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Tropical cyclone forecast from NCMRWF global ensemble forecast system, verification and bias correction

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सार – उत्तरी हिंद महासागर विश्व में उष्णकटिबंधीय चक्रवातों द्वारा सबसे अधिक प्रभावित क्षेत्रों में से एक है। अपनी विस्तृत तटरेखा और तटीय क्षेत्रों में अत्यधिक जनसंख्या की वजह से उष्णकटिबंधीय चक्रवात के तट से टकराने के कारण जान और माल की हानि बहुत अधिक होती है। अत: चक्रवात पथ का समय पर पूर्वानुमान, तट से टकराने का स्थान व समय इस क्षेत्र के लिए अत्यंत महत्वपूर्ण है। इस अध्ययन में उष्णकटिबंधीय चक्रवात पथ पूर्वानुमान लगाने में निर्धारिणात्मक मॉडल NGFS (NCMRWF) भूमंडलीय पूर्वानुमान प्रणाली) और NGEFS (NCMWRF भूमंडलीय समुच्चय पूर्वानुमान प्रणाली (EPS) की सापेक्षिक निपुणताओं के मध्य तुला की गई है। इस तुलना के लिए हाल ही में आए चार चक्रवातों के मामलों नामत: फेलिन (9-12 अक्तूबर, 2013), हेलन(19-23 नवम्बर, 2013), लहर (23-28 नवम्बर, 2013) और माडी (6-12 दिसम्बर, 2013) पर विचार किया गया है। हेलन को छोड़कर, जो प्रचंड चक्रवाती तूफान (SCS) है, उपर्युक्त सभी चक्रवात अति प्रचंड चक्रवाती तूफानों (VSCS) की श्रेणी में आते है । क्षण (मूमंट) समायोजन की पद्धति का उपयोग करते हुए NGEFS मॉडल में क्रमबद्ध बायससमें संशोधनकरने का प्रयास किया गया। तीन मॉडलों से चक्रवातकेपथ, क्रास पथ और पूर्वानुमान पथों से प्रत्यक्ष अवस्थिति वाली त्रुटियों तथा IMD के बेहतर पथ आँकड़ों के आधार पर मॉडलों के निष्पादन की तुलना की गई। यह देखा गया है कि पेलिन जैसे चक्रवात जिसकेपथ में अचानक किसी प्रकार के परिवर्तन का पता नहीं चला है उस समय NGEFS के माध्य से NGFS की तुलना में पथ त्रुटि का पता चला है और NGEFS के बायस संशोधित आऊटपूट से TC पथ पूर्वानुमान में आगे ओर सुधार का पता चला है। तथापि माडी के मामले में जिसकी दिशा में अचानक परिवर्तन दिखा है उस समय NGEFS ने NGFFS और वायस संशोधित दोनों की तुलना में दिशा परिवर्तन से पहले बेहतर पूर्वानुमानदिया है। किंतु दिशा में परिवर्तन के बाद बायस संशोधन सहित NGEFS ने NGEFS और NGEFS की अपेक्षा बेहतर निष्पादन दिया है। 2013 के चार चक्रवाती मामलोंमें कुल मिलाकर यह देखा गया है कि समुच्चय पथ पूर्वानुमान की तुलना में आरम्भिक स्थिति त्रुटि में लगभग 17 प्रतिशत का वायस संशोधन लीडस में सुधार हुआ है और निर्धारणात्मक मॉडल के साथ तुलना करने पर लगभग 80 प्रतिशत सुधार देखा गया है ।5 वें दिन NGEFS और NGEFS की अपेक्ष बायस संशोधित समुच्चय पूर्वानुमान में क्रमश: 24 प्रतिशत 17 प्रतिशत सुधार पाया गया है।

ABSTRACT. The North Indian Ocean is one of the world's worst affected areas by tropical cyclones. It is because of its vast coastline and high population density in the coastal areas that the damage to life and property caused by a landfalling tropical cyclone is huge. Therefore, timely prediction of the cyclone track, landfall location and time is of critical importance for this region. In the present study a comparison is made between the relative skills of a deterministic model NGFS (NCMRWF Global Forecast System) and an ensemble prediction system (EPS) NGEFS (NCMWRF Global Ensemble Forecast System) in predicting the tropical cyclone track. Four cases of recent cyclones, *i.e*., Phailin (9-12 October 2013), Helen (19-23 November, 2013), Lehar (23-28 November, 2013) and Madi (6-12 December, 2013) are considered for this comparison. Except of Helen which was a Severe Cyclonic Storm (SCS), all the above cyclones were in the category of Very Severe Cyclonic Storms (VSCS). Further an attempt is made to correct the systematic biases in NGEFS model by using the method of moment adjustment. A comparison of the performance of the models is made on the basis of along track, cross track and direct position errors obtained from the forecast tracks from the three models and the IMD best track data. It is seen that for a cyclone like Phailin which did not show any sudden changes in the track the mean of NGEFS shows a lower track error as compared to NGFS and the bias corrected output from NGEFS shows a further improvement in the TC track forecast. However, in the case of Madi which showed a sudden change in the direction NGEFS showed a better forecast before the direction change as compared to both NGFS and the bias corrected NGEFS. But after the change in the direction NGEFS with bias correction is seen to be performing better than NGEFS and NGFS. On an average for the four cyclone cases of 2013 it is seen that the bias correction leads to an improvement of about 17% in the initial position error as compared to raw ensemble track forecast and about 38% when compared with the deterministic model. In the day 5 forecasts the improvement in the bias corrected ensemble forecast as compared to NGEFS and NGFS are 24% and 17% respectively.

Key words – Tropical cyclone, Phailin, Helen, Lehari, Madi.

1. Introduction

The north Indian Ocean (NIO), including the Bay of Bengal (BoB) and the Arabian Sea (AS), experiences two TC seasons, *i.e.*, during the post-monsoon season (October-December) and the pre-monsoon season (April-early June) (Mohanty *et al.*, 2010). The Indian subcontinent is also one of the world's worst affected areas by Tropical Cyclones as the coastal population density is very high leading to an extensive damage to life and property. Therefore, forecasting of TC track and landfall location is of critical importance for disaster warnings and mitigation purposes. Track forecast errors over the NIO are high relative to those over the Atlantic and Pacific Oceans (Mohapatra *et al.*, 2013). With advancements in computational power, development of better NWP models (both global and regional), the forecasting capability of meteorologists have greatly increased. Several meteorological centers like NCEP, UKMet office, ECMWF, JMA, JTWC etc give a real time forecast of TC tracks from their global NWP models [deterministic as well as Ensemble Prediction Systems (EPS)] (Hamill *et al.*, 2011; Froude *et al.*, 2007; Buckingham *et al.*, 2010; Heming *et al.*, 1995; Heming and Radford, 1998; ChungTsai and Elsberry, 2013; Yamaguchi and Komori, 2009; Kehoe *et al.*, 2007). Cyclone track prediction from an ensemble forecasting system besides providing a track from each ensemble member also provides the strike probability (Weber, 2005).

In 2012 and 2013 the NIO has observed a total of 5 TC namely: Viyaru (10-17 May, 2013), Phailin (4-14 October, 2013), Helen (19-23 November, 2013), Lehar (23 – 28 November, 2013) and Madi (6-13 December, 2013). In the current study we analyze the skill of NGFS (NCMRWF Global Forecasting System) and NGEFS (NCMRWF Global Ensemble forecast System) in forecasting TC tracks for the four cyclones Phailin, Helen, Lehar and Madi which made landfall over India during 2013. In the case of NGEFS the mean of the ensemble member tracks is used for all verifications. Detailed description about the features of these cyclones is given in section 2. The verification for the TC is done by calculating their along track (ATE) and cross track errors (CTE) as well as direct position errors (DPE) relative to the observed track locations obtained from the best track data given by the India Meteorological Department (IMD).

Further an attempt has been made to correct the bias in the NGEFS forecast. The bias estimation and correction is done based on the method of adjustment of moments (Cui *et al*., 2012). Details about the methodology of bias correction are given in section 4. The forecast tracks are also obtained from the bias corrected NGEFS (NGEFS_BC) and the mean of the member tracks is used for comparison with the observed data to obtain the verification statistics mentioned above. In general it is seen that the errors obtained from the average of the bias corrected ensemble (NGEFS_BC) tracks are lower than that of the deterministic system (NGFS).

