Evolution and Tracks of tropical cyclone in post-monsoon season over Bay of Bengal

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Abstract

The most challenging topics in meteorology and climatology are that of understanding the tropical cyclone. The Bay of Bengal is highly vulnerable to tropical cyclogenesis and the tropical cyclone is one of the most disastrous atmospheric phenomena in the tropics, which forms over the warm oceans and ravage life and property especially over the coastal belt due to extremely strong winds and associated storm surges at the time of landfall. To save the life and minimize the damages it is necessary to make advance warning and prediction of tropical cyclone quite ahead of time before landfall. The October to November is the post-monsoon duration and a study has been conducted to investigate the genesis and forecasting of tropical cyclone in this season using Weather Research and Forecusting (WRF) model with a horizontal resolution of 24 km. In the case of Very Severe Cyclonic Storm (VSCS) Madi the actual landfall position was (11.1°N 80.7°E) but simulated of that is (11.2°N, 79.9°E) and in the case of Very Severe Cyclonic Storm (VSCS) Thane the actual landfall position was (11.8°N 81.1°E) but simulated of that is (12.1°N, 81°E) with mean distance error of 101.5 km which was much lower than the errors of the previous studies. So, the model predicts well the forecasting of probable areas at the time of landfall with high accuracy of prediction.

Keywords: Tropical cyclone, Genesis, WRF-ARW, Bay of Bengal and Very Severe Cyclonic Storm (VSCS)

1. Introduction

The tropical cyclones are perhaps the most devastating of natural disasters of the tropics because of the loss of human life they cause and the large economic losses they induce [1-3,26-28]. A single storm in Bangladesh in 1970 killed nearly half a million people [4,5]. Vulnerability to tropical cyclones is becoming more pronounced because the fastest population growth is in tropical coastal regions. In recent years, attempts to associate tropical cyclone trends with climate change resulting from greenhouse warming has led to additional attention being paid to tropical cyclone predictio [6]. It is a low-pressure system with maximum sustainable winds over 62 km/hr; this can go up to around 300 km/hr. The tropical cyclones being formed in the Bay of Bengal frequently hit the coastal regions of Bangladesh, India and Myanmar to a lesser extent, Sri Lanka and thereby cause damages to lives and properties [13-21]. The Bay of Bengal basin is highly vulnerable to strong tropical cyclogenesis because it generally maintains a temperature between (28-30) °C during the tropical cyclone seasons [6]. The distribution of the average temperature of the Bay of Bengal also indicate that the Bay of Bengal SST is sufficiently warm and has high potential for tropical cyclogenesis due to the existence of sufficiently large energy pool in its deep boundary layer. The above authors have also shown that the depth of 26°C isotherm (D26) varies from (70-100) meter during the cyclone seasons and lies over the central and southern Bay. Besides, high values of Cyclone Heat Potential (CHP> 16 kcal/cm^2) has been found over the regions of the Bay of Bengal with high frequency of tropical cyclone formation. In recent years, attempts to associate tropical cyclone trends with climate change resulting from greenhouse warming has led to additional attention being paid to tropical cyclone prediction [7,8].

1.1 Aspects of the study

For prediction of tropical cyclone, it is necessary to understand the physical mechanism of its. To take proper preparedness and rescue operation the advance warning and prediction of tropical cyclone quite ahead of time is highly important. Several researchers reported modeling experiments to predict the Bay of Bengal cyclones in the recent years [7-12,31-33]. Some researchers have superimposed artificial vortex using bogussing technique based on satellite information in the initial field so that the models are able to predict further intensification and evoluation of the systems. There is a research gap in prediction of the tropical cyclonic genesis and forecasting accurately and this research gap motivated us to find out the genesis and forecasting more accurately. This is the first time an attempt has been made to simulate the post-monsoon tropical cyclonic disturbance with initial field condition. This paper is arranged under section 2 on methodology, section 3 on results and discussions, and section 4 on conclusion.

