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Verification of forecasts of IMD NWP based cyclone prediction system (CPS) for cyclones over the north Indian seas during 2013

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सार – इस शोध पत्र में प्रचालनात्मक पूर्वानुमानकर्ताओं की विशिष्ट आवश्यकताओं को पूरा करने के लिए हमारे प्रयासों से एक उद्‌देश्यपरक NWP के आधार पर चक्रवात प्रागुक्ति प्रणाली (CPS) विकसित की गई और प्रचालनात्मक चक्रवात पूर्वानुमान संबंधी कार्यों के लिए इसे कार्यान्वित किया गया। इस प्रणाली में पाँच पूर्वानुमान घटक शामिल हैं जो इस प्रकार हैं: (क) चक्रवात जनित संभाव्य प्राचल (GPP) (ख) चक्रवात पथ प्रागुक्ति के लिए बहु-निदर्श समुच्चय (MME) (ग) चक्रवात तीव्रता प्रागुक्ति (घ) द्रुत तीव्रीकरण और (ड़) तट से टकराने के बाद तीव्रता के कमज़ोर होने की प्रागुक्ति IMD प्रचालनात्मक भूमंडलीय पूर्वानुमान प्रणाली के मॉडल आऊटपुट से गतिकीय और ऊष्मा गतिकीय प्राचलों पर आधारित GPP प्राप्त किए गए। चक्रवात पथ की प्रागुक्ति के लिए MME की तकनीक बहुल रैखिक समाश्रयण तकनीक का प्रयोग करते हुए 12 घंटे की चक्रवात तीव्रता (72 घंटों तक) की प्रागुक्ति के लिए एक सांख्यिकीय चक्रवात तीव्रता प्रागुक्ति (SCIP) मॉडल विकसित किया गया। चक्रवात के तट से टकराने के पश्चात अन्त: स्थलीय पवन के पूर्वानुमान के लिए एक अनुभवजन्य तकनीक विकसित की गई।

इस शोध पत्र में सात चक्रवाती विक्षोभों के लिए वर्ष 2013 में CPS की विकासात्मक नीति और प्रणाली की निष्पादन कौशलता को बताया गया है। निष्पादन मूल्यांकन से यह पता चला है कि निम्न अवदाब के विकास की आरम्भिक अवस्थाओं में GPP के विश्लेषण इसके और तीव्रीकरण के लिए प्रणाली की संभाव्यता को बता सकता है। MME (12 घंटे में 68 कि.मी. से लेकर 120 घंटे में 187 कि.मी. और SCIP मॉडल (12 घंटे में 5.9 kt से लेकर 72 घंटे में 19.8 kt) द्‌वारा 12 घंटे के पथ पूर्वानुमान से तीव्रता के पूर्वानुमान सुसंगत पाए गए हैं और प्रचालनात्मक पूर्वानुमानकर्ताओं के लिए अत्यधिक उपयोगी हैं । प्रायिकतात्मक द्रुत तीव्रीकरण पूर्वानुमान जलवायु विज्ञान की तुलना में निपुण पाए गए हैं । क्षय मॉडल के त्रुटिपूर्ण सांख्यिकी (6 घंटे में 11 kt से लेकर 24 घंटे में 6 kt) से पता चलता है कि यह मॉडल यथोचित सफलता के साथ तट से टकराने के बाद तीव्रता के कमज़ोर पड़ने का पूर्वानुमान लगा सकता है। निष्पादन सांख्यिकी उत्तरी हिंद महासागर में प्रचालनात्मक चक्रवात पूर्वानुमान सेवा में सुधार लाने हेतु CPS की संभाव्यता को दर्शाता है।

ABSTRACT. As a part of our effort to meet the specific requirement of the operational forecaster, an objective NWP based Cyclone Prediction System (CPS) was developed and implemented for the operational cyclone forecasting work. 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. GPP is derived based on dynamical and thermo dynamical parameters from the model output of IMD operational Global Forecast System. The MME technique for the cyclone track prediction is based on multiple linear regression technique. A Statistical Cyclone Intensity Prediction (SCIP) model for predicting 12 hourly cyclone intensity (up to 72 hours) is developed applying multiple linear regression technique. For forecast of inland wind after the landfall of a cyclone, an empirical technique is developed.

This paper describes the development strategy of the CPS and performance skill of the system during 2013 for seven cyclonic disturbances. The performance evaluation shows that the GPP analysis at early stages of development of a low pressure system was able to indicate the potential of the system for further intensification. The 12 hourly track forecast by MME (with error 68 km at 12 hr to 187 km at 120 hr), and intensity forecast by SCIP model (with error 5.9 kt at 12 hr to 19.8 kt at 72 hr) are found to be consistent and very useful to the operational forecasters. The probabilistic rapid intensification forecasts are found to be skillful compared to climatology. The error statistics (11 kt at 6 hr to 6 kt at 24 hr) of the decay model shows that the model could predict the decaying intensity after landfall with reasonable success. The performance statistics demonstrates the potential of the CPS for improving operational cyclone forecast service over the north Indian Seas.

Key words – Cyclone genesis potential parameter (GPP), Multi-model ensemble (MME) technique, Cyclone track prediction, Cyclone intensity prediction, Rapid intensification, Decay, Forecast verification.

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). Statistical post processing can add skill to dynamical forecasts. In recent studies, efforts are being made (Roy Bhowmik, 2003; Roy Bhowmik *et al*., 2005; Kotal *et al*., 2008 & 2009; Kotal and Roy Bhowmik, 2011 & 2013) towards the development of dynamical-statistical methods to aid operational cyclone forecasting work over the NIO. An NWP based Objective Cyclone Prediction System (CPS) was developed and implemented for the operational cyclone forecasting work to meet the need of the operational forecaster. 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 (Kotal and Bhattacharya, 2013; 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, ECMWF (for Viyaru) and JMA (Kotal and Roy Bhowmik, 2011). SCIP (statistical cyclone intensity prediction) model is run for 12 hourly intensity predictions up to 72 hr (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).

This paper describes the development strategy of the objective cyclone prediction system (CPS) and performance skill of the system during 2013. As averaging for many events smoothen its internal variation, it is worthwhile to compare the performance of individual cases also to verify the consistency. Therefore, we also examine the performance of the CPS for an individual very severe cyclonic storm PHAILIN along with the average performance for all cyclonic storms in 2013 over the NIO. The data used in this study is described in Section 2. Cyclone prediction system (CPS) is described in section 3. Forecast performance of CPS is presented in section 4 and summary and conclusions is given in Section 5.

2. Data

The cyclonic disturbances that developed over the NIO during the year 2013 are shown in Table 1. As per the convention of India Meteorological Department (IMD), the classification of tropical disturbances is given in Table 2. Forecast verification carried out for the systems and corresponding models is shown in Table 3. The data of cyclones during the period, such as observed and forecast intensity and track, and other information are taken from the records of the Cyclone Warning Division of the Regional Specialized Meteorological Centre (RSMC), New Delhi operating at Head Quarter of the India Meteorological Department (IMD). The data table includes date, time, position in latitude and longitude, central pressure, pressure drop at centre, T. No and intensity (maximum sustained surface winds in knot). Primarily, the Dvorak technique (Dvorak, 1975) based on the analysis of cloud patterns in visible and infrared imagery from geostationary satellites (INSAT Kalpana-I) is used to estimate tropical cyclone intensity.

