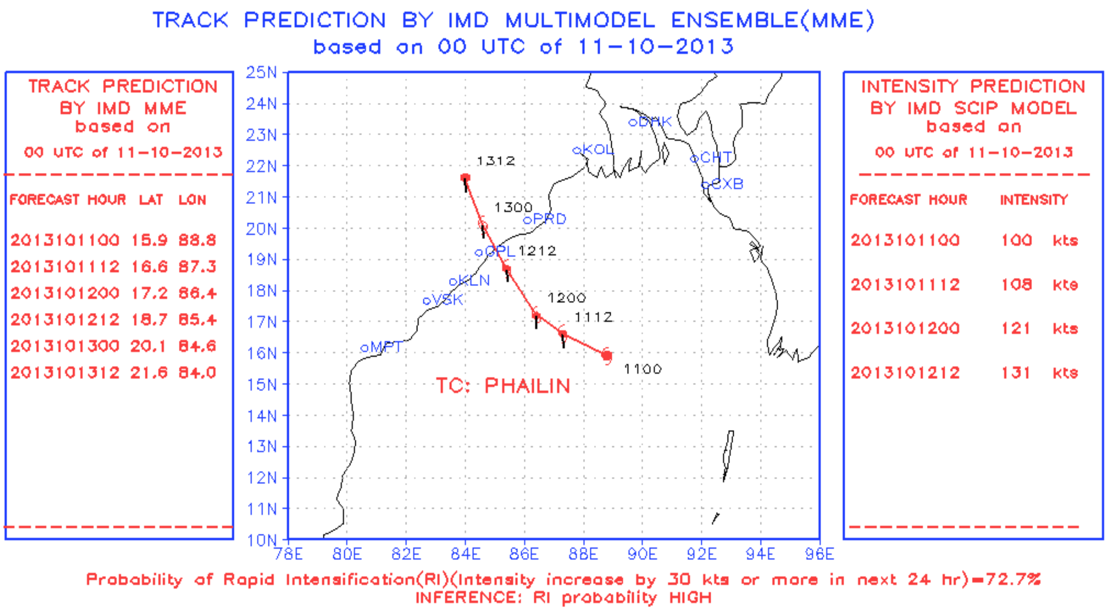

Fig. 11 MME track forecast based on 0000 UTC of 11 October 2013 along with Intensity (SCIP) and Rapid intensification (RI) forecast.

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5.8. <u>NWP BULLETIN No.-8:</u>

<u>BASED ON 1200 UTC of 11 October 2013:</u> MME track and Intensity prediction and Probability of Rapid Intensification

<u>MME Track Forecast</u>: MME track forecast based on 1200 UTC of 11 October 2013 (Fig. 12) shows **<u>landfall near Gopalpur(Odisha), at around 1700 UTC of 12 October 2013.</u>**

<u>SCIP Intensity Forecast</u>: The 12-hourly Intensity prediction by SCIP model based on 1200 UTC of 11 October 2013 shows that the cyclone PHAILIN would intensify to:

(i) 125 kts (Super Cyclonic storm) at 0000 UTC of 12 October 2013

(ii) 135 kts (Super Cyclonic Storm) at 1200 UTC of 12 October 2013

(iii) **Landfall Intensity = 135 kts (Super Cyclonic Storm)**

Probability of Rapid Intensification (RI): Probability of Rapid Intensification (Intensity increase by 30 kts or more in next 24 hr) **= 32 %** ; **Inference:** RI Probability in next 24 hr (12 UTC of 11 October to 12 UTC of 12 October 2013) is **MODERATE.**

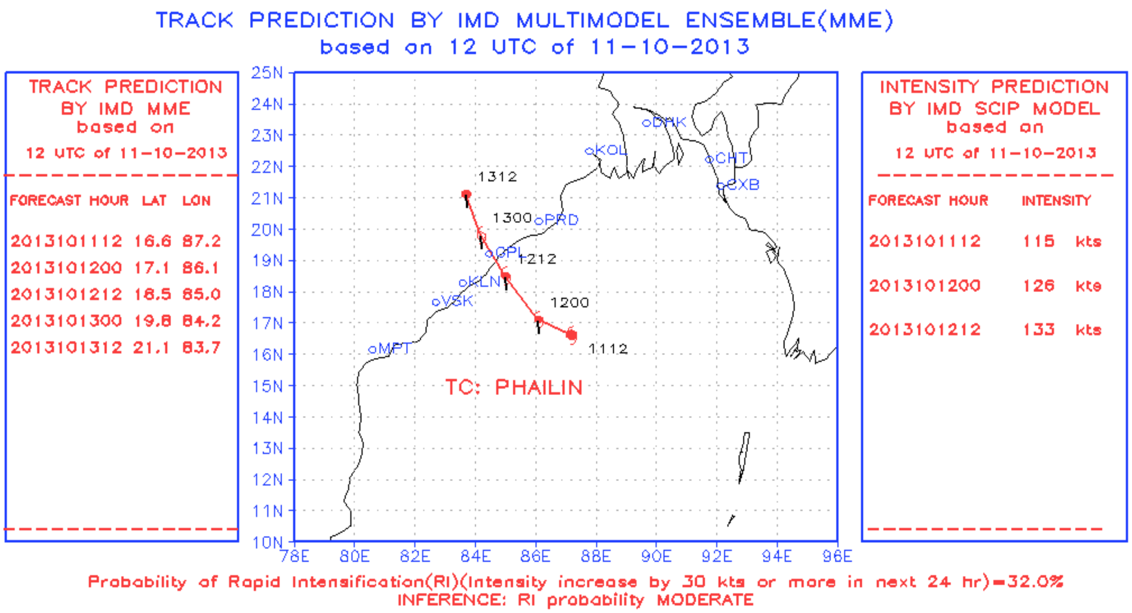

Fig. 12 MME track forecast based on 1200 UTC of 11 October 2013 along with Intensity (SCIP) and Rapid intensification (RI) forecast.

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5.9. NWP BULLETIN No.-9:

BASED ON 0000 UTC of 12 October 2013: MME track, Intensity and Landfall prediction.

MME Track Forecast: MME track forecast based on 0000 UTC of 12 October 2013 (Fig. 13) shows :

(i) Landfall Point: Near Gopalpur(Odisha): 18.9 N/ 84.7 E.

(ii) Landfall Time: Around 1800 UTC of 12 October 2013**.**

(iii) Movement after landfall: Northwestwards till 0000 UTC of 13 October 2013 and

Northwards thereafter.

<u>SCIP Intensity Forecast</u>: The 12-hourly Intensity prediction by SCIP model based on 0000 UTC of 12 October 2013 shows that the cyclone PHAILIN would intensify to:

(i) 125 kts (Super Cyclonic storm) at 1200 UTC of 12 October 2013

(iii) **<u>Landfall Intensity</u> = 125 kts (Super Cyclonic Storm)**

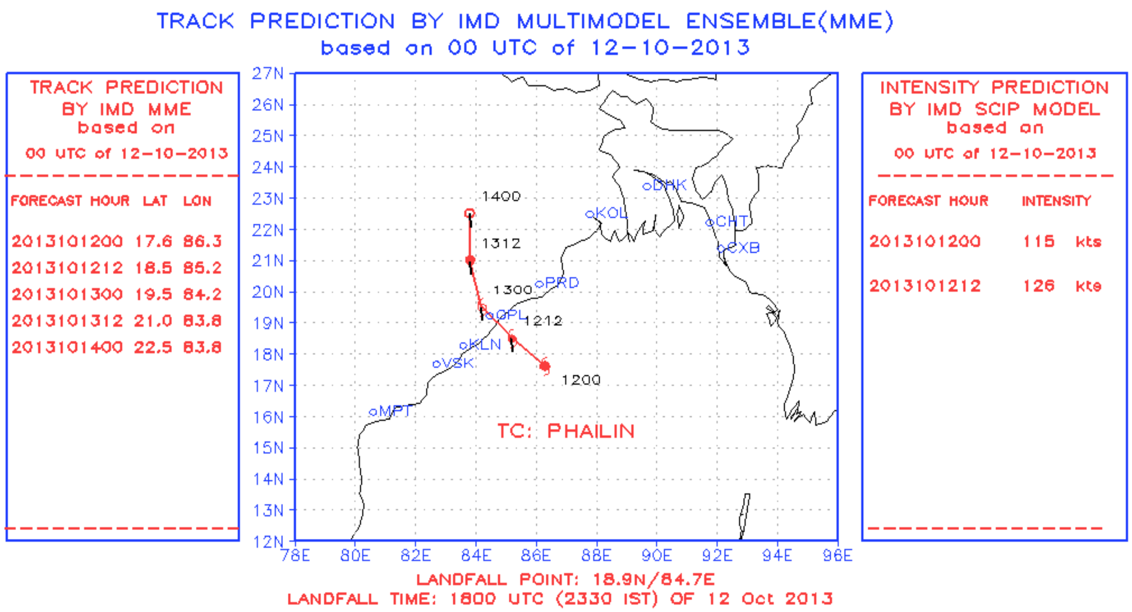

Fig. 13 MME track forecast based on 0000 UTC of 12 October 2013 along with Intensity (SCIP) and Rapid intensification (RI) forecast.

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5.10. <u>NWP BULLETIN No.-10:</u>

<u>BASED ON 1200 UTC of 12 October 2013:</u> MME track and Decay after landfall.

<u>MME Track and Decay Forecast</u>: MME track forecast based on 1200 UTC of 12 October 2013 (Fig. 14) shows that the system would move northwestwards till 0000 UTC of 13 October 2013 and north northwestwards thereafter.

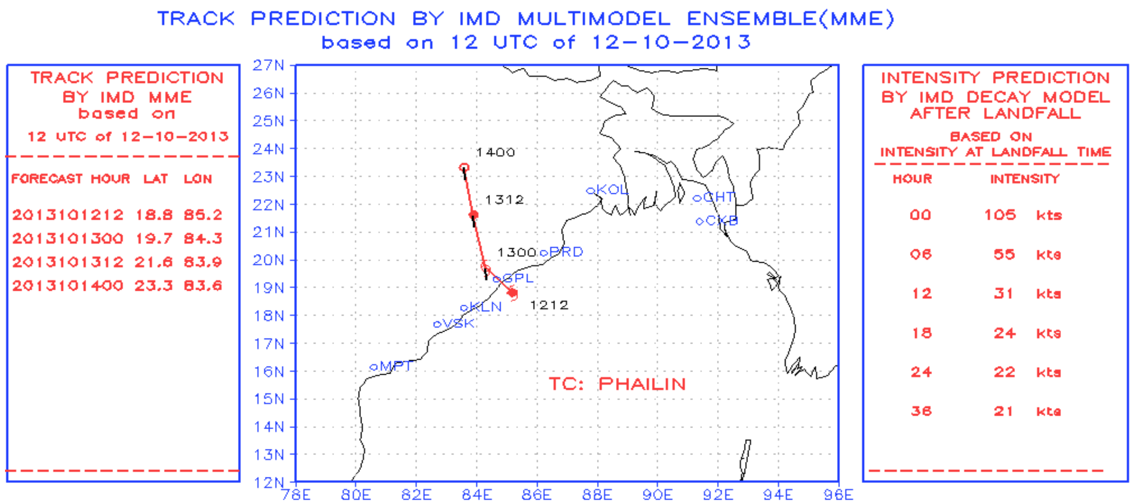

Fig. 14 MME track forecast based on 1200 UTC of 12 October 2013 along with Decay after landfall (DECAY model).

<u>DECAY after landfall</u>: The 6-hourly decaying intensity (Fig.15) prediction by DECAY model based on landfall intensity shows that the very severe cyclonic storm PHAILIN would decay to:

(i) Severe cyclonic storm (55 kt) after 6 hour from landfall time.

(ii) Cyclonic storm (35 kts) after about 12 hour from landfall time and Deep Depression thereafter.

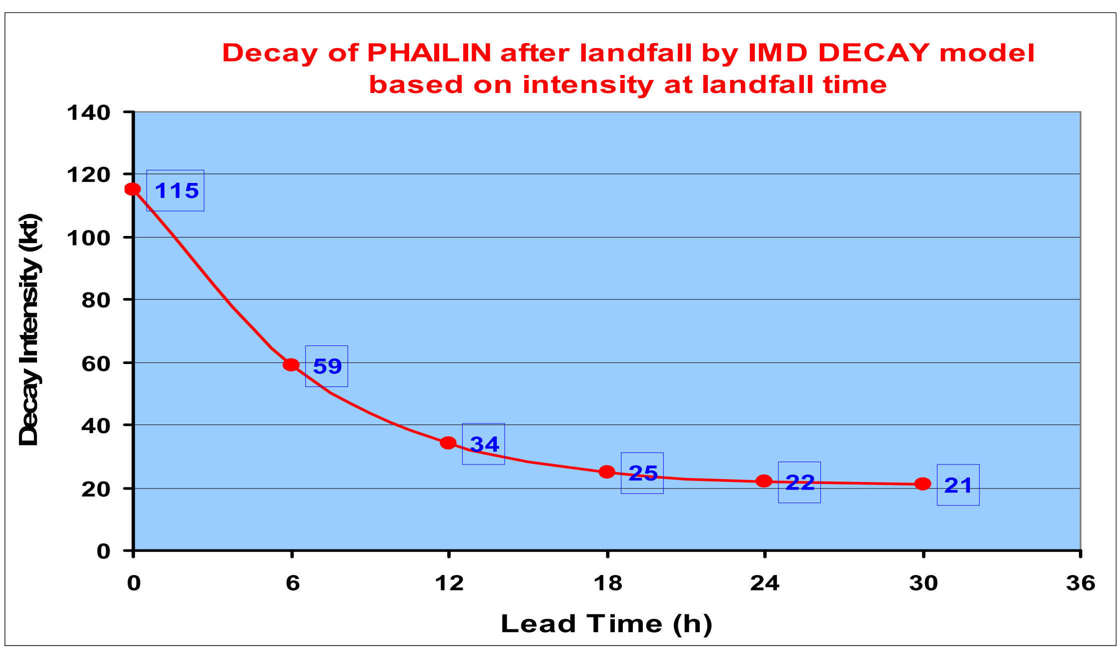

Fig. 15 Decay after landfall based on landfall intensity

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5.11. NWP BULLETIN No.-11:

BASED ON 0000 UTC of 13 October 2013: Decay after landfall.

DECAY after landfall: The 6-hourly decaying intensity (Fig. 16) prediction by DECAY model based on intensity (75 kt) at 0000 UTC of 13 October 2013 shows that the severe cyclonic storm PHAILIN would decay to:

(i) Severe cyclonic storm (51 kt) after 6 hour from landfall time (at 0600 UTC of 13 October 2013).

(ii) Cyclonic storm (37 kt) after 12 hour from landfall time (at 1200 UTC of 13 October 2013).

(iii) Deep Depression (30 kts) after about 18 hour from landfall time (at 1800 UTC of 13 October 2013) and 26 kt after 24 hr (at 0000 UTC of 14 October 2013).

