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RESEARCH REPORT

Tropical Cyclones in NIO - 2013:

Verification of Predicted Tropical Cyclone Tracks by NCMRWF Global Forecast Models

Raghavendra Ashrit, Amit Ashish, Kuldeep Sharma, Anumeha Dube, G. R. Iyengar and E. N. Rajagopal

April 2014

National Centre for Medium Range Weather Forecasting
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10	Abstract (100 words)	In the North Indian basin, storms are most common from April to December, with peaks in May and November. On an average there are approximately 4.8 tropical cyclones observed in the NIO every year. A majority of these cyclones are formed in the Bay of Bengal and make landfall on the east coast of India causing extensive damage to life and property. Timely prediction of cyclone track and the landfall location as well as time is therefore a top priority for weather forecasters in these regions. During May-December 2013, there were 5 tropical cyclones observed in the Bay of Bengal namely: Mahasen (May10-17), Phailin (Oct 4-14), Helen (Nov 19-23), Lehar (Nov 19-28) and Madi (Dec 6-13). This report deals with the real time prediction of these cyclone tracks by the NCMRWF Global Forecast Systems (NGFS, NCUM and NGEFS). Along with this a verification of the tracks based on average forecast track error in comparison with the observed track is also presented.
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Abstract

In the North Indian basin, storms are most common from April to December, with peaks in May and November. On an average there are approximately 4.8 tropical cyclones observed in the NIO every year. A majority of these cyclones are formed in the Bay of Bengal and make landfall on the east coast of India causing extensive damage to life and property. Timely prediction of cyclone track and the landfall location as well as time is therefore a top priority for weather forecasters in these regions.

During May-December 2013, there were 5 tropical cyclones observed in the Bay of Bengal namely: Mahasen (May10-17), Phailin (Oct 4-14), Helen (Nov 19-23), Lehar (Nov 19-28) and Madi (Dec 6-13). This report deals with the real time prediction of these cyclone tracks by the NCMRWF Global Forecast Systems (NGFS, NCUM and NGEFS). Along with this a verification of the tracks based on average forecast track error in comparison with the observed track is also presented.

Verification of Bay of Bengal Cyclonic Storm 'Mahasen' (11-16 May 2013)

The tropical cyclone track forecasts are based on GFS (T574L64) and the Unified Model (UM) of UK Met Office (NCUM) operational at NCMRWF. Additionally the track and intensity forecasts based on the Global Ensemble Forecast System (GEFS;T190L28) is also provided to IMD on experimental basis.

The tropical cyclone forecast tracks are derived based on vertical weighted average of the max or min of several parameters in the vicinity of a vortex in the input first guess (lat,lon) and forecasts. Briefly, for tropical cyclones, seven parameters are tracked, including the relative vorticity maximum, geopotential height minimum and wind speed minimum at both 850 and 700 hPa, as well as the minimum in sea level pressure. The locations based on these parameters are averaged together to provide an average position fix at each forecast hour. In order to avoid tracking weak, transient disturbances (either real or artifacts of model noise), 2 constraints have been added to the tracking criteria in order for a found disturbance to be reported as being a tracked storm: (1) the storm must live for at least 24 hours within a forecast, and (2) the storm must maintain a closed mslp contour, using a 2 mb contour interval.

GFS (T574L64) Forecasts out to 240 hours

NCUM N512L70 Forecasts out to 168 hours

GEFS (T190L28) Forecasts out to 240 hours

The 20-member ensemble prediction system is operational since June 2012. The cyclone module in the GEFS can be used to produce three different kinds of products. (a) Tracks of the cyclone from each of the members of the GEFS. (b)Circle of track uncertainty (based on the ensemble spread) (c) Strike Probability. Additionally forecast probabilities of wind intensity are also provided.

Figure 1 shows the forecast tracks based on the 00UTC 11th May 2013 initial conditions. The forecast based on the two deterministic models (T574 and NCUM) indicate landfall over Myanmar. GEFS tracks consistently show movement towards Myanmar. The ensemble average track and strike probability are also shown. Strike probability is the probability of a given location (grid point) being within a specified distance (~101Km) of an ensemble member track point. Strike probability is calculated both individually for each forecast hour and for the total accumulated probability up to 120 hr forecast.

Forecast Verification

Verification of forecast tracks is carried out against the JTWC best track data as well as the IMD best track data. The track errors computed against the IMD best track data is shown in Figure 2

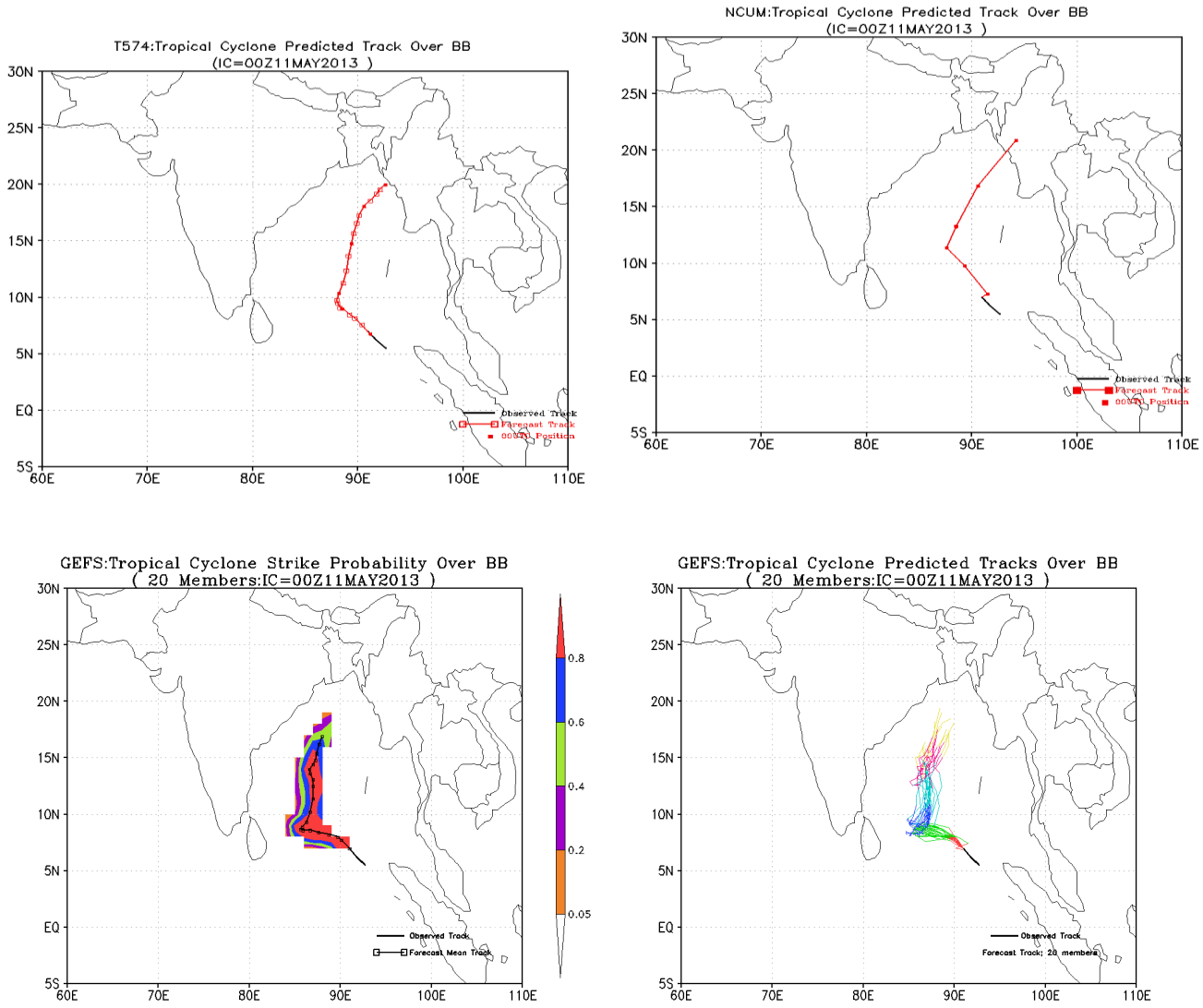
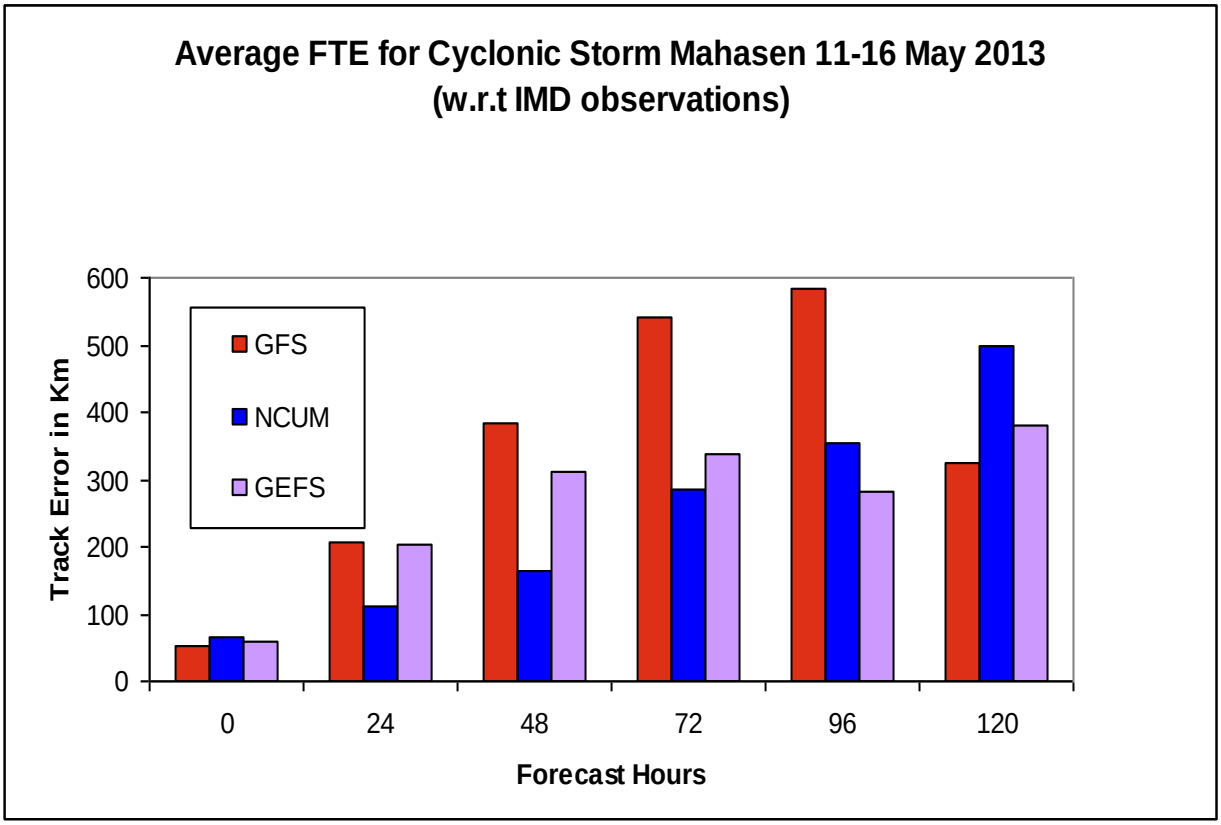


Figure 1. Observed and forecast tracks based on 00UTC 15th May 2013 initial conditions in (a) GFS (T574L64) (b) NCUM and GEFS (c) strike probability and (d) ensemble member tracks



Hours-->	00	24	48	72	96	120
GFS	52	205	383	542	584	324
NCUM	66	111	165	285	355	499
GEFS	59	205	311	336	283	379

Figure 2. Average Forecast Track Errors (in Km) For Cyclonic Storm 'Mahasen' from 11-16 May 2013 (w.r.t IMD)

Verification of Bay of Bengal Cyclonic Storm 'Phailin' (09-12 Oct 2013)

This is a brief summary report on the verification of the NCMRWF model forecasts during the recent VSCS 'Phailin' (9-12 Oct 2013). The study presents the qualitative and quantitative verification of forecast tracks and rainfall (after landfall). The tropical cyclone track forecasts are based on GFS (T574L64) and NCMRWF Unified Model (UM) (NCUM). Additionally the track and intensity forecasts based on the Global Ensemble Forecast System (GEFS;T190L28) is also provided to IMD on experimental basis. The 20-member ensemble prediction system is operational since June 2012.

The tropical cyclone forecast tracks are derived based on vertical weighted average of the max or min of several parameters in the vicinity of a vortex in the input first guess (lat,lon) and forecasts. Briefly, for tropical cyclones, seven parameters are tracked, including the relative vorticity maximum, geopotential height minimum and wind speed minimum at both 850 and 700 hPa, as well as the minimum in sea level pressure. The locations based on these parameters are averaged together to provide an average cyclone position at each forecast hour. In order to avoid tracking weak, transient disturbances (either real or artifacts of model noise), 2 constraints have been added (1) the storm must live for at least 24 hours within a forecast, and (2) the storm must maintain a closed MSLP contour, using a 2 mb contour interval.

1. Forecast Tracks (9-12 Oct 2013)

Figure 1 shows the forecast tracks based on the 00UTC 9th Oct 2013 initial conditions. Forecast positions based on GFS and GEFS are shown at 6 hour interval while the forecast positions based on NCUM is shown at 24 hour interval. The forecasts indicate landfall over Andhra Pradesh and Odisha border. The forecasts closely match with the observed track although with a time delay as can be seen by the time indicated in the Figure 1. The cyclone intensity in the models forecasts is rather weak. Similarly Figure 2-4 show the observed and forecasts tracks based on 00UTC of 10th ,11th and 12th Oct 2013 respectively.

2. Forecast Track Errors (9-12 Oct 2013)

Forecast track errors are computed based on the JTWC reported cyclone positions from 00UTC of 9th – 12th Oct 2013. JTWC reported cyclone positions are used in GFS and GEFS for TC relocation via 'tcvital' which is available through GTS. Hence verification against the JTWC data is justified. (Further, track verification is not presented for UKMO forecasts since the data available from the Met Office does not contain all the fields required for tracking the cyclone.) The average track errors are shown in Figure 5. The initial position errors in all three models are less than 50 km. The highest (lowest) initial position error of 45 km (26km) is seen in GFS (GEFS) while the both NCUM model has initial error of 27 km. NCUM has the least position error at all lead times while GEFS mean track consistently shows lower error than that of GFS.

3. Landfall position and time error.

The IMD reported landfall is considered at 1500UTC of 12th October 2013 at 19.1N 85.0E. Table 1 shows the landfall position and time errors based on all the available track forecasts. NCUM forecasts show least error in predicted landfall position and time with the exception of forecast based on 9th Oct2013. GEFS forecast can be considered next best. Similar to the forecast track errors discussed in the last section, GEFS shows marginal improvement over the GFS in predicting the landfall time and

position. (According to the JTWC track data, the weakening of the cyclone is reported after 1800UTC of 12th Oct 2013. Verification against the JTWC would show much lower errors in the landfall position and time.)

4. Verification of Forecast Rainfall

Rainfall forecast verification is also presented for observed and forecast rainfall over eastern India after the landfall of the cyclone. Figure 6 (and 7) show observed and GFS (NCUM) 72 hour forecast rainfall. The panels show the 24 hour accumulated from 13th Oct 2013 (in mm) along with detailed summary statistics. NCUM forecasts have higher (*lower*) correlation and ETS (*RMSE, bias and false alarm).*

The components of rainfall forecast error based on the CRA method is shown in Figure 8 and 9. Although both the forecasts have comparable rainfall maxima of just over 144 mm/day, the values are underestimated. NCUM has higher average rain rate (53mm/day) and rain volume (20 km^3) which are comparable with the observations (65 mm/day; 24 km^3). GFS has average rain rate of 29 mm/day and 12.7 km^3 rain volume. The average rain rate and rain volume are very low in GFS since the cyclone in the forecast has not made landfall. The GFS forecast has higher RMSE (68.8 mm/day) with main contribution form displacement error (54.5%). The RMSE in the NCUM forecast is lower (51 mm/day) with main contribution from the pattern error (53%).