TABLE 1

Observed maximum sustained wind strengths and coast of landfall of NIO cyclonic disturbances (verified) during 2013 (*cyclones made landfall)

S. No.	Name (Period)	Year	Max. wind speed (kt)	Coast of landfall
1.	VIYARU (10-16 May)	2013	45	Bangladesh*
2.	PHAILIN (8-14 October)	2013	115	Odisha*
3.	Deep Depression (8-11 November)	2013	30	Somali
4.	Depression (13-17 November)	2013	25	Tamil Nadu
5.	HELEN (19-22 November)	2013	55	Andhra Pradesh*
6.	LEHAR (23-28 November)	2013	75	Andhra Pradesh*
7.	MADI (6-12 December)	2013	65	Tamil Nadu

TABLE 2

Classification of tropical disturbances

T. No.	Classification of cyclonic disturbance	Wind speed (kt)	Wind criteria (kt)
T1.0	Low (L)	-	<17
T1.5	Depression (D)	25	17-27
T2.0	Deep Depression (DD)	30	28-33
T2.5	Cyclonic storm (CS)	35	34-47
T3.0	Cyclonic storm (CS)	45	34-47
T3.5	Severe Cyclonic Storm (SCS)	55	48-63
T4.0	Very Severe Cyclonic Storm (VSCS)	65	64-119
T4.5	Very Severe Cyclonic Storm (VSCS)	77	64-119
T5.0	Very Severe Cyclonic Storm (VSCS)	90	64-119
T5.5	Very Severe Cyclonic Storm (VSCS)	102	64-119
T6.0	Very Severe Cyclonic Storm (VSCS)	115	64-119
T6.5	Super Cyclonic Storm (SuCS)	127	≥120
T7.0	Super Cyclonic Storm (SuCS)	140	≥120
T7.5	Super Cyclonic Storm (SuCS)	155	≥120
T8.0	Super Cyclonic Storm (SuCS)	170	≥120

TABLE 3

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	VIYARU, PHAILIN, DD-Arabian Sea, D-Bay of Bengal, HELEN, LEHAR, MADI (one forecast only)
IMD-WRF	VIYARU, PHAILIN, DD-Arabian Sea, D-Bay of Bengal, HELEN, LEHAR
JMA	VIYARU, PHAILIN, DD-Arabian Sea, D-Bay of Bengal, HELEN, LEHAR, MADI
NCEP GFS	VIYARU, PHAILIN, DD-Arabian Sea, D-Bay of Bengal, HELEN, LEHAR, MADI
UKMO	VIYARU, PHAILIN, DD-Arabian Sea, D-Bay of Bengal, HELEN, LEHAR, MADI
IMD-HWRF	VIYARU, PHAILIN, HELEN, LEHAR
IMD-MME	VIYARU, PHAILIN, DD-Arabian Sea, D-Bay of Bengal, HELEN, LEHAR, MADI

WRF model has been running at resolution 27 km and Global forecast system (GFS) has been running at resolution T574L64 (~23 km) at IMD. The HWRF has been running at resolution with nested domain of 27 km and 9 km horizontal resolution and 42 vertical levels with outer domain covering the area of 800 × 800 and inner domain 60 × 60 with centre of the system adjusted to the centre of the observed cyclonic storm.

For the day-to-day weather forecasting, IMD also makes use of NWP products prepared by some other operational NWP Centres including United Kingdom Meteorological Office (UKMO), Global Forecast System (GFS) at NCEP (National Center for Environmental Prediction) and Japan Meteorological Agency (JMA). Multimodel ensemble (MME) track for 2013 was generated in real time using the forecast track of the above models. A collective bias correction is included in the ensemble technique in which a multiple linear regression based minimization principle for the model forecast position against to the observed position is applied (Kotal and Roy Bhowmik, 2011). The regression coefficients are generated dynamically in real-time considering cyclone data from 2009 upto the cyclone immediately prior to the current one. These bias factors are described by separate weights at every 12 hr interval up to the 72 hr forecasts for each of the member model. Various thermodynamical parameters, which are used in Genesis Potential Parameter (GPP), the Statistical Cyclone Intensity Prediction (SCIP) model and for Rapid intensification (RI) are derived from the IMD operational global model (GFS T574L64) output. SST analysis at 1° latitude-longitude grid interval from NCEP is used in this study (Available at ftp://ftp.ncep.noaa.gov/pub/data/nccf/com/gfs/prod/).

3. NWP based objective cyclone forecast system (CPS)

Cyclone forecasting all over the Ocean basin has greatly benefited from the guidance provided by the NWP models. However, limitations remain, particularly in the prediction of intensity of tropical cyclones (Elsberry *et al*., 2007; Houze *et al*., 2007). There is also a wide variation in the prediction of cyclone track and intensity among NWP models which is confusing for an operational forecaster. The statistical post-processing technique provides the forecaster a single (consensus) product in real-time by giving different weightage to the output of different models according to their past performance. As statistical post processing can add skill to dynamical forecasts, various post-processed value added NWP based special products are prepared for real time cyclone forecasting. The five steps NWP based Cyclone Prediction System (CPS) for the operational cyclone forecasting work is described below.

3.1. *STEP-I : Genesis potential parameter (GPP)*

The objective of this step was to locate potential cyclogenesis zone over the Sea and to understand the potential for intensification of a system at early stages of development. A cyclone genesis parameter, termed as the genesis potential parameter (GPP), for the North Indian Sea is developed (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. The four variables used in GPP parameter were computed based on model analysis (horizontal resolution 23 km) of IMD GFS, averaged over a 5° × 5° square grid around the centre of the system. The composite GPP value is found to be around three to five times greater for developing systems than for non-developing systems.

The grid point analysis and forecast of the genesis parameter up to seven days is also generated on real time (Kotal and Bhattacharya, 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.

3.2. *STEP-II : Multi-model ensemble (MME) technique for track prédiction*

The objective of this component was to generate a consensus track forecast of NWP models. The multi model ensemble (MME) technique (Kotal and Roy Bhowmik, 2011) is based on collective bias correction of NWP models by statistical linear regression approach. The forecasts latitude and longitude positions at 12 hr interval of five NWP models (IMD-GFS, IMD-WRF, NCEP GFS, UKMO, JMA) were used to generate MME track for the tropical cyclones over the North Indian Ocean in 2013. Forecast lead time for WRF and JMA are 72 hr and 84 hr respectively while for the other models it has been 120 hr.