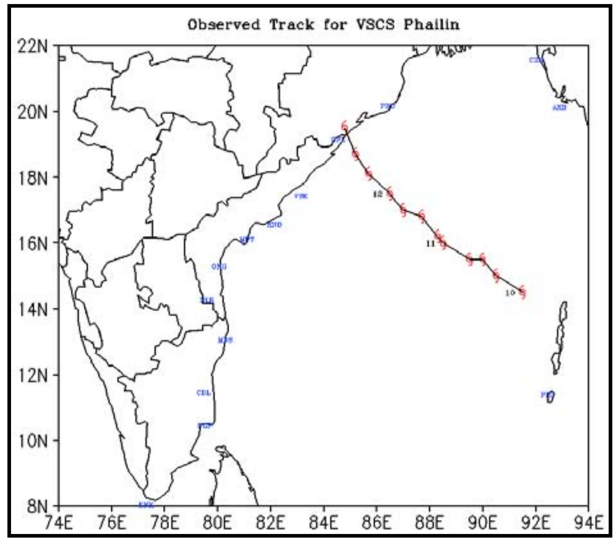


Fig. 1. Observed track of cyclone Phailin (9-12 October, 2013)

This manuscript is divided in the following sections : Section 2 deals with the description of the cyclones. In Section 3 and 3.1 more details about the two NWP models are presented along with the tracker module implemented to obtain the TC track forecast and the hurricane relocation which is used to find the initial guess position of tropical cyclones in NGFS and NGEFS. Section 4 describes the bias correction methodology used in correction of systematic biases in NGEFS. Section 5 describes the results obtained from the two models and their intercomparisons. Finally in section 6 conclusions based on the current study are presented.

2. Cyclones in the NIO (2013)

(a) *Phailin (9-12 October, 2013)*

Phailin was the most intense cyclone that made landfall over India after the Odisha Super Cyclone (29th October, 1999). This cyclone originated from a remnant cyclonic circulation from the South China Sea. It intensified into a cyclonic storm on the 9th of October, 2013 and moved northwestwards. It further intensified into a very severe cyclonic storm on 10th October, 2013 over east central Bay of Bengal. Phailin crossed Odisha

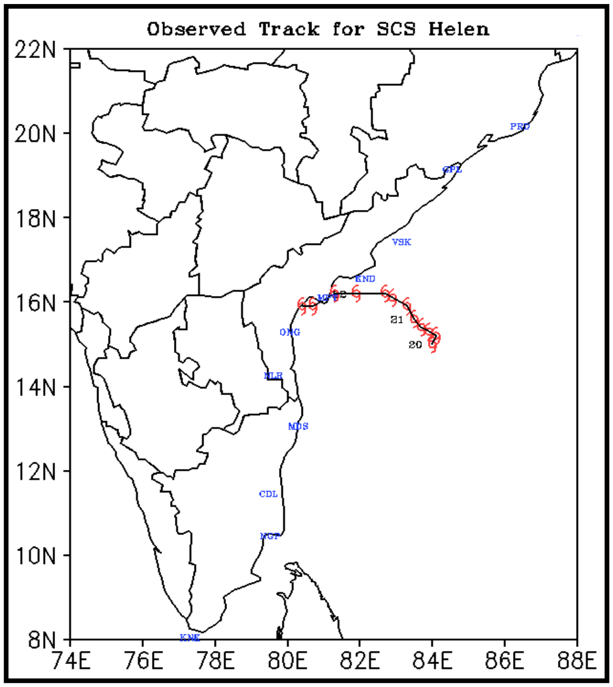


Fig. 2. Observed track of cyclone Helen (19-23 November, 2013)

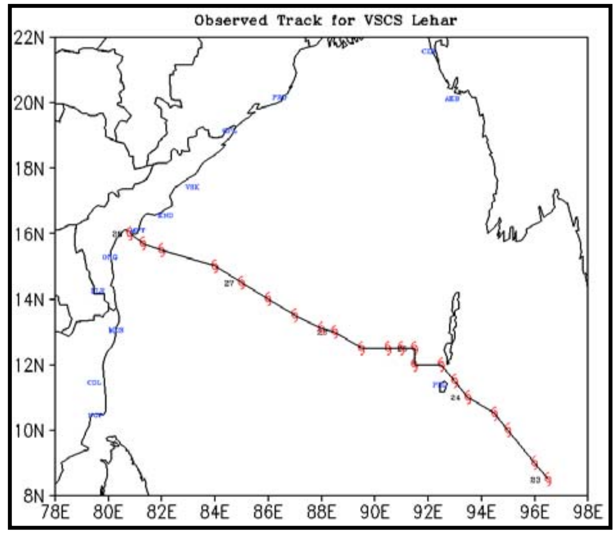


Fig. 3. Observed track of cyclone Lehar (23-28 November, 2013)

coast near Gopalpur around 2230 hrs IST of 12th October, 2013 with a sustained maximum surface wind speed of 200-210 km/hr gusting to 220 km/hr. Some of its unique features included the rapid intensification of the system from 10th October to 11th October, 2013 resulting in an increase of wind speed from 83 km/hr to 215 km/hr. Also, at the time of landfall on 12th October, maximum sustained surface wind speed in association with the cyclone was about 215 km/hr and estimated central pressure was 940 hPa with pressure drop of 66 hPa at the centre compared to surroundings.

Phailin caused heavy rainfall over Odisha leading to floods and storm surge leading to coastal inundation in the state of Odisha. Based on post-cyclone survey report, maximum of storm surge of 2-2.5 meters above the astronomical tide has been estimated in the low lying areas of Ganjam district of Odisha (IMD1). Fig. 1 shows the observed track of VSCS Phailin.

(b) *Helen (19-23 November, 2013)*

Helen a SCS developed from the remnant of the Western Pacific tropical storm Podul on 16th November 2013 and further developed as a trough in the BoB on the 17th of November, 2013. It developed into a well marked low on the 18th of November over the central BoB. This system moved west-northwestwards and intensified to a cyclonic storm on the 19th of November, 2013. On 20th November, 2013 it further attained cyclonic storm intensity (CS) and was named 'Helen'. It further intensified into a Severe Cyclonic Storm (SCS) the following day, reaching its peak intensity of 100 km/h (62 mph) with a central pressure of 990 hPa (29 in Hg). On 22nd November it moved west-southwestwards and crossed Andhra Pradesh coast close to south of Machilipatnam on 22nd November, 2013. Its wind speed was observed to be 80-90 km/h gusting to 100 km/h. Some of the important features of Helen were the rapid weakening after landfall and hence causing lesser rainfall over Andhra Pradesh. Fig. 2 shows the observed track of the cyclonic system Helen obtained from IMD (IMD2).

(c) *Lehar (23-28 November, 2013)*

VSCS Lehar evolved from another low pressure area which moved from South China Sea crossed to Andaman Sea on 22nd November, 2013. It and gradually intensified to depression on the same day. The following day, it further strengthened into a cyclonic storm, and was named Lehar. On 25th November, 2013 it gradually consolidated further and was upgraded to a severe cyclonic storm. The following day, Lehar further intensified into a Very Severe Cyclonic Storm, as both IMD and JTWC reported peak winds of 140 km/hr (87 mph) and a central pressure of 982 hPa (29.0 in Hg). Early on November 27th, the JTWC reported the storm's low-level circulation center (LLCC) was losing its structure due to vertical wind shear, indicating a weakening trend. Thereafter, Lehar rapidly weakened into a depression and made landfall near Machilipatnam on 28th November, 2013. One of its salient features was the rapid weakening from the state of VSCS to depression in a time span of 18 hours. Fig. 3 shows the observed track for cyclone Lehar obtained from IMD (IMD3).

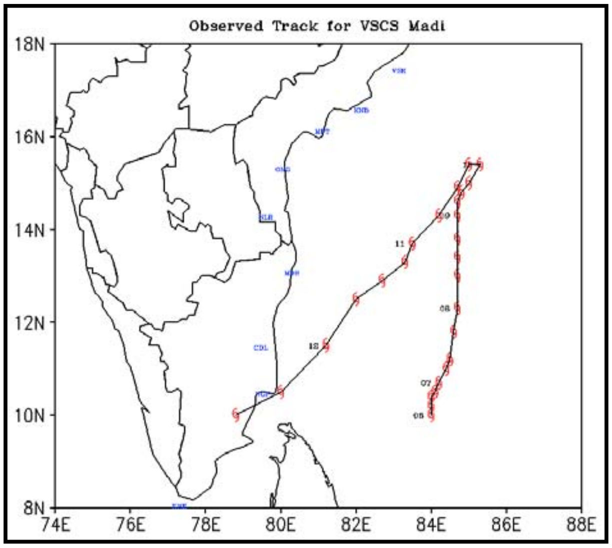


Fig. 4. Observed track of cyclone Madi (6-12 December 2013)

(d) *Madi (6-12 December, 2013)*

VSCS Madi evolved from a low pressure in the easterly wave east of Sri Lanka on 5th December, 2013. It and gradually intensified to Depression (D) on the 6th December, 2013. The following day, it further strengthened into a Cyclonic Storm (CS), and was named Madi. Later on same day it further intensified into SCS. It gradually tracked northwards and was upgraded to a Very Severe Cyclonic Storm (VSCS) on 8th December, 2013. The system weakened on 9th and 10th while kept tracking northwards. It started tracking south-westwards on 10th December and kept weakening. On 12th December, 2013 the system crossed Tamil Nadu coast twice with the intensity of a depression. First near Nagapattinam at around 1200 UTC and the near Tondi at around 1700 UTC (IMD4). The observed track for cyclone Madi is shown in Fig. 4.