Figure 10 shows the skill of the rainfall forecast by both models at al lead times. ETS and CC show that NCUM has higher skill in predicted rainfall after landfall up to 4 days in advance after which skill is generally low in both models.

Conclusions

- The Day-3 and Day-5 forecast location of the cyclone on 9-12th Oct 2013 was consistently to the southwest of the observed location. Forecasts valid for 13th Oct 2013 show improvement as the frecasted system is close to the coast.
- Initial position error is below 50 km. GEFS and NCUM have lower initial position errors compared to GFS.
- Forecast track error is lowest in NCUM forecasts with values lower than 100 km up to 72 hours.
- The models underestimate the intensity by a huge margin for winds and SLP
- The models predicted landfall to occur on 13th Oct 2013.
- Landfall position error is lower in GEFS forecasts while lowest time error is in NCUM.
- Verification of the rainfall forecasts after landfall clearly show higher accuracy in NCUM (cc=0.7;RMSE=14mm/day) compared to GFS (cc=.26;RMSE=20.5mm/day).

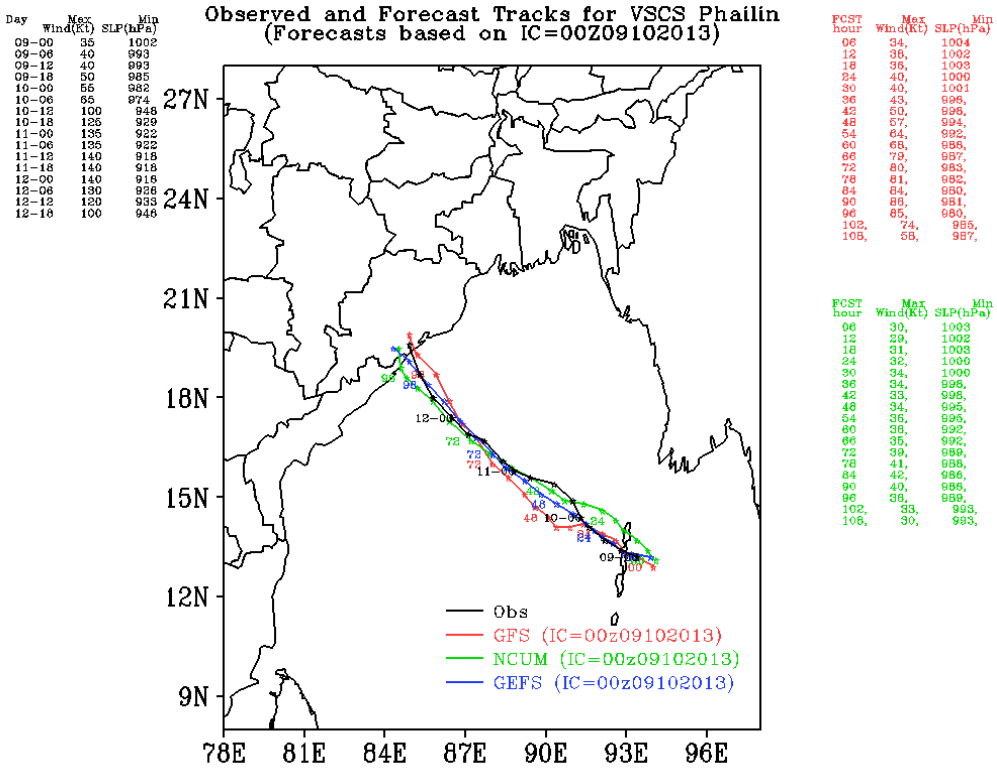


Figure 1 Observed and forecast tracks based on 9th Oct 2013

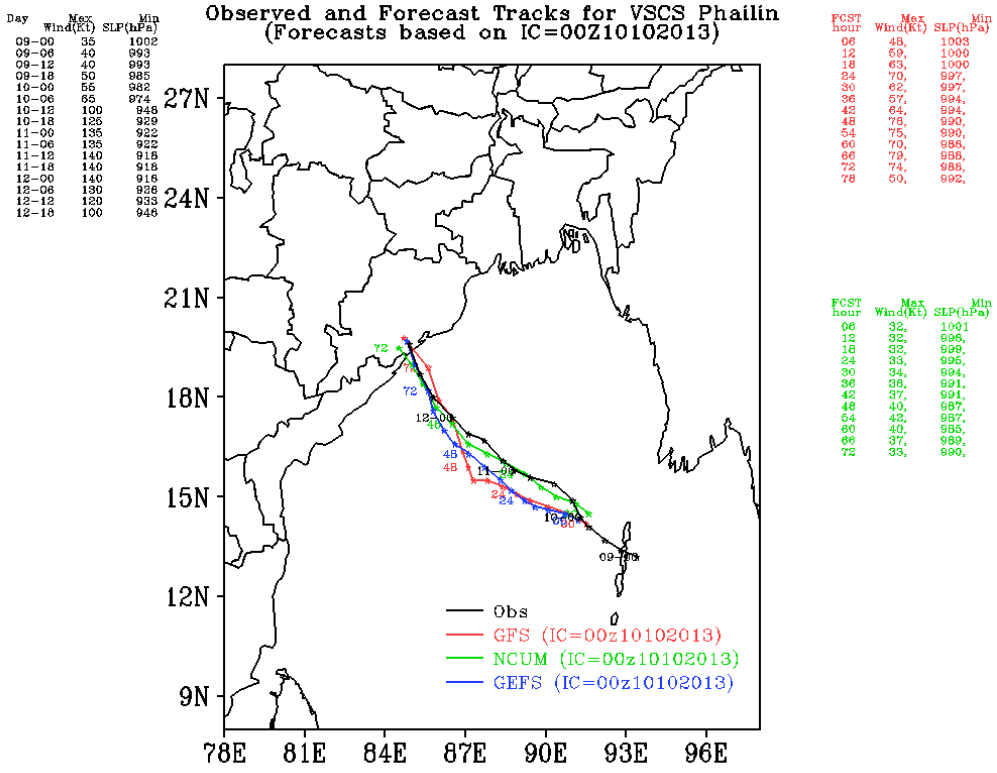


Figure 2 Observed and forecast tracks based on 10th Oct 2013

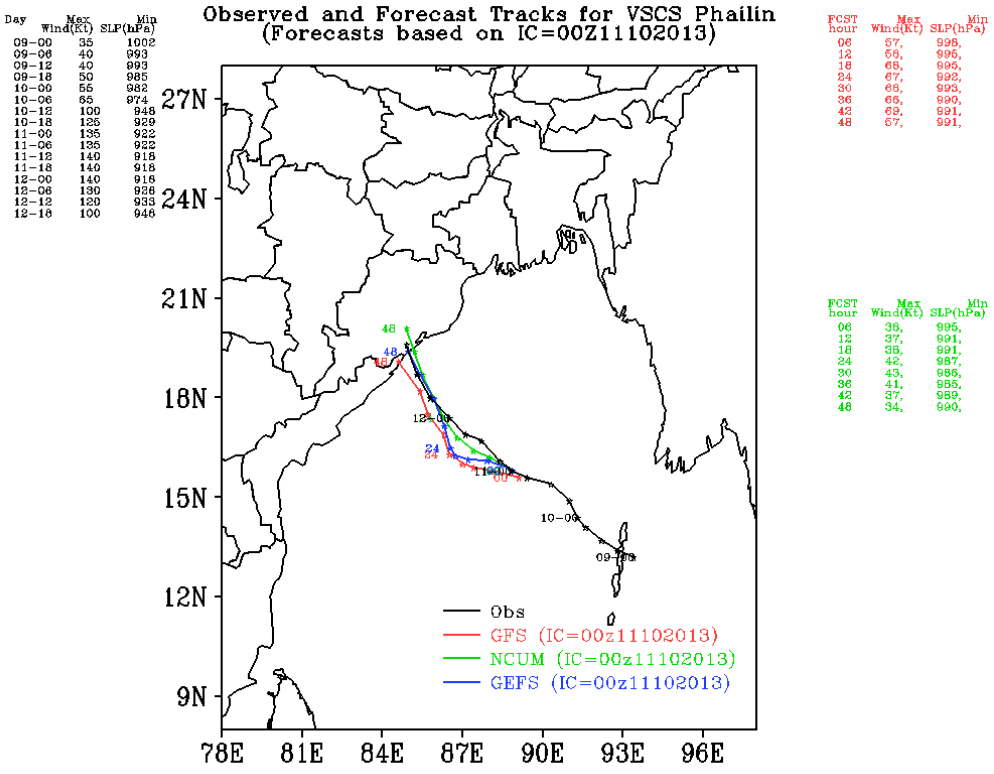


Figure 3 Observed and forecast tracks based on 11th Oct 2013

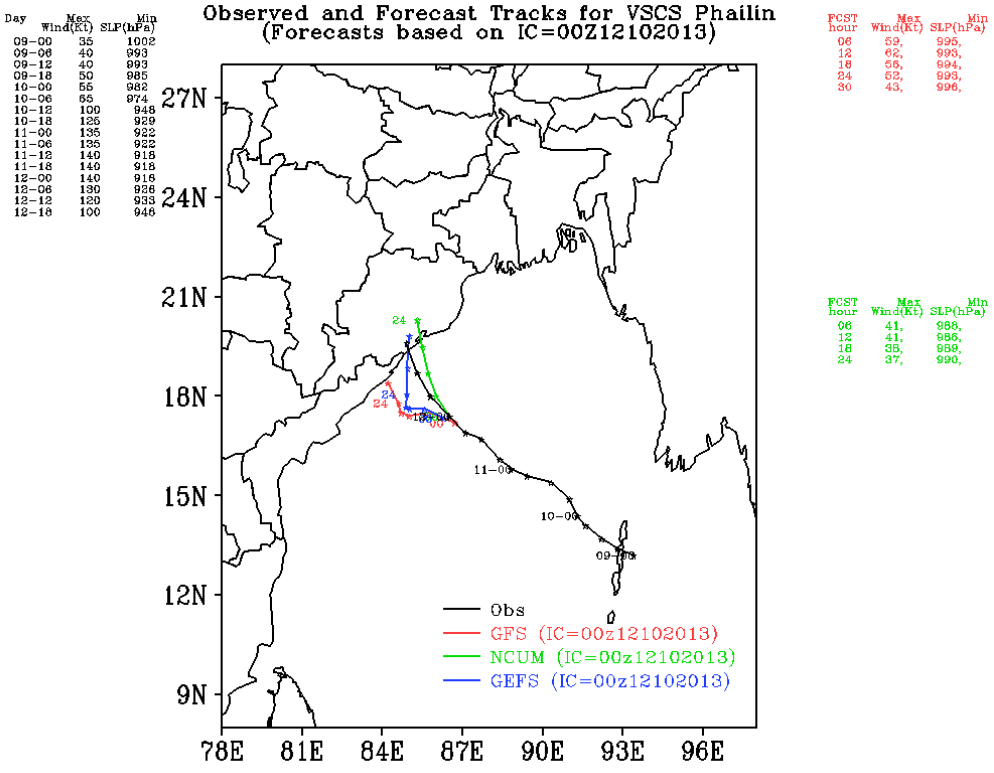


Figure 4 Observed and forecast tracks based on 12th Oct 2013

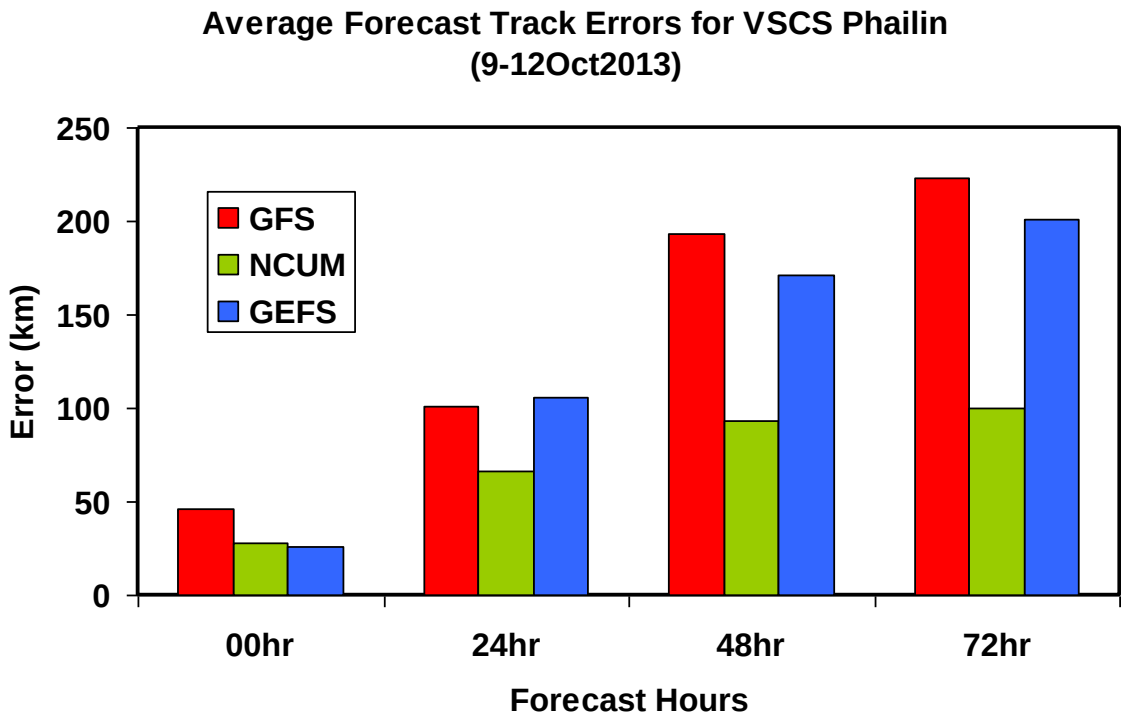


Figure 5. Average forecast track for VSCS 'Phailin' during 9-12Oct 2013.

Table 1. Forecast landfall position error for VSCS Phailin in the ESSO-NCMRWF global models.