3.3. *STEP-III : Dynamical-statistical model for cyclone intensity prediction (SCIP)*

The objective of this component was intensity prediction at 12-hr interval up to 72 hours. A dynamical statistical model (SCIP) (Kotal *et al*., 2008) has been developed and implemented for real time forecasting of intensity at 12 hourly intervals 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 in 2013, model parameters are derived based on the forecast fields of IMD GFS.

3.4. *STEP-IV : Rapid intensification (RI) index*

The Rapid Intensification (RI) is defined as an increase of intensity by 30 kt (15.4 ms^{-1}) or more during 24 hr. A rapid intensification index (RII) is developed for tropical cyclones over the Bay of Bengal (Kotal and Roy Bhowmik, 2013) for probability forecast of Rapid Intensification. The RII uses large-scale characteristics of tropical cyclones to estimate the probability of rapid intensification (RI) over the subsequent 24 hr. 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 hr intensity change, initial storm intensity, vorticity at 850 hPa, divergence at 200 hPa, vertical wind shear, lower tropospheric relative

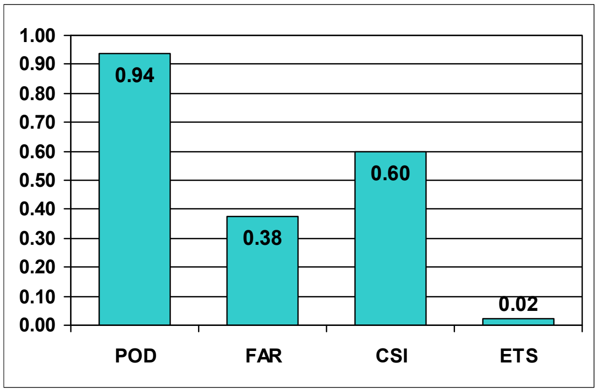
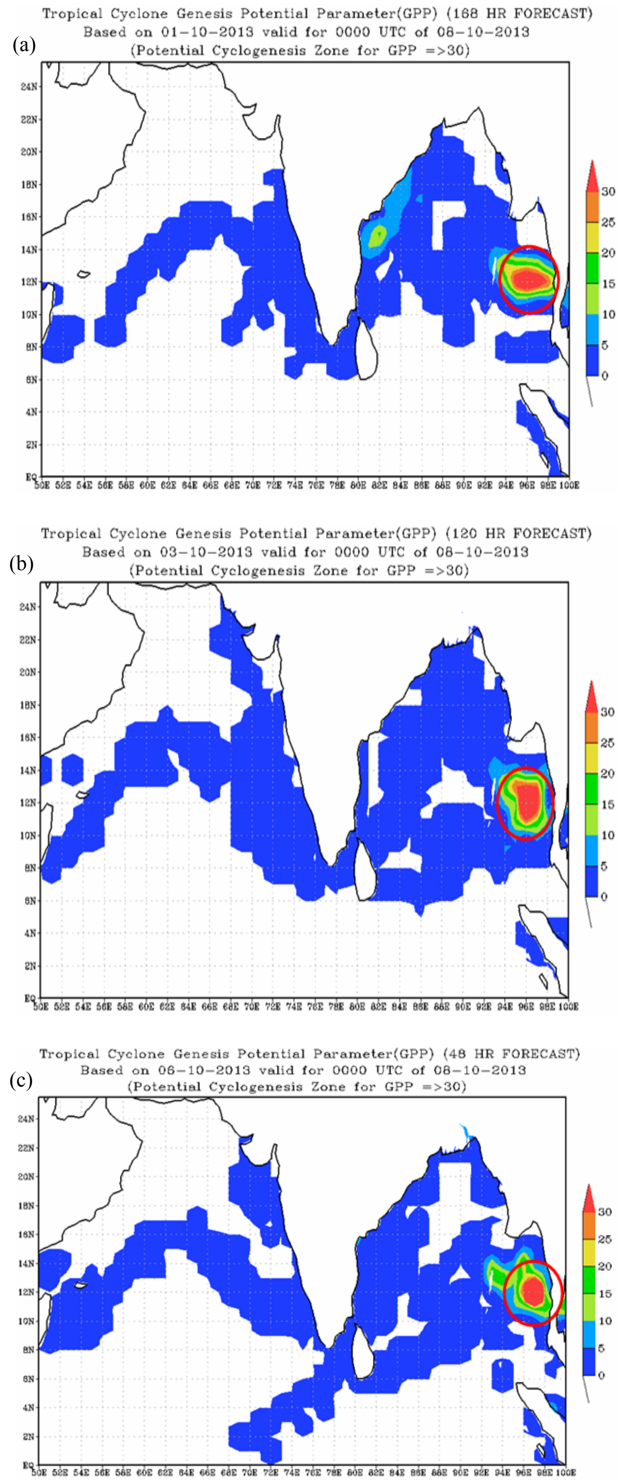


Fig. 1. POD and FAR of cyclogenesis by genesis potential parameter (GPP) during 2013



Figs. 2(a-c). Grid point analysis of genesis potential parameter (GPP) for cyclone PHAILIN for forecast lead time (a) 168 hr, (b) 120 hr and (c) 48 hr

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.

3.5. *STEP-V : 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. 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. The maximum wind speed after the landfall at time t in the decay model (Roy Bhowmik *et al.*, 2005) is written as:

$$V_t = V_b + (V_0 - V_b) \exp(-at)$$

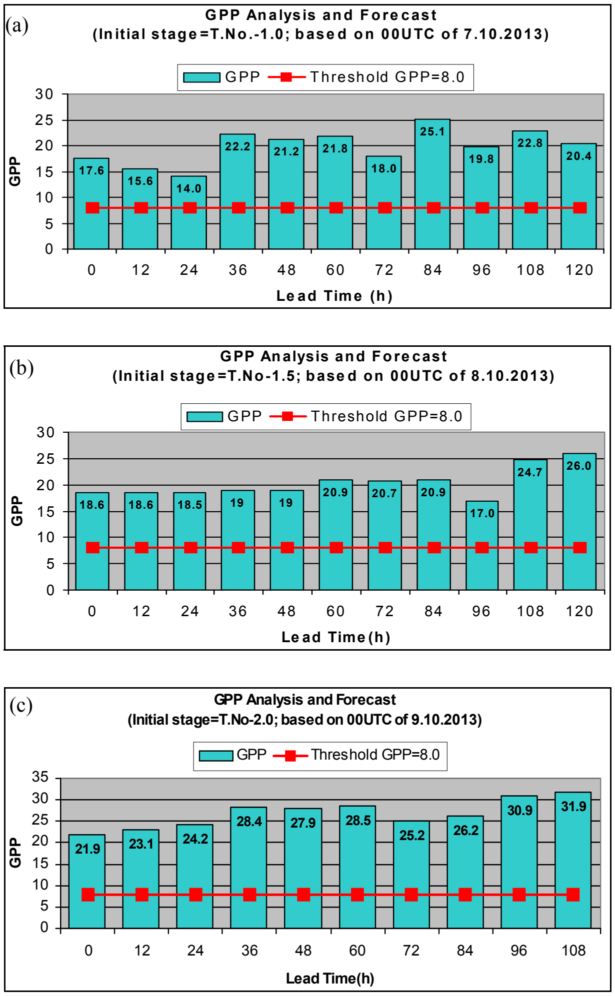
where 'a' is termed as decay constant, V_0 is the maximum sustained surface wind speed at the time of landfall, V_t is the wind speed at time t after the landfall and V_b is the background wind speed.