3. NWP models at NCMRWF

In this section we briefly describe the salient features of two models NCMRWF Global Forecast System (NGFS) and NCMRWF Global Ensemble Forecast System (NGEFS). NGFS is a deterministic model whereas NGEFS is the EPS running operationally at NCMRWF. The resolution of NGFS is T574L64, *i.e.*, approximately 25 km in horizontal and has 64 vertical levels. NGEFS has a resolution of T190L28, *i.e.*, approximately 70 km in the horizontal and has 28 vertical levels. NGEFS is a single-model, global ensemble system consisting of 21 members. This EPS is initialized by the method of Ensemble Transform with Rescaling (ETR) (Wei *et al*., 2008) and Stochastic Total Tendency Perturbation (STTP). The ETR makes use of the operational high resolution (T574) deterministic analysis from NGFS and forecast outputs (Prasad *et al*., 2011). The NGEFS's atmospheric model is a low resolution model of NGFS. The model is run for four cycles daily (0000, 0600, 1200 and 1800 UTC). However, only the 00 cycle is run daily up to 240 hours and the 0600, 1200 and 1800 UTC cycles are used only for shorter runs (till 18 hours). The model outputs are post-processed at 6 hour interval to a 1° × 1° regular latitude-longitude grid. More details about NGFS can be found at (Rajagopal *et al*., 2007 and Prasad *et al*., 2011) and (Ashrit *et al*., 2012) for NGEFS.

3.1. *Cyclone module*

(a) *Tropical cyclone relocation in NGFS and NGEFS*

A tropical cyclone relocation system was implemented in GFS at the National Centers for Environmental Prediction (NCEP) in 2000 (Liu *et al*., 2000). The TC relocation system moves the hurricane vortex in the model guess to the observed location before the data assimilation system updates the analysis. It contains the following major steps: (*i*) locate the TC vortex center in the guess field, (*ii*) separate the TC model vortex from its environment field (Kurihara *et al*., 1995), (*iii*) move the TC vortex to the observed position, and (*iv*) if the vortex is too weak in the guess field, add a bogus vortex to the data analysis (Lord, 1991).

The GFS hurricane relocation was modified to suit the global ensemble forecast system (GEFS) because individual ensemble members show a widely varying hurricane structures (Liu *et al*., 2000; Zhu 2005). The TC relocation scheme was implemented in the NGFS (T254L64) model at NCMRWF during 2008.

(b) *Tropical cyclone tracker*

The cyclone tracking system used for preparing TC tracks from the operational NCMRWF global models is based on an algorithm given by Marchok (2002). This tracking system uses the average position of 5 different primary parameters namely: MSLP, 700 and 850 hPa Relative Vorticity and Geopotential Height and 2 different secondary parameters minimum wind speed in 700 and 850 hPa. To locate the center of a cyclonic system, the tracker algorithm uses a single-pass Barnes analysis (Barnes, 1964) of each parameter mentioned above at grid points initially centered around the observed center of the cyclonic system (Marchok, 2002). The Barnes analysis provides an array of Gaussian weighted-average data values surrounding the initial-guess position.

The center of the TC is then defined as the point at which the Barnes function (Marchok, 2002) is either a maximum or a minimum (depending on the parameter being analyzed). After the first iteration of the Barnes analysis, a center for a parameter is obtained, additional iterations are performed, each time centering the analysis grid on the center position from the previous run, and halving the grid spacing of the analysis grid. Therefore, the center position is obtained on a fine resolution grid. The final center for the TC is then obtained by averaging the center positions obtained for each parameter lying within a specified distance (usually 275 km) from the guess position of a given forecast hour (Gall *et al*., 2011).

4. Bias correction for NGEFS

In spite of their undeniable success in medium range weather forecasting, ensemble systems, like any other numerical weather prediction model also suffer from several shortcomings due to imperfect model physics, errors in initial conditions, and boundary conditions, number of ensemble members etc (Cui *et al*., 2012). Ensemble systems are based on deterministic models (in terms of governing equations, initial and boundary conditions and model physics) therefore the systematic errors and biases inherent in the parent deterministic model are invariably carried over to the ensemble system. These systematic errors or biases cause bias in the 1st and 2nd moments of the ensemble distribution (Toth *et al*., 2003). There are several methods available to remove these systematic errors from a model, for example by applying some statistical post processing algorithms. In the current paper we have made an attempt to correct the bias in the first moment by the method of adjustment of moments.

In this method the first moment is defined to be the mean of the ensemble members and therefore the bias in the first moment is defined as the difference between the mean of the ensemble members and the verifying analysis. The verifying analysis is simply the set of observations available at the previous time step or the analysis (first guess) which is used as initial conditions for a particular model run. Operationally at a particular time ‘t’ the bias is updated by using the bias calculated at a previous time ‘t-1’ by using a weight called the ‘decaying average’ (Cui *et al*., 2012), *i.e*.,

$$\text{Bias (t)} = (1 - \text{w}) \times \text{Bias (t} - 1) + \text{w} \times (\text{Mean of EPS} - \text{Analysis}) \tag{1}$$

This method allows the incorporation of the most recent behaviour of the system into the estimation of the bias. Sensitivity experiments have been performed with this decaying weight and an optimal value of 10% has been adopted for the current study which was also suggested by NCEP (Cui *et al*., 2012).

After the bias estimation has been done for the current time the bias correction of the output is performed by simply taking the difference of the forecast with the estimated bias, *i.e*.,

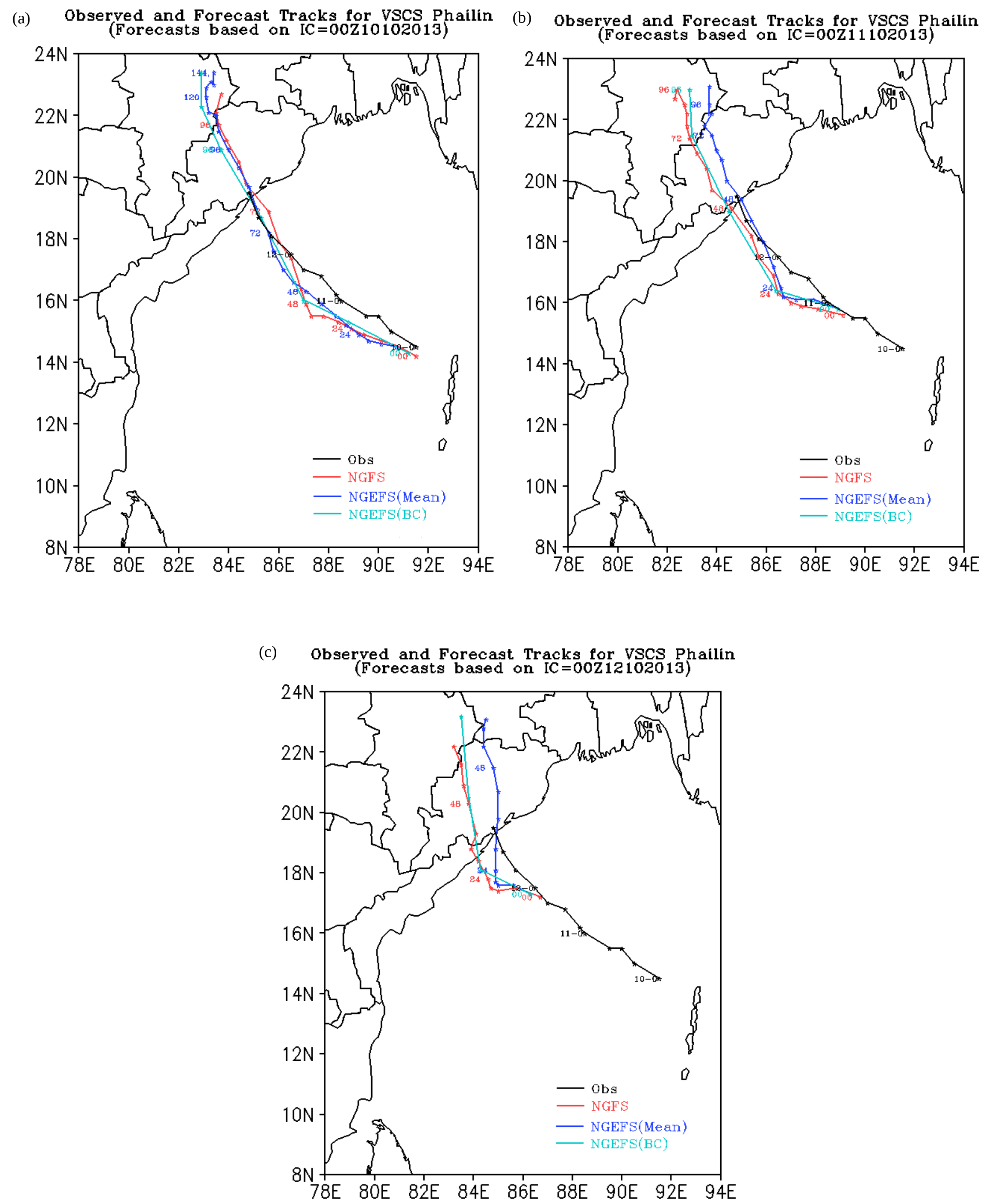
$$\text{Forecast(t)}_{\text{BC}} = \text{Forecast(t)} - \text{Bias(t)} \tag{2}$$

where, $\text{Forecast(t)}_{\text{BC}}$ represents the bias corrected forecast and Forecast(t) is the raw NGEFS output.