(IMD reported landfall at 15UTC of 12th October at location 19.1N,85.0E)

	GFS		GEFS		NCUM	
Initial conditions	*Position error (in km)*	*Time error (in hrs)*	*Position error (in km)*	*Time error (in hrs)*	*Position error (in km)*	*Time error (in hrs)*
IC=09102013	31	-15	10	-6	47	-15
IC=10102013	84	-15	70	-12	11	-3
IC=11102013	42	-9	33	-9	39	-3
IC=12102013	115	-15	78	-21	69	-3

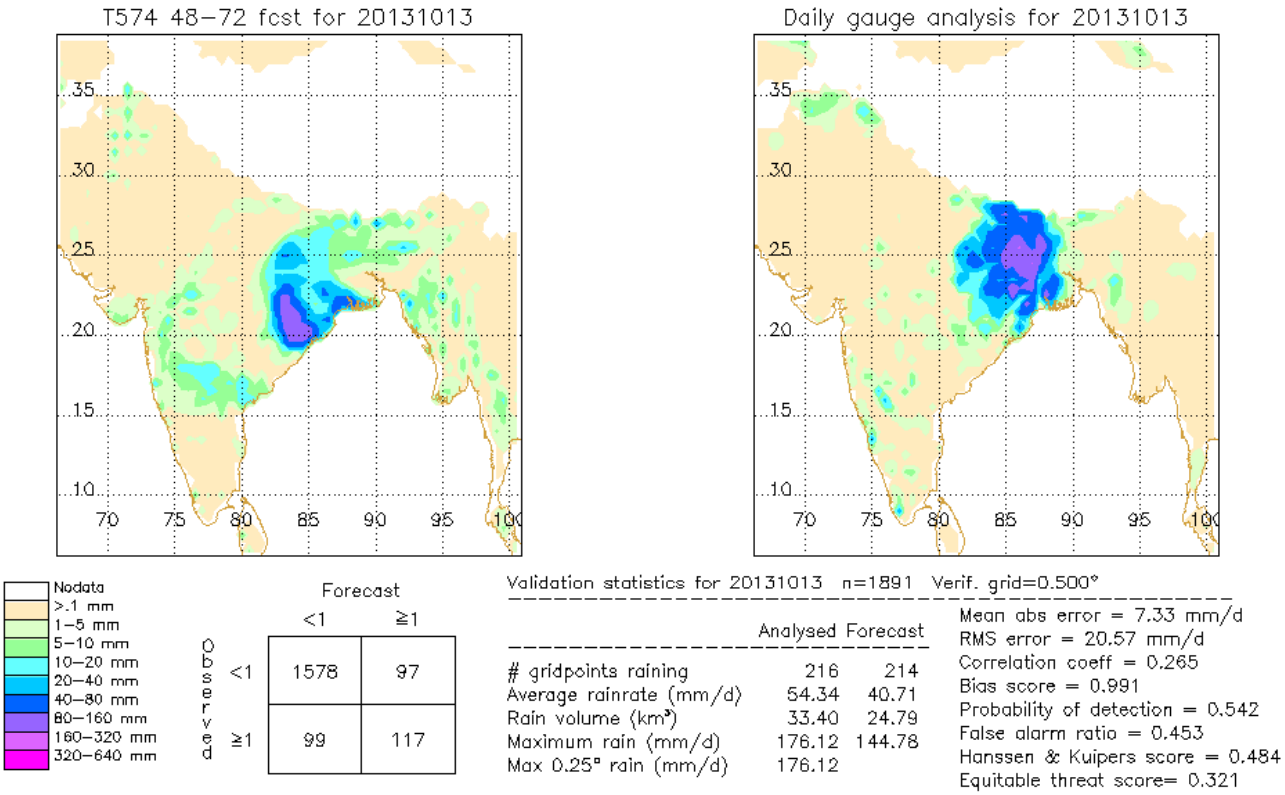


Figure 6. Verification of Day-3 rainfall forecasts valid for 14th Oct 2013 (date at the top of the panels indicate the starting date of 24-hour rainfall accumulation)

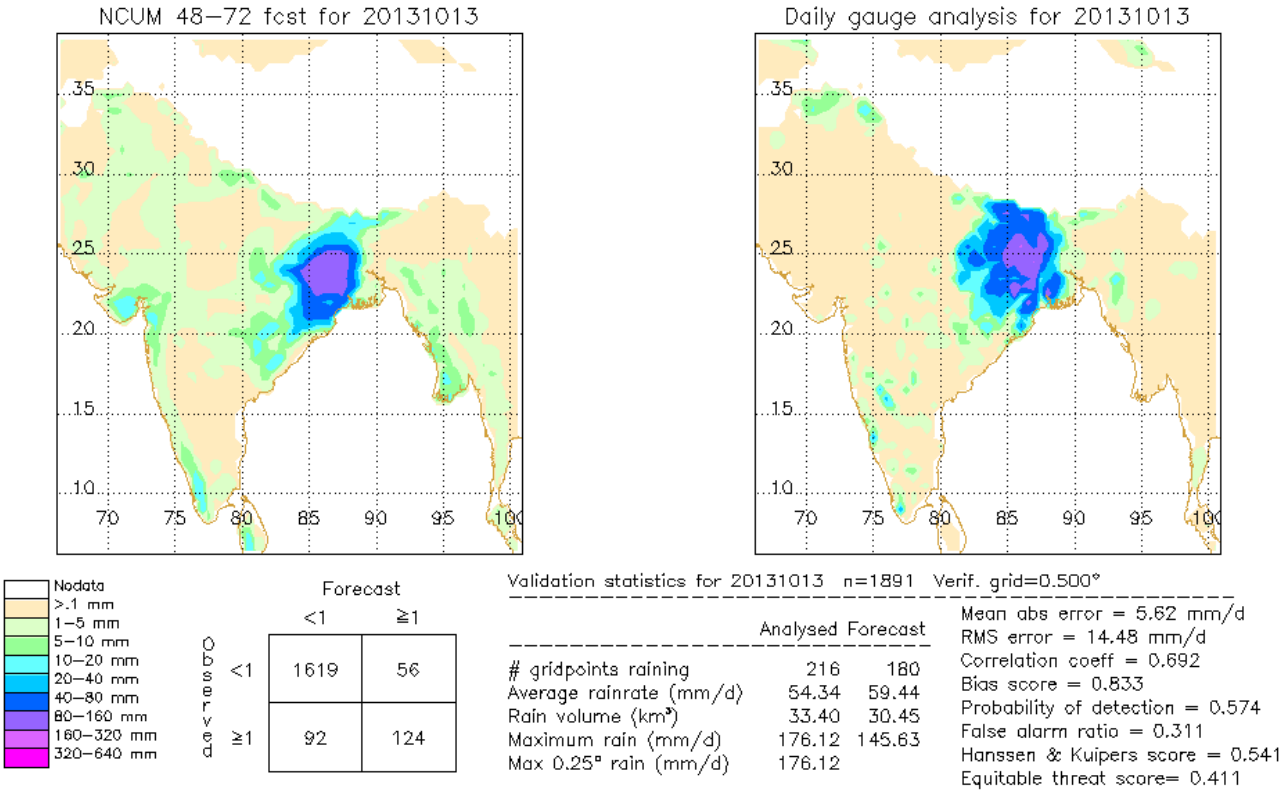
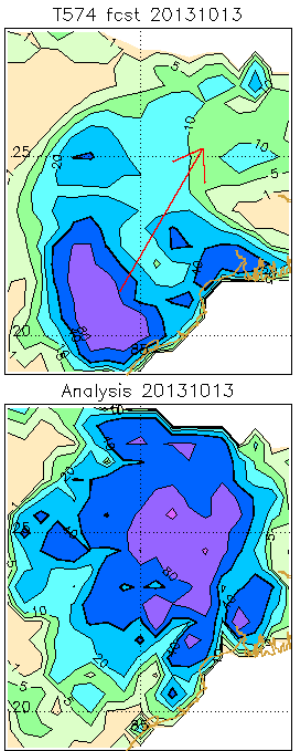
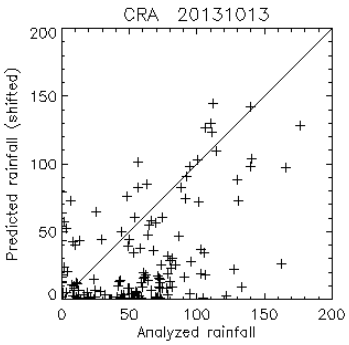


Figure 7 Verification of Day-3 rainfall forecasts valid for 14th Oct 2013 (date at the top of the panels indicate the starting date of 24-hour rainfall accumulation)





T574 48–72 fcst 20131013 n=157
(19.50°,81.50°) to (28.00°,89.00°)
Verif. grid=0.500° CRA threshold=40.0 mm/d

	Analysed	Forecast
# gridpoints ≥40 mm/d	105	46
Average rainrate (mm/d)	56.19	28.84
Maximum rain (mm/d)	176.12	144.78
Rain volume (km³)	24.87	12.76

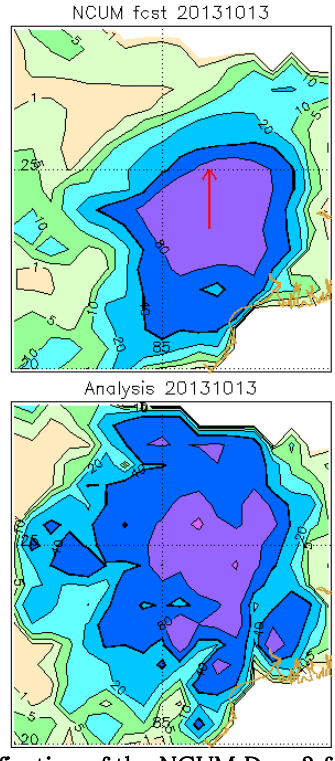
Displacement (E,N) = [−2.50°,−4.00°]

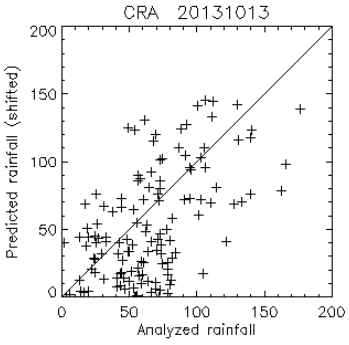
	Original	Shifted
RMS error (mm/d)	68.80	47.82
Correlation coefficient	−0.512	0.452

Error Decomposition:

Displacement error	54.5%
Volume error	13.8%
Pattern error	31.7%

Figure 8 CRA verification of the GFS Day-3 forecast of rainfall associated with the VSCS 'Phailin' after landfall.





NCUM 48–72 fcst 20131013 n=133
(20.50°,81.50°) to (28.00°,89.00°)
Verif. grid=0.500° CRA threshold=40.0 mm/d

	Analysed	Forecast
# gridpoints ≥40 mm/d	105	68
Average rainrate (mm/d)	65.69	53.19
Maximum rain (mm/d)	176.12	145.63
Rain volume (km³)	24.54	19.87

Displacement (E,N) = [0.00°,−1.50°]

	Original	Shifted
RMS error (mm/d)	51.34	38.33
Correlation coefficient	0.232	0.552

Error Decomposition:

Displacement error	36.5%
Volume error	10.5%
Pattern error	52.9%

Figure 9 CRA verification of the NCUM Day-3 forecast of rainfall associated with the VSCS 'Phailin' after landfall.

Table 2. RMSE (mm/day)in the rainfall forecasts valid for 00UTC of 14th Oct 2013 based on GFS and NCUM at different lead times over eastern India (domain as in Figure 8-9).

	Day-1	Day-2	Day-3	Day-4	Day-5
GFS	58.6	62.2	68.8	74.5	85.5
NCUM	47.4	50.9	52.5	55.5	76.9

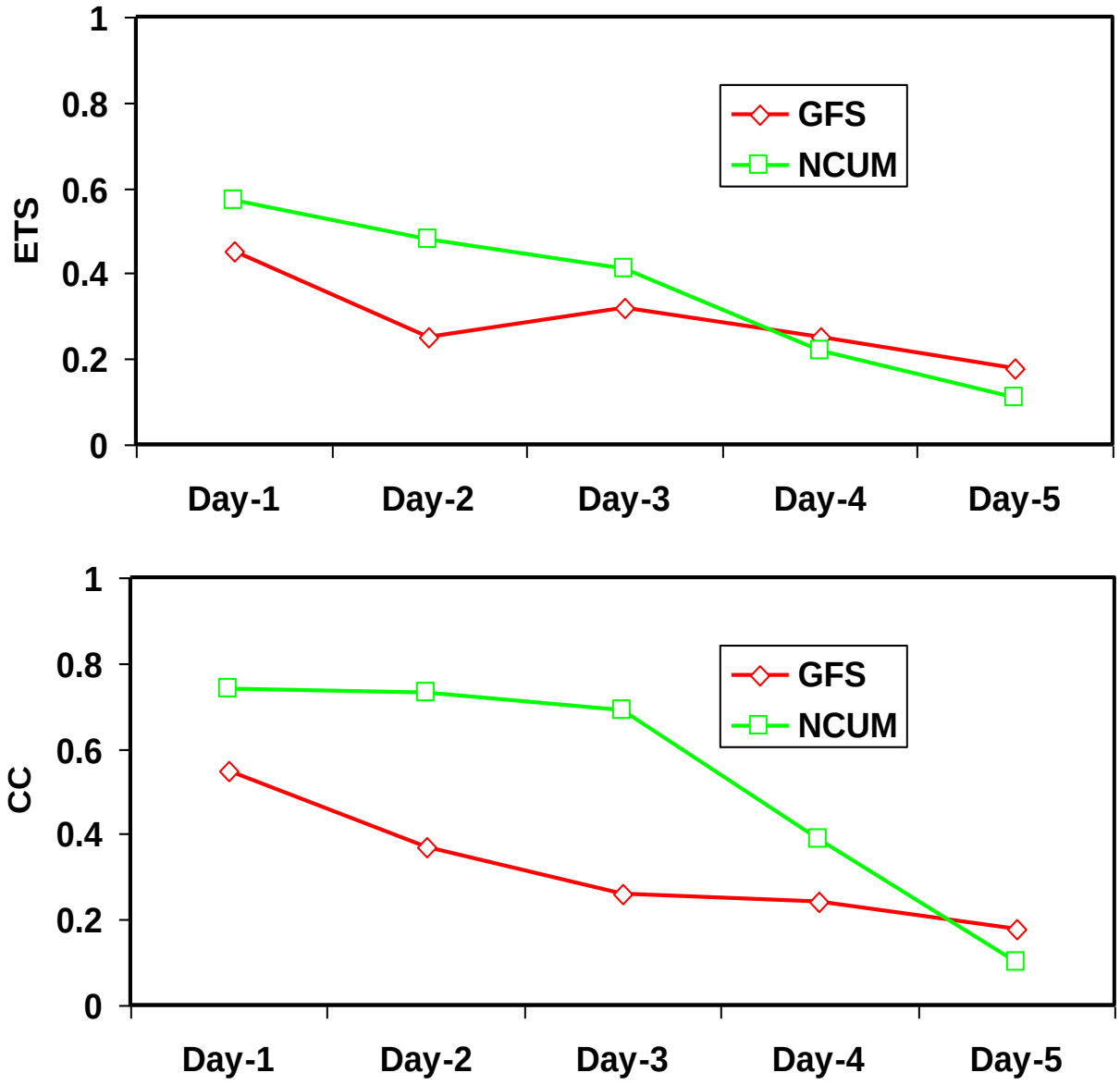


Figure 10 Rainfall forecast skill of the two models at different lead times measured in terms of Equitable Threat Score (top) and correlation coefficient (bottom).

Verification of Bay of Bengal Very Severe Cyclonic Storm 'Helen' (19-23 November 2013)

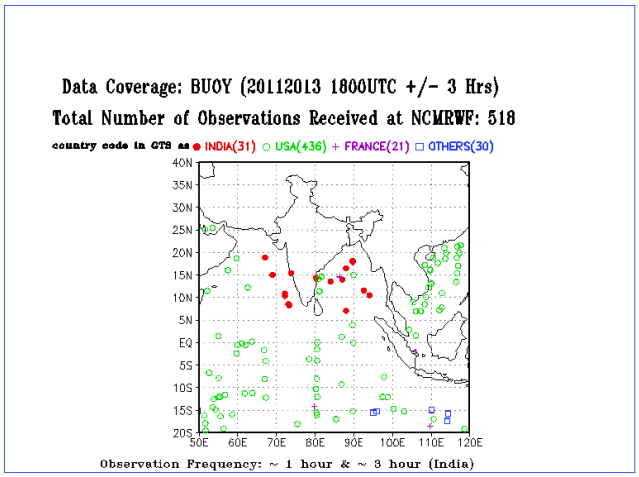
The SCS 'Helen' developed from the remnants of a West Pacific TC which emerged into a trough in Bay of Bengal on 17th Nov 2013 and then developed into a trough on 19th Nov 2013. On same day it intensified into a depression (D) and then into deep depression (DD). On 20th Nov 2013 it further attained cyclonic storm intensity (CS) and was names '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 mbar (29 inHg). Shortly before landfall, the storm weakened and it made landfall south of Machilipatnam, Andhra Pradesh and rapidly deteriorated into a deep depression. A total of 11 deaths have been reported in incidents related to the cyclone.
This is a brief summary report on the verification of the NCMRWF model forecasts during the recent SCS 'Helen' (20-22 Nov 2013). Verification of forecast tracks and landfall position are presented for GFS (T574L64), NCMRWF Unified Model (NCUM) and GEFS (T190L28; 20-member ensemble prediction system). In addition to cyclone tracks GEFS members are used to estimate cyclone strike probability based on the 20 members. The forecasts based on the above mentioned models are provided to IMD in real time.