The objective of this final component was prediction of decaying intensity after landfall at 6-h interval up to 24 hr.

4. Forecast performance of CPS

4.1. *Forecast skill of GPP for prediction of cyclogenesis*

Four parameters, such as the probability of detection (POD), and the false alarm ratio (FAR), critical success index (CSI) and equivalent threat score (ETS) are computed to evaluate the skill of the GPP for genesis forecasts during the period 2013. They were computed



Figs. 3(a-c). Analysis and forecasts of area average genesis potential parameter (GPP) of cyclone PHAILIN

based on hits, misses of occurrence/non-occurrence of cyclonic storms using GPP threshold value 8.0. Fig. 1 illustrates the deterministic verification of GPP forecasts. The figure shows that the POD of the GPP was 0.94, FAR was 0.38, CSI was 0.60 and ETS was 0.02 for 26 forecast events at different lead time for each of the 7 systems during 2013. The results show that POD was much higher than FAR. This indicates the skill of GPP for cyclogenesis prediction.

Grid point Analysis of Genesis Potential Parameter (GPP) for cyclone PHAILIN [Figs. 2(a-c)] shows that 168 hr forecast based on 1 October, 2013 [Fig. 2(a)], 120 hr forecast based on 3 October, 2013 [Fig. 2(b)] and 48 hr forecast based on 6 October, 2013 [Fig. 2(c)] all valid for 0000 UTC 8 October, 2013, correctly indicated the location of potential cyclogenesis zone, where Depression formed on that day.

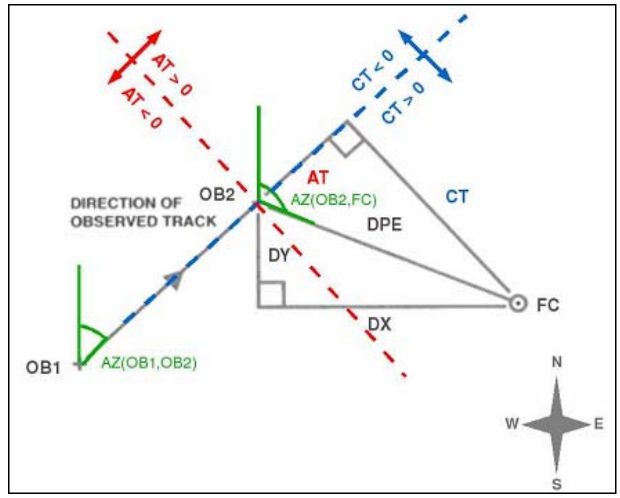


Fig. 4. Types of positional forecast errors. DPE represents the direct positional error, CT is the cross track component, and AT the along track component [Adopted from Heming (1994)]

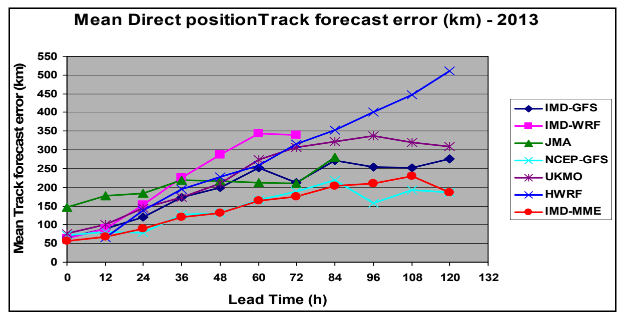


Fig. 5. Mean direct position track (DPE) forecast error (km) during 2013

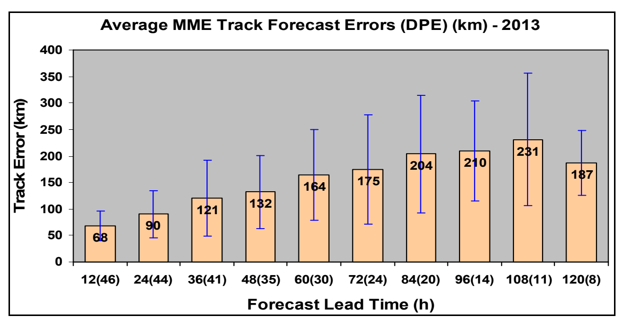


Fig. 6. Average MME track forecast error (DPE) (km) during 2013. Number of forecasts verified is shown in the parenthesis

Analysis and forecasts of GPP [Figs. 3(a-c)] show 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) of the cyclone PHAILIN.

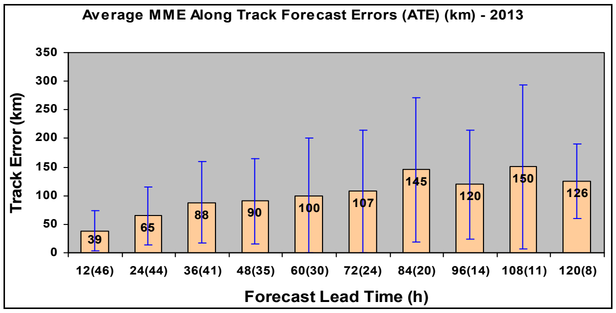


Fig. 7. Mean (absolute) MME along track forecast error (ATE) during 2013

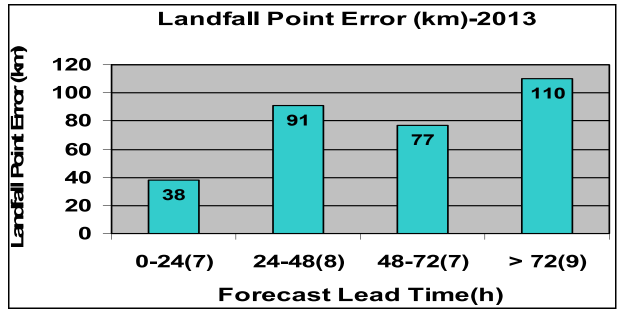


Fig. 9. Mean MME landfall point forecast error (km) during 2013. Number of forecasts verified is shown in the parenthesis