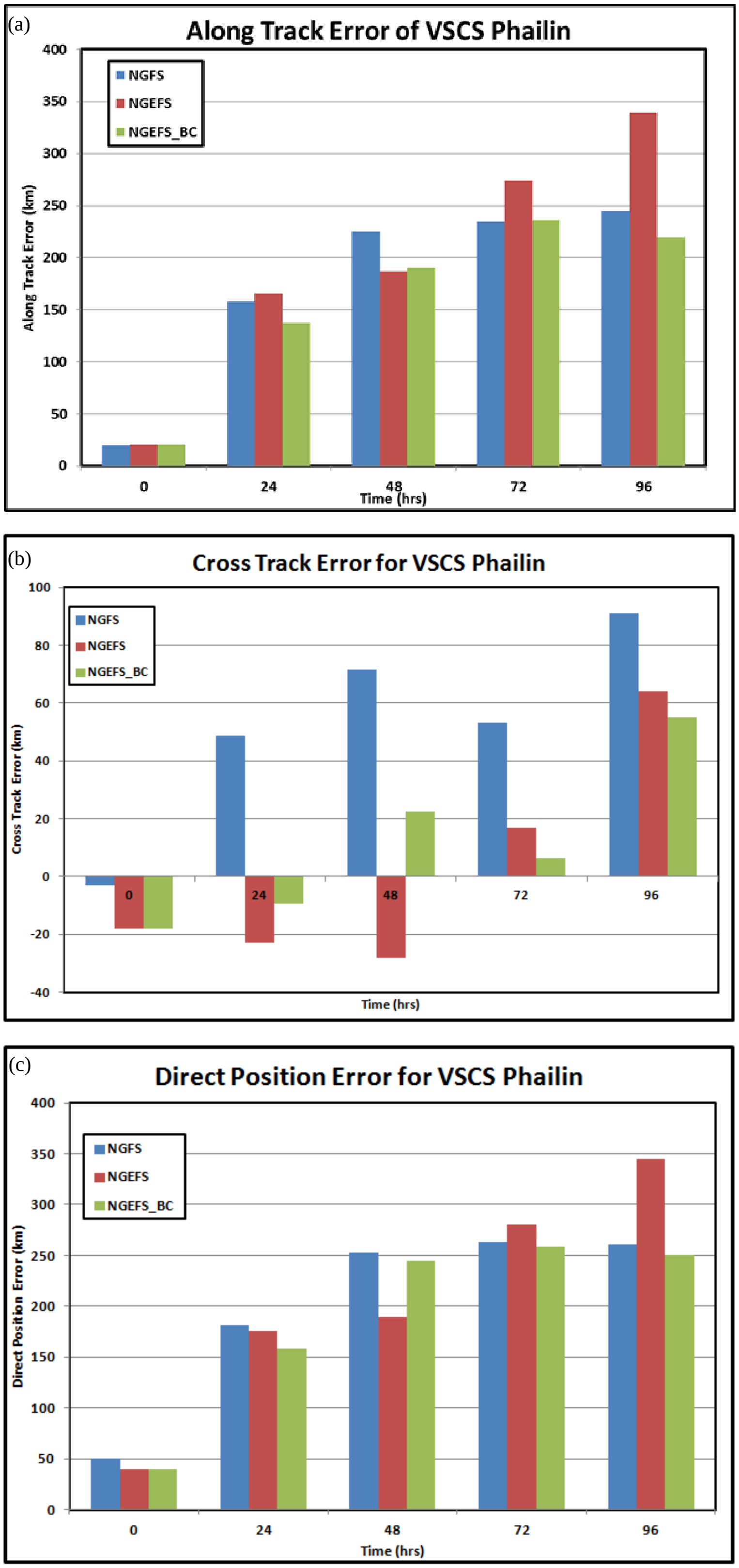
Currently at NCMRWF bias correction of only some specific variables is being done operationally. These variables include: temperature, wind and geopotential height at all levels, mean sea level pressure. Once the bias corrected values of these variables is obtained the cyclone tracker module [defined in section 3.1 part (b)] is run in order to obtain a cyclone track forecast based on the bias corrected values (bias corrected cyclone track forecast).

5. Results and discussion

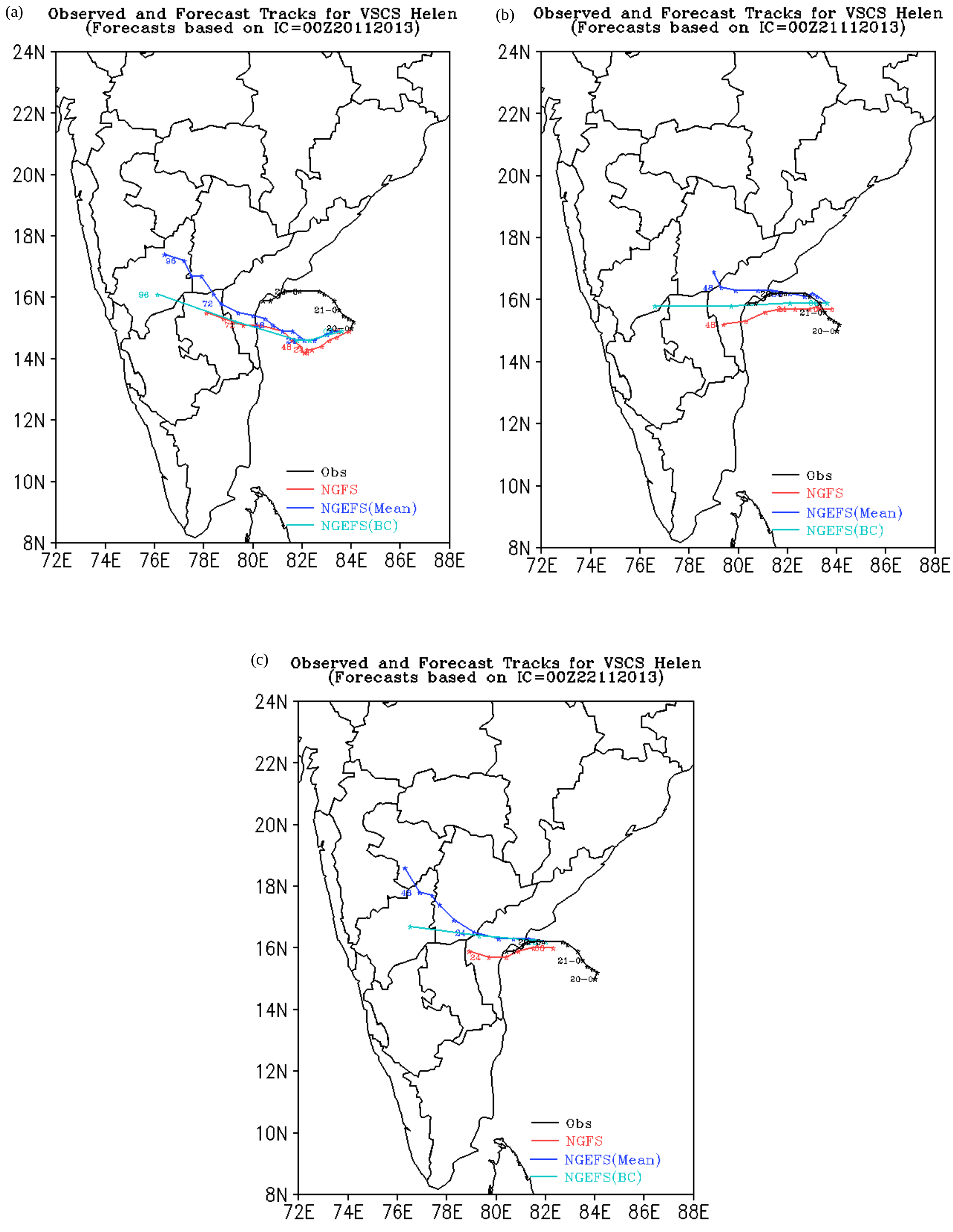
This section deals with the forecast track errors for the four cyclones Phailin, Helen, Lehar and Madi observed in the Bay of Bengal in 2013. These forecast track errors are calculated for the tracks obtained from two global models of NCMRWF namely NGFS and the average of the ensemble tracks from NGEFS and NGEFS_BC. All the verification is done against the best track data of the four cyclones obtained from the IMD. The scores that are calculated for the purpose of verification are the Along Track Error (ATE) which is an indicator how the cyclonic system is moving in comparison to the observed system. Positive (negative) values of the ATE imply that the forecast tracks are moving faster (slower) than the observed system. Cross Track Error (CTE) gives the location of the forecast cyclonic system to the right or the left hand side of the observed cyclone track. If the forecast track is displaced to the right (left) of the observed location then the values of the CTE are positive (negative) (WMO1). Therefore, these two components can give a good indication of the displacement of the forecast from the actual path taken by the system as well as the lag or lead that the forecast system has over the observations. The Direct Position Error (DPE) is defined as the great circle distance between a cyclone’s forecast position and the observed position at the forecast verification time. The error values obtained at the “00” hour are the initial position error which is an indicative of how much the initial position of the cyclone on a given day differs from the observed location at the same time.