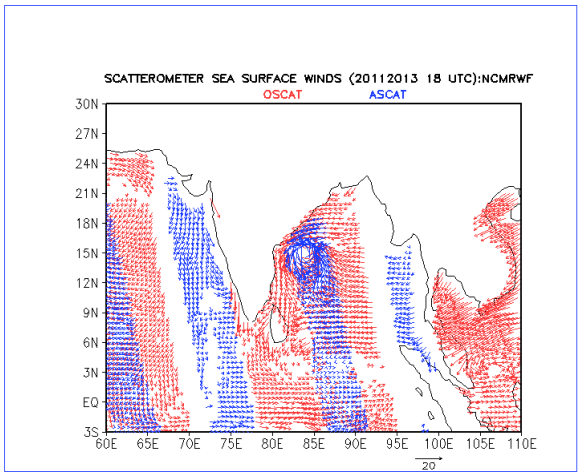
Observations

Observations over India and neighbouring oceanic region received and assimilated in each assimilation cycle of NCMRWF during TC HELEN (20-22 Nov) 2013 is given below.

	0000UTC	0600UTC	1200UTC	1800UTC
TEMP	21	0	8	0
PILOT	39	26	40	32
SYNOP	275	518	479	272
BUOY (Neighbouring Ocean)	443	505	560	537
Indian BUOY	26	26	30	30

Coverage of Buoy observations and scatterometer (ASCAT & OSCAT) ocean surface wind observations received and assimilated at NCMRWF global models (for 1800 UTC of 20th Nov. 2013) are shown in Figure 1 & 2 respectively.





NCMRWF Model Forecasts

(i) Forecast tracks

The observed and forecast tracks from GFS, NCUM and GEFS (mean and control) are presented based on 20th, 21st , and 22nd November 2013 in Figures 1,2 and 3 respectively. The forecast positions are shown at 6 hour interval.

The forecast tracks of all three models are much to the south of observed track. In NCUM the initial position is also much to the south of observed location. Similarly Figure 2-3 show the observed and forecasts tracks based on 00UTC of 21st to 22nd Nov 2013. On both days GEFS mean track closely compares with observed track. The NCUM and GFS track forecast based on 21st and 22nd are also considerably improved compared to the tracks based on 20th Nov 2013.

(ii) Forecast track errors

Forecast track errors are computed based on the JTWC reported cyclone positions from 00UTC of 20th to 22nd Nov 2013 and average track errors are presented in Figure 4(a-c). The direct position error (DPE), Along track error (ATE; time lag/lead in movement) and Cross track error (CT; left/right error) are presented at 6hour interval up to 60 hours. Positive (*negative*) values of ATE indicate that the movement of the cyclone in the forecasts is slower (*faster*) compared to the observations. On the other hand positive (*negative*) values of CTE indicate that forecast track is right (*left*) of the observed track.

The initial position errors in GFS and GEFS models are less than 50 km. The highest (*lowest*) initial position error of 113 km (*14km*) is seen in NCUM (*GEFS*). GEFS mean track shows least error at all lead times while NCUM shows highest average error at all lead times. NCUM and GEFS mean tracks show relatively higher ATE up to 36 hours varying from under 50 km to over 100 km. The prominently negative values in the CTE up to 54 hour, shown in Figure 4c indicate the forecast cyclones tracks lie to the left of observed tracks. GEFS mean track shows least CTE at all lead times.

(iii) Error in forecast landfall position and time

The IMD reported that the SCS Helen crossed the coast between 0900 UTC of 22nd Nov 2013 south of Machilipatnam in Andhra Pradesh at 16.1N 81.3E. Table 1 shows the landfall position and time errors based on all the available track forecasts. Forecasts show highest error in predicted landfall position

based on 20th initial conditions. The predicted land fall time error varies from -3 to +9 hours. Based on 21st and 22nd, GEFS forecast shows least position error (48 and 24 km) and time error (+3 and -3 hours). Both NCUM and GFS have large position error.

Conclusions

- The track forecasts from all the three modelling systems have large errors in the forecasts based on 20th Nov 2013 initial conditions. Subsequently the tracks based on 21st and 22nd initial conditions show improvement in terms of direction of movement.
- Initial position error is below 50 km in GFS and GEFS. NCUM model has large initial position error of over 100 km.
- The forecast track of NCUM shows large error of about 150 km in 24 hour and 300 km in 48 hour forecasts. The errors in GFS (GEFS) are lower at 137km (110km) in 24 hours and 200 km (177km) in 48 hour forecasts.
- Forecast landfall position error (under 50 km) and time error is lowest (+3hr) in GEFS forecasts.

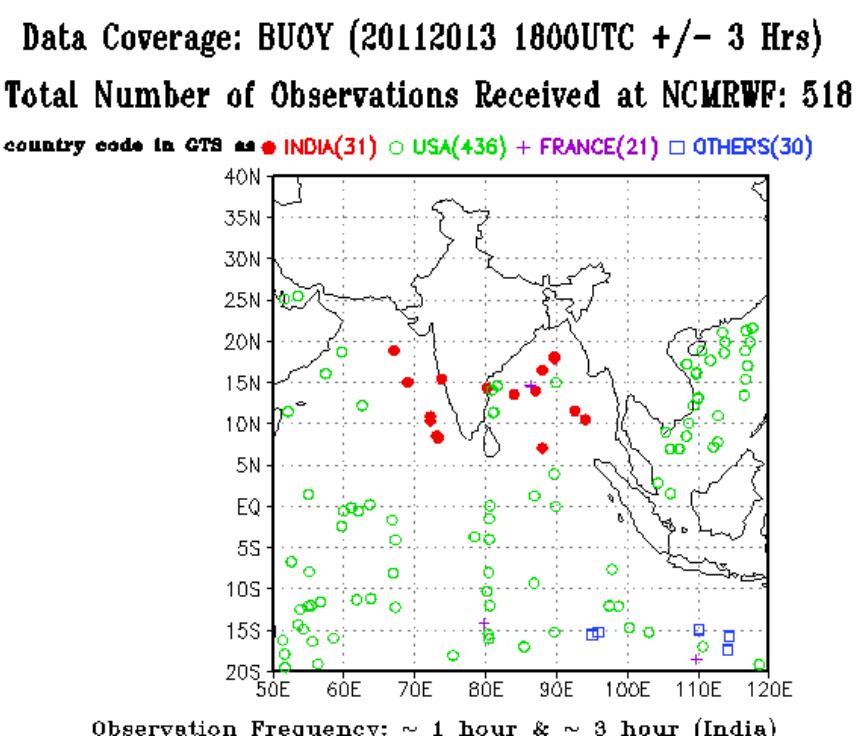


Figure 1.

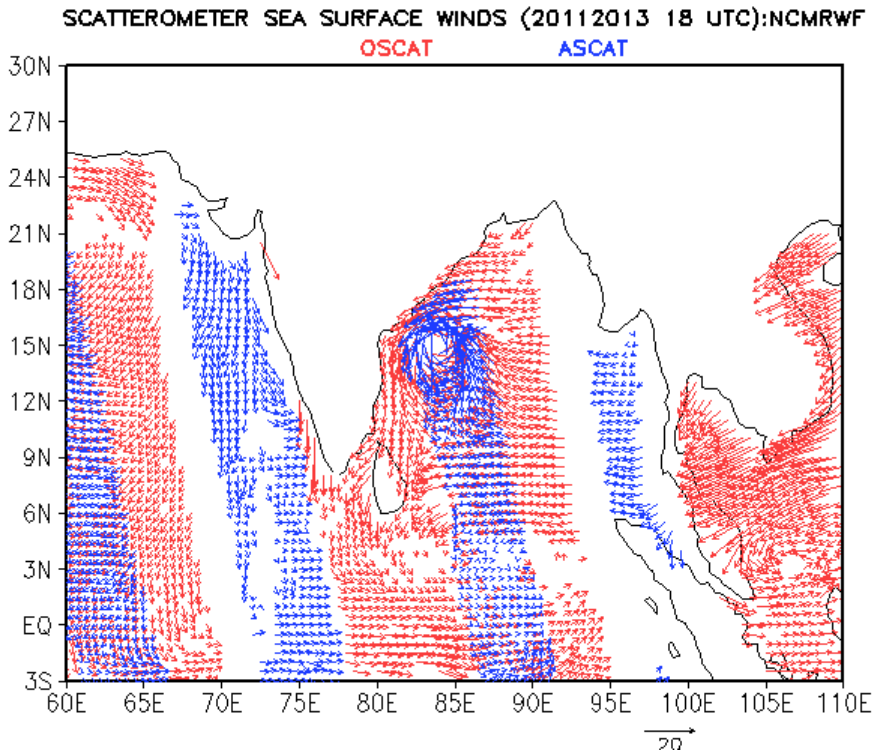


Figure 2

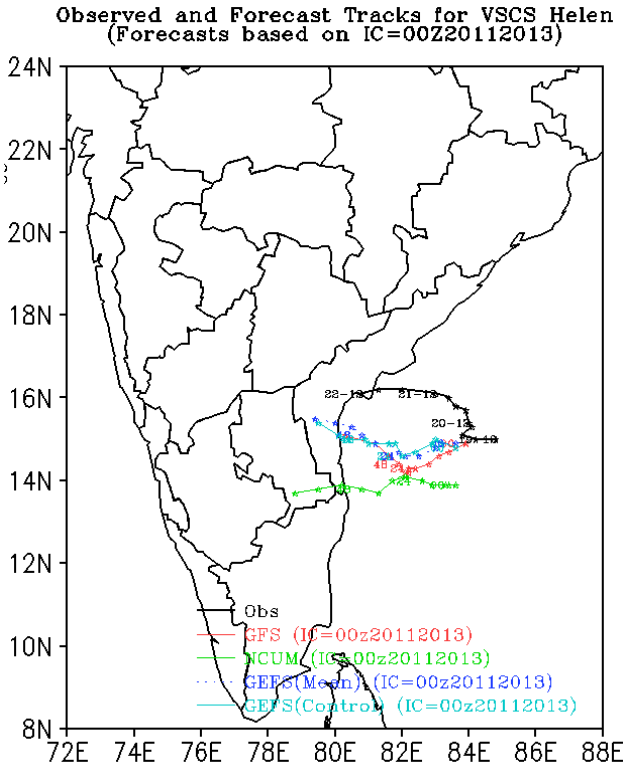


Figure 3 Observed and forecast tracks based on 20th Nov 2013

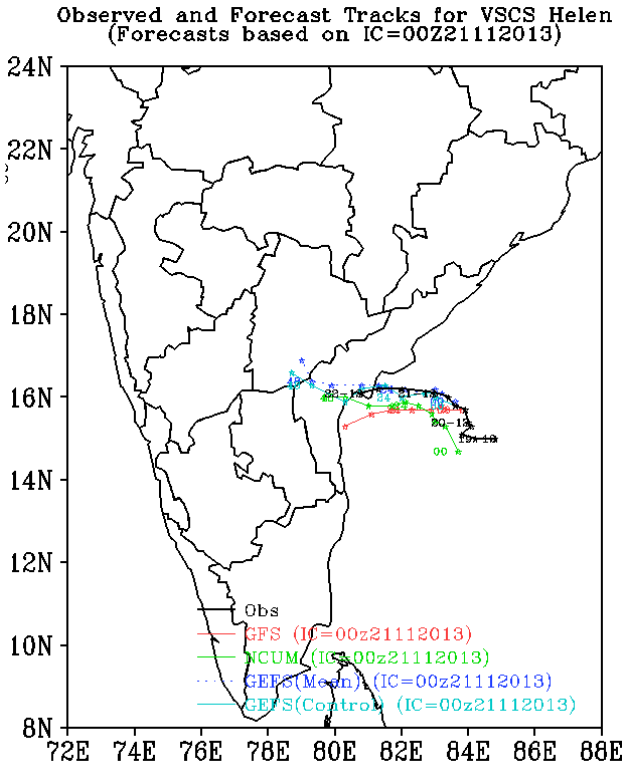


Figure 4 Observed and forecast tracks based on 21st Nov 2013

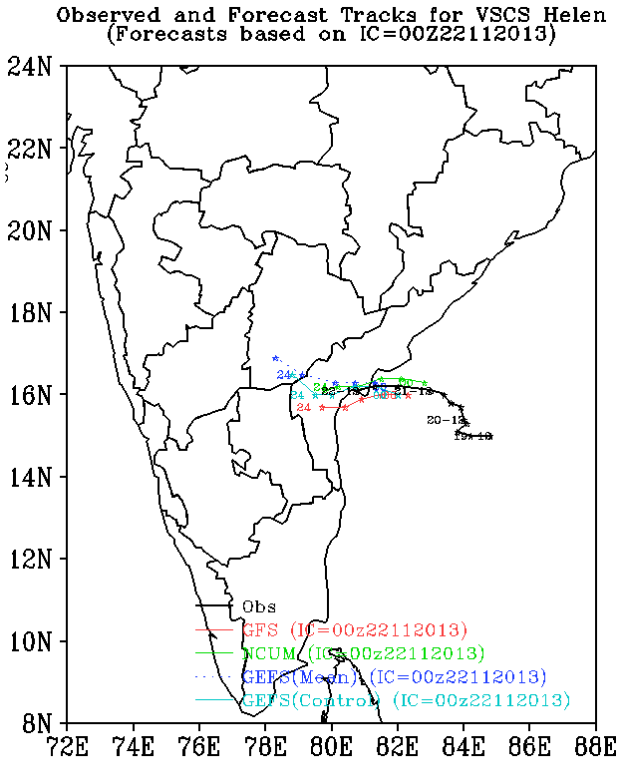


Figure 5 Observed and forecast tracks based on 22st Nov 2013

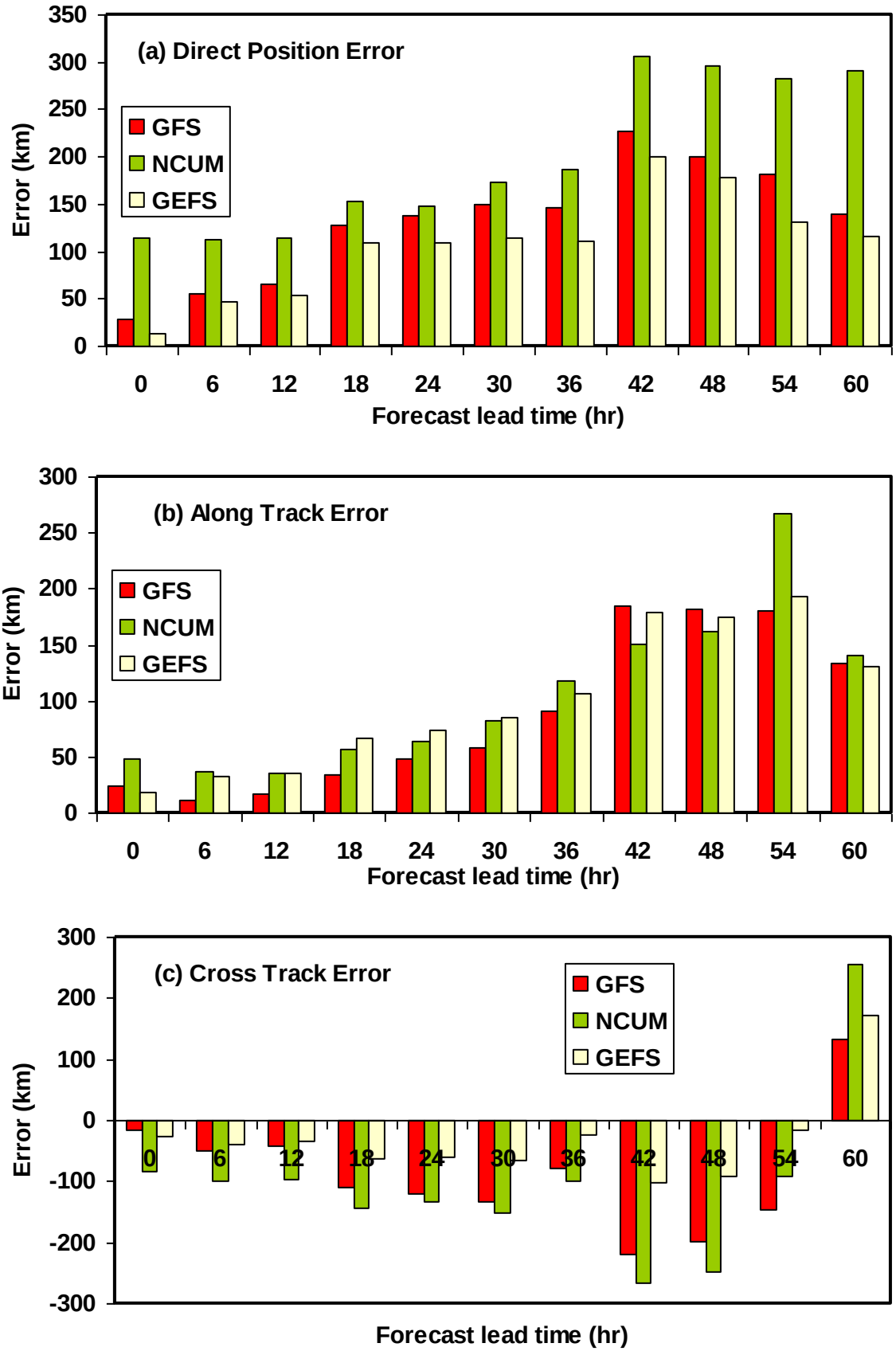


Figure 6 Average forecast track errors for SCS 'Helen' expressed in terms of (a) Direct position error (b) Along track (lag or lead) error and (c) Cross track (left or right) error

Table 1. Forecast landfall position error for SCS Helen in the ESSO-NCMRWF global models.

