Performance of Global Forecast System for the Prediction of Intensity and Track of Very Severe Cyclonic Storm 'PHAILIN'

V.R. Durai, S.D.Kotal and S.K. Roy Bhowmik
India Meteorological Department,
New Delhi – 110003
***Email:* durai.imd@gmail.com**

Abstract

The main objective of this study is to investigate the performance skill of Global Forecast System (GFS) for the Prediction of the tropical cyclogenesis and track of Very Severe Cyclonic Storm (VSCS) 'PHAILIN' formed over the Bay of Bengal (BOB). Under the influence of an upper air cyclonic circulation, a depression formed over north Andaman Sea at 00UTC of 8th October 2013, which became a cyclonic storm (PHAILIN) over east central BOB at 12 UTC of 09th October 2013. PHAILIN intensified into a severe cyclonic storm at 00UTC of 10 Oct 2013 and very severe cyclonic storm at 03 UTC of 12th Oct 2013. Then it moved north-northwestwards and crossed the coast near Gopalpur (Odisha) at 17 UTC of 12th October 2013. The model parameters considered for the cyclone genesis and track forecast study are mean sea level pressure(MSLP), low level wind field, moisture and rainfall. The GFS T574 MSLP and low level wind forecast could capture the genesis location of depression formed over BOB (8th October 2013) up to four to five days in advance. Results demonstrate that GFS T574 provides skillful real-time forecasts of cyclone track and intensity over BOB. The Spatial and temporal comparison of tropical cyclogenesis and track forecasts shows that the GFS is more skillful over central and NW BOB region as compare to other regions of north Indian Ocean. GFS model showed considerable skill in predicting the cyclogenesis and movement of the storm (track) over Bay of Bengal. However, the accuracy in intensity prediction of Cyclone fluctuates considerably. Using the GFS model operational products, the genesis location and track can be predicted up to four to five days in advance with an error less than acceptable range, which can provide useful guidance for real time forecasting of tropical cyclones over Bay of Bengal.

1. Introduction

Tropical cyclone (TC) formation involves interaction of a variety of processes, both on the synoptic scale as well as the mesoscale. Gray (1979) identified several large-scale conditions as necessary for tropical cyclogenesis, including preexisting low-level relative vorticity and high mid-tropospheric humidity. TCs are one of the most dangerous natural calamities throughout the globe. The Bay of Bengal TC disaster is the costliest and deadliest natural hazard in the Indian sub-continent. It has a significant socio-economic impact on the countries bordering the Bay of Bengal, especially India, Bangladesh and Myanmar. Every year, they cause considerable loss of life and do immense damage to property. India and Bangladesh have a coastline of more than 8000 km, which is prone to very severe cyclone formations in the Arabian Sea and Bay of Bengal. Therefore, reasonably accurate prediction of these storms has great importance to avoid the loss of valuable lives.

Prediction of Intensity and Track of TC continues to be a forecasting challenge. Current operational models have difficulty in accurately forecasting TC formation. There are a number of comparative studies on the performance of the mesoscale models for severe weather events triggered by convection. Rama Rao et al. (2010) made a comparative study on the performance of WRF and QLM models for the track forecast. Also sensitivity experiments were conducted with the WRF model to test the impact of various microphysical and cumulus parameterization schemes in capturing the track and intensity of two severe cyclonic storms namely Super Cyclone “GONU” over Arabian Sea and very severe cyclonic storm “SIDR” over Bay of Bengal.

The Cyclone warning Division (CWD) at New Delhi of India Meteorological Department (IMD) functions as a Regional Specialized Meteorological Centre (RSMC) for TC forecasting, as recognized by the World Meteorological Organization (WMO). According to WMO’s Tropical Cyclone Programme (TCP), one of the major responsibilities of RSMC, New Delhi is to provide TC advisories to the member countries in the north Indian seas, apart from its national responsibilities. Cyclone advice for the member countries, which begins from the cyclone stage, includes information related to present and forecast track and intensity based on the use of the sophisticated Numerical Weather Prediction (NWP) models i.e. global and regional mesoscale models.

The main objective of this study is to investigate the performance skill of Global Forecast System (GFS) for the Prediction of the track and intensity of Very Severe Cyclonic Storm (VSCS) 'PHAILIN' formed over Bay of Bengal (BOB) in the medium range (day-1 to day-7) time scale. The performances of the models have been evaluated and compared with observations and verifying analyses. A brief description of the mesoscale models along with the numerical experiments and data used for the present study are given in section 2. The synoptic situation for the above mentioned cyclone used in the present study is described in section 3. The results are presented in section 4 in order to evaluate the performance of the models and the conclusions are in section 5.

2. MODEL DESCRIPTION

The Global Forecasting System (GFS) is a primitive equation spectral global model with state of art dynamics and physics (Saha et al 2010). Inter-comparisons of physics and dynamics options of GFS T574 is shown in **Table 1.** Details about the GFS Model are available at http://www.emc.ncep.noaa.gov/GFS/doc.php . The GFS T574L64 (~ 25 km in horizontal over the tropics), adopted from National Centre for Environmental Prediction (NCEP), was implemented at IMD, New Delhi on IBM based High Power Computing Systems (HPCS; Durai et al. 2011). The assimilation system (for GFS T574) is a global 3-dimensional variational technique, based on NCEP Grid Point Statistical Interpolation (GSI *3.0.0*; Kleist *et al 2009*) scheme, which is the next generation of Spectral Statistical Interpolation (SSI; David et al 1992). The details about model physics and dynamics are discussed in the recent study by Durai and Roy Bhowmik, (2013). The major changes incorporated in T574 GDAS compared to T382 GDAS are: use of variational quality control, flow dependent re-weighting of background error statistics, use of new version of Community Radiative Transfer Model (CRTM 2.0.2), improved TC relocation algorithm, changes in the land, snow and ice skin temperature and use of some new observations in the assimilation cycle.

Table .1 Physics and Dynamics options of GFS T574

Physics and Dynamics	**T574L64**
Surface Fluxes	Monin-Obukhov similarity
Turbulent Diffusion	Non-local Closure scheme (Lock et al., 2000)
SW Radiation	Rapid Radiative Transfer Model (RRTM2) (Mlawer et al. 1997)- aerosols included– invoked hourly
LW Radiation	Rapid Radiative Transfer Model (RRTM1) (Mlawer and Clough 1997). –aerosols included-invoked hourly
Deep Convection	SAS convection (Han and Pan, 2006)
Shallow Convection	Mass flux scheme (Han and Pan, 2010)
Large Scale Condensation	Large Scale Precipitation (Zhao and Carr ,1997; Sundqvist et al., 1989)
Cloud Generation	Based on Xu and Randall (1996)
Rainfall Evaporation	Kessler (1969)
Land Surface Processes	NOAH LSM with 4 soil levels for temperature & moisture (Ek et al., 2003)
Air-Sea Interaction	Roughness length by Charnock (1955), Observed SST, Thermal roughness over the ocean is based on Zeng et al., (1998). 3-layer Thermodynamic Sea-ice model (Winton, 2000)
Gravity Wave Drag & mountain blocking	Lott and Miller (1997), Kim and Arakawa (1995), Alpert et al., (1996)
Vertical Advection	Flux-Limited Positive-Definite Scheme (Yang et al., 2009)

In the operational mode, the Global Data Assimilation (GDAS) cycle runs 4 times a day (00 UTC, 06 UTC, 12 UTC and 18 UTC). The analysis and forecast for seven days are performed using the HPCS installed in IMD Delhi. One GDAS cycle and seven days forecast (0 -168 hour) at T382L64 (~ 35 km in horizontal over the tropics) takes about 30 minutes on IBM Power 6 (P6) machine using 20 nodes with 7 tasks (7 processors) per node, while the same for GFS T574 (~ 25 km in horizontal over the tropics) is approximately 1 hour 40 minutes. Details of data presently being processed for GFS at IMD are available at http://www.imd.gov.in/section/nhac/ dynamic/ data_coverage.pdf .

Forecasted fields of mean sea-level pressure (MSLP), 850 hPa wind, vorticity, and divergence are examined for the track and intensity prediction of Very Severe Cyclonic Storm (VSCS) 'PHAILIN' formed over Bay of Bengal (BOB) during 8-12 Oct 2013. In particular, day-1 to day-7 forecasts of these fields is generated from the GFS. The initial analysis of a low-pressure system by the CWD is taken as the time of cyclogenesis. In most cases, this initial analysis occurred several hours prior to classification as a tropical depression. The model forecasts are verified against the surface analyses produced by GDAS. Forecasts of mean sea level pressure (mslp), 10m wind, 850 hPa wind and vorticity fields are verified against the corresponding GDAS and satellite analyses from the KALPANA-1 Meteorological Satellite images.

The accuracy of a forecast for this study includes both spatial location and timing of the model-generated vortex. The low-pressure system must have developed within a six degree radius of the predicted location to be deemed an accurate forecast. This radius was calculated from the average distance that an easterly wave moves in a day. The forecast trend in terms of location is also noted, to determine the forecast accuracy relative to the analysis as well as to each other. Consecutive forecasts of cyclogenesis events at different forecast periods are deemed successful, as opposed to cases where a model predicts cyclogenesis in a 5-day forecast, and then loses it until the 1-day forecast.