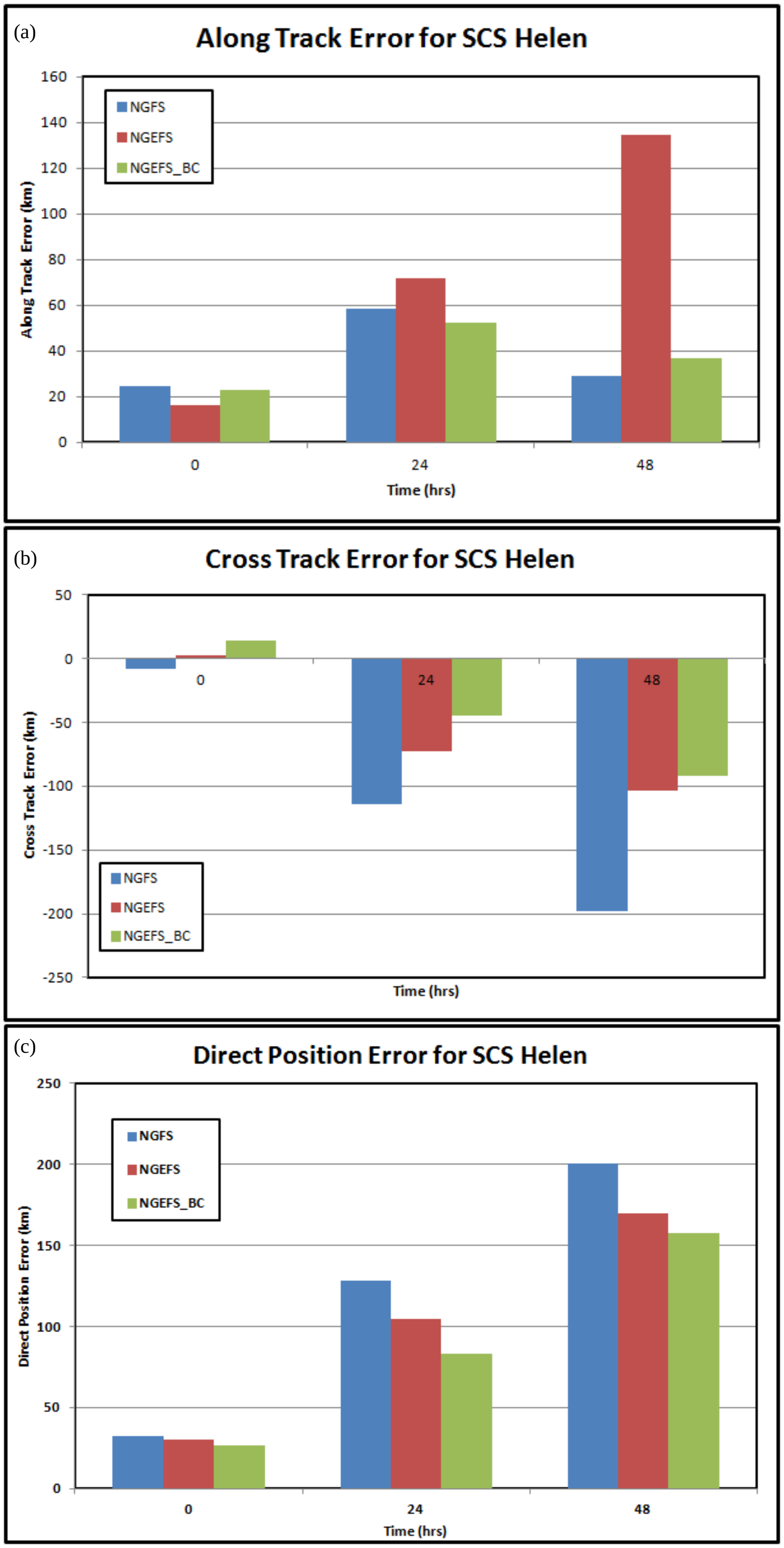
Figs. 5(a-c). Observed and forecast tracks for Phailin based on IC of (a) 10102013, (b) 11102013 and (c) 12102013



Figs. 6(a-c). (a) Along track error (b) Cross track error and (c) Direct position error for VSCS Phailin (9-12 October, 2013) calculated based on the IMD best track data



Figs. 7(a-c). Observed and forecast tracks for Helen based on IC of (a) 20112013, (b) 21112013 and (c) 22112013



Figs. 8(a-c). (a) Along track error (b) Cross track error and (c) Direct position error for SCS Helen (20-22 November, 2013) calculated based on the IMD best track data

The comparison of the forecast tracks is done among the three forecasts obtained from (a) The deterministic model (NGFS) (b) mean of the ensemble of tracks obtained from NGEFS and (c) mean of the ensemble of cyclone tracks obtained from NGEFS_BC. In the current study all the above mentioned error statistics are calculated for daily track forecasts for each cyclone and all the models. The daily error values are then averaged to obtain the mean of the ATE, CTE and DPE at 24 hour intervals, which are presented in the subsections below. In the following subsections a detailed discussion about the track errors obtained from the four cyclones is given.

Phailin (9-12 October, 2013)

(*i*) *Forecast tracks*

Figs. 5 (a-c) show the observed and forecast tracks based on the 0000 UTC 10th, 11th and 12th October, 2013 initial conditions respectively. Forecast positions based on both NGFS and NGEFS are shown at 6 hour intervals. However, for NGEFS_BC the tracks are shown at 24 hour interval. The forecasts indicate landfall over Andhra Pradesh and Odisha border. It can be seen from the figures that the forecast from NGEFS matches well with the observations after the 24 hour forecast. From all the figures it is observed that the landfall location being predicted by NGEFS is closer to the actual location as compared to NGFS and NGEFS_BC. It is also, seen from Fig. 5(c) that the forecast tracks from all the models are much to the south of the observed track.

(*ii*) *Forecast track errors*

Forecast track errors are computed based on the best track available from IMD from 0000 UTC of 10th to 12th October, 2013 and the average ATE, CTE and DPE for Phailin are presented in Figs. 6 (a-c) respectively. Fig. 6(a) shows that the ATE is always positive for all the three models which implies that the models show a fast bias in TC prediction. This means that on an average the forecast tracks tend to move faster than the observed tracks. It is also observed from his figure that the ATE from NGEFS_BC is lower than the other two models (except for the 48 and 72 hour forecast where the ATE from NGEFS_BC is comparable to NGFS and NGEFS). From Fig. 6(b), which shows the CTE (averaged over 3 forecast days) from the three models, it can be seen that for the first 48 hours the errors obtained from NGEFS are negative which implies that on an average the forecast track from this model lies to the left of the observed track (also seen from Fig. 5). On the other hand the CTE values starting from 24 hour forecast obtained from NGFS and from 48 hours for NGEFS_BC are positive implying that the forecast tracks lie to the right of the observed track. It is also seen from this figure that NGEFS_BC shows the least CTE among all the three models. From Fig. 6(c), showing the direct position error (average of 3 days DPE), it can be seen that except for the 96 hour forecast, where NGEFS shows a DPE of more than 350 km, the DPE from all the models is always less than 300 km. Also, except for the 48 hour forecast the error obtained from NGEFS_BC is lower than the DPE in NGFS and NGEFS. From the same figure the initial position error from all the models is seen to be less than 50 km. The initial position error is the highest in NGFS and is comparable for both NGEFS and NGEFS_BC.