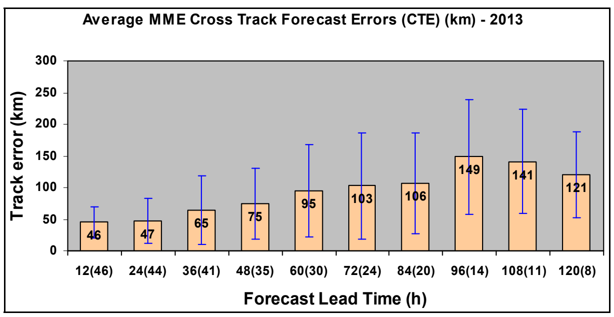


Fig. 8. Mean (absolute) MME cross track forecast error (CTE) during 2013

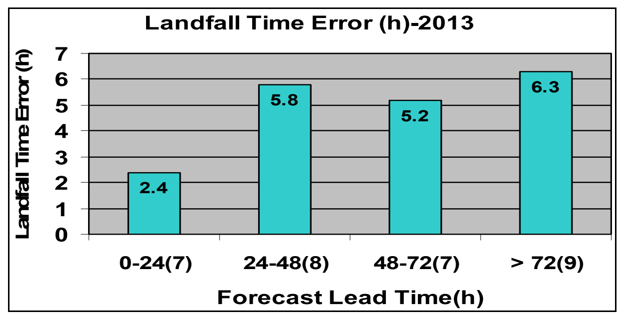


Fig. 10. Mean MME landfall time forecast error (km) during 2013. Number of forecasts verified is shown in the parenthesis

4.2. *Performance of MME for track prediction*

The forecast error (direct position error (DPE)) is defined as the straight-line distance between the observed and forecast positions of the TC and gives an indication of how well a TC track was forecast, The along track error (ATE) occurs, if the forecast storm moves at a different speed than the TC. The ATE is negative when the forecast cyclone is slow and positive when it is fast. The cross track error (CTE) measures the deviation of forecast positions from TC track and is positive when the forecast position lies right of the observed track and negative when forecast position lies left of the observed track. Full details of the verification technique can be found in Heming (1994). Direct position errors (DPE), cross track error (CTE) and along track error (ATE) component of track forecast are calculated based on the Fig. 4 adopted from Heming (1994).

4.2.1. *Direct position error (DPE)*

Fig. 5 shows the mean error (DPE) of NWP models, details are presented in Table 4. 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, 72 hr track forecast errors is less than 200 km for NCEP and MME, 96 hr track forecast errors is less than 200 km for NCEP and 210 km for MME, 120 hr track forecast errors is less than 200 km for NCEP and MME. Fig. 6 shows the mean error (DPE) of the MME track forecast for the cyclones in 2013. Mean MME track errors during the period are 68 km at 12 hr, 90 km at 24 hr, 121 km at 36 hr, 132 km at 48 hr, 164 km at 60 hr, 175 km at 72 hr, 204 km at 84 hr, 210 km at 96 hr, 231 km at 108 hr and 187 km at 120 hr. The standard deviation (SD) of MME track error spreads from 28 km at 12 hr to 61 km at 120 hr with maximum spreads 125 km at 108 hr (Fig. 6).

4.2.2. *Along track error (ATE) and cross track error (CTE)*

Fig. 7 shows that the mean MME along track errors (ATE) ranged from 39 km at 12 hr to 126 km at 120 hr with maximum error of 150 km at 108 hr. The cross track error *(*CTE) ranged from 46 km at 12 hr to 121 km at 120 hr with maximum spreads 149 km at 96 hr (Fig. 8). Details of ATE and CTE of NWP models are presented in Table 5 and Table 6 respectively. This result indicates that the DPE was contributed by both the ATE and CTE by nearly similar magnitudes for cyclonic storms during 2013.

TABLE 4

Mean track forecast error (DPE) (km) during 2013 (Number of forecast verified shown in the parenthesis)

Forecast hr →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
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)
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)

TABLE 5

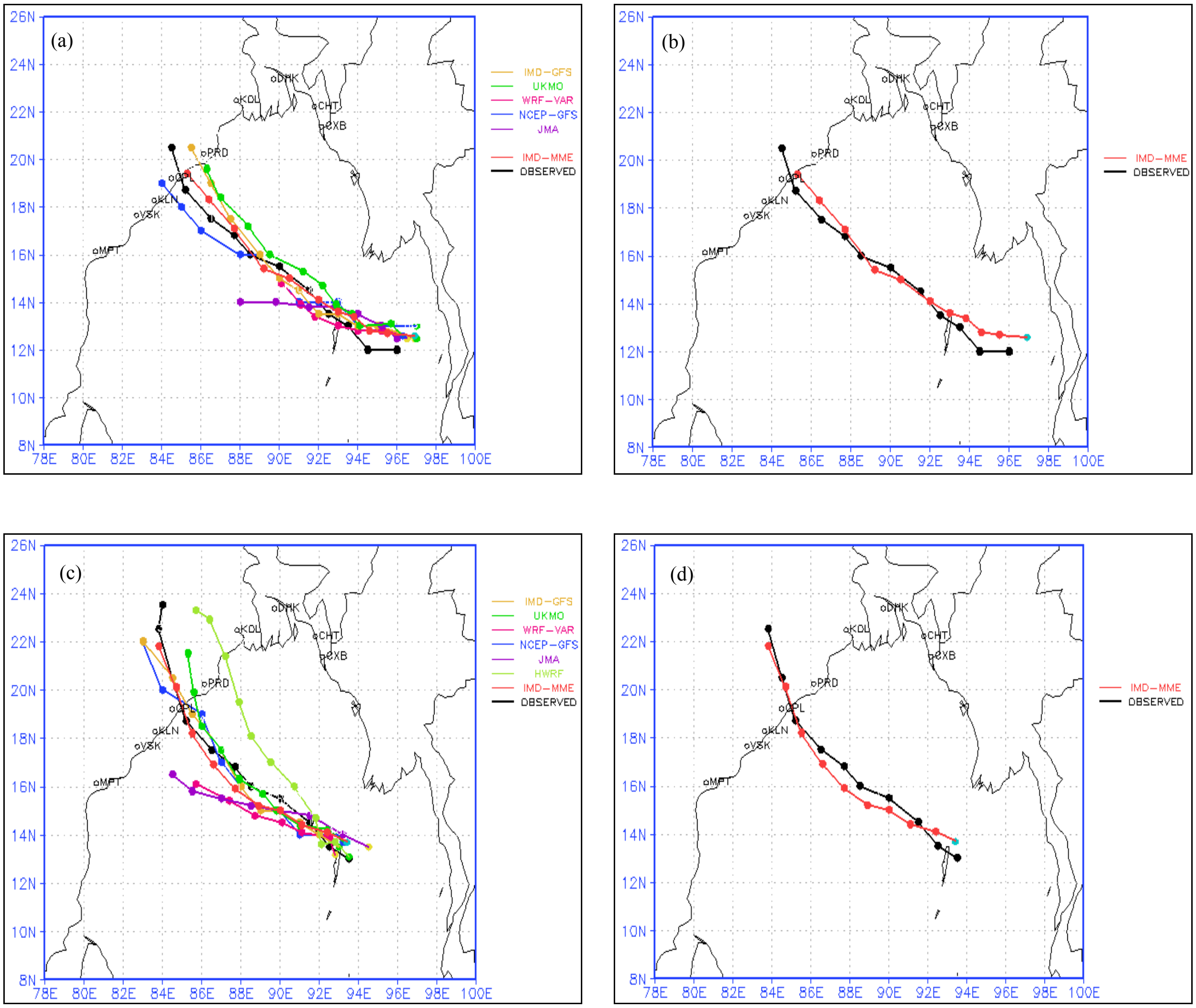
Mean along track forecast error (ATE) (km) during 2013