3. SYSTEM DESCRIPTION:

A low pressure system that formed over North Andaman Sea on 7 October 2013 intensified into depression at 0300 UTC of 8 October 2013 near latitude 12.0^{o} N and longitude 96.0^{o} E. It moved northwestwards and intensified into a deep depression at 0000 UTC of 9 October 2013 and further intensified into a cyclonic storm (T.No. 2.5), PHAILIN at 1200 UTC of the same day. The cyclonic storm continued to move in northwesterly direction and intensified into severe cyclonic storm (T.No. 3.5) at 0300 UTC of 10 October 2013 and subsequently intensified into very severe cyclonic storm (T. No. 4.0) at 0600 UTC of same day. Moving northwestward direction the system further rapidly intensified to T.No. 4.5, T.No. 5.0, and T.No. 5.5 at 1200 UTC, 1500 UTC and 2100 UTC of same day (10 October 2013) respectively. At 0300 UTC of 11 October 2013 the system intensified to T.No. 6.0 and continued to move northwesterly direction with same intensity towards Odisha and crossed coast near Gopalpur at around 1700 UTC of 12 October 2013. The system maintained its intensity of very severe cyclonic storm upto seven hours after landfall and cyclonic storm intensity till 1200 UTC of 13 October 2013. The system continued to decay and weakened to deep depression at 1800 UTC of 13 October 2013 and further to depression at 0300 UTC of 14 October 2013. The observed track of the cyclone PHAILIN is shown in **Fig. 1**.

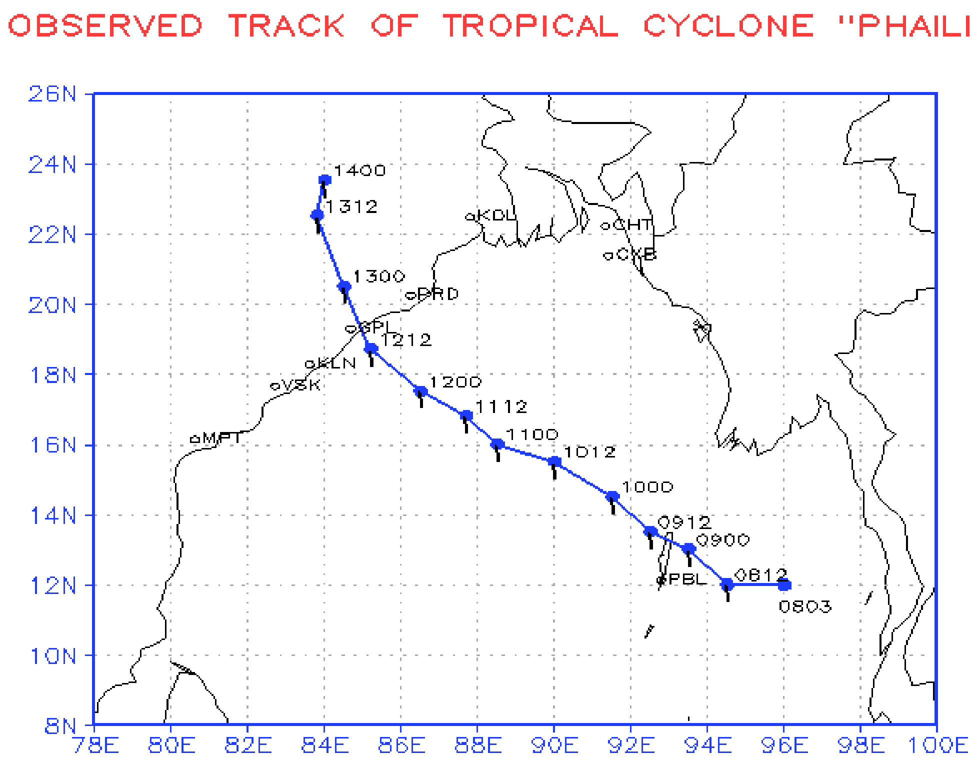


Fig.1 Observed track of VSCS PHAILIN: 8th-14th Oct 2013.

4. Result & Discussions

4.1 GDAS ANALYSIS of PHAILIN (8-12 October)

In order to assess the ability of the GDAS to capture center and structure of the cyclone PHAILIN, the wind analysis at 200 and 500 hPa for 7-12 October 2013 is shown in **Fig.2**. The ridge line at 200 hPa was around 20 deg N, which was quite north of the system center. This feature was helpful in moving the system as its normal NWly direction. The GDAS analysis of wind at middle level (500 hPa) also supports the circulation on 8-12 October 2013.

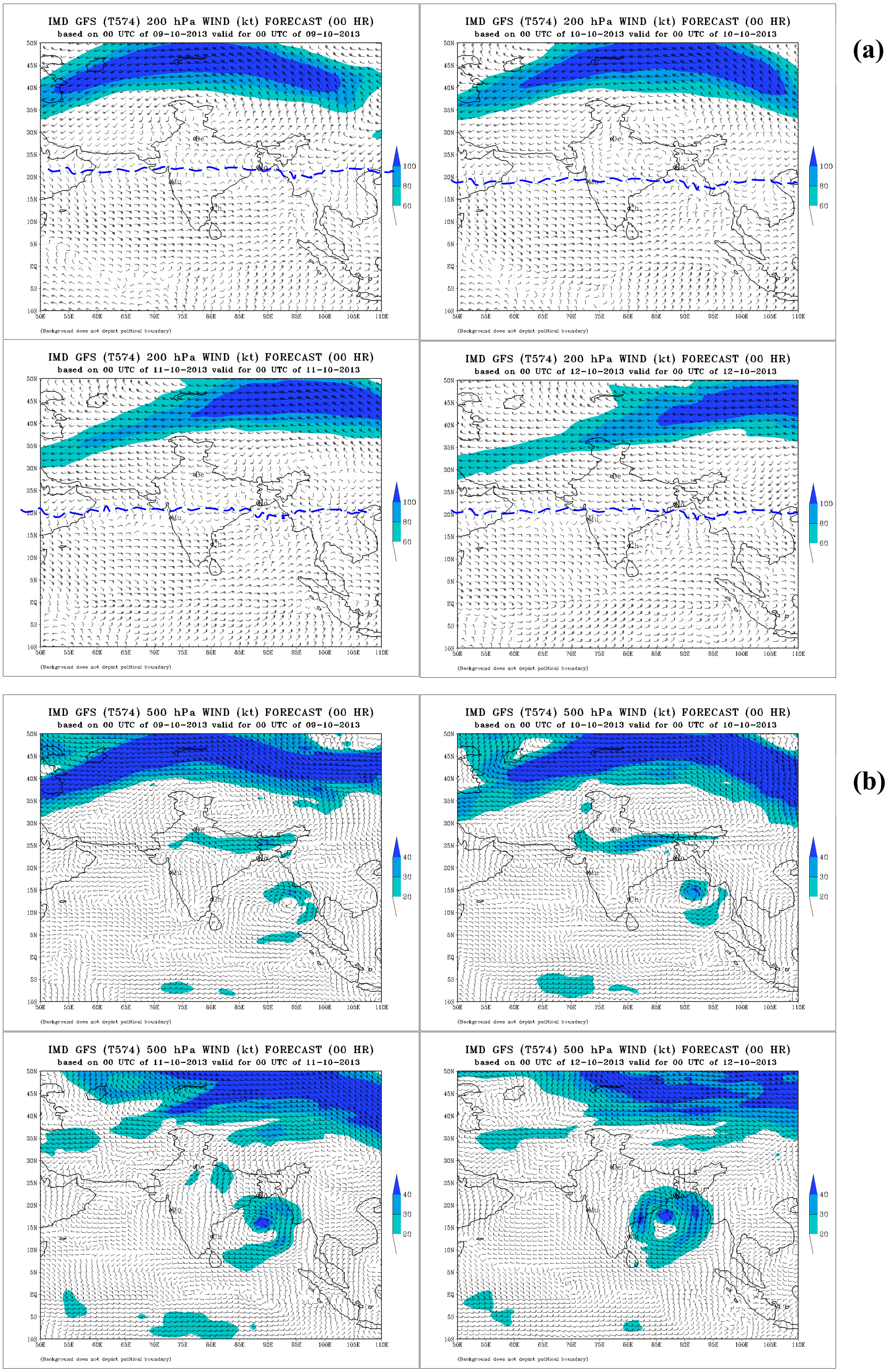


Fig .2 The GDAS analysis of (a) 200 hPa wind (b) 500 hPa wind during 9 -12 October 2013