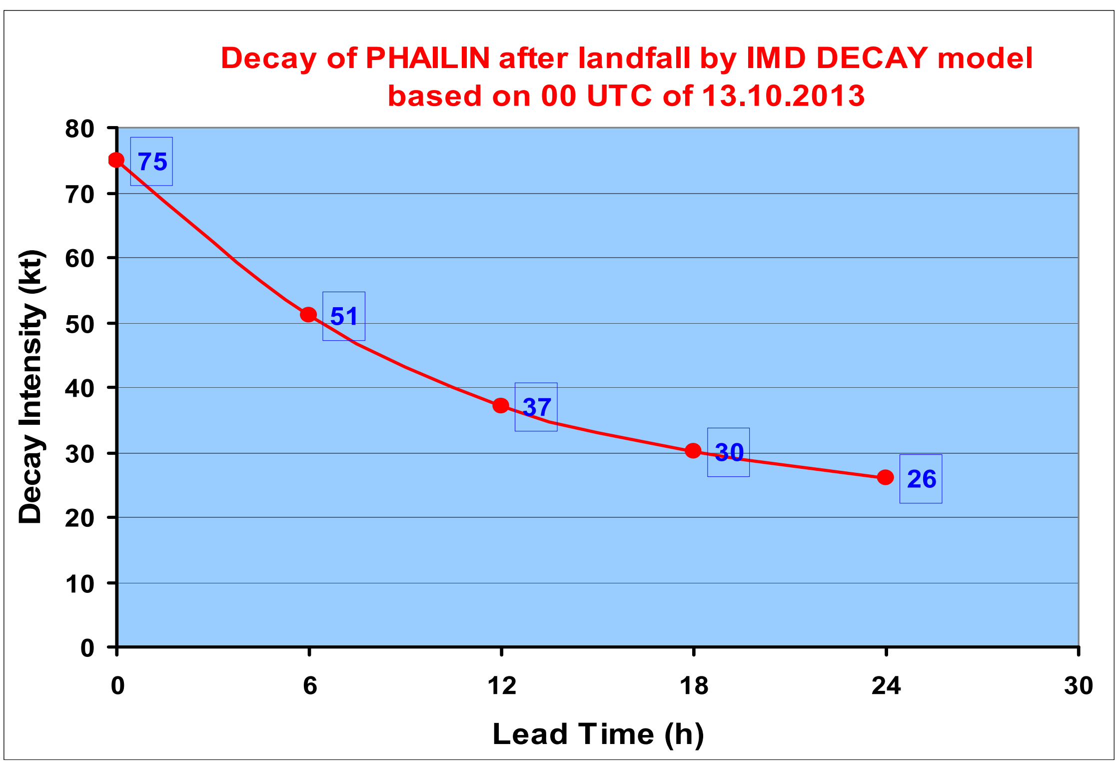

Fig. 16 Decay after landfall based on 0000 UTC of 13 October 2013

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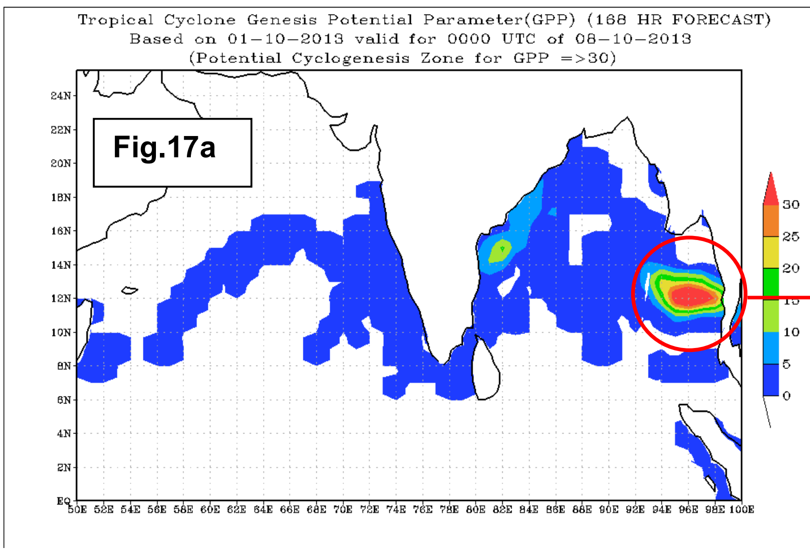
6. Forecast Performance

6.1 Prediction of cyclogenesis (Genesis Potential Parameter (GPP))

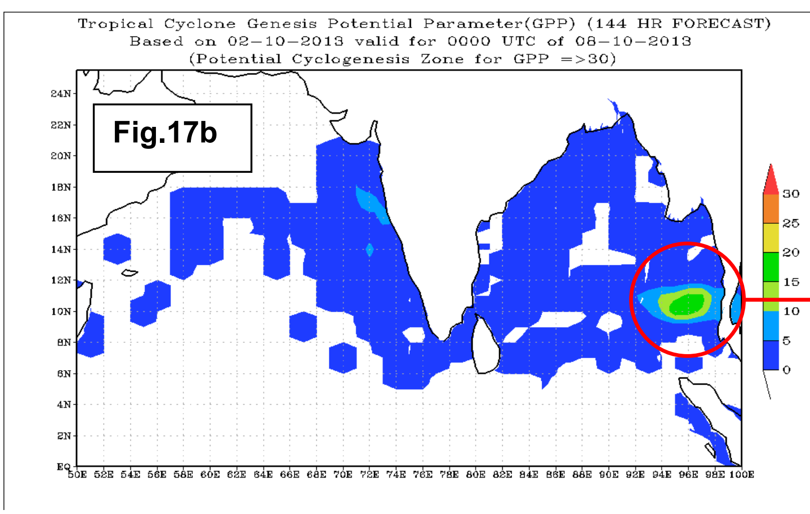
6.1.1. Grid point analysis and forecast of GPP

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

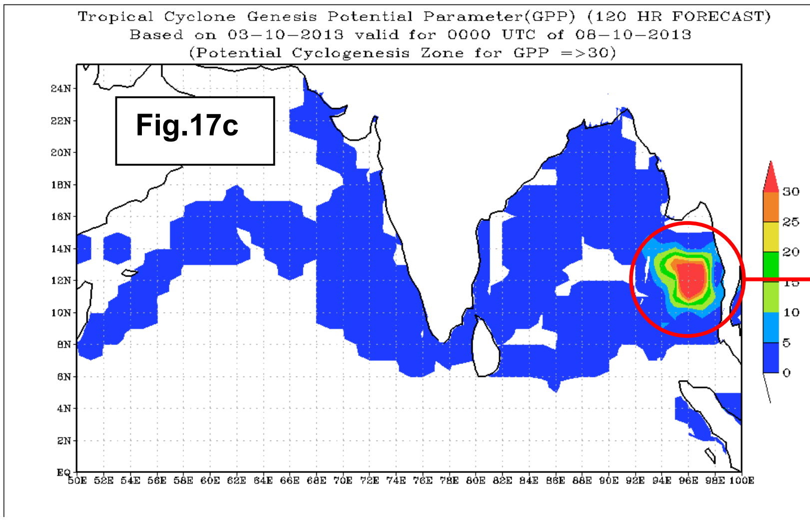
Figure 17(a-h) below shows the predicted zone of formation of cyclogenesis.



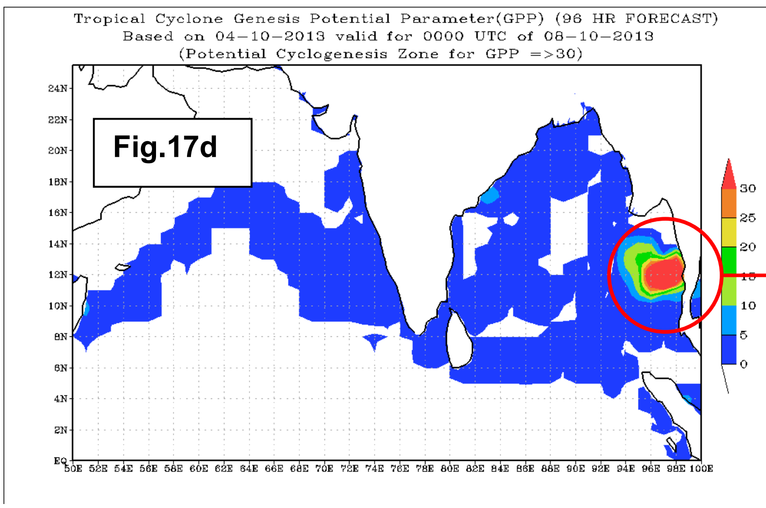
168 hour forecast of GPP valid for 00 UTC 08 October 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



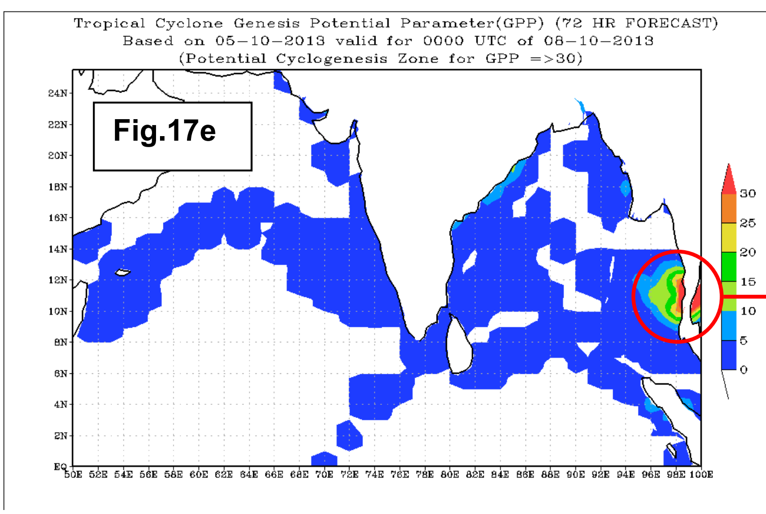
144 hour forecast of GPP valid for 00 UTC 08 October 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



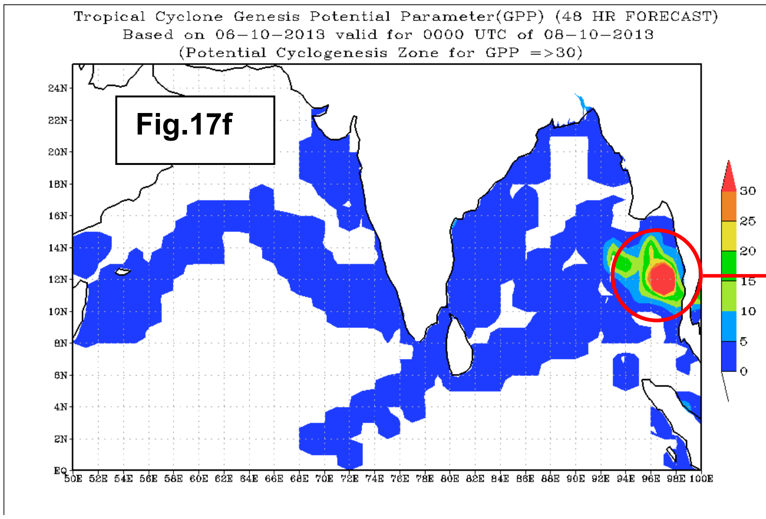
120 hour forecast of GPP valid for 00 UTC 08 October 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



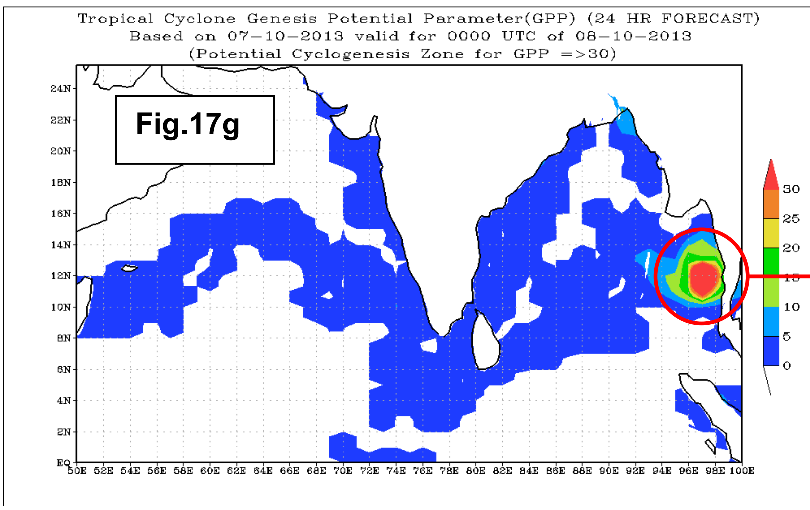
96 hour forecast of GPP valid for 00 UTC 08 October 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



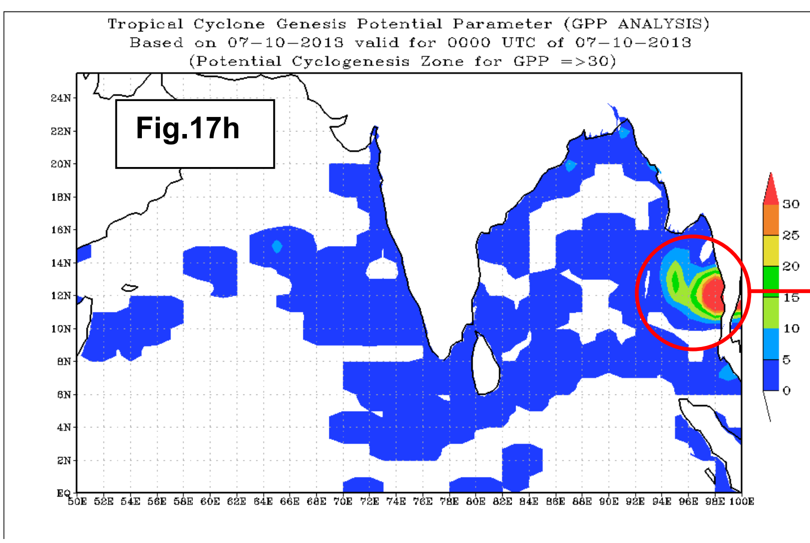
72 hour forecast of GPP valid for 00 UTC 08 October 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



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



48 hour forecast of GPP valid for 00 UTC 08 October 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.

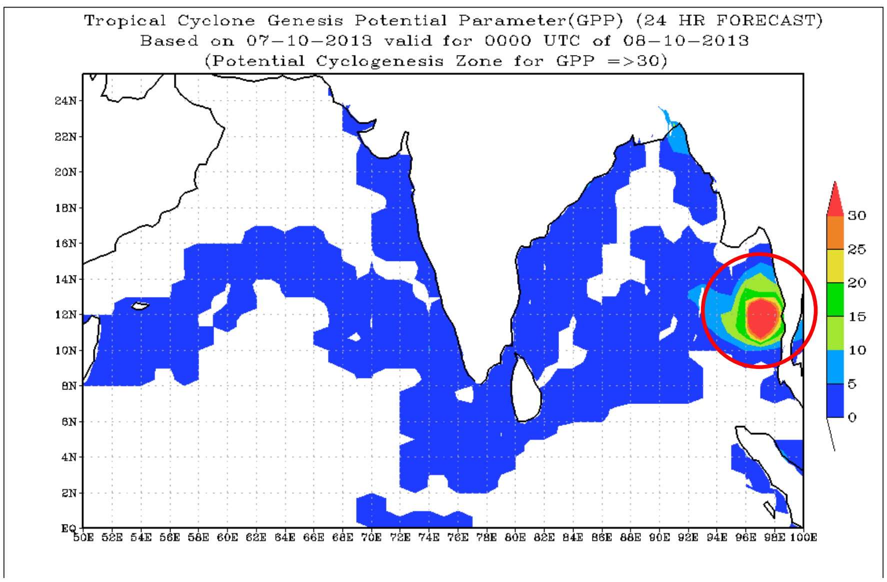
Figure 17(a-h): Predicted zone of cyclogenesis.