(IMD reported landfall at 09UTC of 22nd November at location 16.1N, 81.3E)

	GFS		GEFS		NCUM	
Initial conditions	*Position error (in km)*	*Time error (in hrs)*	*Position error (in km)*	*Time error (in hrs)*	*Position error (in km)*	*Time error (in hrs)*
IC=20112013	147	+9	154	+9	267	-3
IC=21112013	131	+9	48	+3	39	+9
IC=22112013	39	+3	24	-3	101	-3

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

Verification of Bay of Bengal Very Severe Cyclonic Storm 'Lehar' (23-28 November 2013)

VSCS Lehar evolved from another low pressure area which moved form South China Sea crossed to Andaman Sea on 22nd Nov 2013. It and gradually intensified to Depression (D) on the same day. The following day, it further strengthened into a Cyclonic Storm (CS), and was named Lehar. On 25th Nov it gradually consolidated further and was upgraded to a Severe Cyclonic Storm (SCS) by the IMD. The following day, Lehar further intensified into a Very Severe Cyclonic Storm (VSCS), as both IMD and JTWC reported peak winds of 140 km/h (87 mph) and a central pressure of 982 mbar (29.0 inHg). Early on November 27, 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 Nov 2013.

This is a brief summary report on the verification of the NCMRWF model forecasts during the recent VSCS 'Lehar' (24-28 Nov 2013). Verification of forecast tracks and landfall position are presented for GFS (T574L64), NCMRWF Unified Model (NCUM) and GEFS (T190L28; 20-member ensemble prediction system). In addition to cyclone tracks GEFS members are used to estimate cyclone strike probability based on the 20 members. The forecasts based on the above mentioned models are provided to IMD in real time.

Observations

Observations over India and neighbouring oceanic region received and assimilated in each assimilation cycle of NCMRWF during TC LEHAR (24-28 Nov) 2013 is given below.

	0000UTC	0600UTC	1200UTC	1800UTC
TEMP	20	0	9	0
PILOT	37	26	39	30
SYNOP	279	516	478	275
BUOY (Neighbouring Ocean)	416	522	504	520
Indian BUOY	24	30	30	29

Coverage of Buoy observations and scatterometer (ASCAT & OSCAT) ocean surface wind observations received and assimilated at NCMRWF global models (for 0600 UTC of 24th Nov. 2013) are shown in Figure 1 & 2 respectively.

NCMRWF Model Forecasts

(i) Forecast tracks

The observed and forecast tracks from GFS, NCUM and GEFS (mean and control) are presented based on initial conditions of 24th to 28th November 2013 in Figures 1 to 5. The forecast positions are shown at 6 hour interval.

Forecasts based on 24, 25 and 26th initial conditions clearly suggest GEFS mean track closely follows the observed track for most of the forecast period. The NCUM forecasts on the other hand show large

deviation. GFS forecasts too (to a lesser extent) show some deviation from the observed track. Forecasts based on 27th and 28th also show wide dispersion from the observed track.

(ii) Forecast track errors

Forecast track errors are computed based on the JTWC reported cyclone positions from 00UTC of 24th to 28th Nov 2013 and average track errors are presented in Figure 6(a-c). The direct position error (DPE), Along track error (ATE; time lag/lead in movement) and Cross track error (CT; left/right error) are presented at 6hour interval up to 60 hours. Positive (*negative*) values of ATE indicate that the movement of the cyclone in the forecasts is slower (*faster*) compared to the observations. On the other hand positive (*negative*) values of CTE indicate that forecast track is right (*left*) of the observed track.

The initial position errors in GFS and GEFS models are less than 50 km. The highest (lowest) initial position error of 72 km (19km) is seen in NCUM (GEFS). Up to 48 hours all three models have comparable track errors with marginally higher errors in GEFS. Beyond 48 hours, GEFS and GFS forecasts show comparable errors while NCUM track shows very large error. The ATE values range from about less than 10 km (GEFS) in the first 24 hours to about 200 km in NCUM up to 72 hour forecasts. The predominantly positive values of CTE in NCUM shown in Figure 6c indicate the forecast cyclones tracks lie to the right of observed tracks. GFS (GEFS mean) tracks lie to the left up to 24 hours (60 hours). Subsequently both GFS and GEFS mean tracks lie to the left of observed tracks.

(iii) Error in forecast landfall position and time

The IMD reported that the VSCS Lehar crossed the coast between 0900 UTC of 28th Nov 2013 south of Machilipatnam in Andhra Pradesh at 15.9N 81.1E. Table 1 shows the landfall position and time errors based on all the available track forecasts. Forecasts show highest error in predicted landfall position and time based on 24th Nov 2013 initial conditions. Highest landfall position error of about 500km is seen in NCUM forecast based on 24th Nov 2013. The predicted land fall time error varies from -3 to +27 hours. GFS and GEFS show landfall position errors over 100 km in all the forecasts. On 27th and 28th NCUM forecasts show least landfall position errors of 35km with landfall time errors of +15 hours and +3 hours respectively.

Conclusions

- All the NCUM and most (4 out of 5) of GFS forecast tracks lie to the north of observed tracks (with very large errors at higher lead times particularly in NCUM). GEFS mean (and control) tracks lie mostly (4 out of 5) to the south of observed track.
- Initial position errors in GFS, GEFS and NCUM are 36km, 20km and 72km respectively.
- The 24 hour forecast track errors in GFS, GEFS and NCUM are 136km, 170 and 136km respectively. These errors grow to 174km, 203km and 252km in 48 hours. In 72 hour forecasts the errors are 230km, 245km and 451km.
- The predicted land fall time error varies from -3 to +27 hours. GFS and GEFS show landfall position errors over 100 km in all the forecasts. On 27th and 28th NCUM forecasts show least landfall position errors of 35km with landfall time errors of +15 hours and +3 hours respectively.

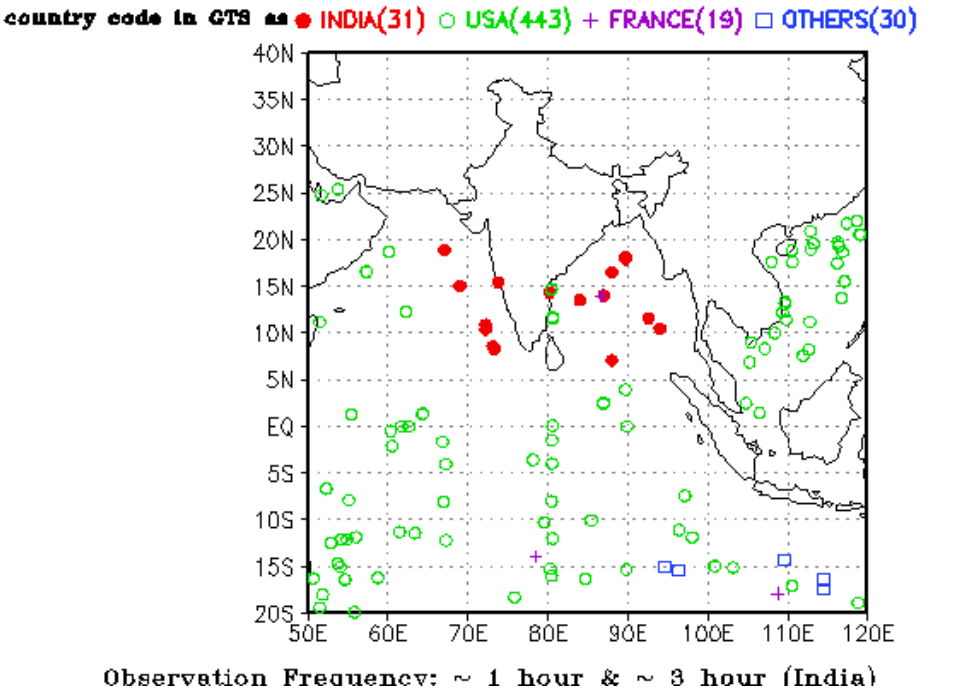


Figure 1.

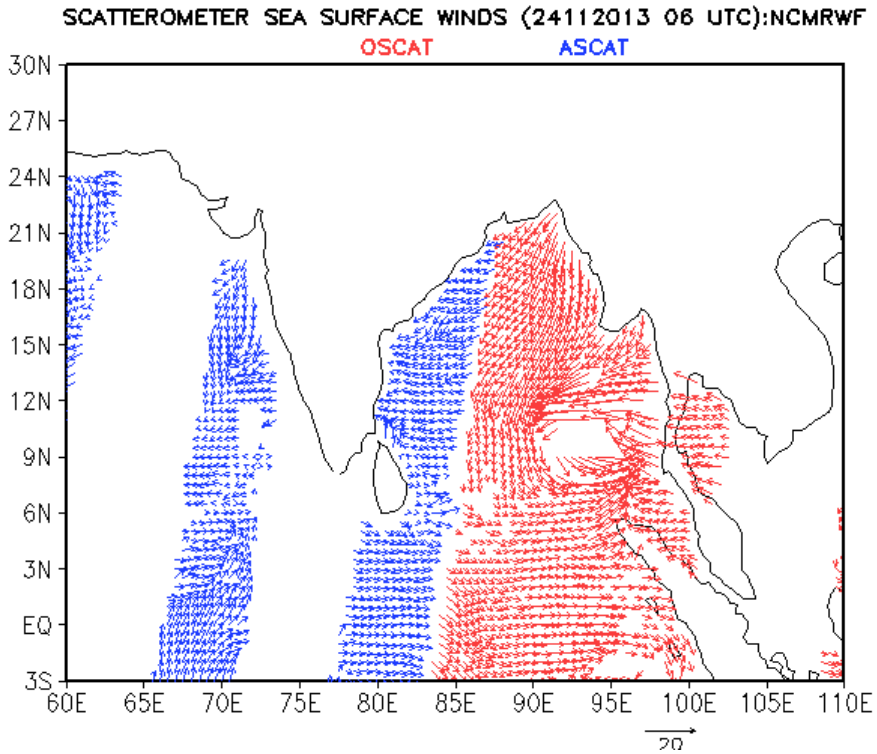


Figure 2.