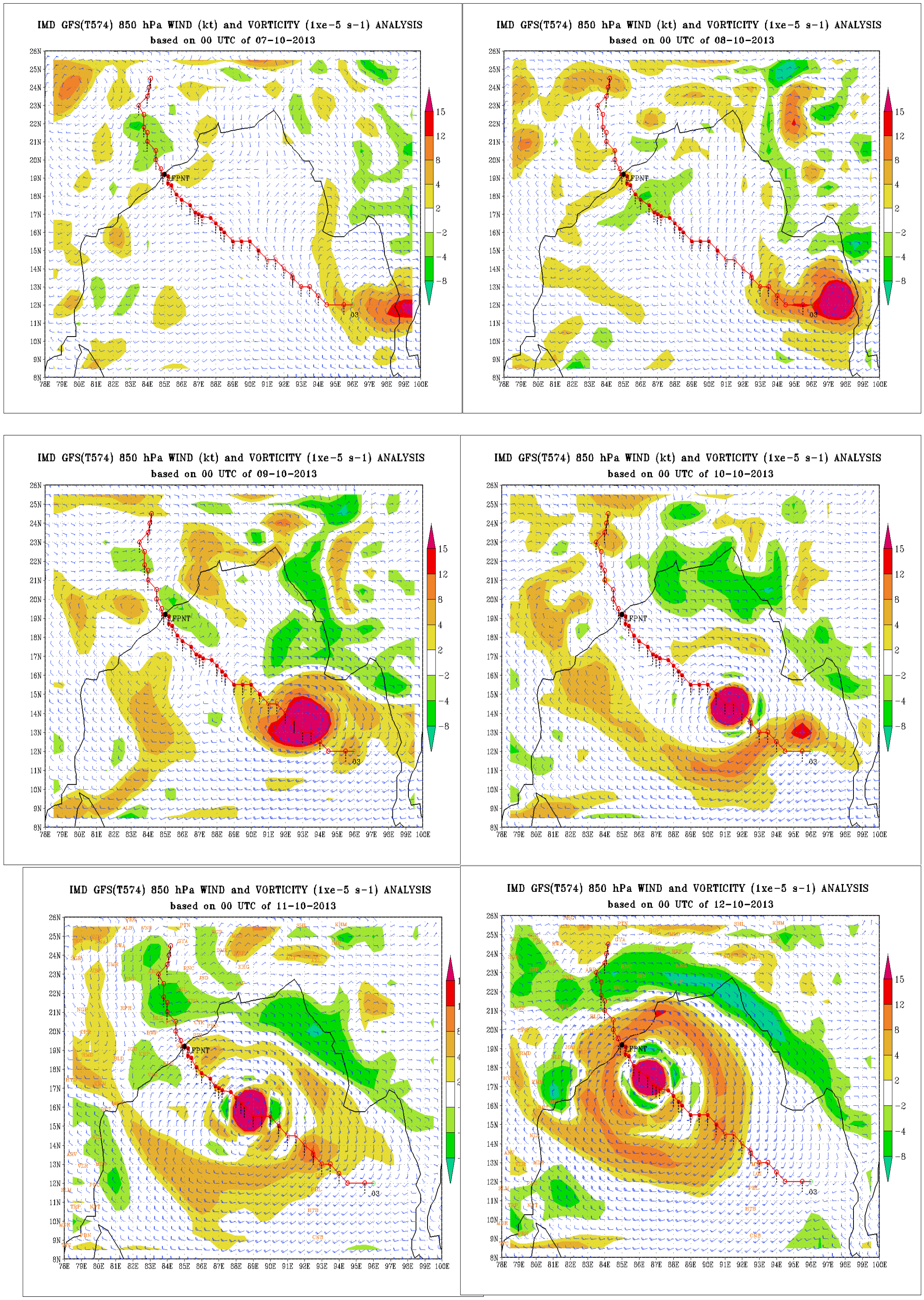


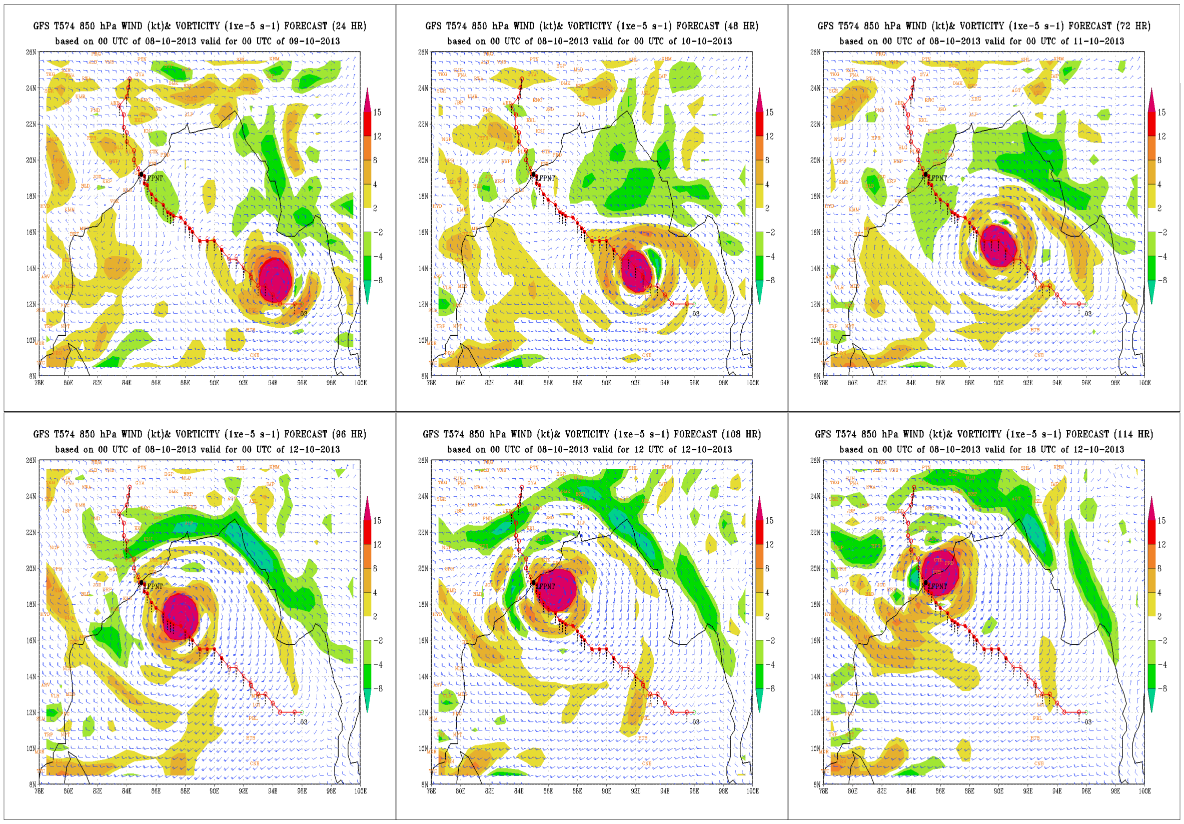
Fig .3 The GDAS analysis of 850hPa wind and vorticity during **7 -12 October 2013**

The upper level winds at 200 hPa during the period from 8 October to 12 October 2013 shown in Fig.2 to highlight the role of steering current. The GDAS Analysis of wind and vorticity at 850 hPa (**Fig.3**) captured the position and intensity of the VSCS PHAILIN with reasonable accuracy during 7-12 October 2013. The observed cyclone track (red dot line) of 'PHAILIN' is superposed in the Fig .3. On 7th October a trough at 850 hPa over north Andaman Sea was seen in the analysis. .It became a cyclonic circulation with wind speed of about 25-30 knots on 8th October. The 850 hPa vorticity maximum of the order of 15 $\times$ 10−5/sec on 9 October was situated around 13.5◦N/93.5◦E. In all days from 7 -12 October the GDAS analyzed cyclonic center with circulation pattern is matching very much with the observed track. The magnitude of 850 hPa vorticity value gradually increases from 7 to 12 October along the track in the northwest direction.

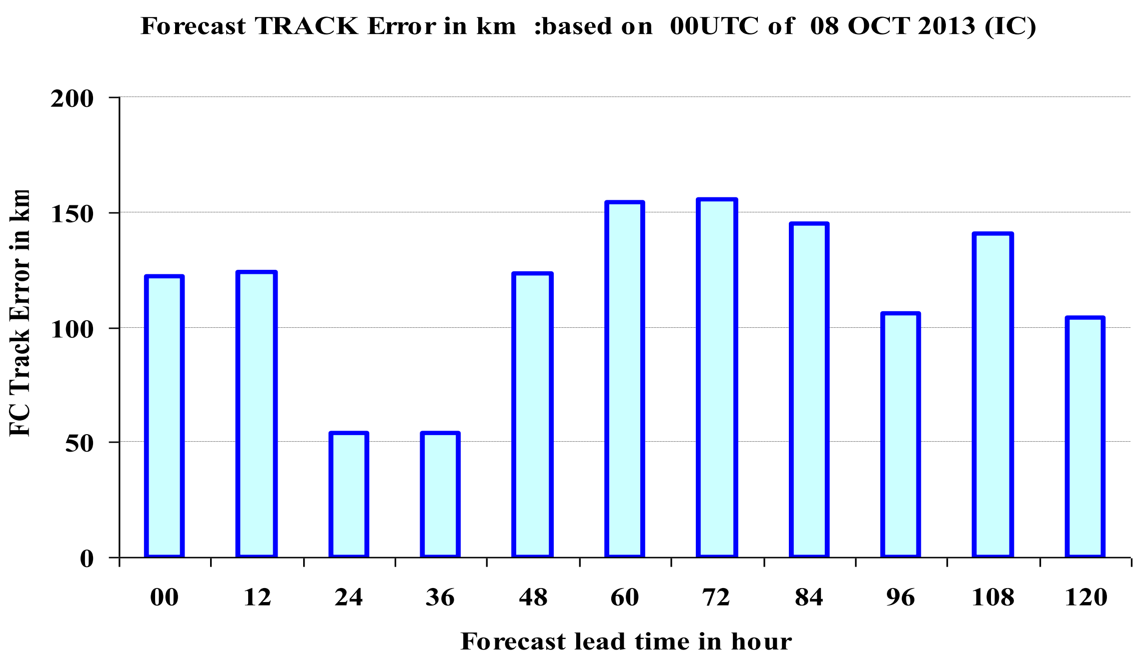
The GDAS analysis (Fig. 3) based on 00 UTC of 07 October 2013 shows that the Depression near Andaman Sea would intensify into a Deep Depression at 00 UTC of 09 October 2013 and became a cyclonic storm (CS) at 12 UTC of 09 October 2013. GDAS analysis of 06 UTC of 10 October 2013 shows the severe CS (SCS) and at 06 UTC of 11 October 2013 it became Very Severe Cyclonic storm (VSCS).