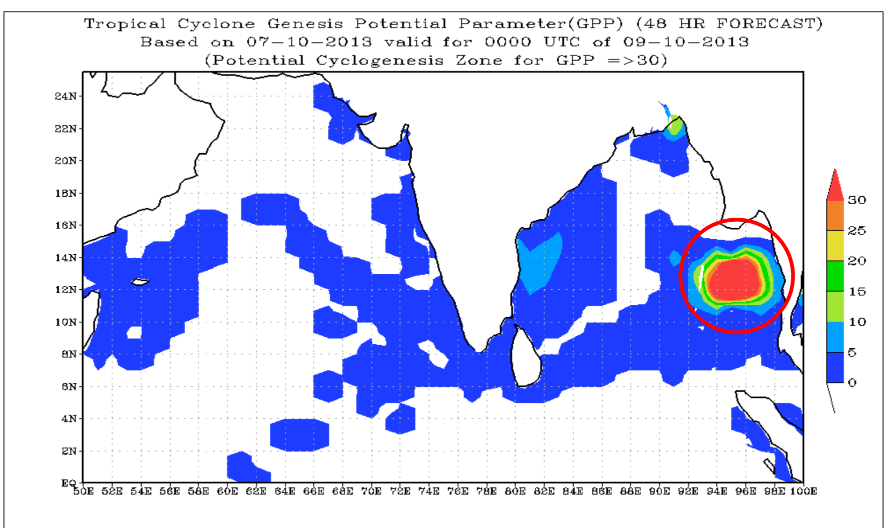
Inference: Grid point analysis and forecasts of GPP (Fig.17(a-h)) shows that it could able to predict the formation and location of the system before 168 hours of its formation.

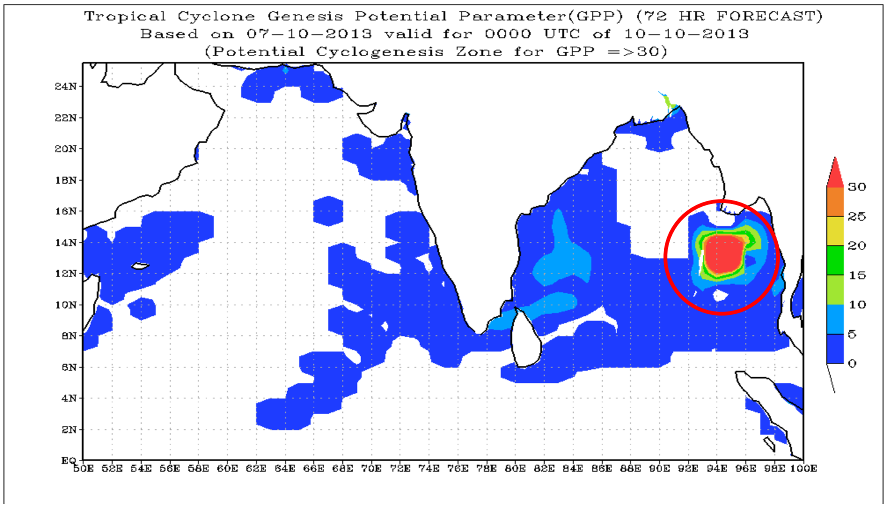
(Product available athttp://www.imd.gov.in/section/nhac/dynamic/Analysis1.htm)

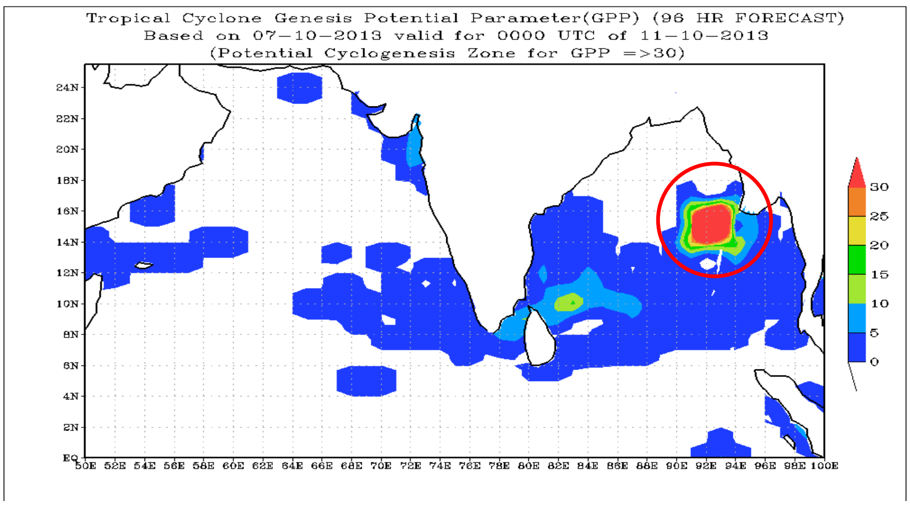
6.1.2. Course of movement of cyclogenesis zone

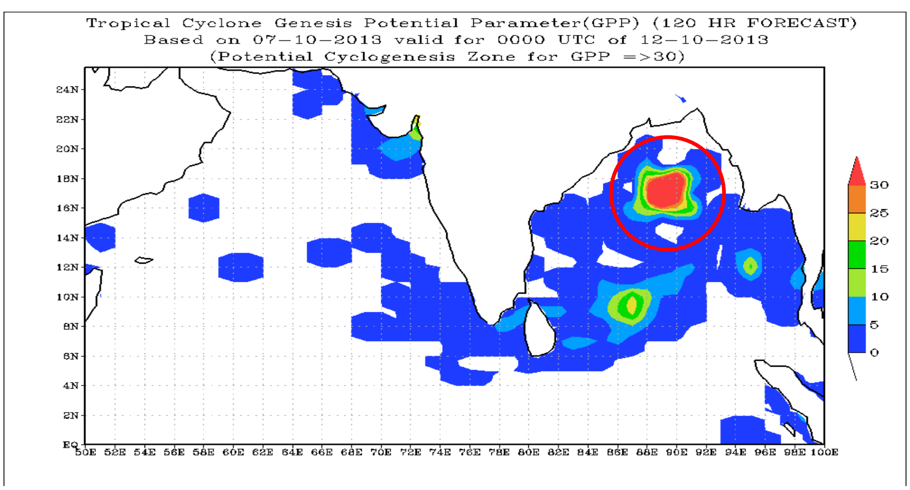
Figure 18(a-h) below shows the course of movement of cyclogenesis zone based on 0000 UTC of 07.10.2013.






Tropical Cyclone Genesis Potential Parameter(GPP) (72 HR FORECAST)
Based on 07–10–2013 valid for 0000 UTC of 10–10–2013
(Potential Cyclogenesis Zone for GPP =>30)


Tropical Cyclone Genesis Potential Parameter(GPP) (96 HR FORECAST)
Based on 07–10–2013 valid for 0000 UTC of 11–10–2013
(Potential Cyclogenesis Zone for GPP =>30)


Tropical Cyclone Genesis Potential Parameter(GPP) (120 HR FORECAST)
Based on 07–10–2013 valid for 0000 UTC of 12–10–2013
(Potential Cyclogenesis Zone for GPP =>30)

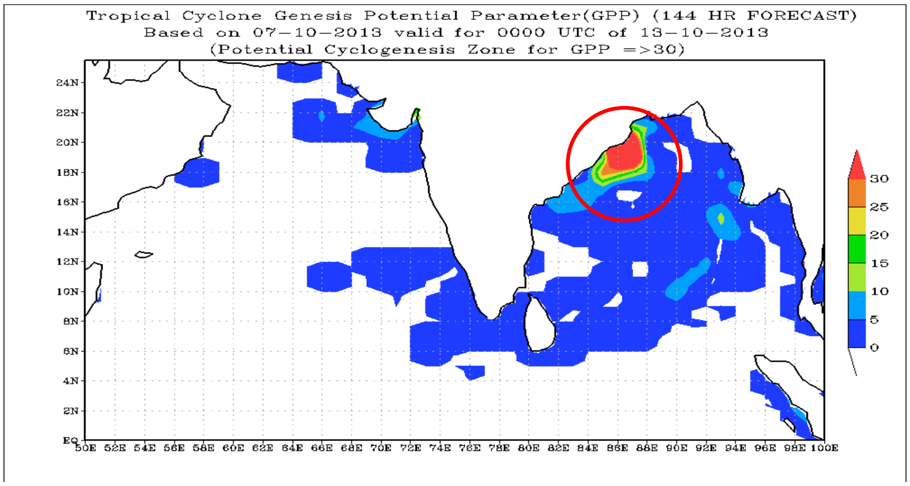


Fig. 18(a-g) course of movement of cyclogenesis zone

Inference: Figure 18(a-g) shows that the prediction of course of movement of cyclogenesis zone based on 0000 UTC of 07.10.2013 correctly predicted northwestward movement to Odisha coast.

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

6.1.3. 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.

Conditions for: (i) Developed system: Threshold value of GPP ≥ 8.0

(ii) Non-developed system: Threshold value of GPP < 8.0

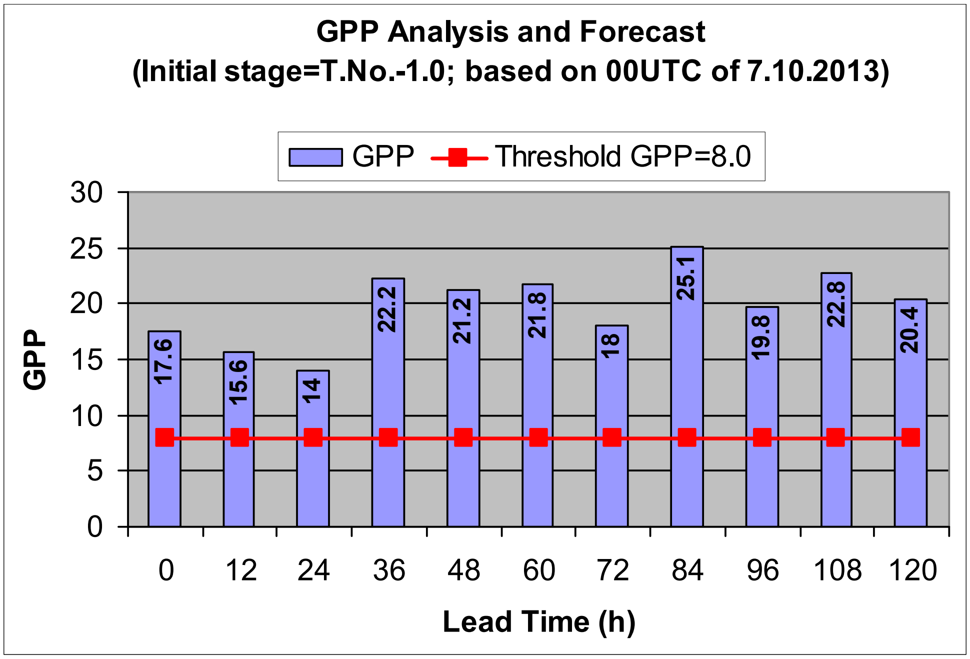


Fig 19a: Analysis and forecasts of GPP shows that GPP ≥ 8.0 (Threshold) at very early stage of development (**T.No.-1.0**) indicated its potentential to intensify into a cyclone.

Fig.19a

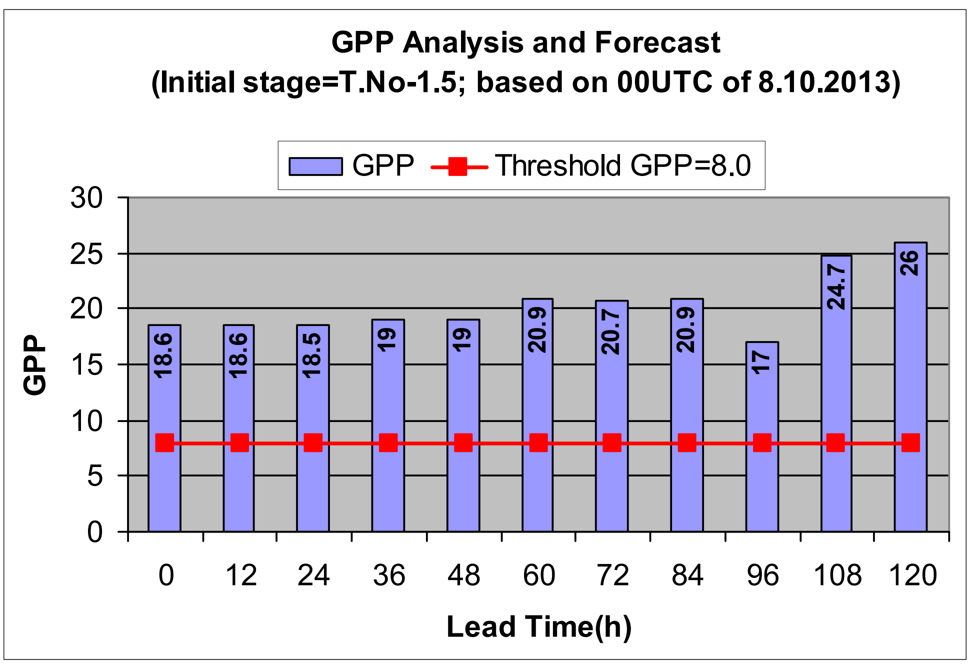


Fig 19b: Analysis and forecasts of GPP shows that GPP ≥ 8.0 (Threshold) at very early stage of development (**T.No. 1.5**) indicated its potentential to intensify into a cyclone.