Forecast hr →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
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
HWRF	46	67	110	100	107	89	87	101	147	242
IMD-MME	39	65	88	90	100	107	145	120	150	126

TABLE 6

Mean cross track forecast error (CTE) (km) during 2013

Forecast hr →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
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
HWRF	44	74	80	102	114	145	165	179	209	216
IMD-MME	46	47	65	75	95	103	106	149	141	121



Figs. 11(a-d). MME forecasts track based on different initial conditions of cyclone PHAILIN: (a) PHAILIN observed and NWP model tracks based on 0000 UTC 8 October, 2013, (b) PHAILIN observed and MME tracks based on 0000 UTC 8 October, 2013, (c) PHAILIN observed and NWP model tracks based on 0000 UTC 9 October, 2013 and (d) PHAILIN observed and MME tracks based on 0000 UTC 9 October, 2013

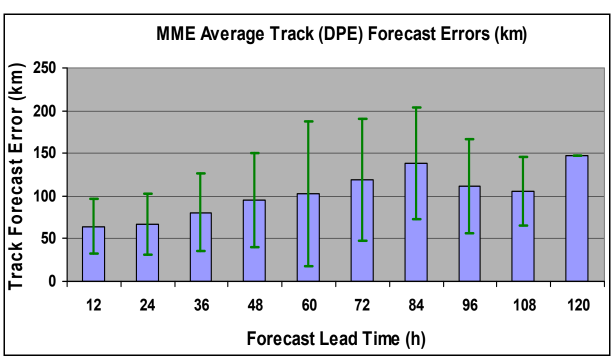


Fig. 12. Average direct position error (DPE) of MME (along with range (thick green line of cyclone PHAILIN (Number of forecasts verified for cyclone Phailin was 9, 9, 9, 8, 6, 5, 4, 3, 2,1 for forecast lead time 12 hr, 24 hr, 36 hr, 48 hr, 60 hr, 72 hr, 84 hr, 96 hr, 108 hr and 120 hr respectively)

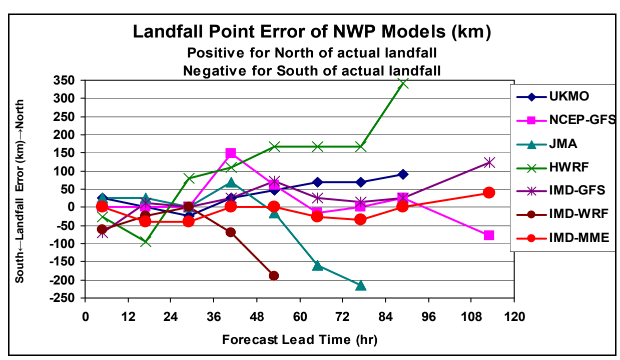


Fig. 13. Landfall point forecasts errors of NWP model at different forecast lead times for cyclone Phailin

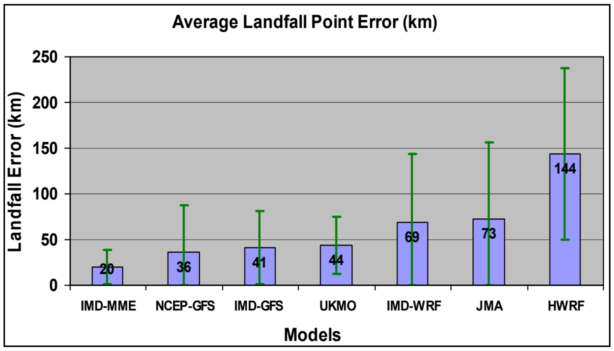


Fig. 14. Average landfall point error (km) of Models (along with range (thick green line)) of cyclone PHAILIN

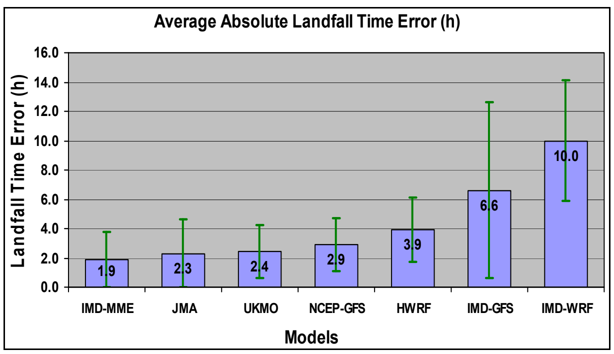


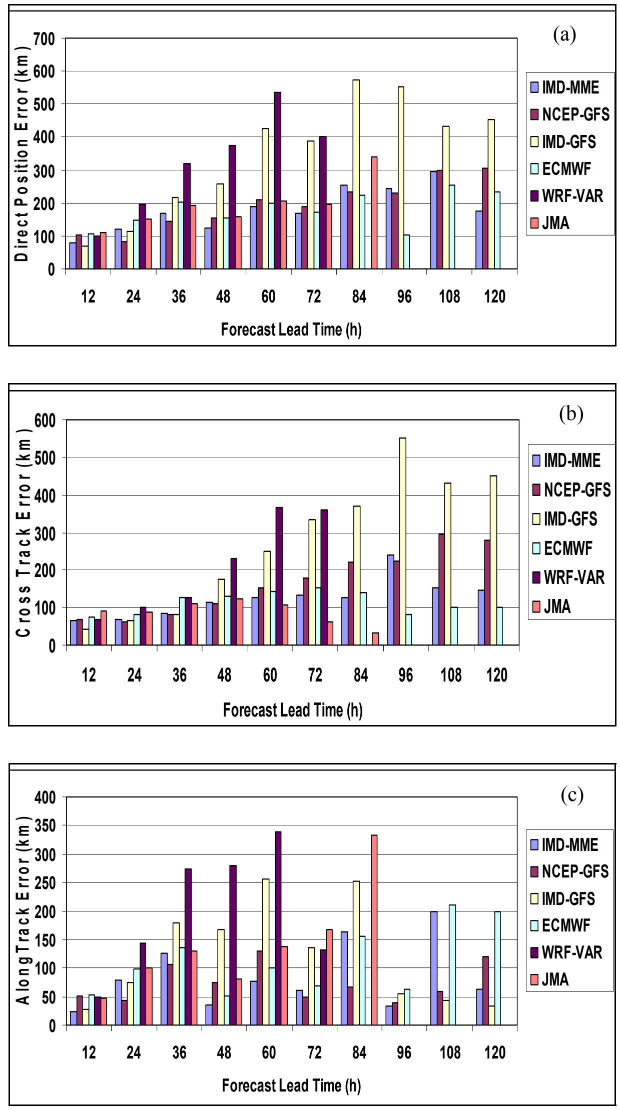
Fig. 15. Average landfall time error (hr) of Models (along with range (thick green line)) of cyclone PHAILIN

4.2.3. *Landfall forecast errors*

The landfall errors were evaluated for four cyclones (Viyaru, Phailin, Helen and Lehar) out of 7 systems those made landfall. The sample size is given in Fig. 9. The average landfall point error (Fig. 9) is 38 km at 12 hr to 24 hr, 91 km at 24 hr to 48 hr and 77 km at 48 hr to 72 hr before landfall.