2. Methodology

Some parameters like the Minimum Sea Level Pressure (MSLP), Pressure drop (ΔP), Maximum Wind Speed (MWS) are analysis using WRF model which is a new generation mesoscale numerical weather forecasting community model which has the potential to simulate meteorological phenomena ranging from meters to thousands of kilometers. Also it is a dynamic solver [16], which is compatible with the WRF system to simulate broad spectrum of meteorological phenomena. The model is developed by the Mesoscale and Microscale Meteorological (MMM) Division of National Centre for Atmospheric Research (NCAR) of USA. It integrates the compressible, non-hydrostatics Euler equation, which are cast in flux from with terrain-following mass vertical coordinates [9]. The model simulated results have been presented in the graphical and tabular forms. Grid Analysis and Display System (GrADS) have been employed for visualization of model outputs. Finally the model outputs have been compared with Joint Typhoon Warning Center (JTWC) best track data [7], to demonstrate the performance of the modeling exercise. The discussions of the results are provided with necessary physical interpretation. Model was run for 24, 48, 72, 96 hrs to study the genesis and forecasting of selected tropical cyclones developed over the Bay of Bengal. National Centre for Environment Prediction (NCEP), Final Reanalysis (FNL) data ($1^{\circ}\times1^{\circ}$ resolution) was utilized as initial and lateral boundary conditions (LBCs) which are updated at six hourly intervals. The model was initialized with 0000, 0600, 1200 and 1800 UTC initial field of corresponding date.

2.1 Domain selection

To simulate above selected tropical cyclones a domain of dimension (3.0-24.0)°N and (69.0-98.0)°E was selected to cover the Bay of Bengal basin at 24 km horizontal resolution with 27 vertical η levels. Figure 1: shows the horizontal domain of the model.

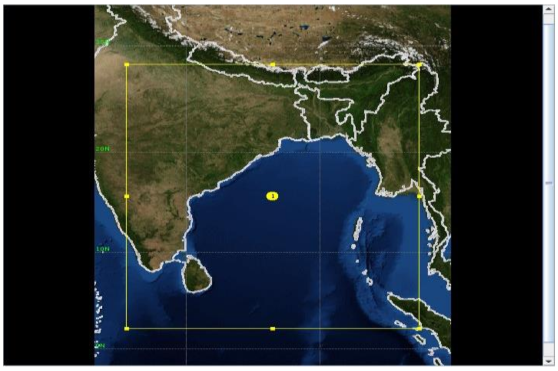


Figure 1: Model domain with 24 km×24 km horizontal resolution Bay of Bengal

3. Results and Didcussion

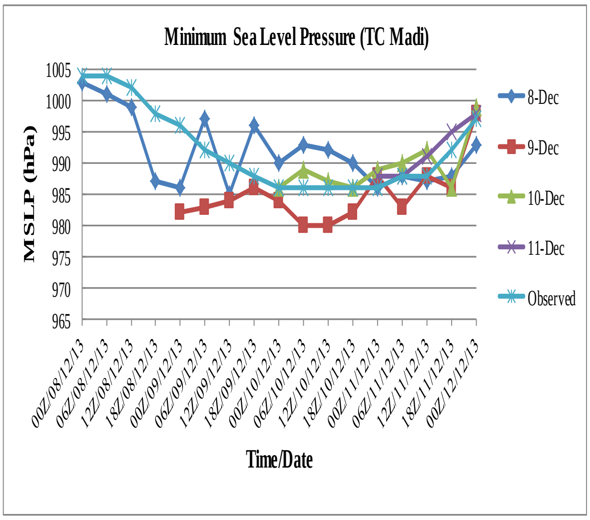
3.1 Minimum Sea Level Pressure

Minimum sea level pressure (MSLP) of a tropical cyclone is of great importance as it helps to measure the intensity of a cyclone. Since tropical cyclones develop over the vast oceanic areas, where observations are spares or not available, it is of great difficulty to make any validation of model simulated MSLP with sea truth data before the landfall. The model simulated and observed MSLP of all selected cyclones at the stage of their highest intensity are summarizesd in Table 1. In the Table, initial conditions are written in column 2 and the corresponding simulated lowest values of MSLP along with its obtaining time are written in column 4. The observed MSLP at the time of lowest simulated MSLP is writen in column 5. Finally, the lowest observed value of MSLP is written in column 6.