Fig. 19b

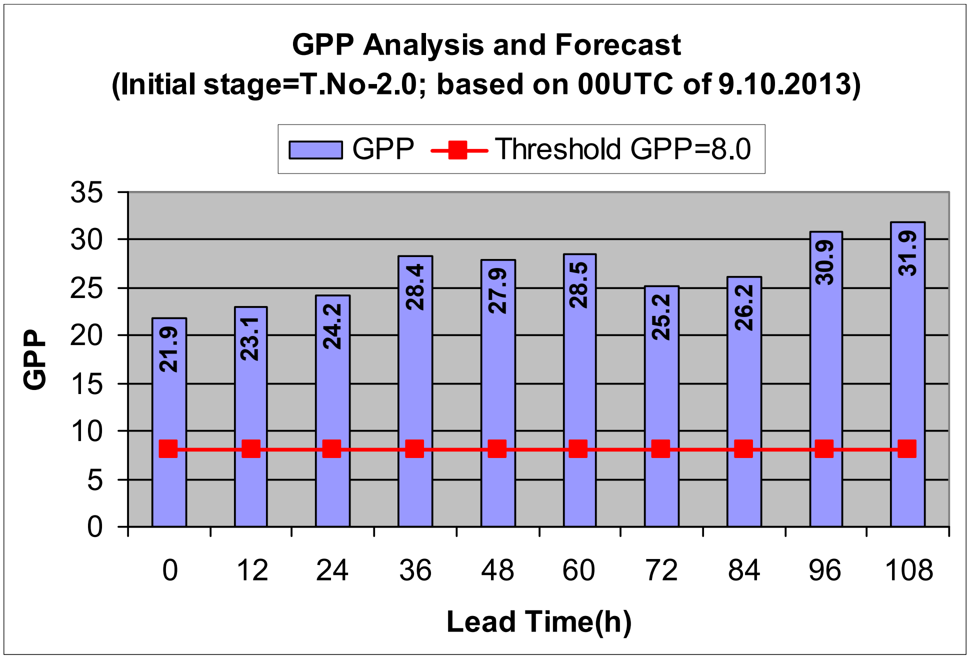


Fig 19c: Analysis and forecasts of GPP shows that GPP ≥ 8.0 (Threshold) at very early stage of development (**T.No. 2.0**) indicated its potentential to intensify into a cyclone.

Fig. 19c

Fig. 19(a-c) Area average analysis of GPP

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

Inference: Analysis and forecasts of GPP (Fig.19(a-c)) shows that GPP ≥ 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, 2.0).

6.2 Track prediction

Direct position errors (DPE), cross track (CT) and along track (AT) component of track forecast are calculated based on the following Fig. 20 adapted from Heming (1994).

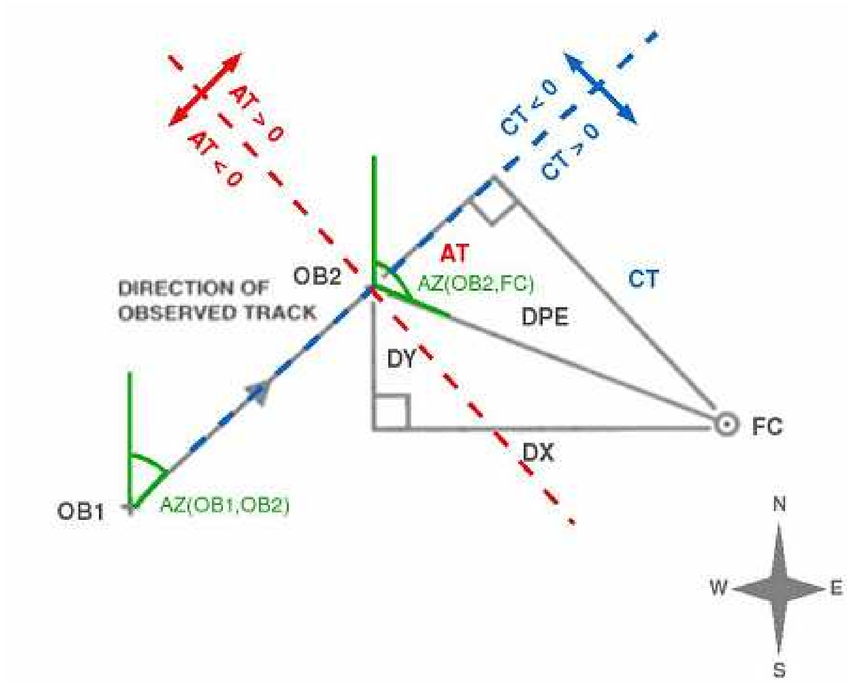
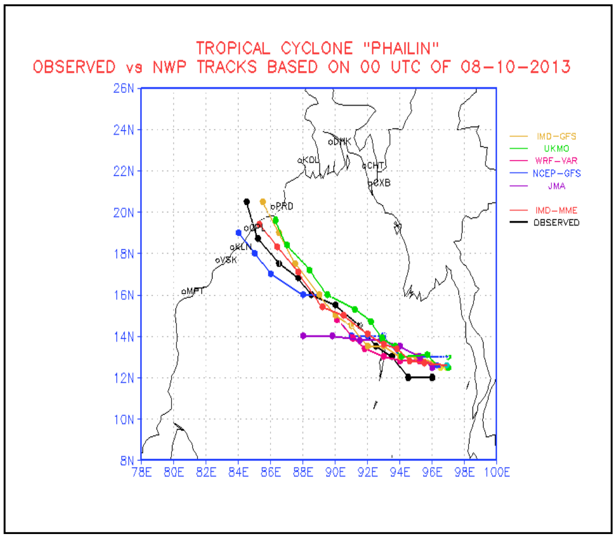
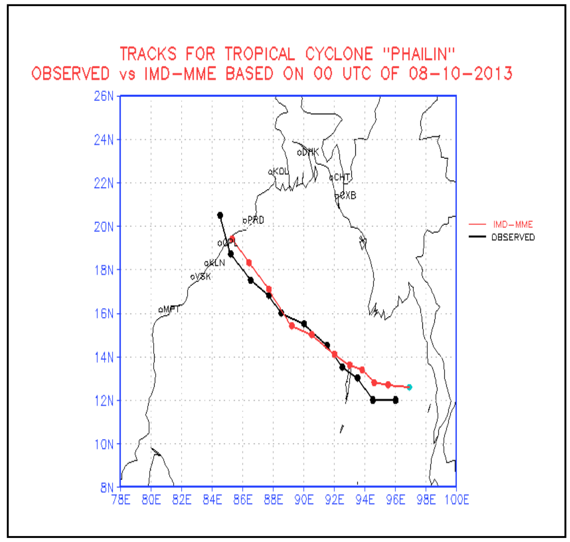
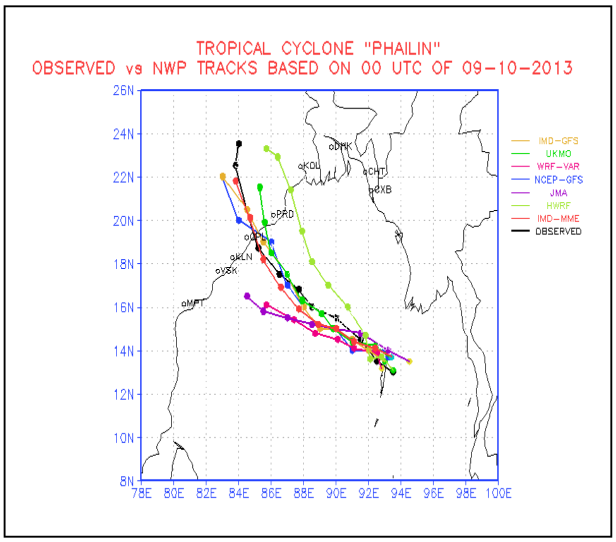


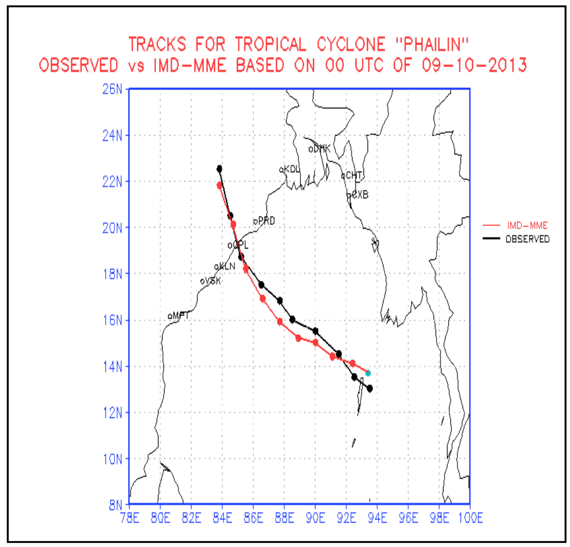
Fig 20: Types of positional forecast errors. DPE represents the direct positional error, CT is the cross track component, AT the along track component. DX represents the longitudinal component and DY is the latitudinal component. (Adapted from Heming (1994))

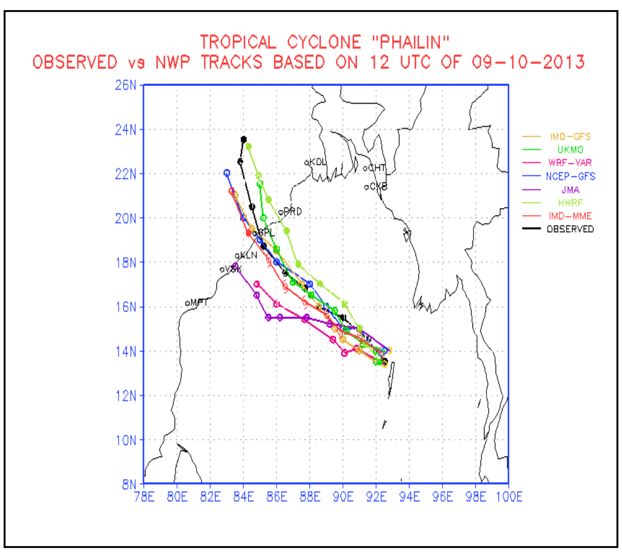
The average track forecast errors (DPE, CTE, ATE) of NWP models along with the consensus forecast by Multi-model ensemble (MME) forecast are presented in the Table 1, Table 2 and Table 3 respectively. Landfall forecast of MME is presented in Table 4. The landfall point error (km) and landfall time (hour) is presented in Table-5 and Table-6 respectively. The MME forecasts track based on different initial conditions along with the observed track is depicted in Fig 21. The figure shows that from the day1 (00 UTC 8 October to 12 UTC 12 October 2013), MME could able to predict correctly and consistently the landfall at Gopalpur (Odisha).

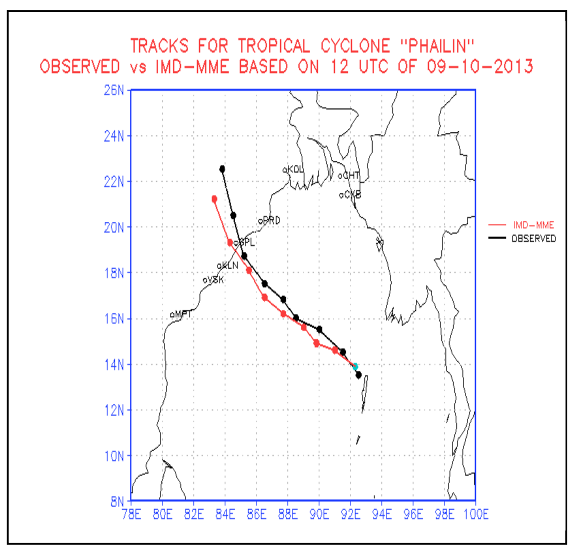

TROPICAL CYCLONE "PHAILIN"
OBSERVED vs NWP TRACKS BASED ON 00 UTC OF 08-10-2013
IMD-GFS
UKMO
WRF-VAR
NCEP-GFS
JMA
IMD-MME
OBSERVED

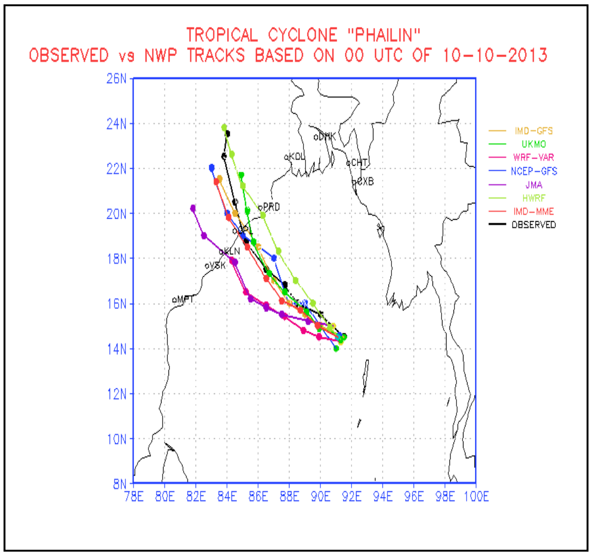

TRACKS FOR TROPICAL CYCLONE "PHAILIN"
OBSERVED vs IMD-MME BASED ON 00 UTC OF 08-10-2013
IMD-MME
OBSERVED

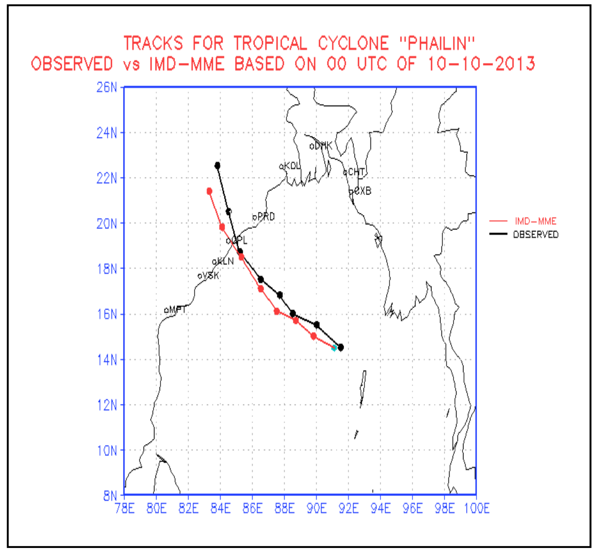

TROPICAL CYCLONE "PHAILIN"
OBSERVED vs NWP TRACKS BASED ON 00 UTC OF 09-10-2013
IMD-GFS
UKMO
WRF-VAR
NCEP-GFS
JMA
HWRF
IMD-MME
OBSERVED

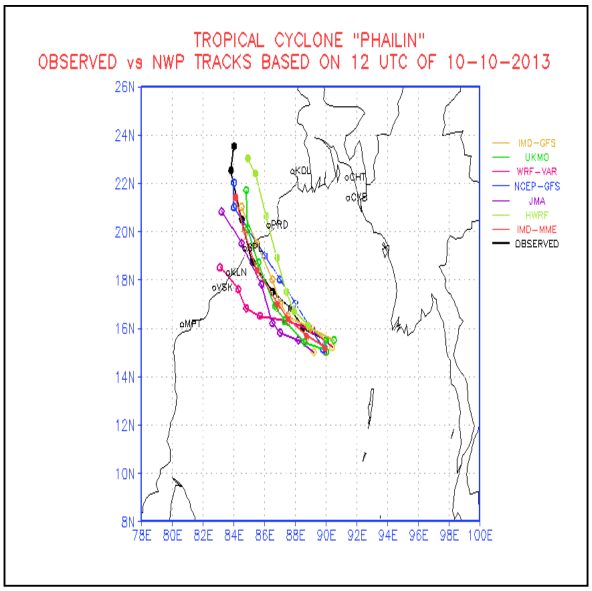

TRACKS FOR TROPICAL CYCLONE "PHAILIN"
OBSERVED vs IMD-MME BASED ON 00 UTC OF 09-10-2013
IMD-MME
OBSERVED

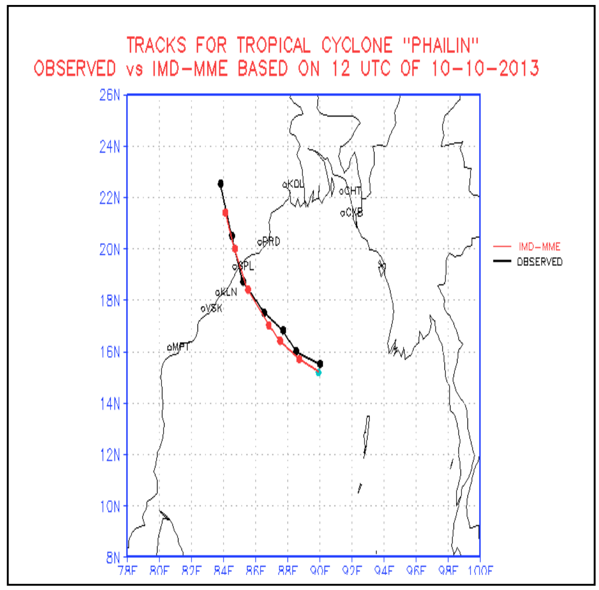

TROPICAL CYCLONE "PHAILIN"
OBSERVED vs NWP TRACKS BASED ON 12 UTC OF 09-10-2013
IMD-GFS
UKMO
WRF-VAR
NCEP-GFS
JMA
HWRF
IMD-MME
OBSERVED