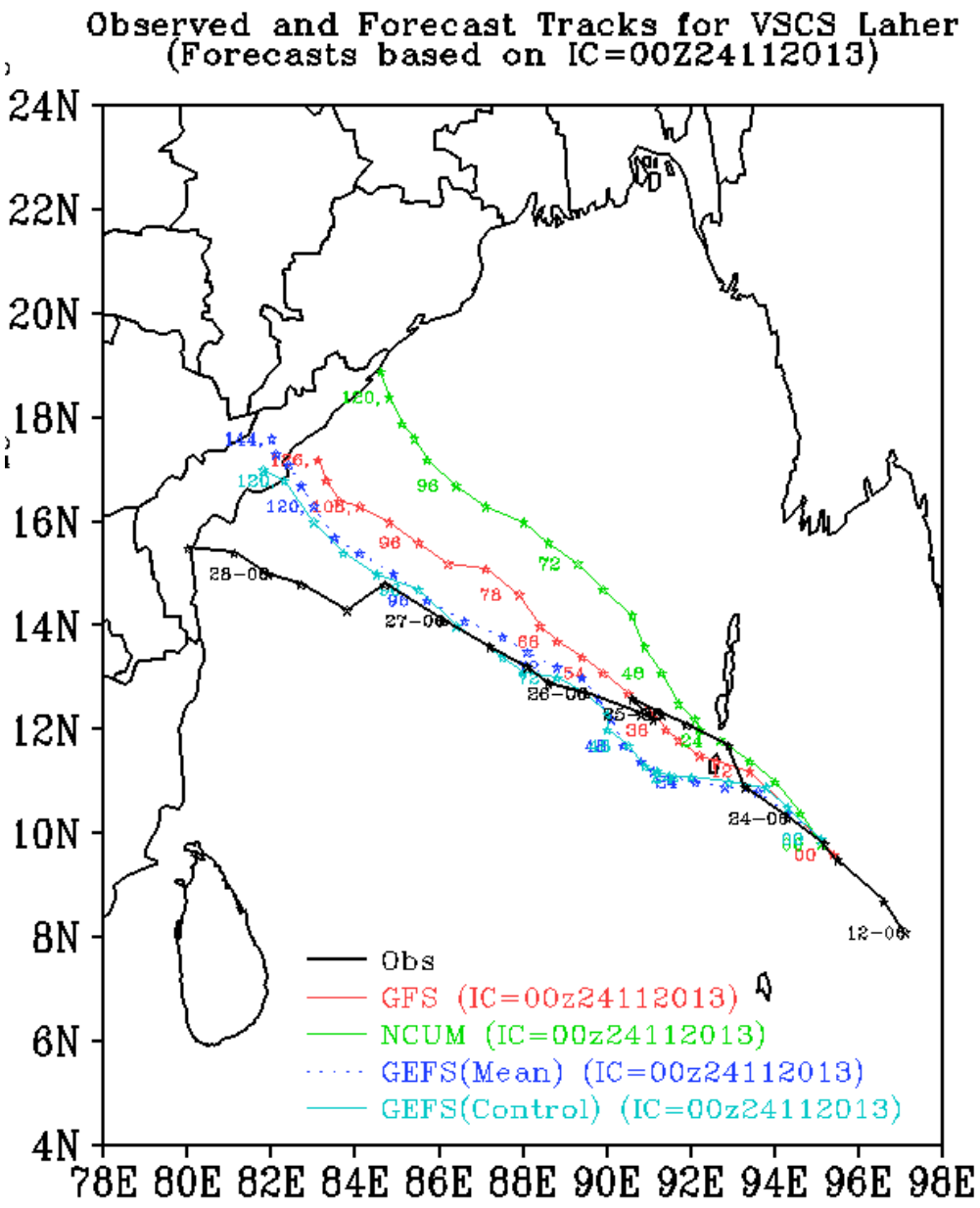


Figure 3 Observed and forecast tracks based on 24th Nov 2013

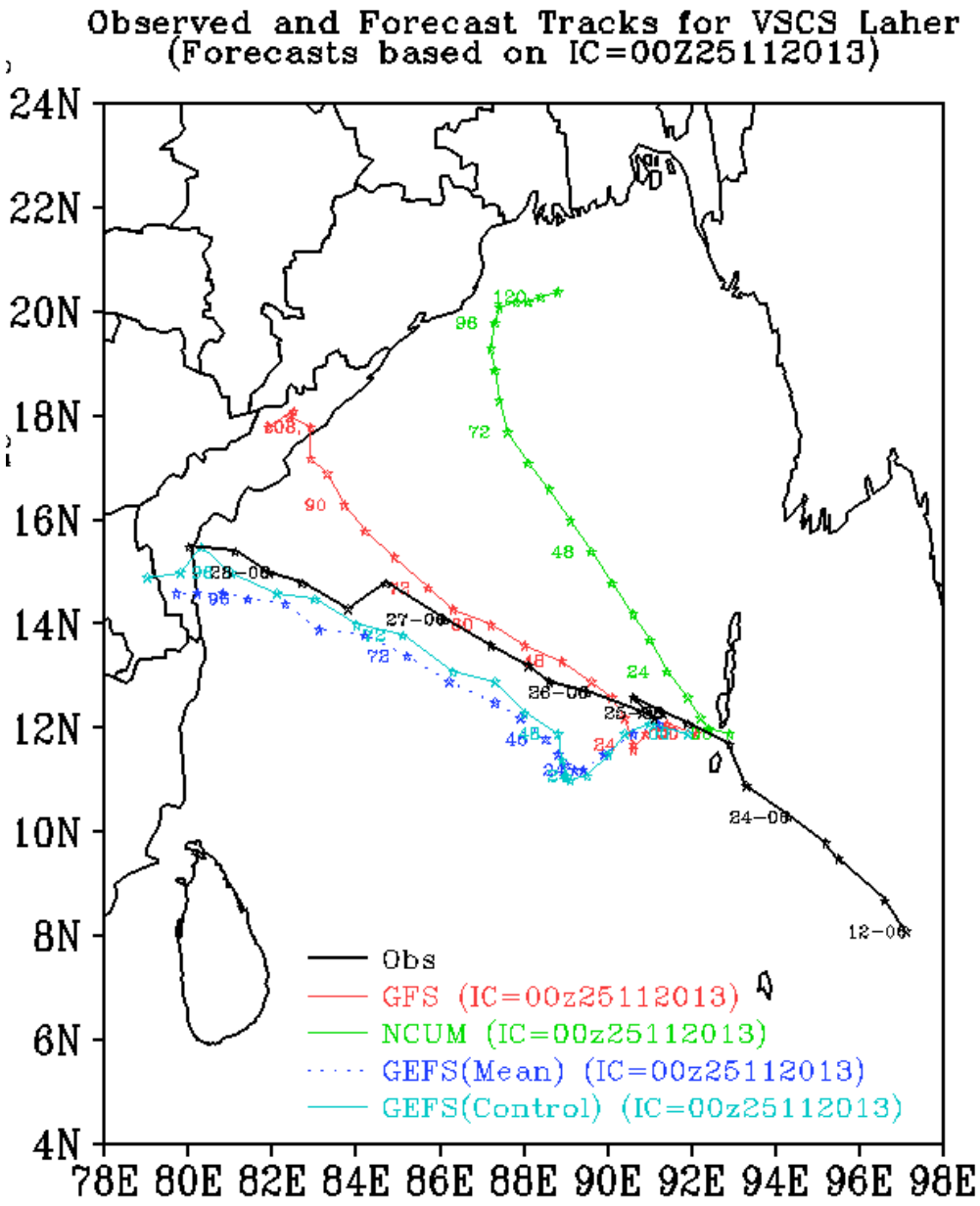


Figure 4 Observed and forecast tracks based on 25st Nov 2013

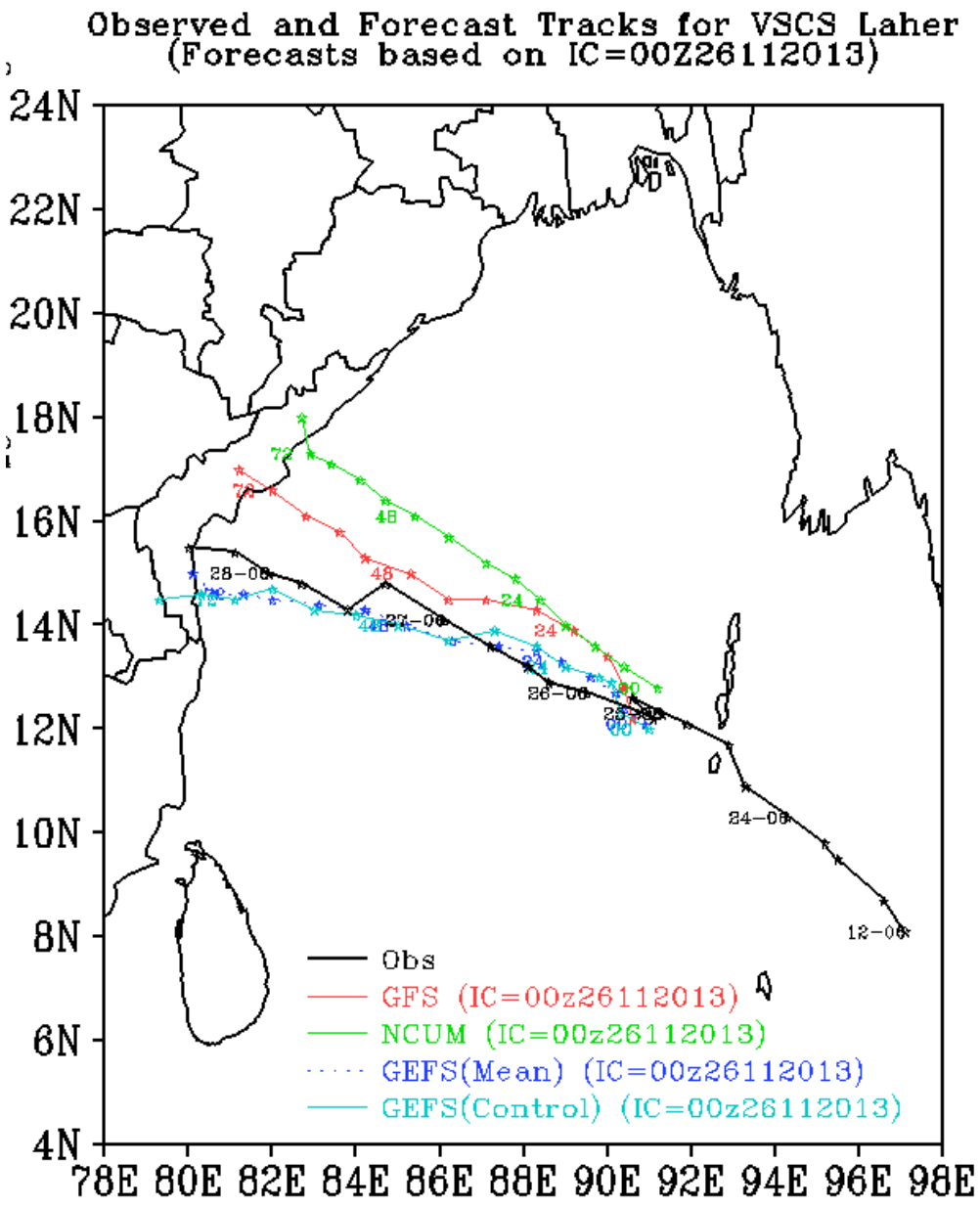


Figure 5 Observed and forecast tracks based on 26st Nov 2013

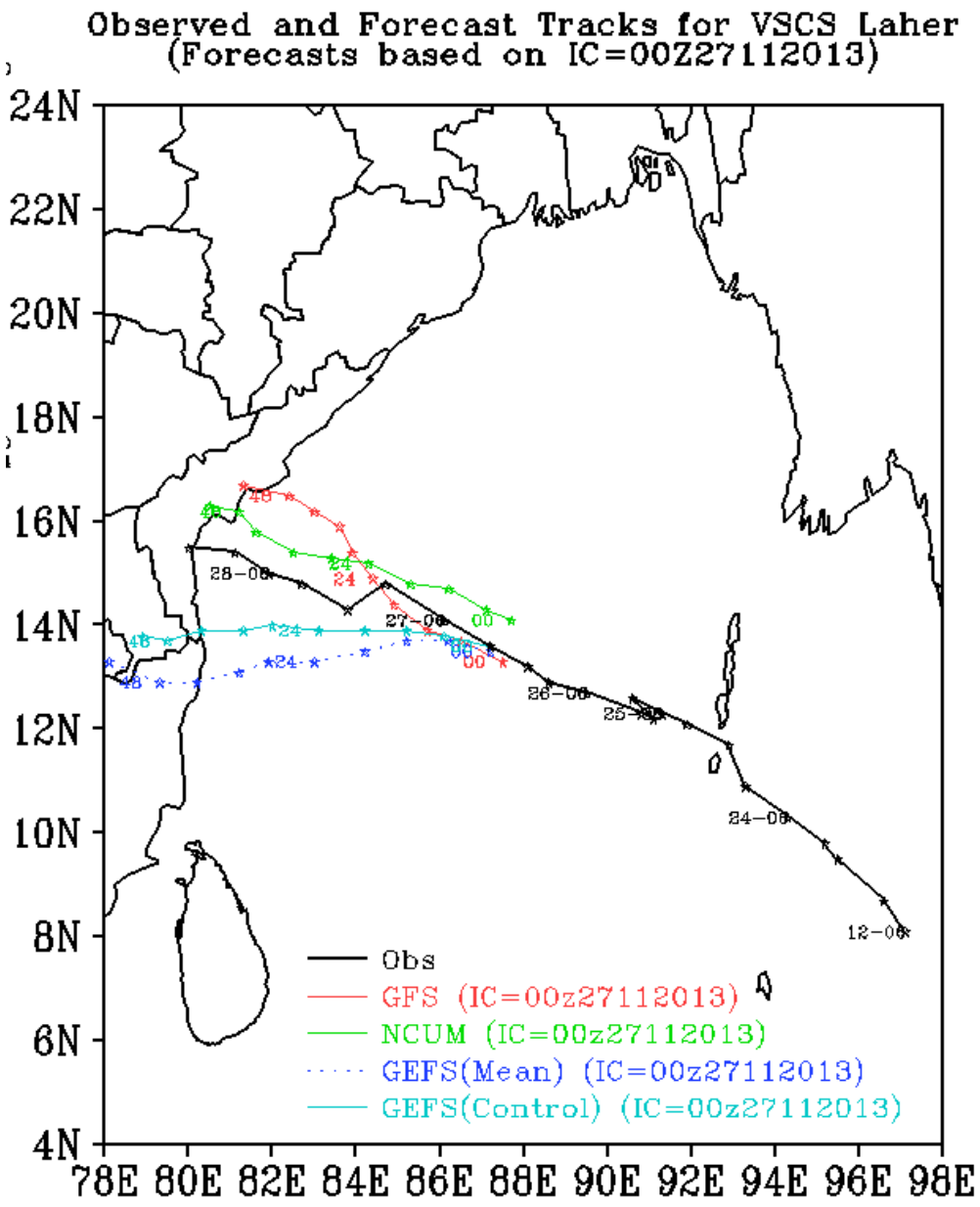


Figure 6 Observed and forecast tracks based on 27st Nov 2013

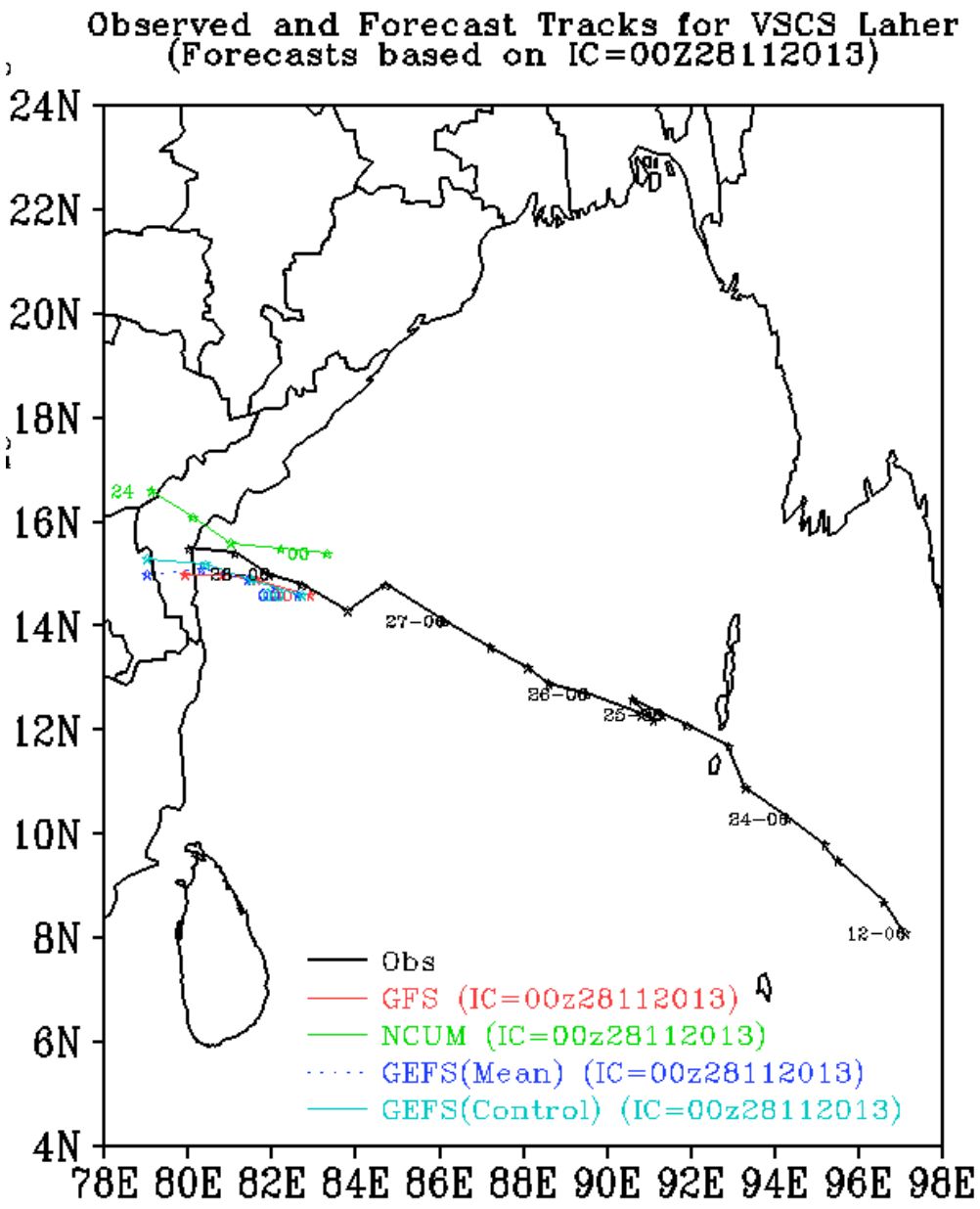


Figure 7 Observed and forecast tracks based on 28st Nov 2013

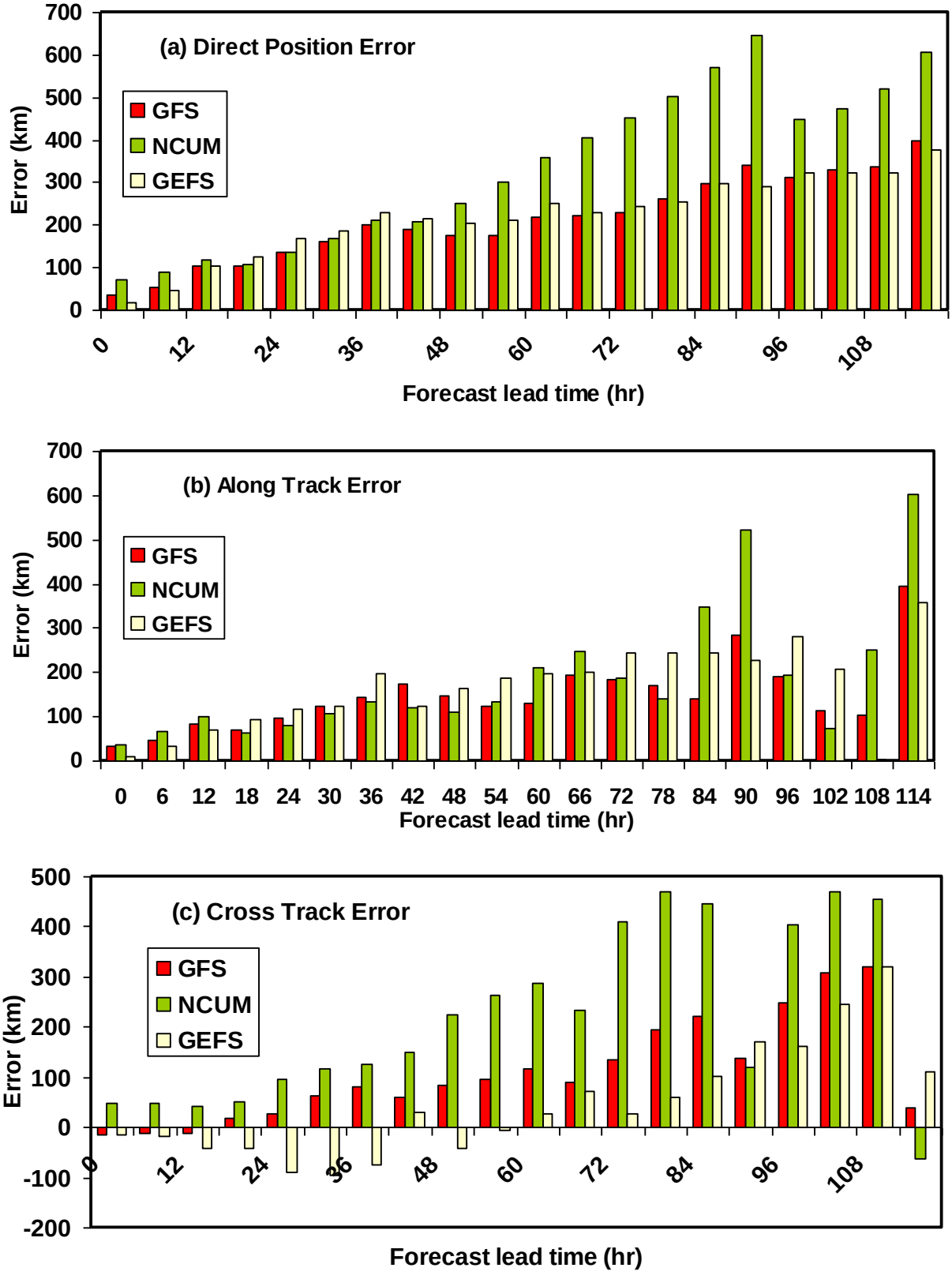


Figure 8 Average forecast track errors for VSCS 'Lehar' expressed in terms of (a) Direct position error (b) Along track (lag or lead) error and (c) Cross track (left or right) error

Table 1. Forecast landfall position error for VSCS Lehar in the ESSO-NCMRWF global models.

(IMD reported landfall at 09UTC of 28nd November at location 15.9N, 81.1E)

	GFS		GEFS		NCUM	
Initial conditions	*Position error (in km)*	*Time error (in hrs)*	*Position error (in km)*	*Time error (in hrs)*	*Position error (in km)*	*Time error (in hrs)*
IC=24112013	257	+21	192	+27	499	+21
IC=25112013	240	-3	148	+21	–	-
IC=26112013	123	+15	154	+21	246	+15
IC=27112013	154	+15	347	+9	35	+15
IC=28112013	163	+9	123	+3	35	+3

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

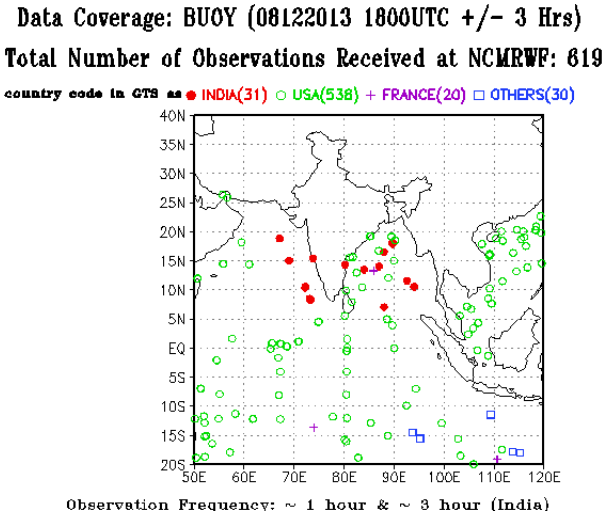
Verification of Bay of Bengal Very Severe Cyclonic Storm 'Madi' (06-12 December 2013)

VSCS Madi evolved from a low pressure in the easterly wave east of Sri Lanka on 5th Dec 2013. It and gradually intensified to Depression (D) on the 6th Dec 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 Dec 2013. The system weakened on 9th and 10th while kept tracking northwards. It started tracking south-westwards on 10th Dec and kept weakening. On 12th Dec 2013 the system crossed Tamil Nadu coast twice with the intensity of a depression. First near Nagapattinam at aroung 1200UTC and the near Tondi at around 1700UTC.

This is a brief summary report on the verification of the NCMRWF model forecasts during the recent VSCS 'Madi' (6-12 Dec 2013). Verification of forecast tracks and landfall position are presented for GFS (T574L64), NCMRWF Unified Model (NCUM) and GEFS (T190L28; 20-member ensemble prediction system). In addition to cyclone tracks GEFS members are used to estimate cyclone strike probability based on the 20 members. The forecasts based on the above mentioned models are provided to IMD in real time.

Observations

Observations over India and neighboring oceanic region received and assimilated in each assimilation cycle of NCMRWF during TC MADI (6-12 Dec) 2013 is given in Table 1. Coverage of Buoy observations and scatterometer (ASCAT & OSCAT) ocean surface wind observations received and assimilated at NCMRWF global models (for 0600 UTC of 8th Dec. 2013) are shown in Figure 1 & 2 respectively.



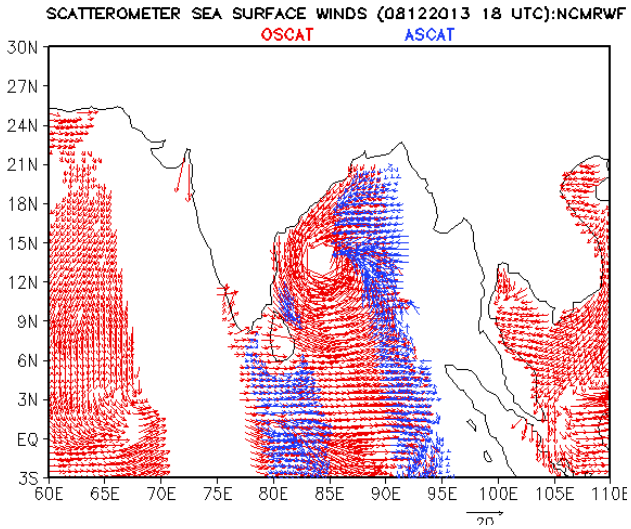


Table 1. Observed data received and assimilated in the NCMRWF models during VSCS 'Madi' 6-12 Dec 2013.

Date/Time		Synop	Buoy		RS/RW		Pilot Balloon
(± 3) UTC			Total	Indian	All	Above 250 hPa	
06-12-2013	0000	277	268	27	13	11	24
	0600	521	543	22	0	0	21
	1200	454	521	23	7	1	42
	1800	275	609	32	0	0	29
07-12-2013	0000	280	488	24	23	17	22
	0600	508	606	30	0	0	18
	1200	478	614	32	7	1	39
	1800	268	605	32	0	0	29
08-12-2013	0000	278	338	26	10	7	15
	0600	507	594	30	0	0	24
	1200	465	636	28	8	1	32
	1800	273	619	31	0	0	27
09-12-2013	0000	271	398	26	12	10	15
	0600	521	630	33	0	0	23
	1200	467	635	21	8	1	37
	1800	264	617	31	0	0	30
10-12-2013	0000	281	434	28	11	10	14
	0600	527	630	33	0	0	21
	1200	483	648	31	8	1	31
	1800	277	636	32	0	0	30
11-12-2013	0000	279	423	27	12	10	16
	0600	518	636	30	0	0	21
	1200	478	621	31	4	1	34
	1800	278	595	34	0	0	25
12-12-2013	0000	282	436	28	13	9	15
	0600	504	616	32	0	0	19
	1200	476	612	20	8	1	36
	1800	278	535	27	0	0	27

Most of the 00UTC RS/RWs reach altitude higher than 250 hPa. For 06, and 18 UTC the count is always zero (and for 12UTC it is one).

NCMRWF Model Forecasts

(i) Forecast tracks