The average landfall time error (Fig. 10) is 2.4 hr, 5.8 hr and 5.2 hr before 24 hr, 48 hr and 72 hr of landfall respectively. Analysis of landfall time also shows that, on average, the MME predicted delayed landfall, therefore slow in movement. The whole process is carried out to safeguard the coastal community. While it is desired to have more accurate landfall time forecast, in this paper it is found that the MME track on an average was slow by 2-6 hours in predicting the landfall time. This finding will provide useful guidance to the operational forecasters for landfall forecasts in real time.

MME track forecast error for PHAILIN - The MME forecasts track based on different initial conditions along



Figs. 16(a-c). Average track forecast errors for cyclone Viyaru: (a) DPE, (b) CTE and (c) ATE

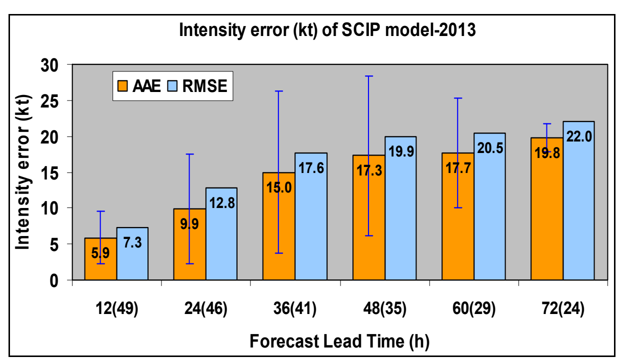


Fig. 17. Average absolute error (AAE) and root mean square error (RMSE) of SCIP intensity (kt) forecast along with standard deviation (thick blue line over AAE) during 2013. Number of forecasts verified is shown in the parenthesis

TABLE 7

Landfall point and landfall time error of consensus NWP model (MME) forecasts for cyclone Phailin

Forecast based on	Forecast Lead Time (hr)	Landfall Point Error (km)	Landfall Time Error (hr)
0000 UTC / 08 Oct 2013	113	39	7 hrs Delay
0000 UTC / 09 Oct 2013	89	0	3 hrs Delay
1200 UTC / 09 Oct 2013	77	35	3 hrs Delay
0000 UTC / 10 Oct 2013	65	25	1 hr Delay
1200 UTC / 10 Oct 2013	53	0	1 hr Delay
0000 UTC / 11 Oct 2013	41	0	1 hr Delay
1200 UTC / 11 Oct 2013	29	39	0 hr
0000 UTC / 12 Oct 2013	17	39	1 hr Delay
1200 UTC / 12 Oct 2013	5	0	0 hr

TABLE 8

Probability of RI for cyclone PHAILIN

Forecast based on	Probability of RI predicted	Chances of occurrence predicted	Intensity changes (kt) in 24 hr	Occurrence
0000 UTC / 08 Oct 2013	9.4 %	Very Low	5	No
0000 UTC / 09 Oct 2013	9.4 %	Very Low	15	No
1200 UTC / 09 Oct 2013	9.4 %	Very Low	40	Yes
0000 UTC / 10 Oct 2013	72.7 %	High	65	Yes
1200 UTC / 10 Oct 2013	72.7 %	High	40	Yes
0000 UTC / 11 Oct 2013	72.7 %	High	5	No
1200 UTC / 11 Oct 2013	32.0 %	Moderate	0	No

with the observed track is depicted in Figs. 11 (a-d). The figure shows that from the day 0000 UTC 8 October and 0000 UTC 9 October, 2013, MME could able to predict correctly and consistently the landfall at Gopalpur (Odisha). The mean MME track error was about 65 km at 12 hr to 150 km at 120 hr (Fig. 12 along with their range).

Landfall Point Error (PHAILIN) - Landfall point forecasts errors of NWP model at different forecast 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 up to about 340 km towards north and up to 215 km towards south. Under this wide extent of landfall point forecasts, MME could able to predict near actual landfall point (Gopalpur) consistently (Table 7). Average land fall point error (Fig. 14) shows that MME forecast error was least (20 km) compared to other models before 5 hr to 113 hr of landfall.

Landfall Time Error (PHAILIN): Average land fall time error (Fig. 15) shows that MME landfall time forecast error was least (1.9 hr) compared to other models which ranged from 2.3 hr to 10 hr.

Track forecast errors (DPE, CTE, ATE) for cyclone Viyaru is also presented in Figs. 16(a-c).

4.3. *Performance of SCIP for intensity prediction*

Fig. 17 shows the mean error of the SCIP intensity forecast for the period 2013. Mean forecast errors (Average absolute error (AEE)) ranged from about 6 kt at 12 hr to about 20 kt at 72 hr. The figure also shows that the root mean square error (RMSE) ranged from 7 kt at 12 hr to 22 kt at 72 hr. The standard deviation (SD) of the mean error ranged from 3.6 at 12 hr to 2.0