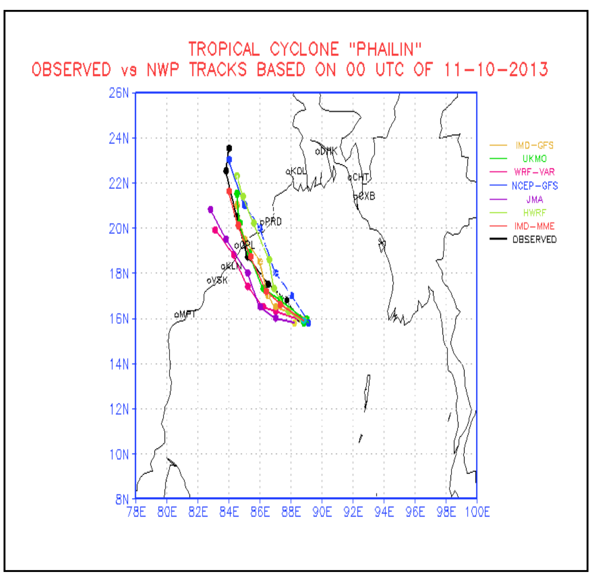

TRACKS FOR TROPICAL CYCLONE "PHAILIN"
OBSERVED vs IMD-MME BASED ON 12 UTC OF 09-10-2013
IMD-MME
OBSERVED

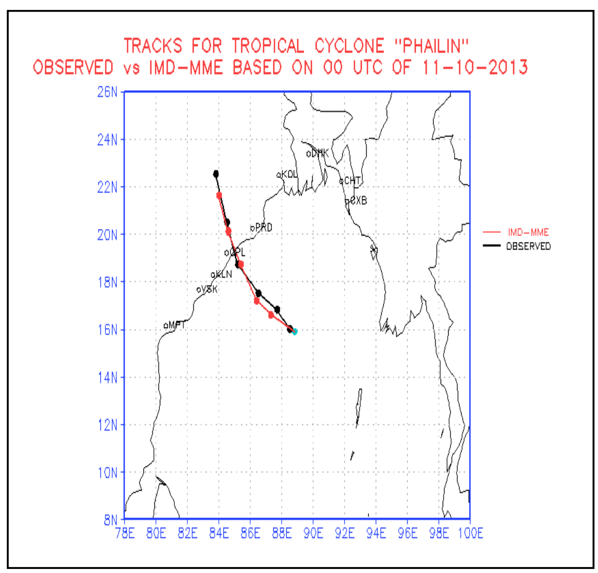

TROPICAL CYCLONE "PHAILIN"
OBSERVED vs NWP TRACKS BASED ON 00 UTC OF 10-10-2013
IMD-GFS
UKMO
WRF-VAR
NCEP-GFS
JMA
HWRF
IMD-MME
OBSERVED


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


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


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


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

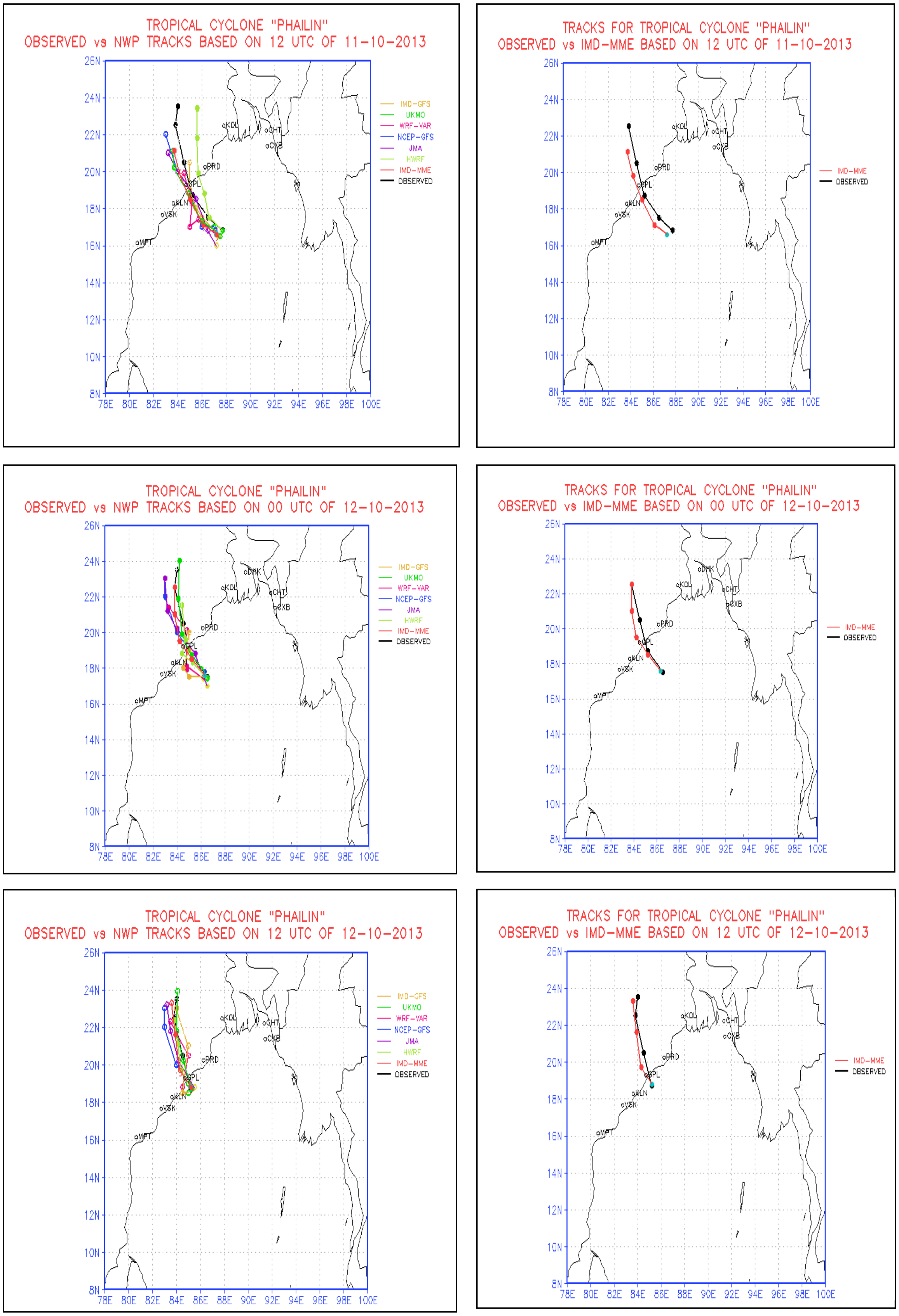


Fig. 21. MME forecasts track based on different initial conditions

Direct position Error (DPE): Average track forecast error (direct position error (DPE)) 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-1). The DPE of all models are shown in Fig. 22.

Table-1. Average track forecast errors (DPE) in km (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-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)

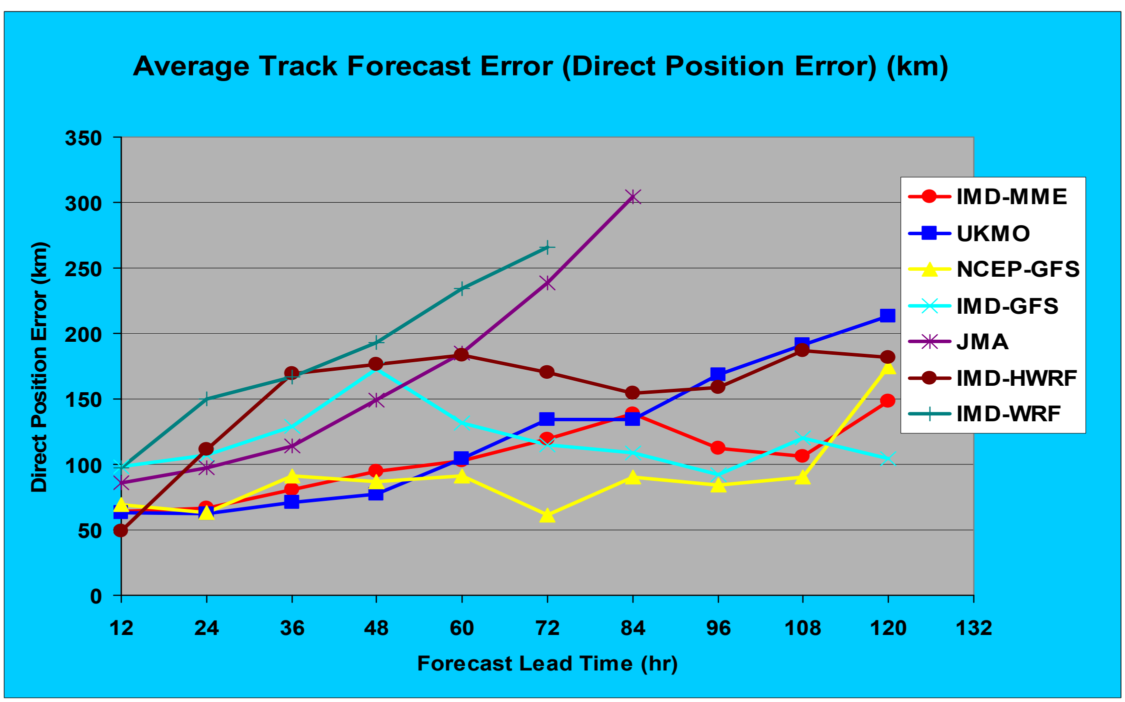


Fig. 22: Average track forecast errors (DPE) of NWP models

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-2). The CTE of all models are shown in Fig. 23.

Table-2. Average cross track error (CTE) in km

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

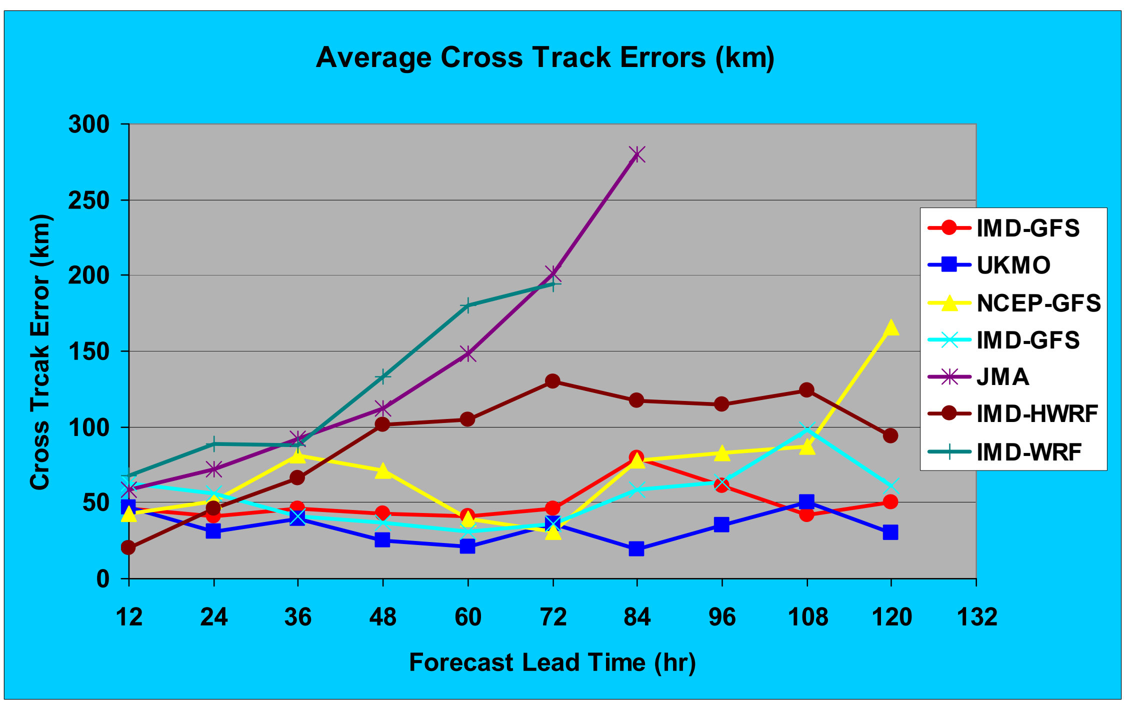


Fig. 23: Average cross track errors (CTE) of NWP models

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-3). The ATE of all models is shown in Fig. 24.

Table-3. Average along track error (ATE) in km

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

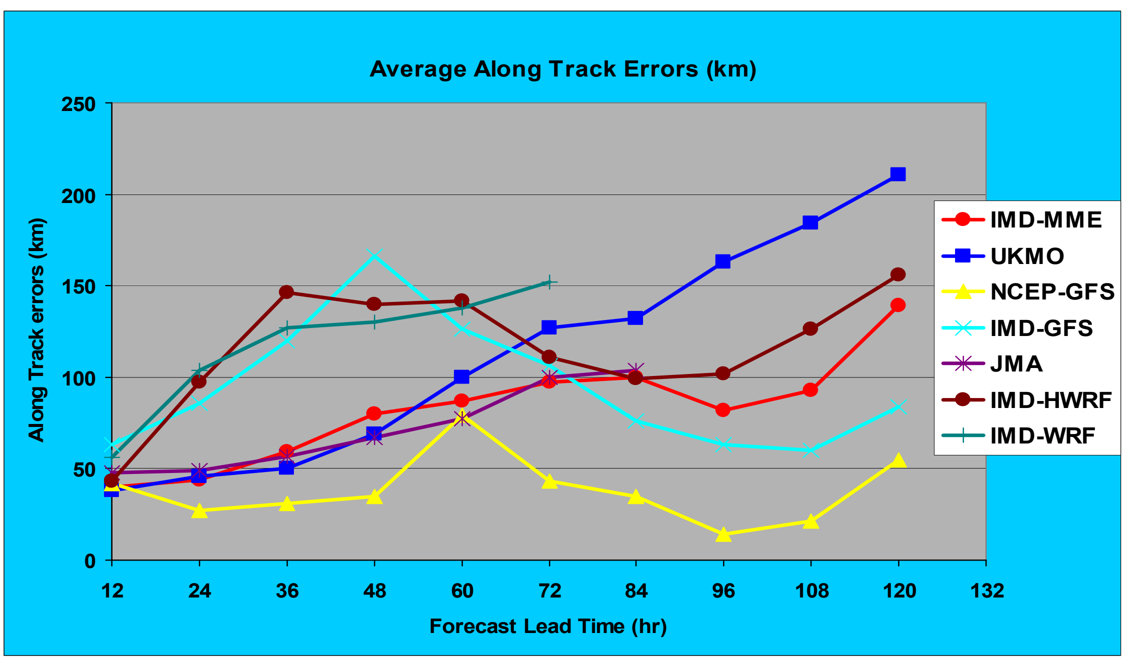


Fig. 24: Average along track errors (ATE) of NWP models

Track Forecast Error of MME: The DPE, ATE and CTE of consensus forecast of NWP models (MME) along with their Standard Deviation (SD) are shown in Fig 25, Fig 26 and Fig 27 respectively.