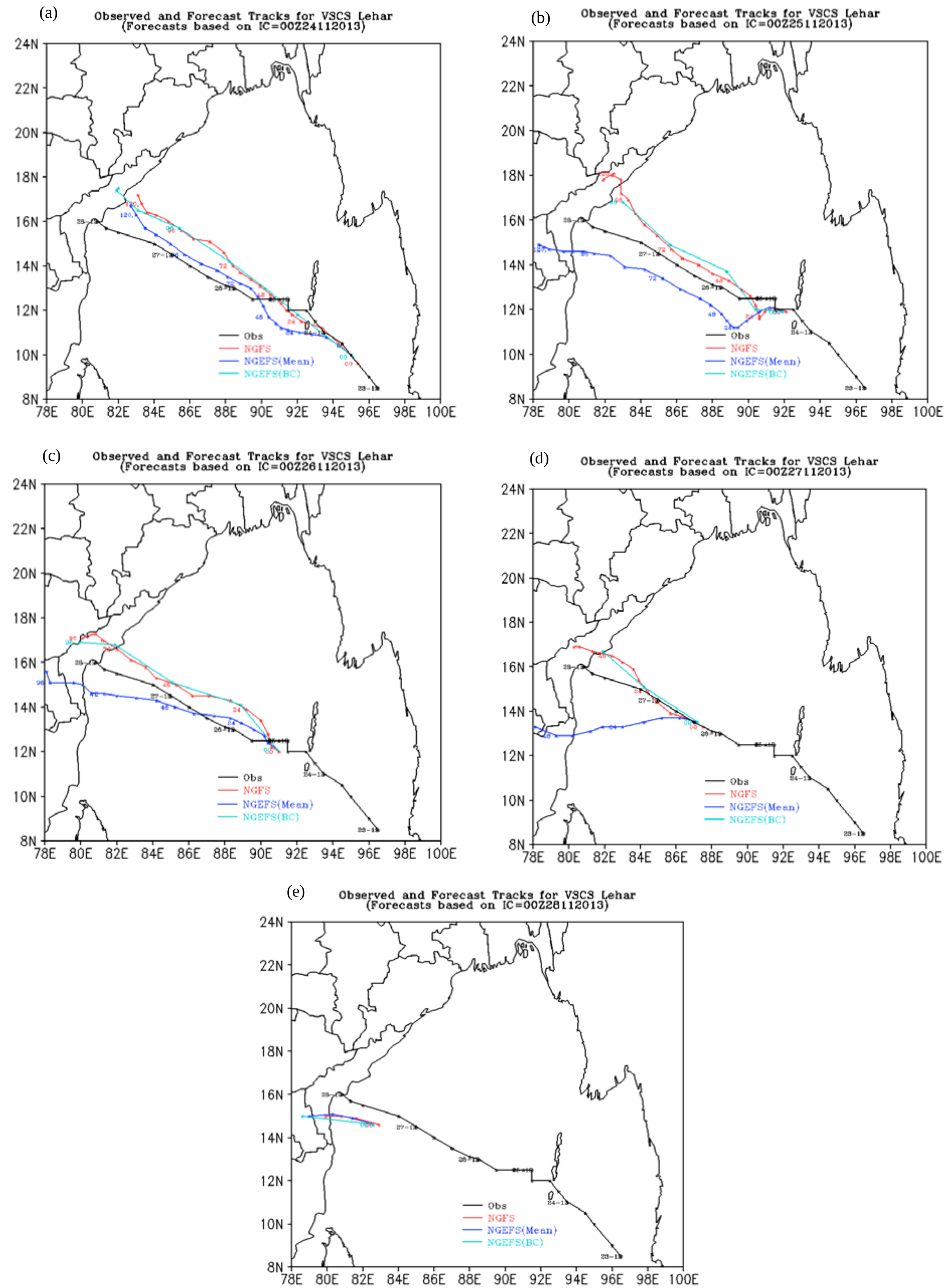
Helen (19-23 November, 2013)

(*i*) *Forecast tracks*

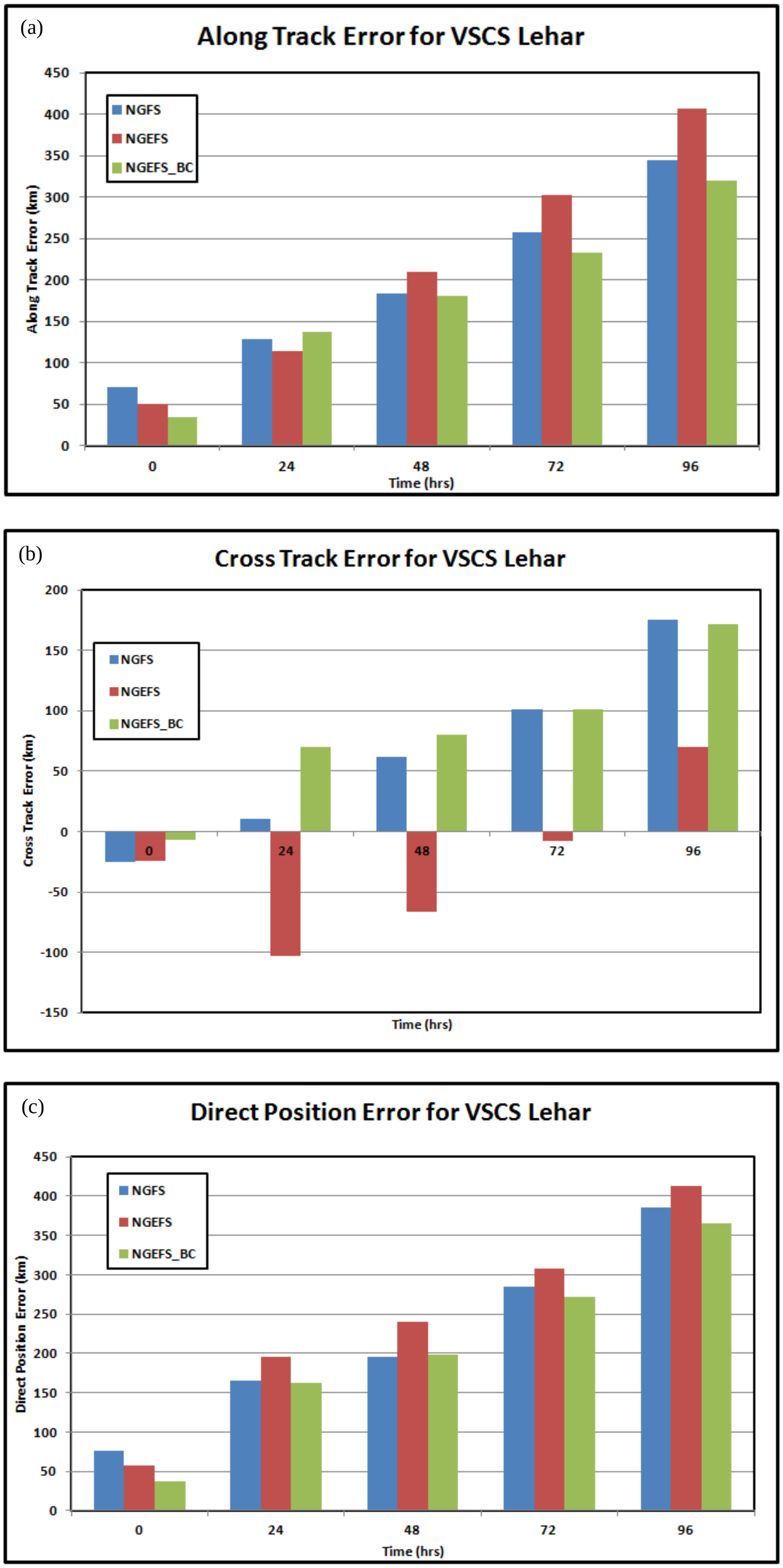
The observed (IMD best track) and forecast tracks from NGFS, NGEFS and NGEFS_BC are presented based on 20th, 21st, and 22nd November, 2013 in Figs. 7(a-c) respectively. The forecast positions are shown at 6 hour interval for NGFS and raw NGEFS and at 24 hour interval for NGEFS_BC. The track forecasts from all the models based on the initial conditions of 20th November are seen to be much to the south of the observed track. Based on the initial conditions of 21st the track forecasts obtained from NGEFS and NGEFS_BC are better matched with the observed track as compared to NGFS. Forecasts tracks based on initial conditions of 22nd November NGFS seems to be closer to the observed track as compared to the other two models.