The observed and forecast tracks from GFS, NCUM and GEFS (mean and control) are presented based on initial conditions starting from 6th to 12th Dec 2013 in Figures 3 to 9. The forecast positions are shown at 6 hour interval. Forecasts based on 6th and 7th Dec 2013 initial conditions do not show clear movement and landfall of the cyclonic system (Figure3-4). On 8th and 9th Dec 2013 the forecasts generally indicated northward movement in the beginning and then south-westwards(Figure5-6). GFS on both days (and GEFS on 9th Dec 2013) suggested the cyclone would strike Sri Lanka coast, while NCUM consistently predicted the cyclone crossing Tamil Nadu. Tracks based on 10th, 11th and 12th consistently showed cyclone would cross the Tamil Nadu coast near Nagapattinam(Figure7-9).

(ii) Forecast track errors

Forecast track errors are computed based on the JTWC reported cyclone positions from 00UTC of 6th to 12th Dec 2013 and average track errors are presented in Figure 10(a-c). The direct position error (DPE), Along track error (ATE; time lag/lead in movement) and Cross track error (CT; left/right error) are presented at 6hour interval up to 126 hours. Positive (*negative*) values of ATE indicate that the movement of the cyclone in the forecasts is slower (*faster*) compared to the observations. On the other hand positive (*negative*) values of CTE indicate that forecast track is right (*left*) of the observed track.

The initial position errors in GFS and GEFS models are less than 50 km. The highest (lowest) initial position error of 86 km (13km) is seen in NCUM (GEFS). Up to 24 hours NCUM has high DPE of about 100 km while GFS and GEFS mean show DPE increasing from under 50 km to over 100 km. From 24 to 78 hours the GFS (and GEFS) DPE increase rapidly 463 km (434km). Growth of DPE in NCUM is gradual in the 78 hours with highest value of 325 km and 78 hours. The DPE in GFS and GEFS gradually reduce after 78 hours (after 102 hours in NCUM). Similar pattern of error growth is seen for ATE (figure 10b). The predominantly negative values of CTE in NCUM shown in Figure 10c indicate the forecast cyclones tracks lie to the left of observed tracks. This is also evident from tracks based on 6th-9th Dec 2013 (Figure3-6). The GEFS mean track lies to the right of observed track on 10-12th Dec 2013. During the same period the GFS and NCUM tracks show varying movement on both sides of the observed track.

(iii) Error in forecast landfall position and time

The IMD reported that the VSCS Madi crossed the Tamil Nadu coast near Tondi around 1700 UTC of 12th Dec 2013 at 10.0N 78.5E. Table 2 shows the landfall position and time errors based on the track forecasts from 8-12 Dec 2013 (Track forecasts on 6 and 7 Dec 2013 did not show landfall). On 8th Dec GFS shows a large time error of -41 hours with a landfall over Sri Lanka. GFS and GEFS tracks on 9th Dec 2013 showed landfall over Sri Lanka while NCUM showed landfall over Tamil Nadu coast with position error of 125km. GFS and GEFS have large position error on 10th Dec 2013 while NCUM has least error in terms of time as well as distance. Similarly on 11 and 12 Dec 2013 NCUM has least distance and time error in the predicted landfall.

Conclusions

- The forecast tracks based on 6th and 7th Dec 2013 show no proper movement and landfall in all three models. Tracks based on 8th to 12th Dec consistently predict southwestward movement of the system.
- On 8th and 9th Dec 2013 GFS forecasts show landfall over Sri Lanka, while GEFS predicts landfall over Sri Lanka on 9th Dec 2013. NCUM tracks cross Tamil Nadu coast in each of the five forecasts.
- Initial position errors in GFS, GEFS and NCUM are 32km, 13km and 86km respectively.
- The 24 hour forecast track errors in GFS, GEFS and NCUM are 100km, 147 and 118km respectively. These errors grow to 244km, 300km and 184km in 48 hours. In 72 hour forecasts the errors are 454km, 392km and 268km. However, the Day-5 errors are slightly lower at 284km, 262km and 301 km respectively.
- The predicted land fall time error varies from +1 to -41 hours. Landfall position error is least in NCUM forecasts on all days. GFS and GEFS tracks show large errors. GFS forecasts show highest position error (403km) and time error (-41hours)