The average DPE of MME was about 65 km at 12 h to 150 km at 120 h (Fig. 25).

The average ATE of MME was about 40 km at 12 h to 140 km at 120 h (Fig. 26).

The average CTE of MME was about 45 km at 12 h to 50 km at 120 h (Fig. 27).

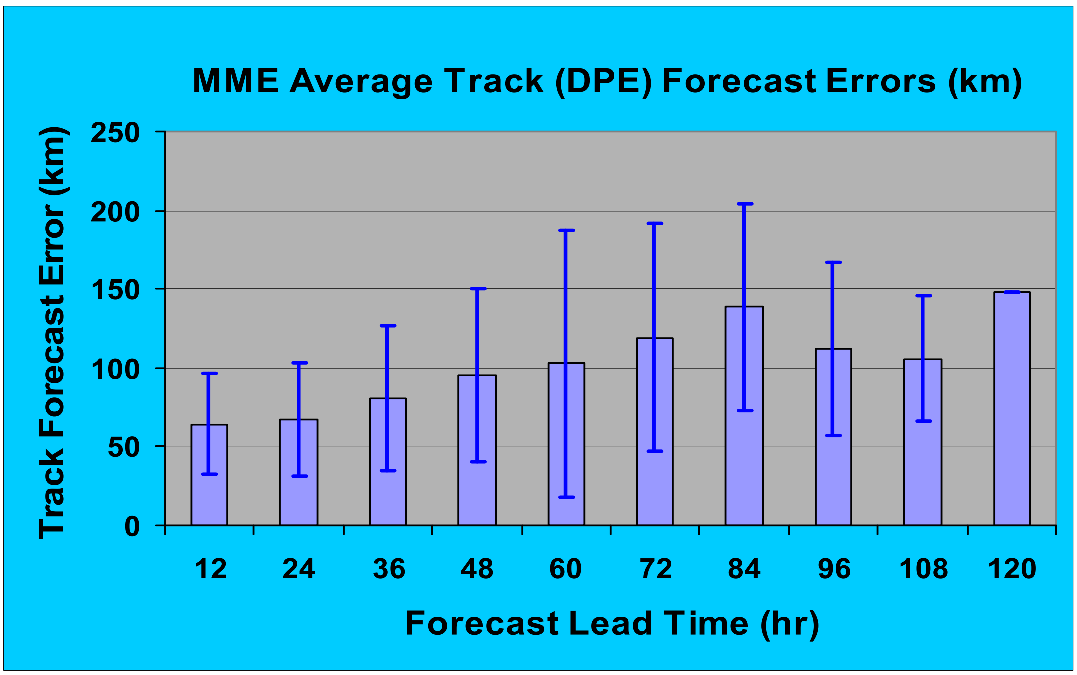


Fig. 25: Average direct track error (DPE) of MME (along with range(thick blue line))

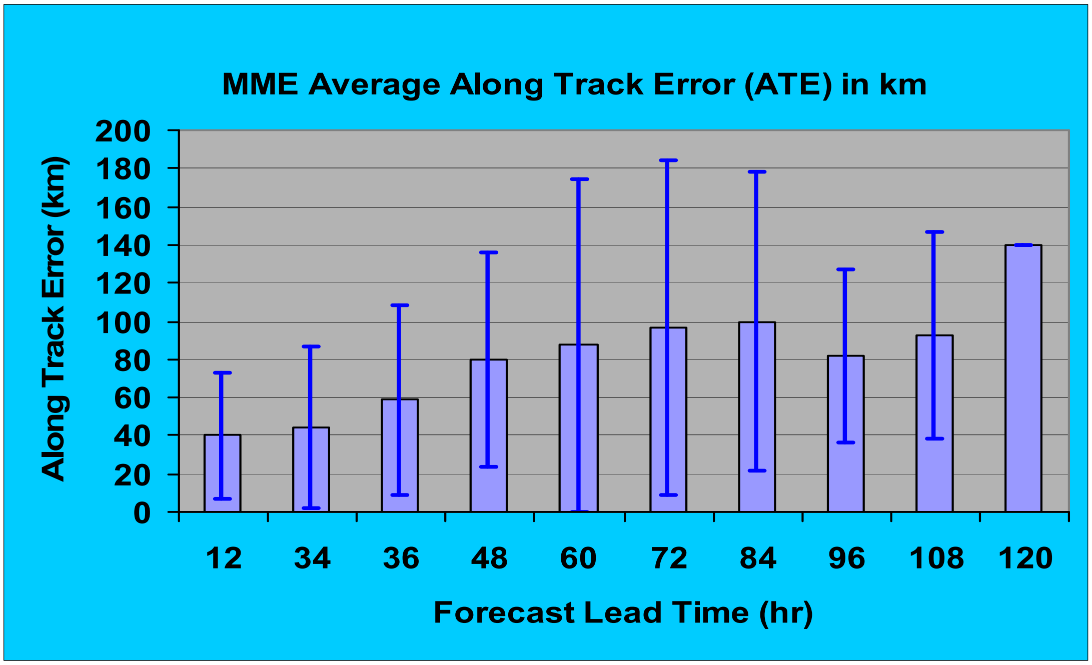


Fig. 26: Average along track error (ATE) of MME (along with range(thick blue line))

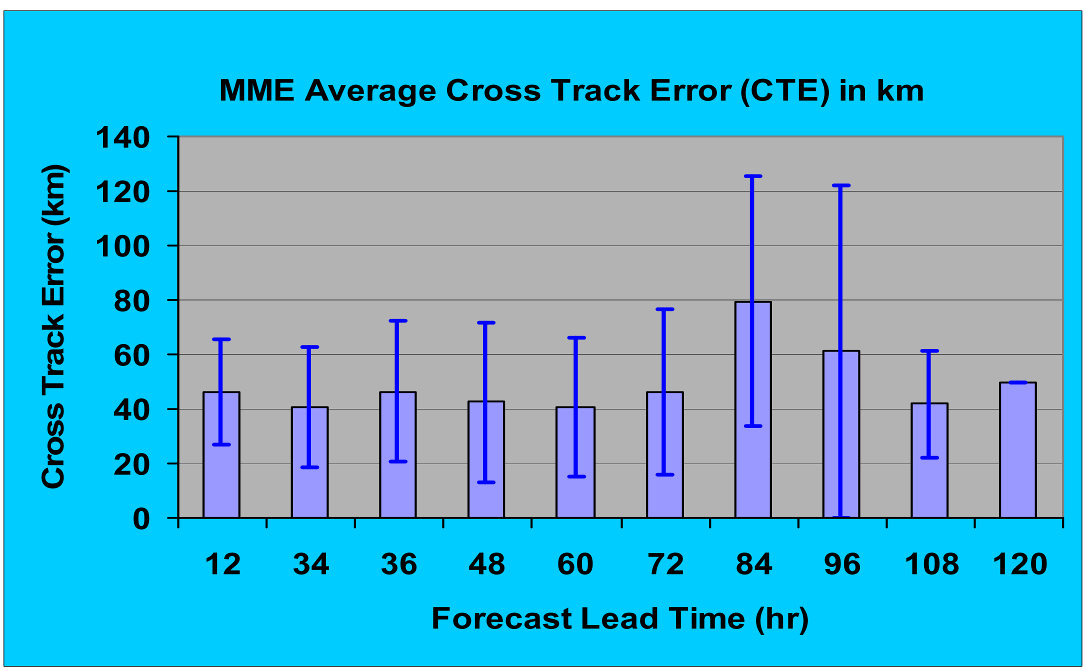


Fig. 27: Average cross track error (CTE) of MME (along with range(thick blue line))

Landfall Point Error: Landfall point forecasts errors of NWP model at different forecast lead times (Fig. 28) 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 could able to predict near actual landfall point (Gopalpur) consistently (Table-4).

Table-4. Landfall Point and Landfall time error of consensus NWP model (MME) forecasts

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

Table-5. Landfall point forecast errors (km) of NWP Models at different lead time (hour)

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

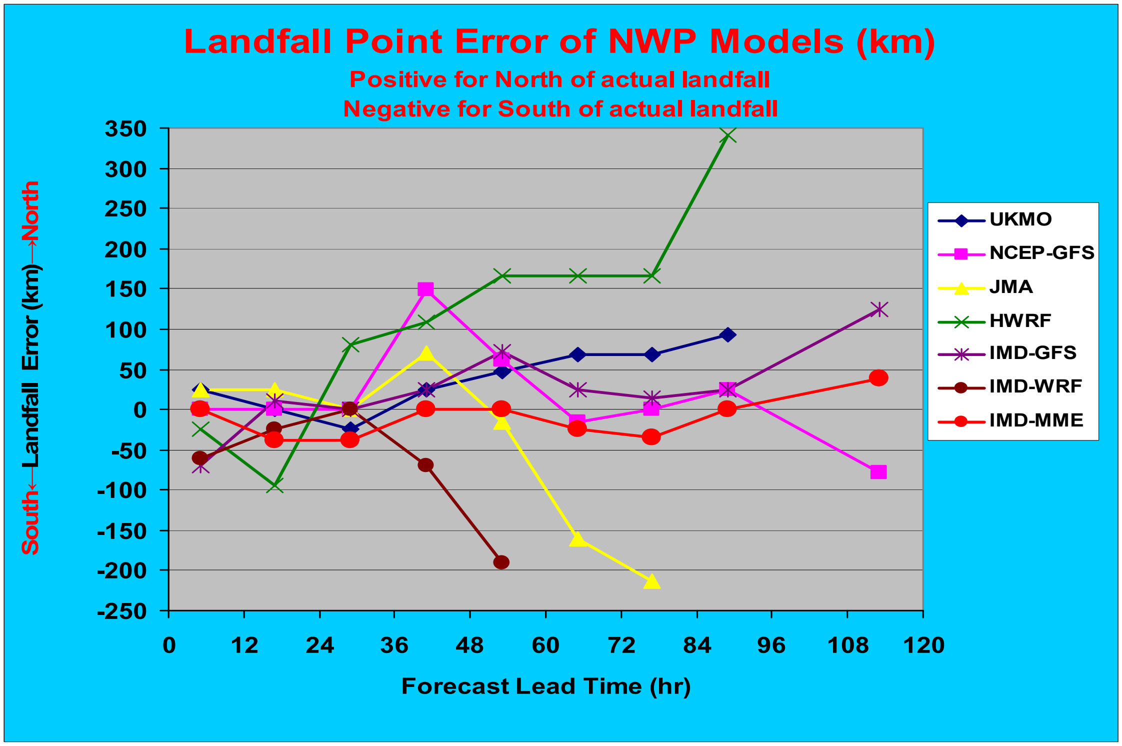


Fig. 28: Landfall point error (hr) of Models

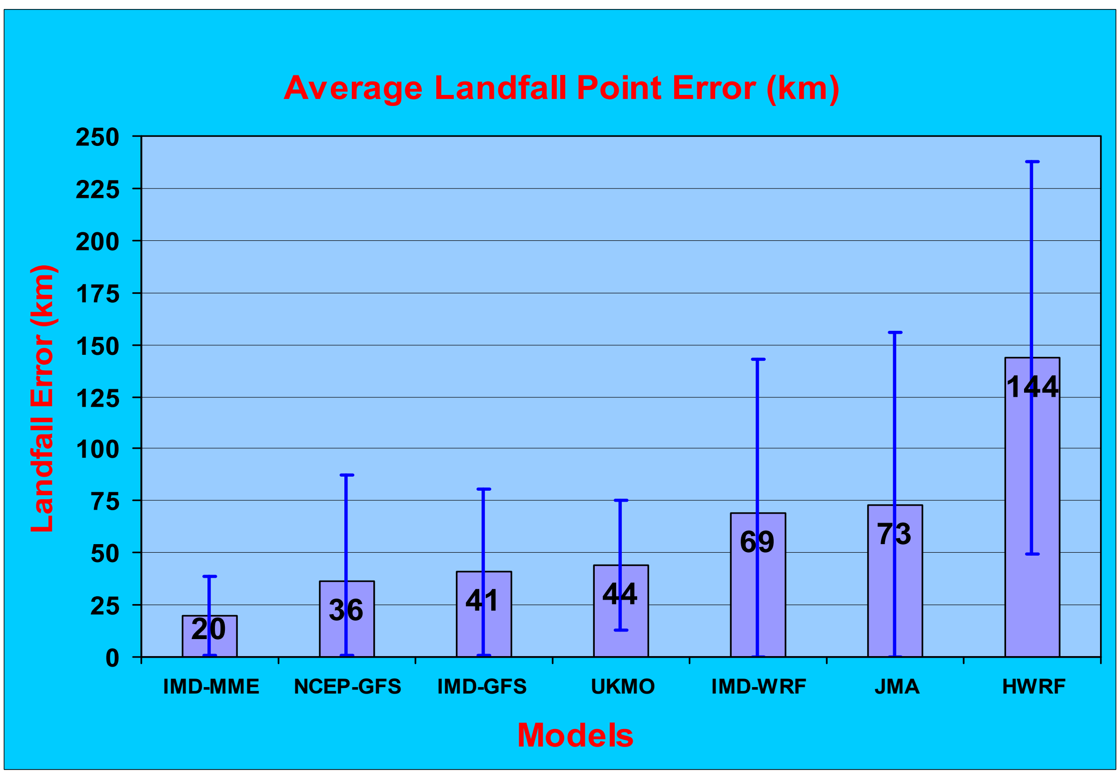


Fig. 29: Average landfall point error (km) of Models (along with range(thick blue line))

Average land fall point error (Fig. 29) 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. 30) 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-6). Average land fall time error (Fig. 31) shows that MME landfall time forecast error is least (1.9 hr) compared to other models.