4.3 Track Forecast

The real time track forecast and the corresponding track Errors of the VSCS 'PHAILIN' using GFS model at 25 km resolution starting from the initial conditions of 8 Oct 2013 at 00UTC is shown in Fig.4. The model 12 hourly direct positional errors are calculated as the geographical distance between the observed and forecast point. The 850 hPa wind and vorticity forecast valid at 24 h to 120 h takes the system along with the observed track. The 850 hPa vorticity maximum of the order of 15 $\times$ 10−5/sec on 9 Oct was situated around 13.5°N/93.5°E. Like the observed track, the GFS day-1 to day-5 forecast based on 8 Oct 2013 initial condition (Fig. 4) also clearly indicated that the system was going to hit the Odisha coast around 17 UTC of 12 Oct 2013. The 12 hourly forecast track error of the cyclone as given Fig 4b based on the initial condition of 8 Oct is found to be within the range of 120 km till 48 h of its forecast and the error increased to 150 km in 120 h as the forecast track showed northwesterly movement along with the observed track (fig.4).

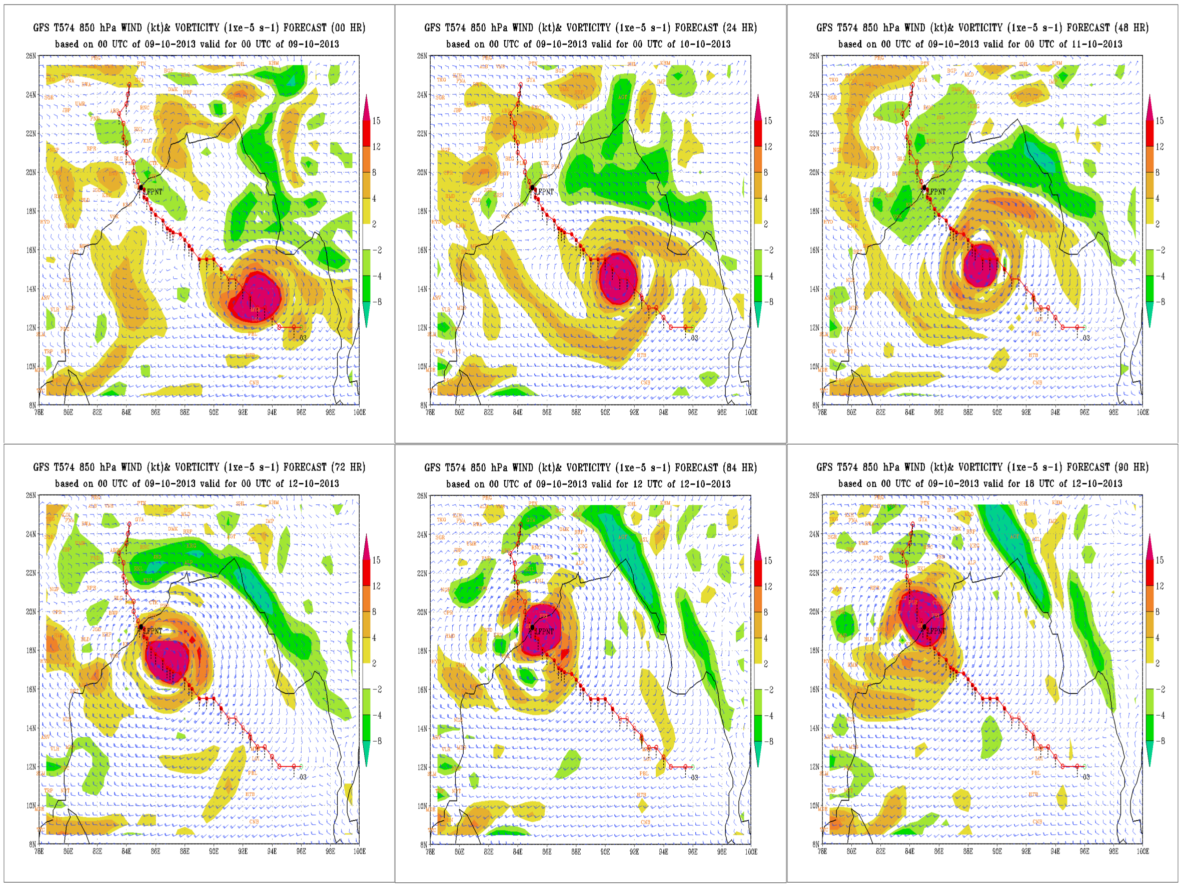


(a)



(b)

Fig .4 The Day-1 to Day-5 GFS forecast of (a) wind and vorticity at 850hPa, (b) track error in km based on initial condition of 00 UTC of 08 October 2013.



(a)

(b)

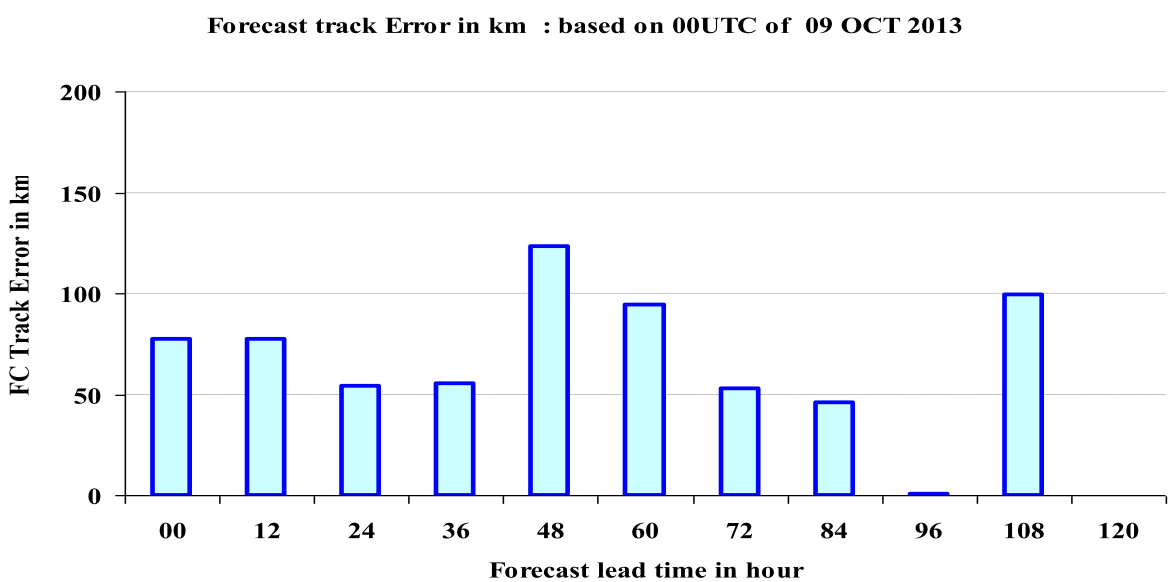


Fig .5 GFS forecast of (a) wind and vorticity at 850hPa and (b) track error in km based on initial condition of 00 UTC of 09 October 2013.

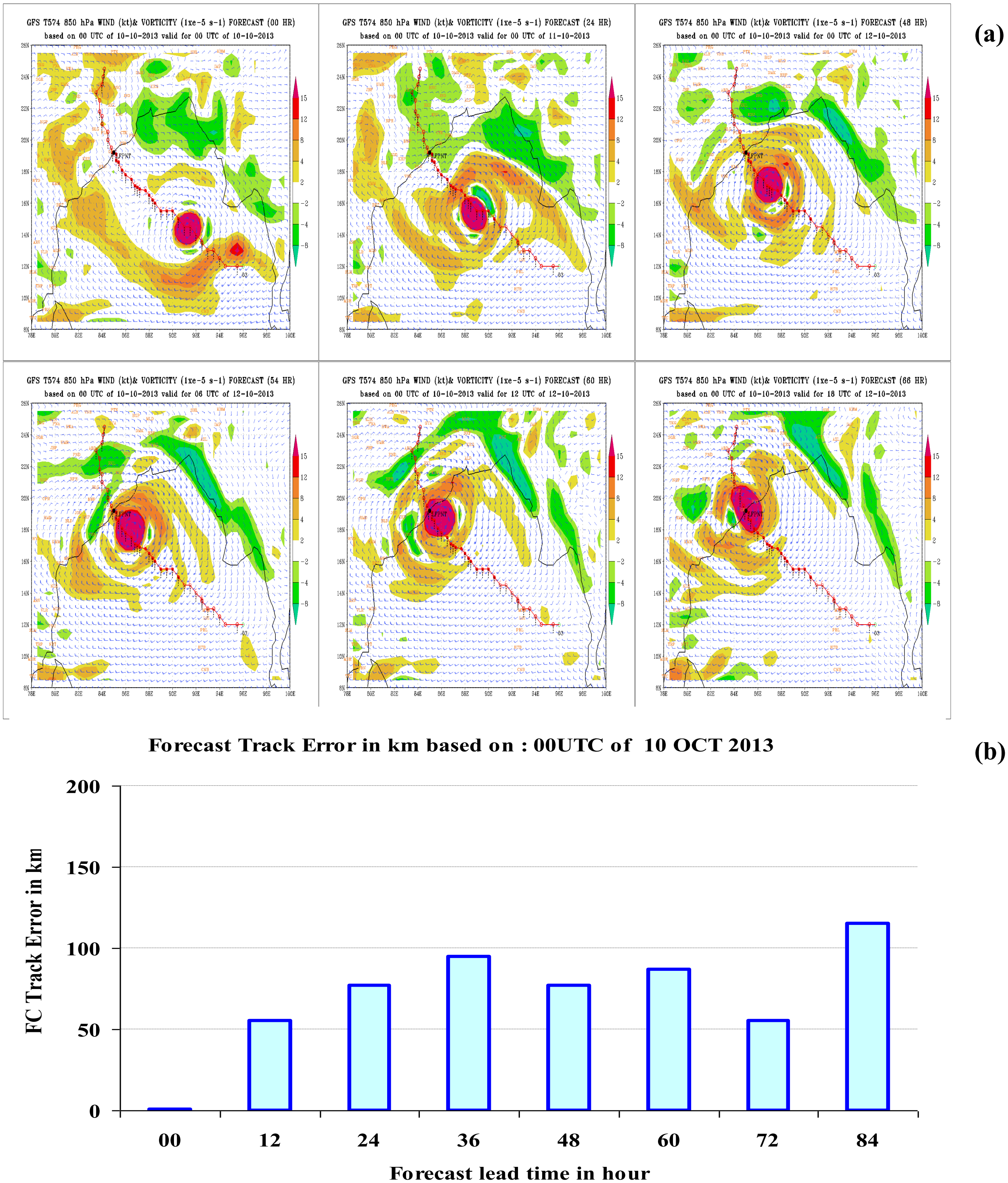


Fig .6 GFS forecast of (a) wind and vorticity at 850hPa and (b) track error in km based on initial condition of 00 UTC of 10 October 2013.