(*ii*) *Forecast track errors*

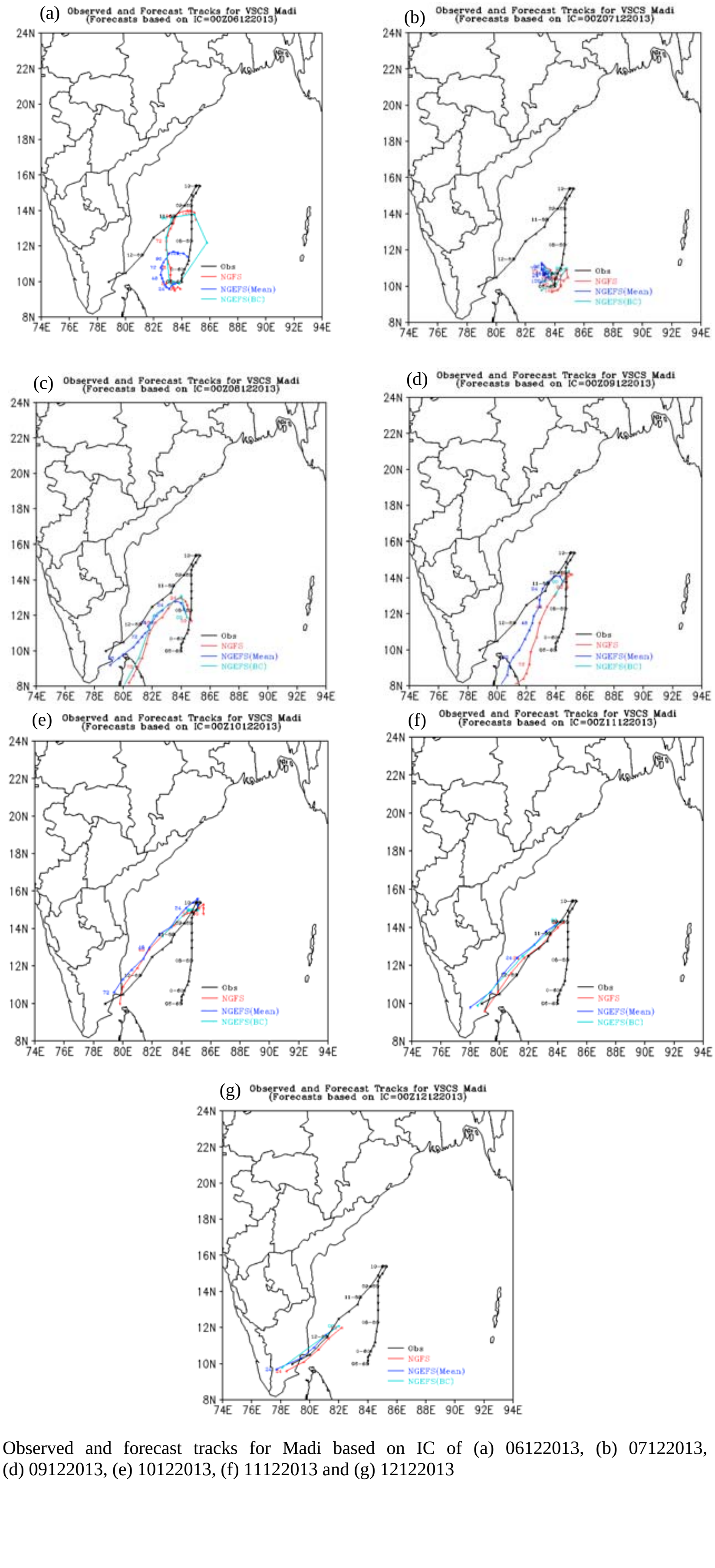
Forecast track errors computed based on the best track data obtained from IMD reported cyclone positions from 0000 UTC of 20th to 22nd November, 2013 were averaged over the three days to obtain the mean of ATE, CTE and DPE for Helen. These errors are presented at 24 hour interval in the Figs. 8(a-c). From Fig. 8 (a) showing the average ATE, it is observed that at initial time NGEFS shows the least error and NGFS shows the highest error. It is also seen from this figure that the ATE values for all the three models are always positive (as in the previous case) indicating faster movement of forecast tracks as compared to the observations. From the average CTE shown in Fig. 8 (b) it is observed that NGEFS_BC has the least cross track error at 24 and 48 hour forecasts. NGFS consistently shows the highest CTE among all the three models. Also, the CTE values for 24 and 48 hour forecasts from all the three models are negative indicating that the forecast tracks lie to the left of the observed track. However for initial time (00 hour) the CTE values are positive implying that the forecasts are to the right of the observed initial location. From the Fig. 8 (c) which depicts the average DPE it is seen that the initial position errors in NGFS and NGEFS (raw and bias corrected) models are



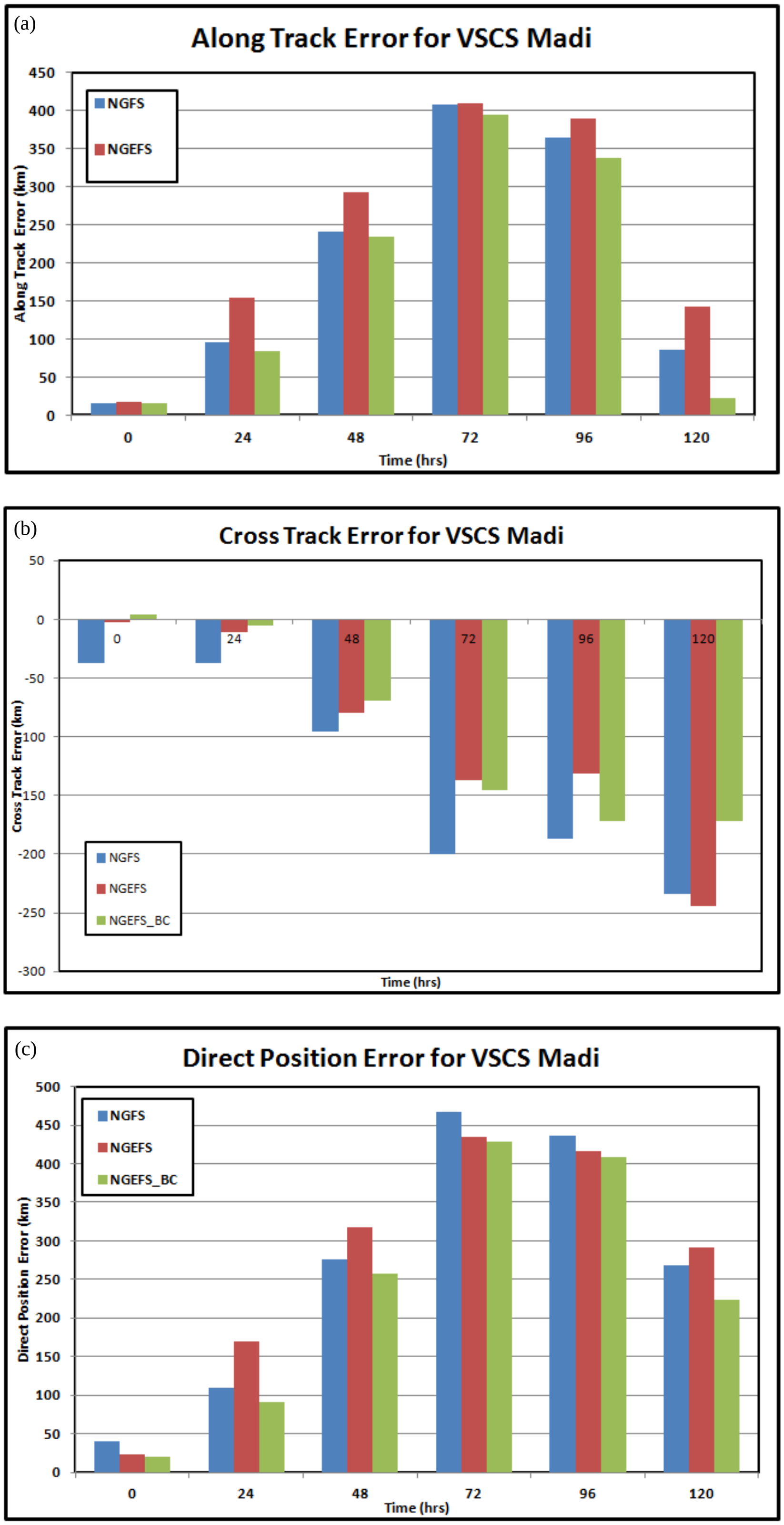
Figs. 9(a-e). Observed and forecast tracks for Lehar based on IC of (a) 24112013, (b) 25112013, (c) 26112013, (d) 27112013 and (e) 28112013



Figs. 10(a-c). (a) Along track error (b) Cross track error and (c) Direct position error for VSCS Lehar (24-28 November, 2013) calculated based on the IMD best track data



Figs. 11(a-g). Observed and forecast tracks for Madi based on IC of (a) 06122013, (b) 07122013, (c) 08122013, (d) 09122013, (e) 10122013, (f) 11122013 and (g) 12122013



Figs. 12(a-c). (a) Along track error (b) Cross track error and (c) Direct position error for VSCS Madi (6-12 December, 2013) calculated based on the IMD best track data less than 50 km. The highest (lowest) initial position error of 33 km (28 km) is seen in NGFS (NGEFS_BC). NGEFS bias corrected mean track shows least DPE at all lead times while NGFS shows the highest DPE. The DPE from all the models is always less than 200 km in this case.

Lehar (23-28 November, 2013)

(*i*) *Forecast tracks*

The observed (IMD best track) and forecast tracks from NGFS, NGEFS (raw and bias corrected) are presented based on initial conditions of 24^{th} to 28^{th} November, 2013 in Figs. 9(a-e). The forecast positions are shown at 6 hour interval for NGFS and raw NGEFS and at 24 hour interval for NGEFS_BC. Forecasts based on 24, 25 and 26^{th} initial conditions it is seen that NGEFS track lies closer to the observed track for most of the forecast period. However for the tracks obtained on the basis of 27^{th} and 28^{th} initial conditions, NGFS and NGEFS_BC forecast tracks seem to be closer to the observations. Also, forecasts based on 27^{th} and 28^{th} also show wide dispersion from the observed track. The forecasts from all the models, based on 28^{th} November initial conditions, show a big difference in even the initial positions of the cyclone Lehar.