Table-6. Landfall time forecast errors (hour) at different lead time (hr)

('+' 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

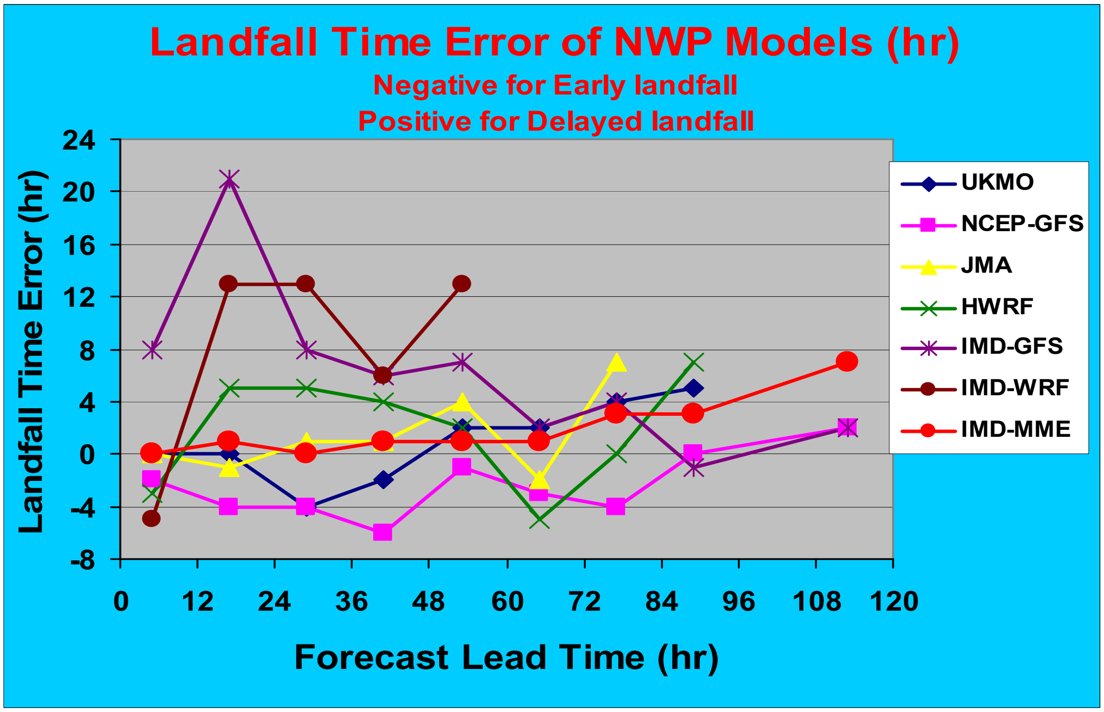


Fig. 30: Landfall time error (km) of models at different lead time (hr)

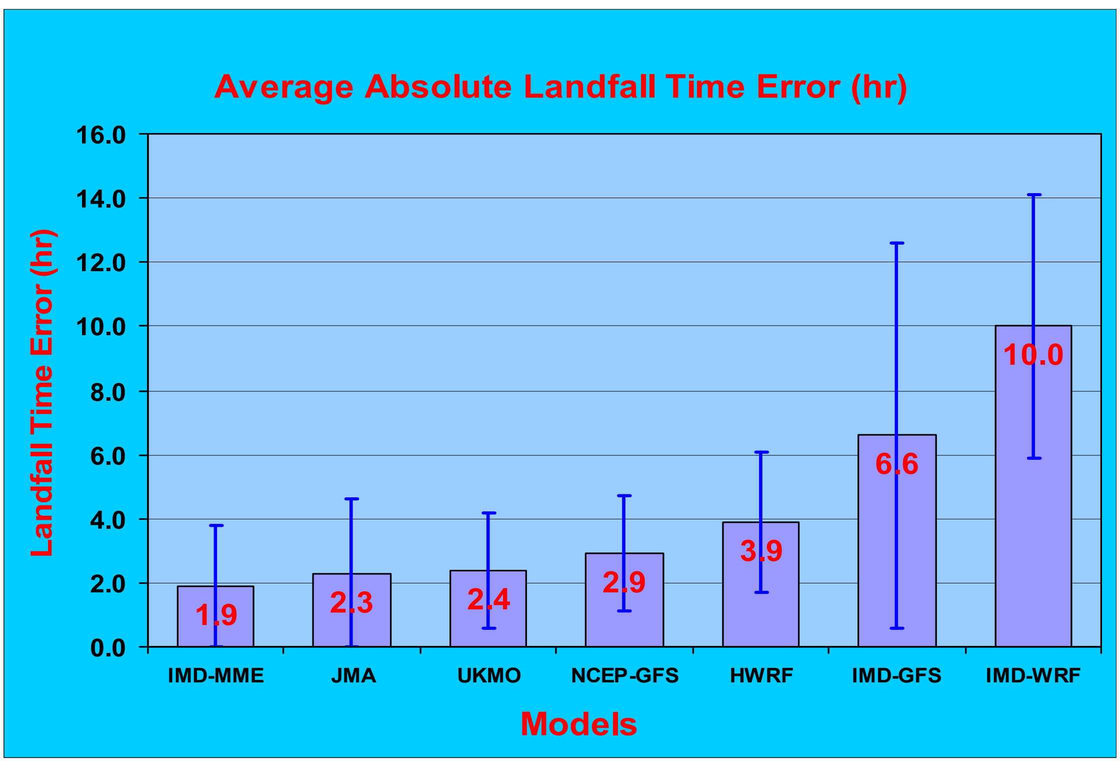


Fig. 31: Average landfall time error (hr) of Models (along with range(thick blue line))

6.3 Intensity prediction

Intensity prediction (at stages of 12-h intervals) by statistical-dynamical model SCIP and dynamical model HWRF are shown in Fig. 32 and Fig. 33 respectively. Both the SCIP and HWRF model could 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.

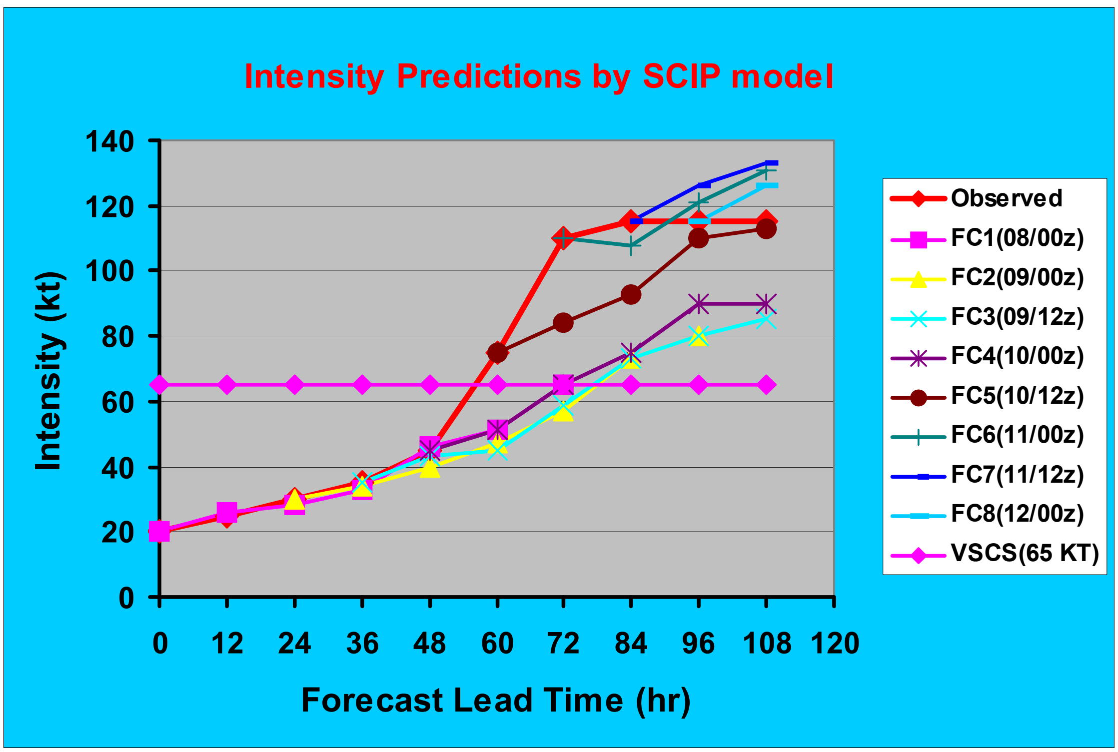


Fig. 32. Intensity forecasts of SCIP model

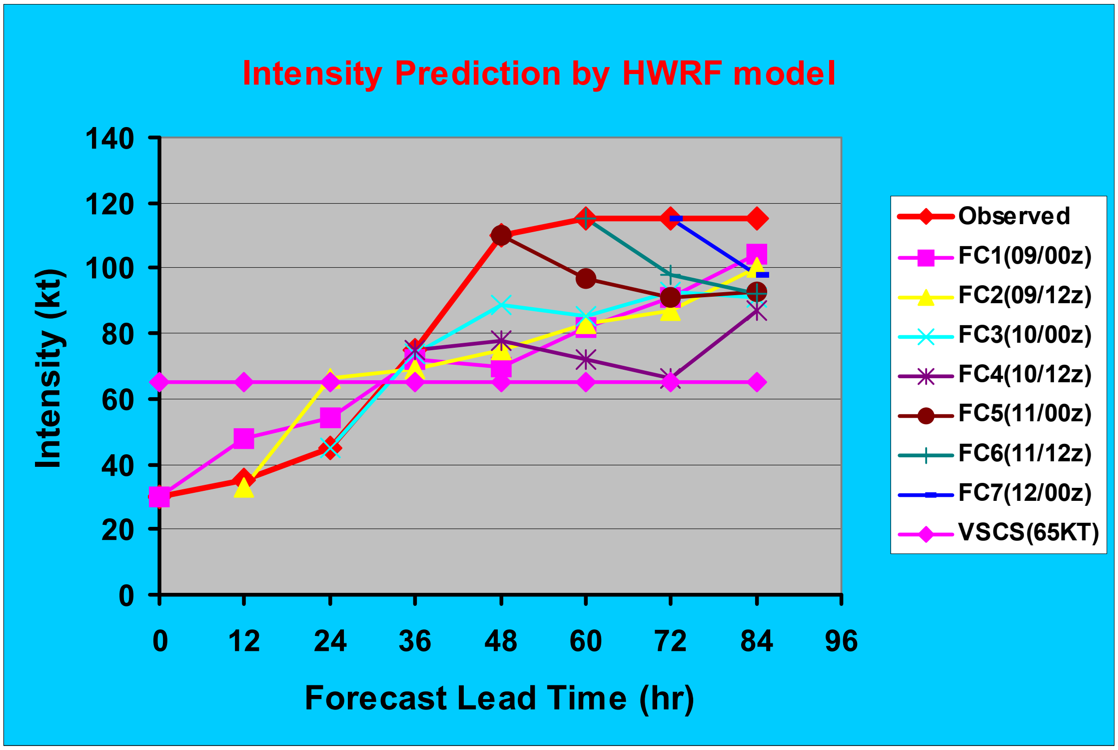


Fig. 33. Intensity forecasts of HWRF model

Average absolute error (AEE) and Root mean square error (RMSE) of SCIP and HWRF forecast error is presented in the following Table-7 and Table-8. 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-7 Average absolute errors (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
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)

Table-8 Root Mean Square (RMSE) errors (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
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)

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. 34).

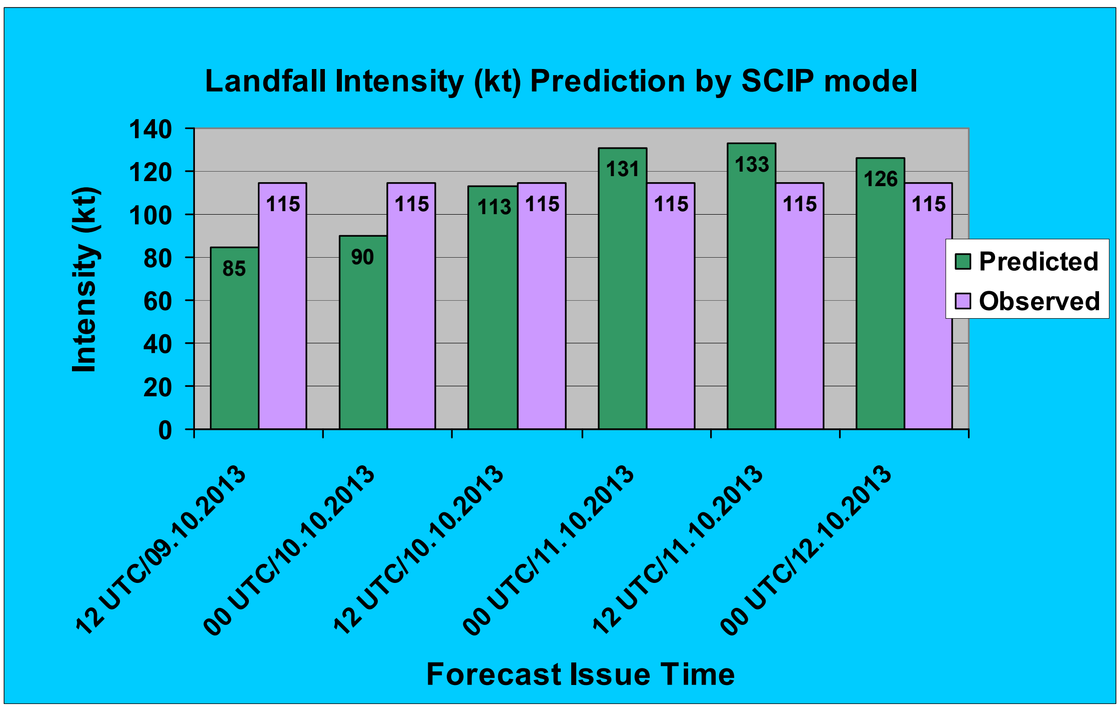


Fig. 34: Landfall Intensity (kt) prediction by SCIP Model

6.4 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-9 Probability of Rapid intensification

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 could 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.				

6.5 Decay after landfall

Decay (after landfall) prediction curve (6-hourly up to 30 hr) (Fig. 35(a-b)) shows slightly first decay compared to observed decay. Decay model could correctly predict the decaying nature of the PHAILIN after landfall.