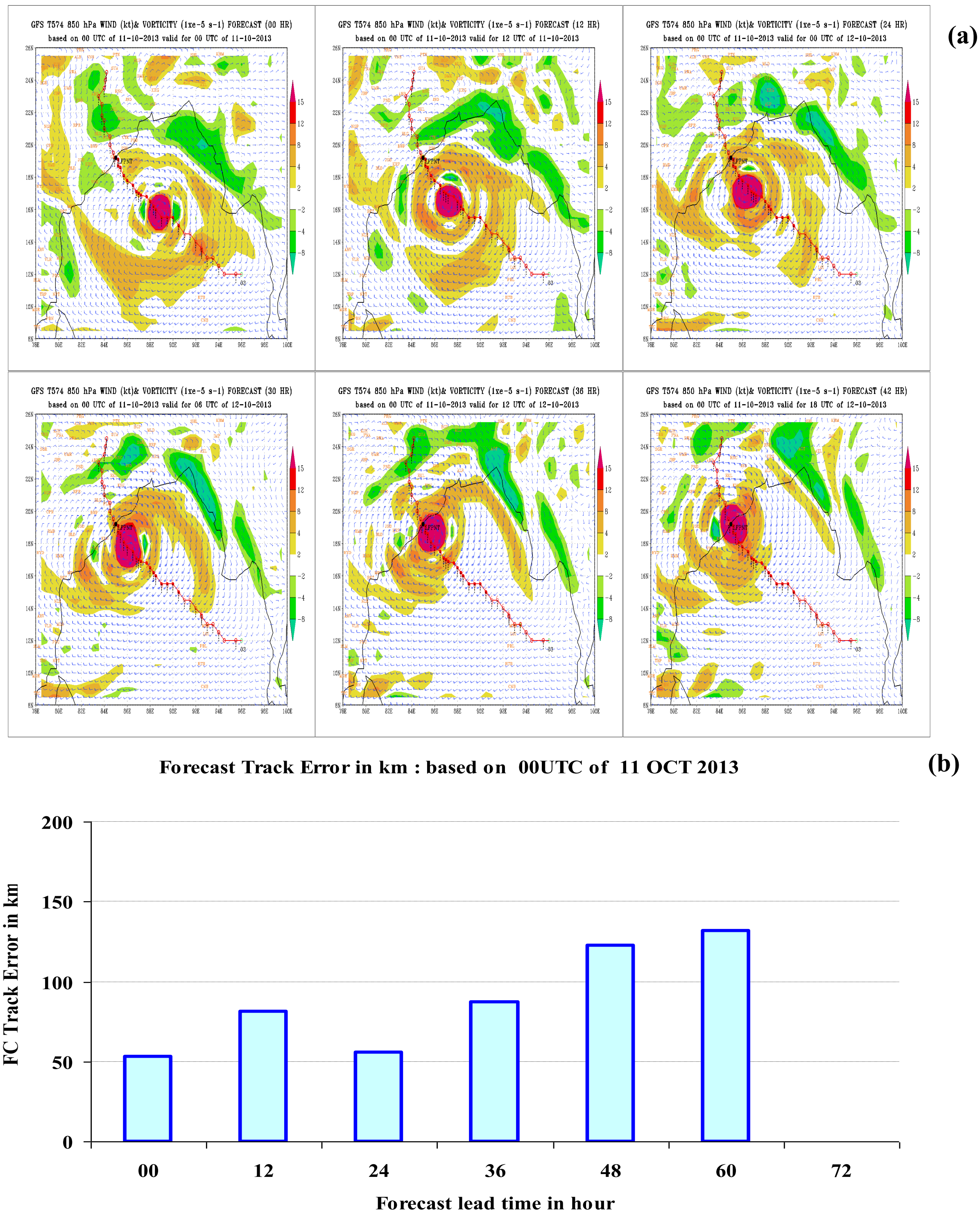


Fig .7 GFS forecast of (a) wind and vorticity at 850hPa and (b) track error in km based on initial condition of 00 UTC of 11 October 2013.

Based on the initial condition of 9 Oct, when the system was in the stage Deep Depression, the initial error is about 50 km (Fig 5b) and the corresponding forecast errors also reduced substantially. The real time forecast using 9 October initial condition also shows landfall around 18 UTC of 12 Oct near Gopalpur in Orissa coast. However, the 96 h forecast position shows that the system was expected to hit the Orissa coast as it followed the northwestward movement (Fig. 5a) like that of observed track . The forecast based on the initial condition of 10 Oct (Fig.6) also shows northwestward movement of the cyclone and crossed the coast in its 84 h forecast position. The forecast and observed tracks showed northwestward movement of the system, although the forecast track showed slight north of the actual landfall point. The model forecast speed and landfall of the system is very close to that of observation.

Similarly the 12 hourly forecast error based on 11 Oct initial condition as given in Fig.7 is basically due to the movement of the system slightly to the north of the observed track although it had a very similar track parallel to that of the observed track. It is also indicated from figure 7 that the forecast tracks are improved with the initial conditions of 8 to 11 Oct with landfall error of range between 50 km and 150 km. The mean initial error and 12 hourly mean forecast errors found from the GFS model runs as given in Fig 4 -7 is found to be less than 150. The track of the cyclone as obtained from the model simulations using different initial conditions are evaluated and compared with the best-fit track as estimated by IMD. Figure 4 (a), 5 (a), 6 (a) and 7(a) represents the track of the cyclone PHAILIN as obtained with GFS model simulations from different initial conditions. Forecast from all the initial conditions show that, in each case the cyclone moves to the Orissa coast, what ever the initial condition is being chosen. The vector displacement error is also calculated at the landfall point.

3.3 Cyclone Intensity Forecast

The classification of cyclone storm intensity based on radius of maximum wind and the pressure difference between outermost closed isobars and center pressure is given in Table 2. GFS 10m wind and MSLP for the Intensity forecast based on 00 UTC of 08 October 2013 shows that the Depression near Andaman Sea would intensify into a (i) DD at 00

UTC of 09 October 2013. (ii) Cyclonic storm at 12 UTC of 09 October 2013 (iii) Severe CS at 06 UTC of 10 October 2013, and (iv) Very Severe Cyclonic storm at 06 UTC of 11 October 2013. Fig 8 represents the 12 hourly forecast of the (MSLP) and 10m wind from GFS model simulation based on 8 Oct initial condition. On 8 Oct the system was only a depression with maximum wind speed of around 20 -30 knots. Then it became cyclonic storm with wind speed reaching around 40 knots in the 36 hour forecast. In the 54 hour forecast the system became severe cyclonic storm (SCS) with wind speed reaching around 60 knots. Finally in the 78 hour forecast, the system became very severe cyclonic storm (VSCS) with wind speed reaching in the range of 60 -100 knots. GFS 84 -114 hours forecast shows that the intensity of VSCS was maintained till it made landfall on 17 UTC of 12 Oct 2013. The central MSLP with the maximum sustainable wind of 100 kts is simulated in model forecast. The central MSLP with the maximum sustainable wind of 100 kts is simulated in 78 to 114 hour forecast of GFS model based on 8 Oct initial condition very reasonably. Similarly, the GFS intensity forecast based on the initial condition of 9 Oct using 12 hourly forecast of the mean MSLP and 10m wind is shown in Fig.9. From the results it may be inferred that, simulation with GFS model wind at 10m forecast gives the storm intensification reasonably accurate with observation. It may also be noticed that, GFS intensify the storm with less time delay, which is in reasonable accuracy with observation. The system was VSCS at the time of crossing the coast, then it become SCS at 00 UTC of 13 Oct and then became CS at 06 UTC of 13 Oct 2013.