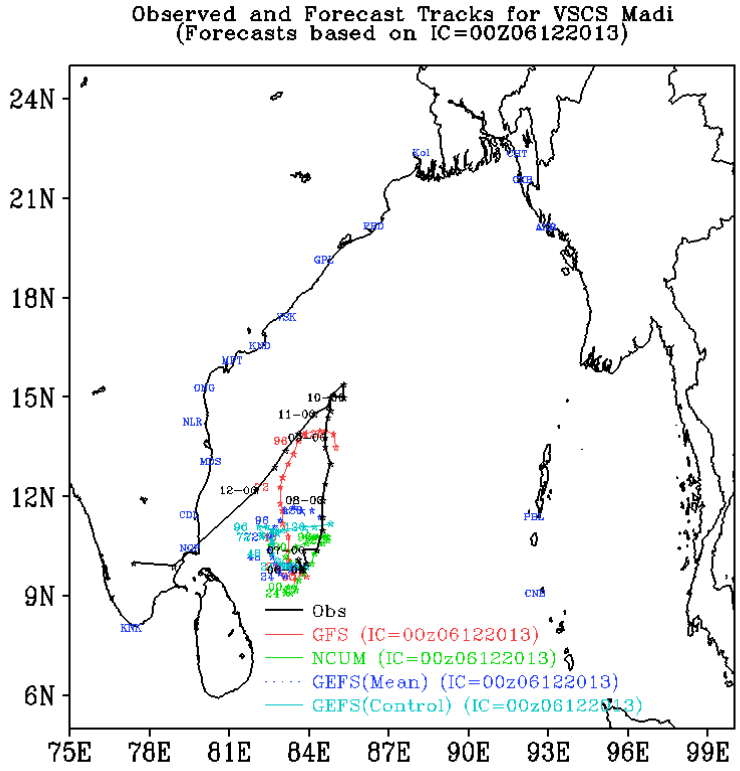


Figure 3 Observed and forecast tracks based on 6th Dec 2013

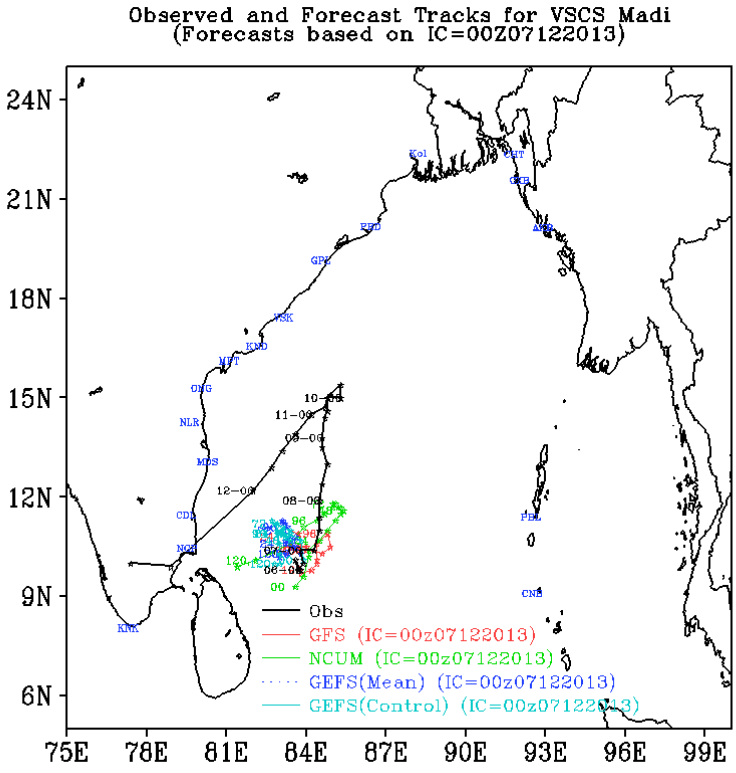


Figure 4 Observed and forecast tracks based on 7th Dec 2013

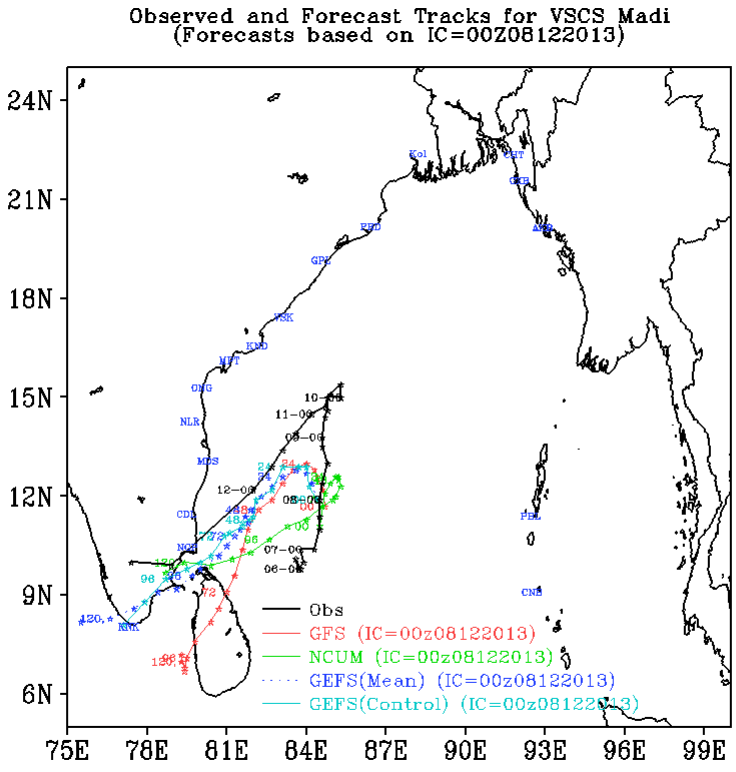


Figure 5 Observed and forecast tracks based on 8th Dec 2013

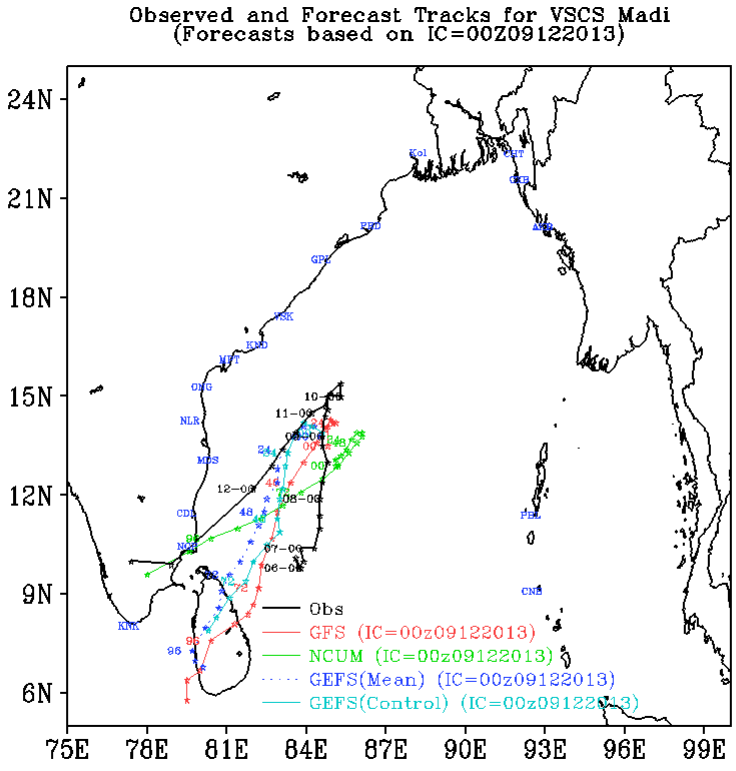


Figure 6 Observed and forecast tracks based on 9th Dec 2013

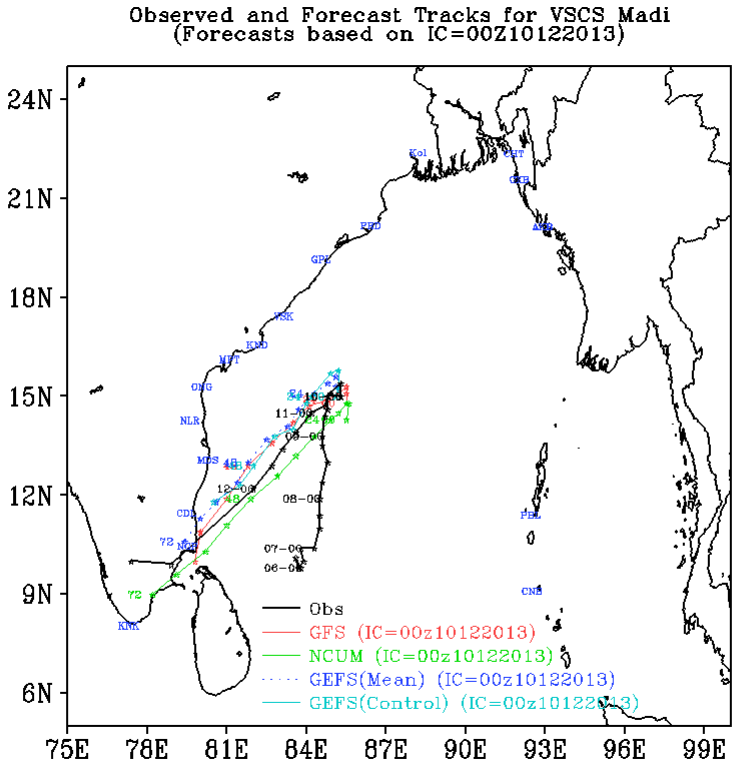


Figure 7 Observed and forecast tracks based on 10th Dec 2013

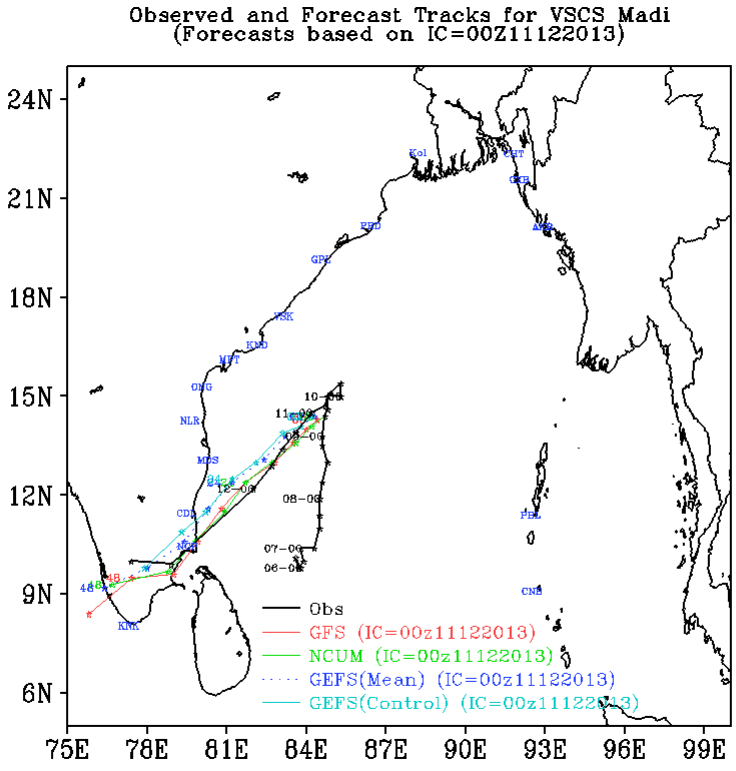


Figure 8 Observed and forecast tracks based on 11th Dec 2013

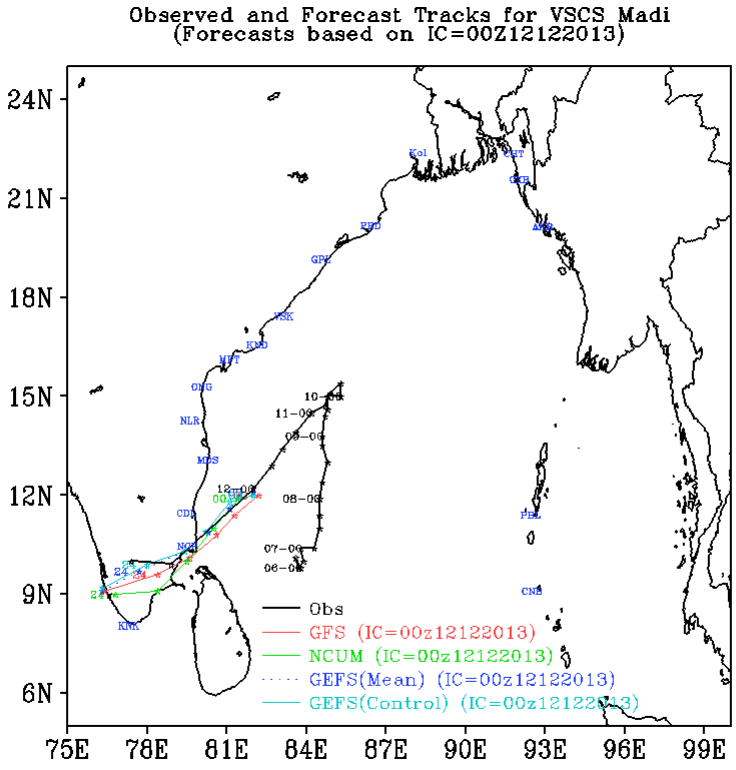


Figure 9 Observed and forecast tracks based on 12th Dec 2013

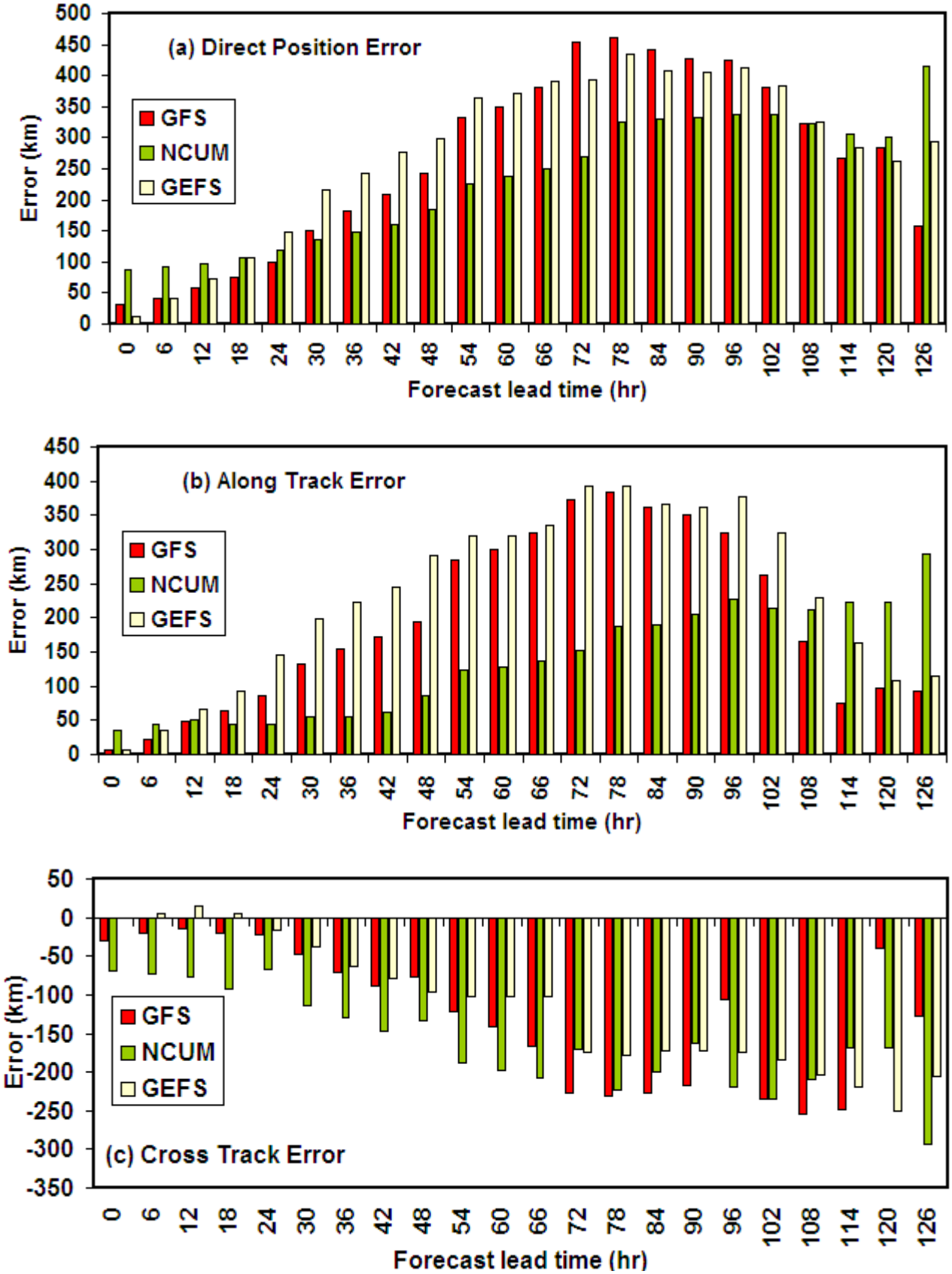


Figure 10 Average forecast track errors for VSCS 'Madi' expressed in terms of (a) Direct position error (b) Along track (lag or lead) error and (c) Cross track (left or right) error

Table 2. Forecast landfall position error for VSCS Madi in the ESSO-NCMRWF global models.

(IMD reported landfall at 1700UTC of 12th Dec 2013 at location 10N, 78.5E near Tondi in Tamil Nadu)

	GFS		GEFS		NCUM	
Initial conditions	*Position error (in km)*	*Time error (in hrs)*	*Position error (in km)*	*Time error (in hrs)*	*Position error (in km)*	*Time error (in hrs)*
IC=08122013	291	-41	110	+13	77	+7
IC=09122013	403	-5	271	-5	125	+13
IC=10122013	270	-5	218	+1	79	+1
IC=11122013	171	-5	265	-11	171	-5
IC=12122013	121	+1	104	+1	100	+1

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