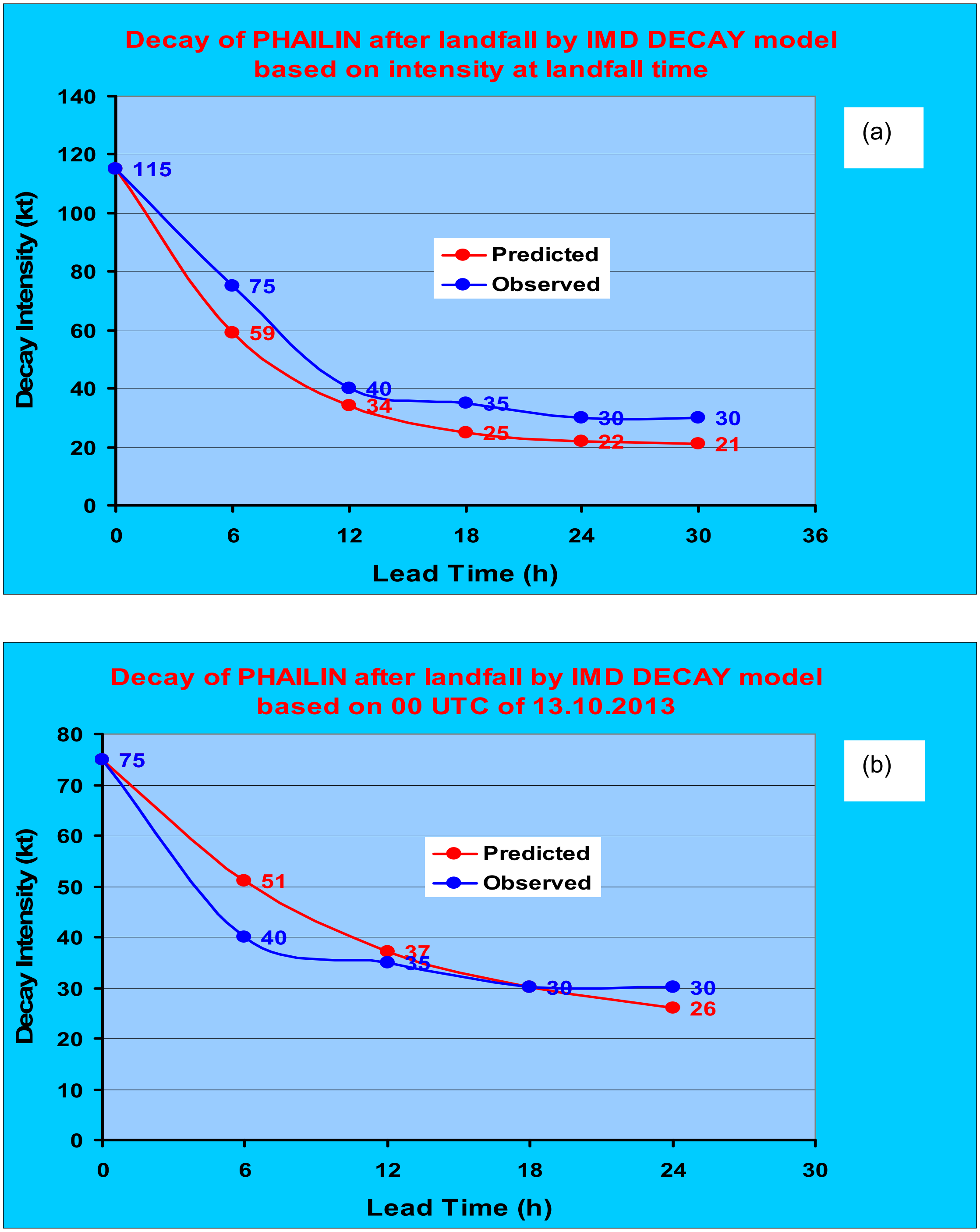
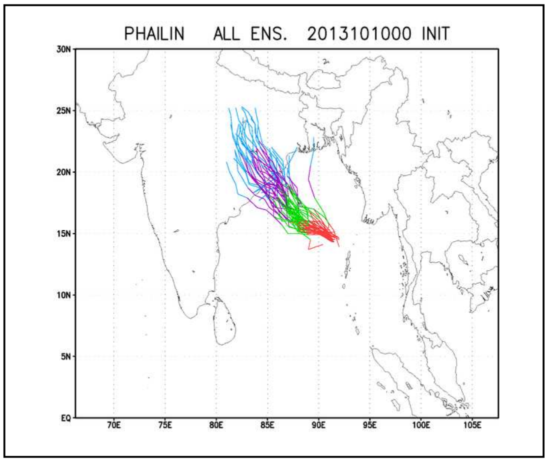
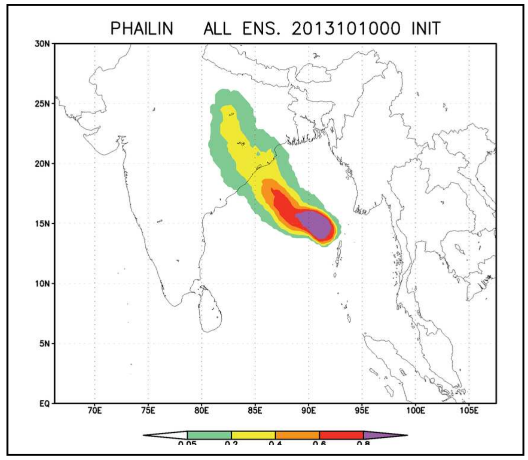


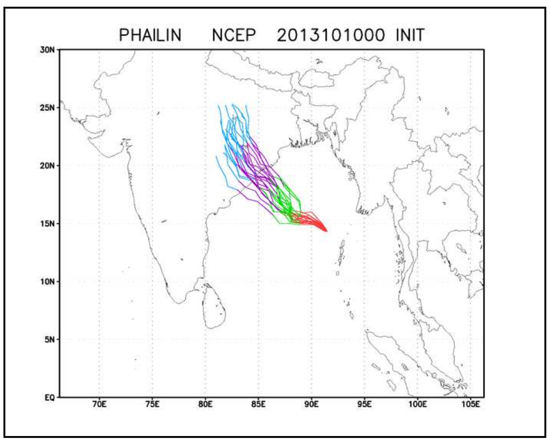
Fig. 35. Decay after landfall

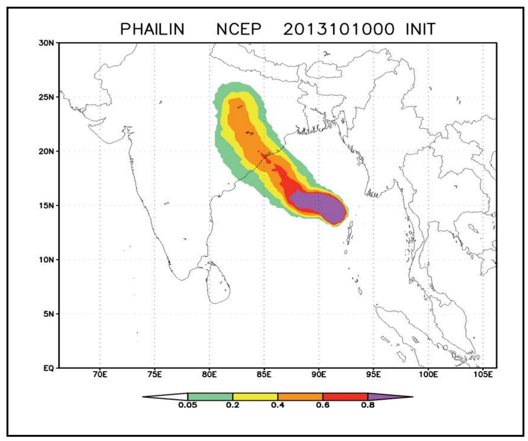
7. Ensemble track and Strike Probability forecast

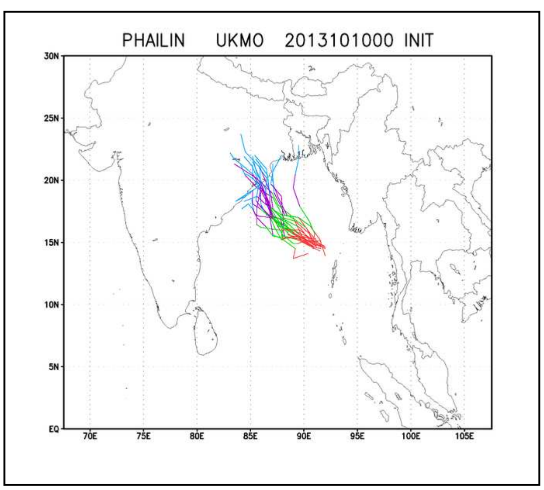
a. Based on 0000 UTC 10.10.2013

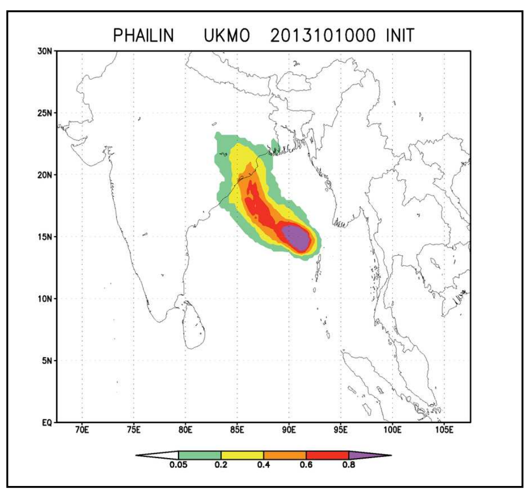




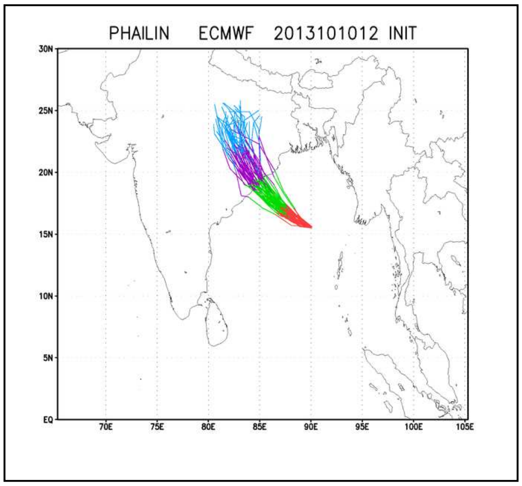


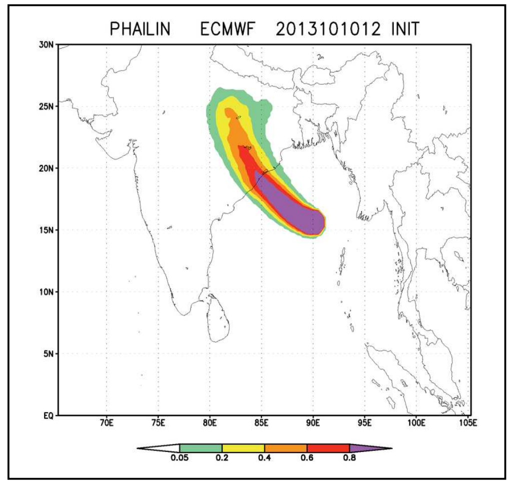


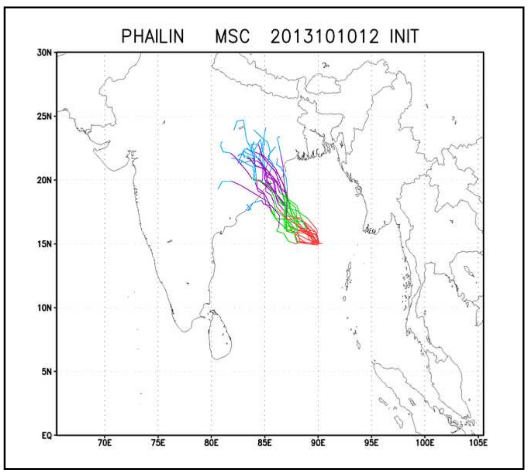


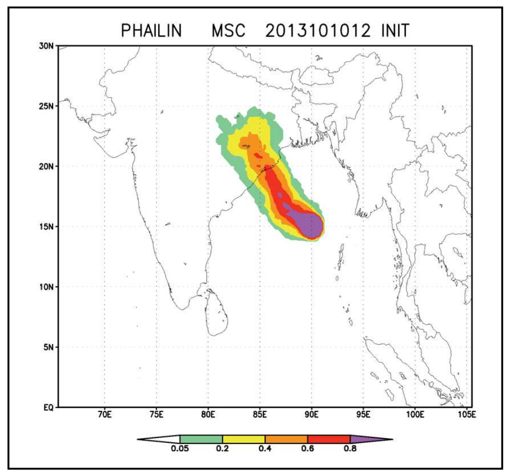


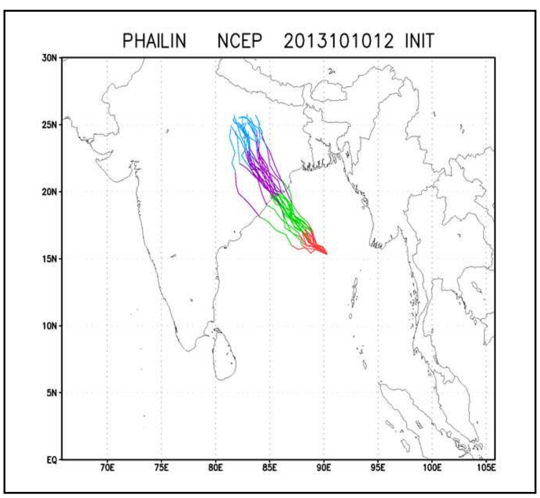
b. Based on 1200 UTC 10.10.2013

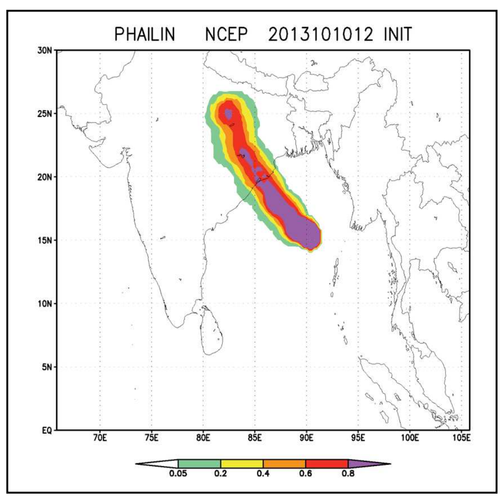












Ensemble track and strike probability forecast based on 00 UTC 10.10.2013 and 12 UTC 10.10.2013 shows that UKMO, UKMO, MSC and NCEP all predicted towards Odisha coast.

8. Summary

The performances of NWP guidance for cyclone PHAILIN are summarized below:

1. CYCLOGENESIS:

(1) Grid point analysis and forecasts of GPP could able to predict the formation and location of the system before 168 hours of its formation.

(2) Analysis and forecasts of area average GPP indicated its potentential to intensify into a cyclone at early stages (T.No. 1.0, 1.5, 2.0) of its development.

2. TRACK:

(1) **Average track forecast error (direct position error (DPE))** 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.

(2) **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). IMD-GFS was also comparable with UKMO and MME up to 96 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).

(3) **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.

(4) **Landfall point forecasts errors** of NWP model at different forecast lead times show that some model predicted north of actual landfall 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 could able to predict near actual landfall point (Gopalpur) consistently.

(5) Average land fall point error shows that MME forecast error is least compared to other models before 5 h to 113 h of landfall. Average land fall point error of MME was 20 km and it varied from 36 km (NCEP-GFS) to 144 km (HWRF) for other models.

(6) **Average land fall time error** shows that MME landfall time forecast error was least (1.9 hr) compare to other models (2.3 hr (JMA) to 10 hr (WRF)).

3. INTENSITY:

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. Average absolute error (AAE) for SCIP ranged from 10 kt at 12 hr to 25 kt at 48 hr and it was 17 kt at 12 hr to 31 kt at 48 hr for HWRF. 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.

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

4. RAPID INTENSIFICATION:

RI-Index could 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.

5. DECAY AFTER LANDFALL:

Decay (after landfall) prediction curve (6-hourly up to 30 hr) (Fig. 34(a-b)) shows slightly first decay compared to observed decay. Decay model could correctly predict the decaying nature of the PHAILIN after landfall.

6. ENSEMBLE TRACK AND STRIKE PROBABILITY:

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

All the components of cyclone forecasts (cyclogenesis, track, intensity, rapid intensification, decay after landfall) by CYCLONE PREDICTION SYSTEM (CPS) generated at IMD NWP division show that statistical post processing added skill to

dynamical forecasts and provided very useful guidance on landfall point, landfall time, intensity, rapid intensification phases and decay after landfall for operational cyclone forecasting.

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