Table.2 Classification of Cyclonic Storm Intensity

T. Number/ C.I. Number	Classification of Cyclonic Disturbance	Wind speed in Knots (Mean)	Wind criteria in Knots	DP
T1.0	Low		<17	
T1.5	D	25	17-27	
T2.0	DD	30	28-33	4.5
T2.5	CS	35	34-47	6.1
T3.0		45		10.0
T3.5	SCS	55	48-63	15.0
T4.0	VSCS	65	64-119	20.9
T6.5	SuCS	127	>120	80.0

D= Depression, DD= Deep Depression, CS= Cyclonic Storm, SCS= Severe Cyclonic Storm, VSCS= Very Severe Cyclonic Storm & SuCS= Super Cyclonic Storm

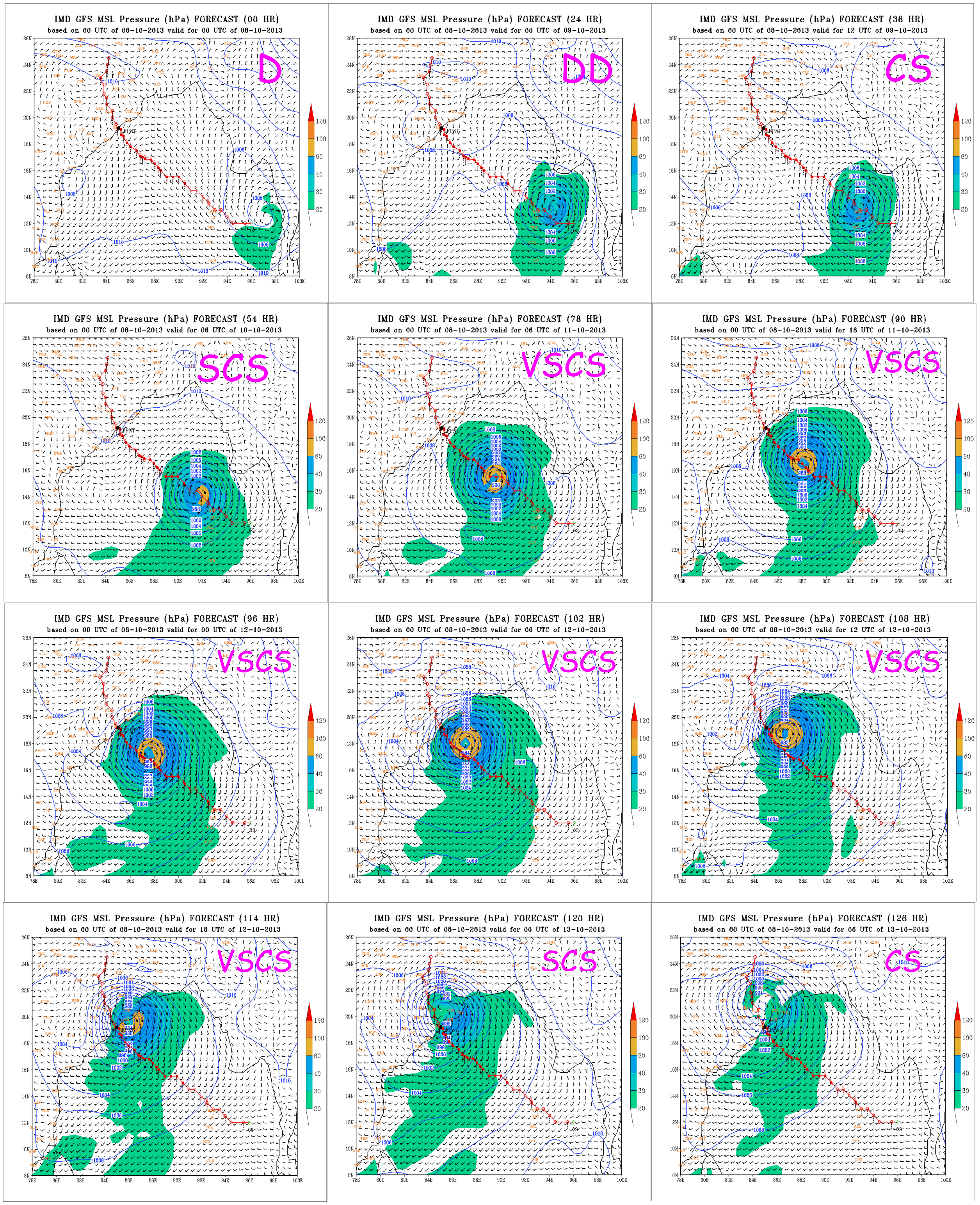


Fig .8 GFS forecast of (a) 10m wind (kt) and MSLP (hPa) based on initial condition of 00 UTC of 08 October 2013.

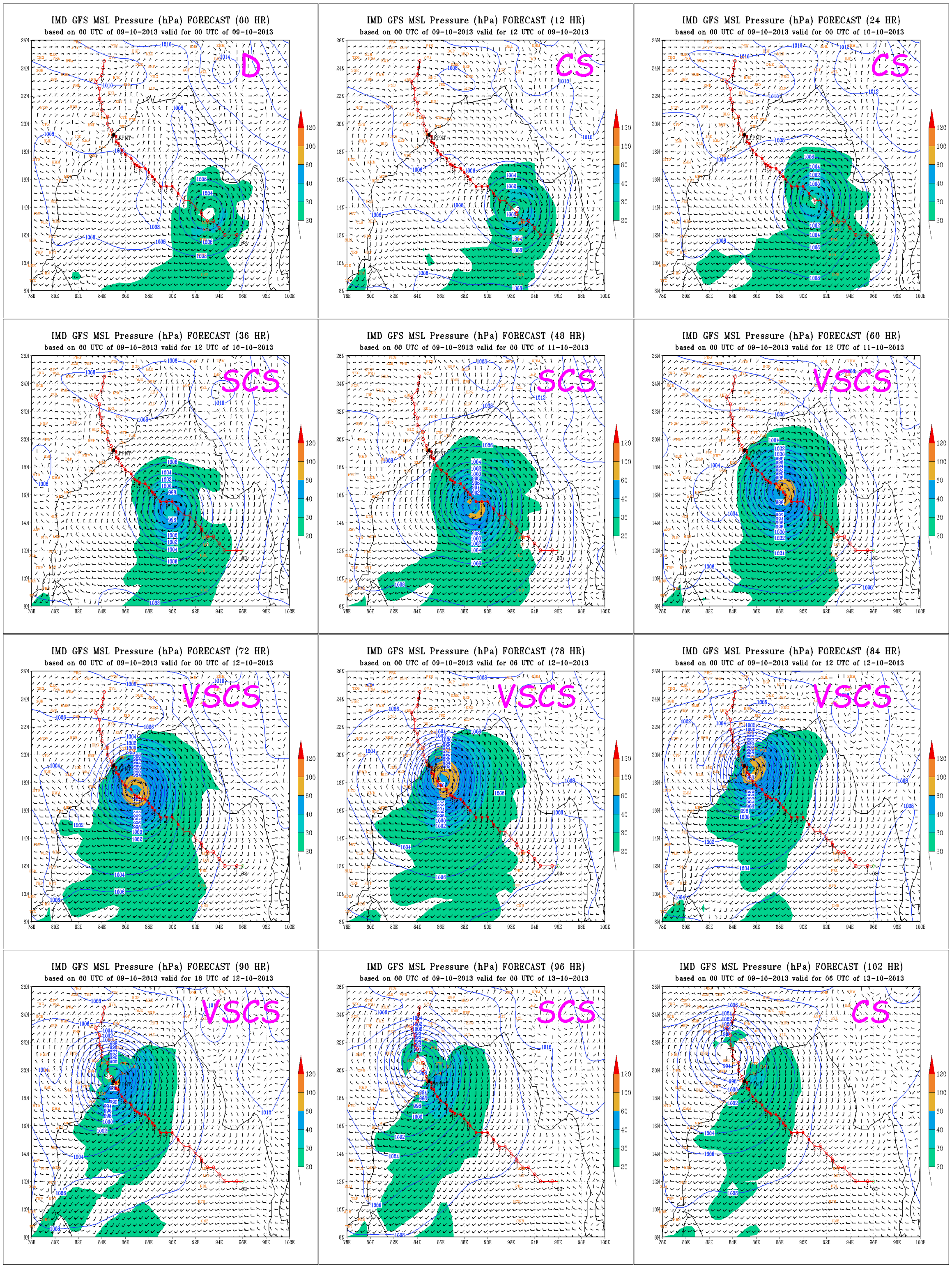


Fig .9 GFS forecast of (a) 10m wind (kt) and MSLP (hPa) based on initial condition of 00 UTC of 09 October 2013.