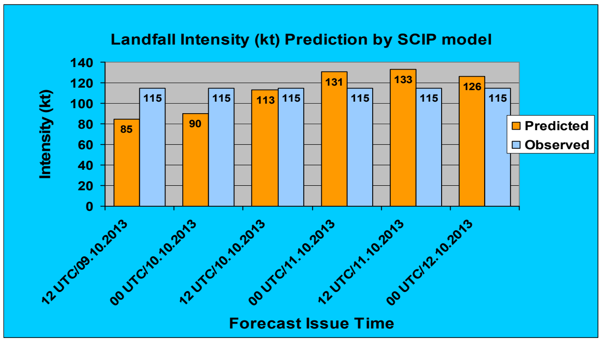


Fig. 18. Landfall intensity (kt) prediction by SCIP Model of cyclone PHAILIN

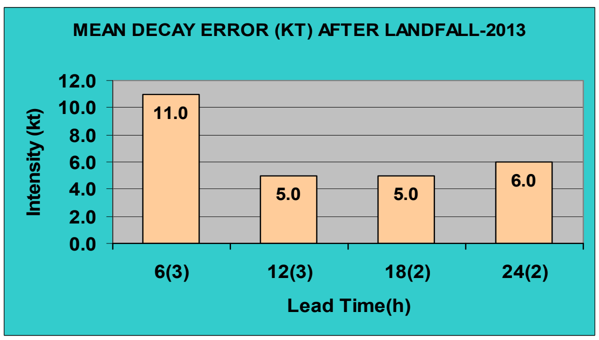
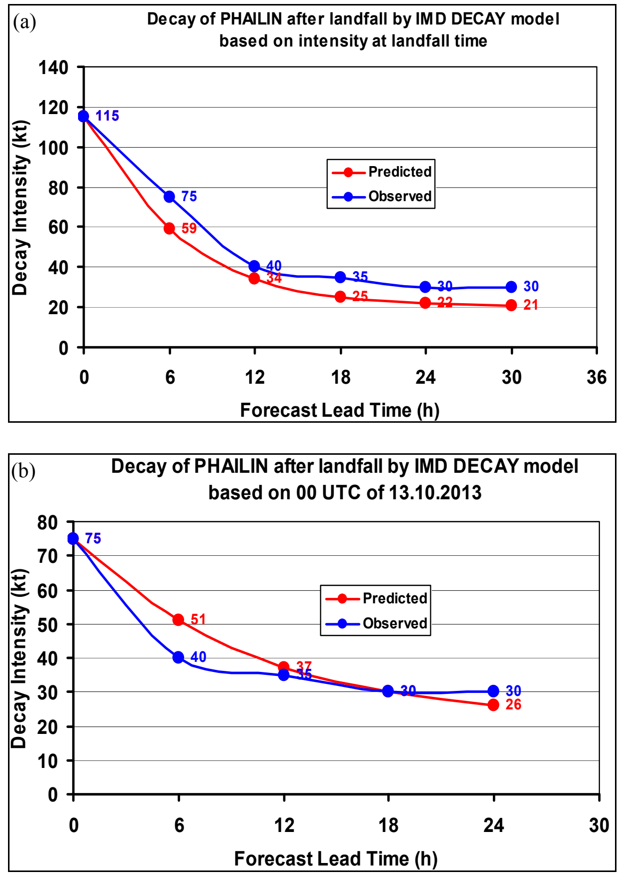


Fig. 19. Mean decay (after landfall) forecast error (kt) during 2013. Number of forecasts verified is shown in the parenthesis (The errors for 6 hr and 12 hr are for cyclones Phailin and Viyaru. The errors at 18 hr and 24 hr for Phailin only)



Figs. 20(a-b). Decay after landfall of cyclone PHAILIN (a) based on landfall intensity at 1700 UTC of 12 October, 2014 and (b) based on intensity at 0000 UTC of 13 October, 2014

at 72 hr with maximum spread 11.2 and 11.1 at 36 hr and 48 hr respectively (Fig. 17).

Landfall intensity of cyclone PHAILIN predicted by SCIP model in 2-3 days before landfall (from initial cyclonic storm stage at 1200 UTC of 9 October, 2013) shows that the model could predict the landfall intensity of very severe cyclonic storm with a reasonable success (Fig. 18).

4.4. *Forecast skill of RI-Index for prediction of rapid intensification*

The Brier score (BS) (Wilks, 2006) is computed to assess the skill of the RI forecasts. The Brier score is computed using the formula

$$\text{BS} = \frac{1}{N}\sum (F - O)^2$$

where, F is the probability that was forecast, O the actual outcome of the event ($O = 0$ if it doesn't happen and 1 if it happens) and N is the number of forecasting instances. The BS is 0 and 1 for the best and worst score achievable respectively. During 2013, for 42 forecast events, the BS was found to be 0.05, which shows RII achieved a good score for RI forecasting during the period. The same methodology is also used to obtain the BS for the climatological forecasts. The skill of the RII is then evaluated using the Brier skill score (BSS) (Wilks, 2006):

$$\text{BSS} = \left[1 - \left(\frac{BSR}{BSC}\right)\right] \times 100\ \%$$

where, BSR is the Brier score of the RII forecasts and BSC is the Brier score of the climatological forecasts. Thus, positive values of BSS indicate higher skill of RII than that of climatology while negative values indicate that the RII was not skillful. The BSS of the RII for the TCs during the period 2013 was found to be 24%. Thus, the positive value of BSS shows that the RII was skillful relative to the climatological forecast. The climatological

RII forecast obtained from a long-term climatology (1981-2010).

The probability forecasts of RI for cyclone PHAILIN is given in Table 8. The table shows that the RI-Index could able to predict occurrence as well as non-occurrence of RI of cyclone PHAILIN during its lifetime except forecast for 1200 UTC of 9 October, 2013 and 0000 UTC of 11 October, 2013.

4.5. *Performance of DECAY model for intensity prediction after landfall*

Mean forecast error (kt) at 6-hourly interval valid up to 24 hours in 2013 is shown in Fig. 19. The Average absolute error (AAE) is ranged from 6 kt to 11 kt for forecasts up to 24 hr. The error statistics shows that the model forecasts were reasonably good for decaying intensity after landfall.

For the cyclone PHAILIN, decay (after landfall) prediction curve (6-hourly up to 24 hr) shows slightly fast decay compared to observed decay [Figs. 20(a-b)].

5. Summary and conclusion

This paper described the development strategy of an NWP based objective cyclone prediction system (CPS) and performance skill of the system during 2013. The CPS 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.

The performance of Genesis potential parameter (GPP) shows that the POD was 94%, FAR was 38% and CSI was 0.60 during the period 2013. The result shows that the Genesis potential parameter (GPP) was able to provide the potential for intensification of a low pressure system at early development stages. For the cyclone PHAILIN, grid point analysis and forecasts of GPP could able to predict the formation and location of the system before 168 hours of its formation. 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.

The mean track forecast error of MME is ranged from 68 km at 12 hr to 187 km at 120 hr during the period 2013 with maximum error 231 km at 108 hr. Average land fall point error of MME was ranged from 38 km, 91 km and 77 km and landfall time error was ranged from 2.4 hr, 5.8 hr and 5.2 hr for lead time 24 hr, 48 hr and 72 hr respectively. For the cyclone PHAILIN, The average DPE for MME was about 65 km at 12 hr to 150 km at 120 hr. Average land fall point error of MME was 20 km. Average land fall time error shows that MME landfall time forecast error was 1.9 hr. The result shows that the MME could provide a useful consensus track forecast of NWP models.

The mean intensity forecast errors of SCIP in 2013 was ranged from about 6 kt at 12 hr to about 20 kt at 72 hr and corresponding root mean square error was ranged from about 7 kt at 12 hr to about 22 kt at 72 hr. For the cyclone PHAILIN, average absolute error (AAE) for SCIP ranged from 10 kt at 12 hr to 25 kt at 48 hr, 31 kt at 60 hr and 37 kt at 72 hr. Landfall intensity predicted by SCIP model in 2-3 days before landfall shows that the model could predict the landfall intensity of very severe cyclonic storm PHAILIN with a reasonable success.

The Brier score (BS = 0.05) shows that the Rapid intensification index (RI) could provide probability of rapid intensification during next 24 hr. The RI-Index could able to predict occurrence as well as non-occurrence of Rapid Intensification of cyclone PHAILIN during its lifetime.

The decay model could predict the decaying intensity at 6 hr interval up to 24 hr after landfall with reasonable accuracy (decay error = 5 kt to 11 kt). Decay model correctly predicted the decaying nature of the PHAILIN after landfall.

Finally, the performance statistics of each component demonstrates the potential of the system for improving operational cyclone forecast service over the Indian Seas.

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