(*ii*) *Forecast track errors*

Forecast track errors as in the previous sections are computed based on the IMD best track data for VSCS 'Lehar' from 0000 UTC of 24^{th} to 28^{th} November, 2013 and the average ATE, CTE and DPE are presented in Figs. 10(a-c). All these errors are presented at 24 hour intervals only up to 96 hours. Fig. 10(a) shows, as in the previous cases, that all the models have a positive value for ATE which once again implies a faster moving forecast track as compared to the observed track. NGEFS_BC shows the lowest ATE except for 24 hour forecast where NGEFS shows the lowest ATE. This implies that the movement of the bias corrected NGEFS forecast track is the closest to the observed track among the three models. From Fig. 10(b) which shows the average CTE it is seen that for the first 48 hour the forecasts obtained from the NGFS have the least CTE followed by NGEFS_BC. However from 72 to 96 hour forecasts the mean track from NGEFS shows the lowest CTE and NGFS has the highest CTE. Also, the CTE values obtained from NGFS and NGEFS_BC are positive at all lead times except at the initial time (00 hour); this implies that the forecast tracks lie to the right of the observations, which is also seen from Figs. 9(a-e). On the other hand the CTE values obtained from raw NGEFS show that for the first 72 hours the forecast track lies to the left of the observed track (negative CTE) and at 96 hour the forecast track is to the right of the observations. From Fig. 10(c) which depicts the average DPE from all the above models, it is seen that the initial position errors (at 00 hour) in NGEFS_BC is less than 50 km. Also, NGFS shows the highest initial position error of about 77 km. It is also seen that the NGFS shows the maximum and NGEFS_BC forecast tracks shows the minimum DPE among all the models.

Madi (6-12 December, 2013)

(*i*) *Forecast tracks*

The observed and forecast tracks from NGFS, NGEFS (mean) and NGEFS_BC (mean) are presented based on initial conditions starting from 6^{th} to 12^{th} December, 2013 in Figs. 11 (a-g). The forecast positions are shown at 6 hour interval for NGFS and mean of the raw NGEFS and 24 hours for NGEFS_BC. Based on the track forecasts obtained from the initial conditions of 6^{th} December, it is seen that the tracks from NGFS and NGEFS_BC follow the observed track more closely as compared to the mean of the raw NGEFS. However, the tracks do not indicate any landfall location clearly. Forecasts based on 7^{th} December, 2013 initial conditions do not show clear movement and landfall of the cyclonic system [Fig. 11(b)] from any of the models. On 8^{th} and 9^{th} December, 2013 the forecasts generally indicated northward movement in the beginning and then south-westwards [Figs. 11(c-d)]. NGFS on both days (and NGEFS on 9^{th} December, 2013) suggested the cyclone would strike Sri Lanka coast. Tracks based on 10^{th}, 11^{th} and 12^{th} consistently showed cyclone would cross the Tamil Nadu coast near Nagapattinam [Figs. 11(e-g)].

(*ii*) *Forecast track errors*

Forecast track errors are computed based on the IMD best track data from 0000 UTC of 6 - 12 December, 2013 and then averaged to obtain the ATE, CTE and DPE from all the three models at 24 hour interval up to 120 hours as shown in Figs. 12(a-c). From Fig. 12(a) depicting the ATE values, it is seen that all the models exhibit a positive ATE at all forecast lead times indicating a faster movement of cyclone tracks in the models. Also, the tracks from the NGEFS_BC forecasts shows the lowest ATE followed by NGFS and the NGEFS raw forecasts shows the highest ATE at all lead times. This implies that the forecasts of the movement of the cyclonic system from the NGEFS_BC, although faster, are still the closest to the observed track. From Fig. 12(b) which shows the average CTE it is observed that the values are always negative (except for the CTE from mean of NEGFS_BC model at initial time) which implies that all the predicted tracks lie to the left of the observed track at all forecast lead times.

Figs. 13(a-c). Average (a) Along track error (b) Cross track error and (c) Direct position error for the four cyclones Phailin, Helen, Lehar and Madi in the Bay of Bengal in 2013

Also, for the 72 and 96 hour forecasts mean track obtained from NGEFS raw shows the least CTE and at all the other forecast lead times NGEFS_BC shows the lowest CTE among all the three models. NGFS shows the highest CTE at all forecast lead times.

Average Errors

A simple average of the ATE, CTE and DPE is performed in order to be able to see the overall trend in the error patterns for all the four cyclones which made landfall over India in 2013. The results are shown in Figs. 13 (a-c) which shows the ATE, CTE and DPE respectively. The first thing that is observed from all the figures is that in general the NGEFS_BC shows lower values of all the three errors as compared to NGFS and NGEFS. It is also seen from these figures that at initial time the DPE is less than 50 km for all the models. From Fig. 13 (c) showing the DPE it is observed that except for the 96 hour forecast the error values are always less than 350 km from all the models.

A paired Student’s t-test was performed in order to determine whether the in the errors difference (reduction or increase in the Direct position errors) obtained from the three models were statistically significant. From this test it was found that for the error in the initial position (00 hour forecast, df = 17) the difference between NGFS and NGEFS as well as NGFS and NGEFS_BC is statistically significant at 95%, *i.e.*, the improvement in the track error between the deterministic and both the raw and bias corrected ensemble models is statistically significant. For the error at 24 hours (df = 14) the difference (reduction in DPE) between NGFS and NGEFS_BC is found to be statistically significant at 95% whereas between NGFS and NGEFS it is only significant at 90%. From 48 to 120 hour forecast the DPE is seen to be higher in NGEFS as compared to NGFS whereas it is lower in NGEFS_BC as compared to NGFS [Fig. 13(c)]. Also, in this case the results of the Student’s *t*-test show no statistical significance on comparing the DPE from the three models. This may be attributed to a decrease in the sample size and also the increase in the variance among the track errors with the increase in forecast lead time. Also, the difference in errors between NGEFS and NGEFS_BC are not found to be statistically significant at any forecast lead time.

6. Conclusions

In this paper a comparison between the relative skills of the two models from NCMRWF namely : NGFS (deterministic) and NGEFS (ensemble prediction system), is made in predicting the tropical cyclone tracks. Further an attempt is made to correct the systematic biases present in the NGEFS model by using the methods of moment adjustment. The biases in the first moment i.e., the mean of the ensemble are estimated and then corrected and the output obtained is used to calculate the forecast tracks of four NIO cyclones during 2013: Phailin, Helen, Lehar and Madi. This intercomaprison of the skill of the models is done by calculating the along track, cross track and direct position errors for the tracks obtained from NGFS and the average of the ensemble tracks from raw and bias corrected NGEFS. All the errors are calculated against the best track data for the four cyclones from IMD.

It is seen from the current study that in most of the cases the bias corrected form of NGEFS (NGEFS_BC) performs better than NGFS and NGEFS in predicting the TC tracks in terms of having lower ATE, CTE and DPE. Even in the case of VSCS Madi, which had a track which shows a sudden recurving, the bias corrected model was able to perform better as compared to the other 2 models. This is seen in the higher values of errors in case of Madi (highest value of ATE is greater than 400 km, CTE is around - 250 km and DPE is greater than 450 km). In the case of Madi it is also seen in that the CTE from NGEFS was lower than NGFS and NGEFS_BC in the 72-96 hour forecast. A reason for this could be that due to a higher spread of members from NGEFS, it was able to capture the actual movement of the system better than NGFS (no members) and NGEFS_BC (smaller spread). Apart from this, only in the case of 48 hour forecast ATE and DPE from Phailin and the 24 hour forecast ATE and CTE from Lehar the values in NGEFS are seen to be lower than NGEFS_BC. In all of the other cases NGEFS_BC has lower error values as compared to NGFES. On calculating the average DPE for the four cyclone cases of 2013 it is seen that the bias correction leads to an improvement of about 17% in the initial position error as compared to raw ensemble track forecast and about 38% when compared with the deterministic model. In the day 5 forecasts the improvement in the bias corrected ensemble forecast as compared to NGEFS and NGFS are 24% and 17% respectively. This shows that the bias correction is definitely of some importance in predicting the TC tracks.

However, there is a limitation of having a very small data set for further analysis and experimenting. Therefore a lot more work is required in trying to perfect this scheme. This study does not focus on the intensity forecasts for tropical cyclones as some of the global models, due to their coarser resolution, are not well suited for predicting the intensity of TC. Especially in the case of NGFS the globally analyzed vortex is, often an incomplete representation of the true TC structure. For this reason, the NGFS is typically more suited to producing track and outer wind structure forecasts than to producing intensity forecasts. There have been studies which indicate that increasing the resolution of the models can lead to better intensity forecasts and hence we are in the process of upgrading the models to a finer resolution in order to obtain better TC intensity forecasts.

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