3.4 Heavy Rainfall

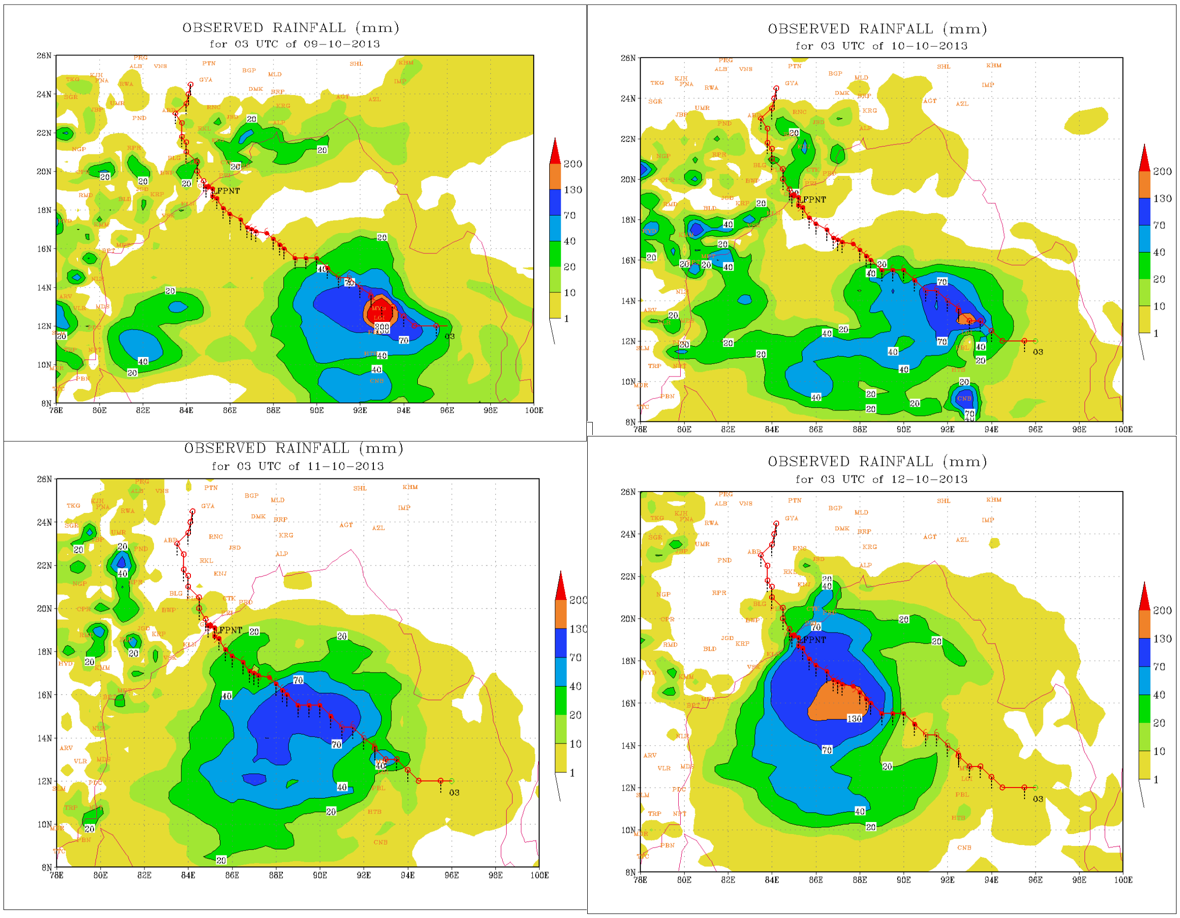
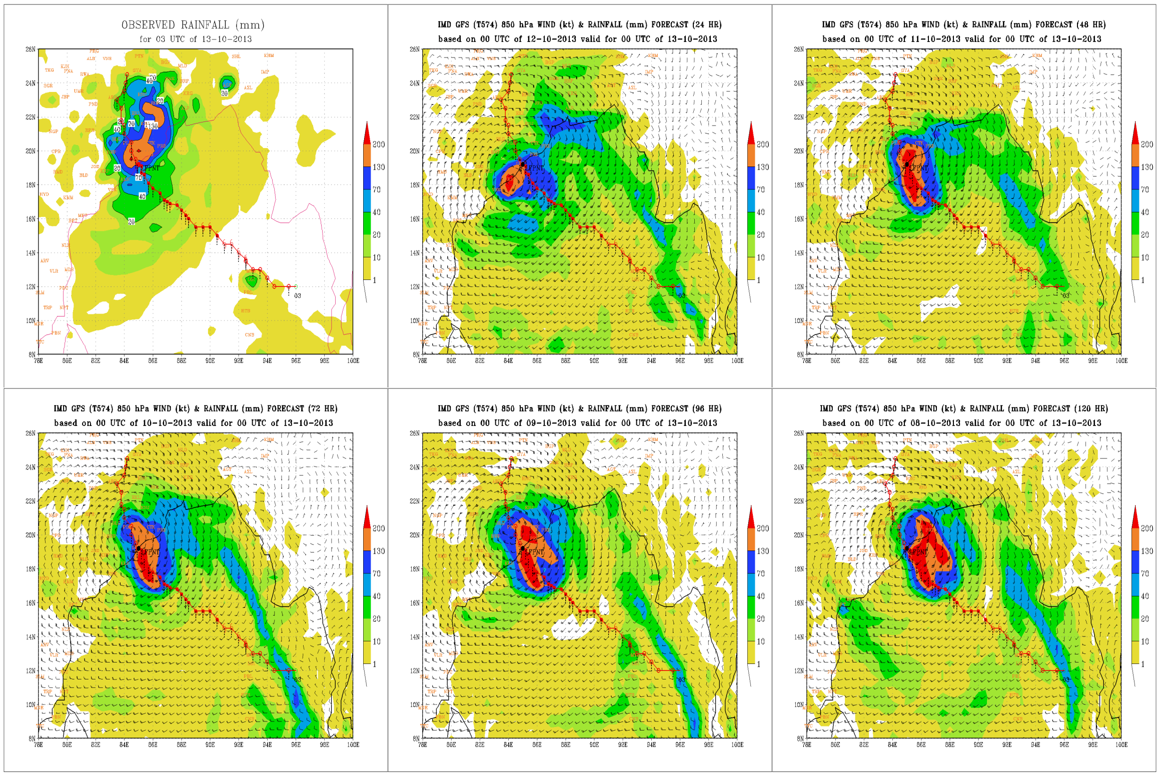


Fig .10 Observed Rainfall from Rain gauge (land) and TRMM (Sea) for (a) 09, (b) 10, (c) 11 and (d) 12th October 2013.

The observed heavy rainfall associated with the PHAILIN cyclonic storm over east central BOB from 03 UTC of 09th October to 12th October 2013 is shown in Fig.10. The 24 hour accumulated rainfall analysis at the resolution of 50 km is based on the merged rainfall data combining gridded rain gauge observations prepared by IMD Pune for the land areas and Tropical Rainfall Measuring Mission (TRMM) 3B42RT data for the Sea areas (Durai et al. 2010). It is seen from the Fig.10 that the heavy rainfall occurred over the sea to the south west sector of the center of the TC with a peak of >200mm on 9, 10 and 12 October, but on 11th October it showed rainfall in the order of 70 to 130 mm only. In general, the rainfall estimate by TRMM could capture the magnitude and location of heavy rainfall associated with low pressure system reasonably well over the sea areas.

(a)



(b)

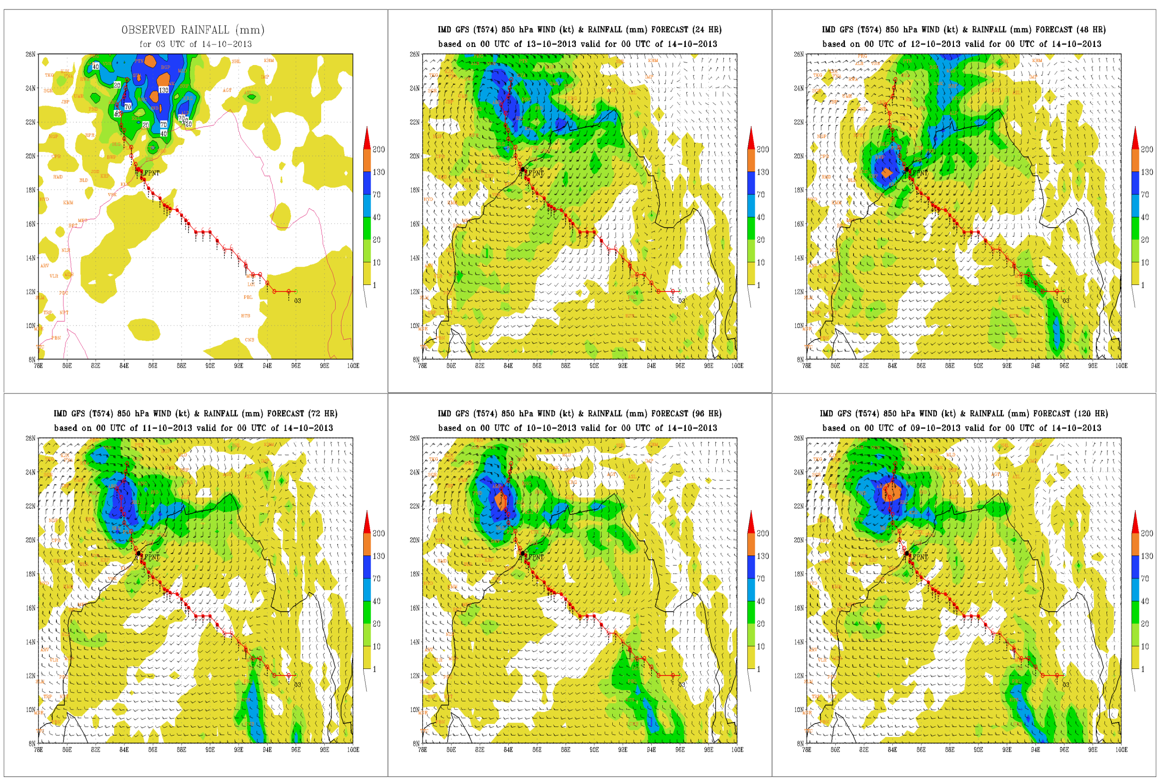


Fig .11 (a) Observed rainfall and GFS T574 day-1 to day-5 forecasts of wind at 850 hPa and heavy rainfall on 13 Oct 2013 (top panel) and **(b),** 14 October 2013 (bottom panel)

The spatial distributions of observed rainfall along with GFS forecast of wind at 850 hPa and rainfall valid for 13 Oct 2013 (top panel) and 14 October 2013 (bottom panel) in relation to movement of the system and occurrences of heavy rainfall are examined (Fig 11). It ushered the landfall of the VSCS PHAILIN over Orissa coast caused excess rainfall over these regions on 13 and 14 Oct 2013. Under the influence of this VSCS a heavy to very heavy rainfall occurred over coastal Orissa and adjoining areas during 13-14 October 2013. The case study selected is the exceptionally heavy rainfall due to PHAILIN on 13 and 14 October over Orissa.

On 13th October 2013 heavy rainfall was reported over Orissa and adjoining Jharkhand areas. Fig.11a shows the observed rainfall and 24 to 120 hour rainfall forecast from GFS T574L64 valid for 13th over many parts of Orissa. The 24 hour forecast could capture the spatial pattern of observed rainfall, but the magnitude is less than the actual. The location and magnitude of heavy rainfall on 13 Oct due to the landfall during 17UTC of 12th Oct near Gopalpur is better captured by GFS T574 day-1 to day5 forecast. The spatial distribution pattern suggested that the GFS T574 model forecasts, in general are better skillful in predicting heavy rainfall. Using the GFS T574 operational products, the location and intensity of heavy rainfall can be predicted up to three days in advance with an accuracy of spatial error less than 200 km, which can provide useful guidance for real time forecasting of heavy rainfall during monsoon depression over India.

The heavy rainfall on 14th October 2013 was reported over north Orissa and adjoining Jharkhand and Gangetic West Bengal areas as shown in Fig.11b. The observed rainfall and 24 to 120 hour rainfall forecast from GFS T574L64 valid for 14th Oct shows over northern parts of Orissa. The VSCS PHAILIN moved northwards after the landfall, so the very heavy rainfall occurred in the northern parts of Orissa on 14th. The 24 – 120 hour forecast could capture the spatial pattern of observed rainfall, but the magnitude is more or less matching with the observed rainfall. The spatial distribution pattern suggested that the day to day GFS T574 model forecasts, in general are better skillful in predicting heavy rainfall. GFS T574 model showed considerable skill in predicting the Heavy rainfall due to Cyclone. However, the accuracy in prediction of location and intensity fluctuates considerably.

5. Conclusion

NCEP based GFS system has been in operational use at IMD New Delhi for daily medium range forecasts. This paper assesses the skill of GFS for the Prediction of the intensity and track of Very Severe Cyclonic Storm (VSCS) ‘PHAILIN’ formed over Bay of Bengal (BOB). The GFS T574 MSLP and low level wind (10m wind) forecast could capture the genesis location of depression formed over BOB (8th October 2013) up to four to five days in advance. Results demonstrate that GFS T574 provides skillful real-time forecasts of cyclone track and intensity over BOB. Using the GFS T574 operational products, the genesis location could be predicted up to five to six days in advance with an error less than 150 km, which provided useful guidance for real time forecasting of this TC over BOB. Due to inaccurate location of low-pressure systems by NWP models, in general, some mismatch prevails between the spatial distribution of forecast heavy rainfall and the observed one. Because of this double penalty, rainfall prediction skill deteriorates over Indian monsoon region.

The day to day GFS analysis is consistence with the observed cyclone track position of PHAILIN. The real time track forecast using GFS indicated that, the system was expected to cross the Orissa coast near Gopalpur, around 18 UTC of 12 Oct 2013, with landfall error of 50 - 150 km and landfall time delay of 3 -6 hour. The movement and intensity of this system have been better captured by the GFS T574 wind and vorticity at 850 hPa and MSLP based on 8 Oct 2013 initial condition as illustrated in Fig 4. The GFS forecast captured the formation and movement of ‘PHAILIN’ reasonably well, almost 120 hour in advance with very less forecast error. In general, the high resolution GFS model (22 km) provided very useful guidance interms of landfall point, landfall time, rapid intensification and decay after landfall. Further improvement in the forecast is expected with the possible inclusion of 3 Dimensional Hybrid Ensemble Kalmen Filter (Hamill *et al 2011)* data assimilation and multiple physics in the GFS. However, the accuracy in prediction of location and intensity of cyclone fluctuates considerably.

Acknowledgements: Authors are grateful to the Director General of Meteorology, India Meteorological Department for providing all facilities to carry out this research work. Acknowledgements are due to NCEP, USA for providing the source codes and support for the implementation of the upgraded Version GFS T574 at IMD. Authors acknowledge the technical support provided by NCMRWF for the implementation of the data decoders at IMD. Authors also acknowledge the use of TRMM Products of NASA, USA in this work

References

Alpert, J.C., S-Y Hong and Y-J Kim, 1996: Sensitivity of cyclogenesis to lower troposphere enhancement of gravity wave drag using the Environmental Modeling Center medium range model.*Proc. 11th Conference. on NWP, Norfolk, 322-323.*

Charnock, H., 1955: Wind stress on a water surface. *Quart. J. Roy. Meteor. Soc., 81*, 639-640.

David F. Parrish and John C. Derber, 1992: The National Meteorological Center's Spectral Statistical-Interpolation Analysis System. *Monthly Weather Review, 120, 1747-1763.*

Durai V.R. Kotal, S.D., Roy Bhowmik, S.K., **2011**, Performance of Global Forecast System of IMD during Summer Monsoon 2010, Edited by: Ajit Tyagi, S. K. Roy Bhowmik and S. D. Kotal, Meteorological Monograph No. NWP/Annual Report/**01/2011**, pp 1-41.

Durai V.R. and Roy Bhowmik, S.K., **2013**, Prediction of Indian summer monsoon in short to medium range time scale with high resolution global forecast system (GFS) T574 and T382, ***Climate Dynamics*****,** Volume **42,** Issue 5-6, pp. 1527-1551.

Durai V R., Roy Bhowmik S K and Mukhopadhaya B., **2010** Evaluation of Indian summer monsoon rainfall features using *TRMM and KALPANA-1* satellite derived precipitation and rain gauge observation, ***Mausam,*** *61(3), 317-336.*

Ek M.B., K.E. Mitchell, Y. Lin, E. Rogers, P. Grunmann, V. Koren, G. Gayno, and J.D. Tarplay, 2003:Implementation of the Noah land-use model advances in the NCEP operational mesoscale Eta model. *J. Geophys. Res.,* 108, 8851, doi:10.1029/2002JD003296.

Gray, W.M., 1979: Hurricanes: Their formation, structure, and likely role in the tropical circulation. Meteorology over the tropical oceans, D.B. Shaw, Ed. *Royal Meteorological Society, 155-218.*

Hamill, Thomas M., Jeffrey S. Whitaker, Michael Fiorino, Stanley G. Benjamin, 2011: Global Ensemble Predictions of 2009's Tropical Cyclones Initialized with an Ensemble Kalman Filter. *Mon. Wea. Rev., 139, 668–688.*

Han, J. and H.-L. Pan, 2006: Sensitivity of hurricane intensity forecast to convective momentum transport parameterisation, *Mon. Wea. Rev*., 134, 664-674.

Han, J. and H.-L. Pan, 2010: Revision of Convection and Vertical Diffusion Schemes in the NCEP Global Forecast System, *NCEP Office Note 464*, 42pp. [Available online at: http://www.emc.ncep.noaa.gov/officenotes/newernotes/on464.pdf]

Kleist, Daryl T., David F. Parrish, John C. Derber, Russ Treadon, Wan-Shu Wu, Stephen Lord, 2009: Introduction of the GSI into the NCEP Global Data Assimilation System. *Weather Forecasting, 24, 1691–1705.*

Kessler, E., 1969: On the distribution and continuity of water substance in atmospheric circulation,*Meteorological Monographs*, 10, 84pp.

Kim, Y.-J., A. Arakawa, 1995: Improvement of Orographic Gravity Wave Parameterization Using a Mesoscale Gravity Wave Model. *J. Atmos. Sci.*, 52, 1875–1902.

Lock, A.P, A.R. Brown, M.R. Bush, G.M. Martin, and R.N.B. Smith, 2000: A new boundary layer mixing scheme. Part-I: Scheme description and single column model tests, *Mon. Wea. Rev*., 128, 3187-3199

Lott, F. and M.J. Miller, 1997: A new subgrid-scale orographic drag parameterization: its performance and testing, Quart. J. Roy. Meteor. Soc., 123, 101-127.

Mlawer, E.J., S.J. Taubman, P.D. Brown, M.J. Iacono, and S.A. Clough, 1997: Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave. *J. Geophys.Res., 102*, 16663-16682.

Rama Rao Y.V, Madhu Latha.,A., Suneetha.P., 2010, Evaluation of the WRF and Quasi-Lagrangian Model (QLM) for Cyclone Track Prediction Over Bay of Bengal and Arabian Sea ,Books entitled Indian Ocean Tropical Cyclones and Climate Change, Springer, Book part 3 ,2010,pp 105-114.

Sundqvist, H., E. Berge, and J. E. Kristjansson, 1989: Condensation and cloud studies with mesoscale numerical weather prediction model. *Mon. Wea. Rev.,* 117, 1641-1757.

Winton, M., 2000: A Reformulated Three-Layer Sea Ice Model. *J. Atmos. Oceanic Technol.*, 17, 525–531.

Xu, K. M., and D. A. Randall, 1996: A semiempirical cloudiness parameterization for use in climate models. *J. Atmos. Sci., 53*, 3084-3102.

Yang, F, et al., 2009: On the negative water vapor in the NCEP GFS; Sources and Solutions, *23rd Conference in Weather Analysis and Forecasting/19th Conference on Numerical Wether Prediction*,Amer. Meteor. Society, 1-5 June, 2009, Omaha, NE.

Zeng, X., M. Zhao, and R.E. Dickinson, 1998: Intercomparison of bulk aerodynamical algorithms for the computation of sea surface fluxes using TOGA COARE and TAO data. *J. Climate, 11*, 2628-2644.

Zhao, Q. Y., and F. H. Carr, 1997: A prognostic cloud scheme for operational NWP models. *Mon. Wea. Rev., 125*, 1931-1953.