Table 1: Minimum Sea Level Pressure (MSLP) at the stage of highest intensity

Name of Cyclone	Initial Date/Time (UTC)	Forecast Hours	Simulated MSLP (hPa) [Date/Time]	Observed MSLP (hPa) [Corrospondind of simulation Date/Time]	Full track observed MSLP (hPa) [Date/Time]
Madi (2013)	8 December/0000	96	985 [9 Dec./1200]	990 [9 Dec./1200]	986[11 Dec./0000]
	9 December/0000	72	982 [9 Dec./0000]	996 [9 Dec./0000]	
	10 December/0000	48	986 [10 Dec./0000]	986 [10 Dec./0000]	
	11 December/0000	24	988 [11 Dec./0600]	988 [11 Dec./0600]	
Thane (2011)	26 December/0000	96	974 [29 December/0600]	978 [29 December/0600]	974[29 December/1200]
	27 December/0000	72	990 [29 December/0000]	982 [29 December/0000]	
	28 December/0000	48	982 [29 December/1800]	998 [29 December/1800]	
	29 December/0000	24	991 [29 December/1800]	998 [29 December/1800]	

Conclusion from table 1 that for Very Severe Cyclonic Storm Madi among all simulated MSLP values, the 72 hrs predicted MSLP 982[9 December/0000] is nearest the observed value 986 [11December/0000]. For Very Severe Cyclonic Storm Thane among all simulated MSLP values, the 96 hrs predicted MSLP 974 [29 December/0600] is nearest the observed value 974 [29 December/1200]. So it is also seen that the model underestimates the intensity in terms of MSLP for all the selected tropical cyclones under consideration. The figure 2 show the comparative evalution of observed and model simulated MSLP.



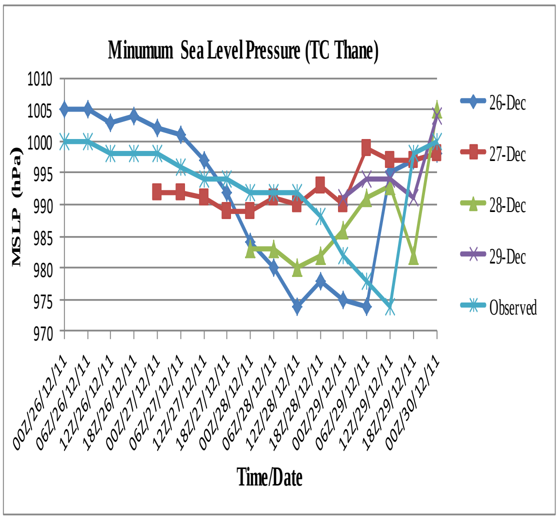


Figure 2: Minimum Sea Level Pressure with time of Very Severe Cyclonic Storm Madi and Very Severe Cyclonic Storm Thane

3.2 Pressure Drop

Pressure drop (Δp) is another important parameter of tropical cyclone in measuring its intensity. Pressure drop of the tropical cyclone is determined as the difference between pressure of the outer most closed isobar and MSLP. In the Table 2 initial conditions are written in column 2 and the corresponding simulated highest values of pressure drop along with its obtaining time are written in column 4 and its estimated (√Δp) is in column 5. The observed pressure drop at the time of highest simulated pressure drop is writen in column 6. Finally, the highest observed value of Pressure drop is written in column 7.

Table 2: Maximum pressure drop **(Δp)** at the stage of highest intensity

Name of Cyclone	Initial Date/Time (UTC)	F/H	Simulated (Δp) [Date/Time]	Estimated (√Δp) [Date/Time]	Observed (Δp) [Corresponding of simulation [Date/Time]	Full track observed (Δp) [Date/Time]
Madi (2013)	8 December/0000	96	15 [9 Dec./1200]	3.87[9 Dec./1200]	12 [9 Dec./1200]	19 [9 Dec./0000]
	9 December/ 0000	72	18 [9 Dec./0000]	4.24[9 Dec./0000]	16 [9 Dec./0000]	
	10 December/0000	48	10 [10 Dec./0000]	3.16[10 Dec./0000]	6[10 Dec./0000]	
	11 December/0000	24	6 [11 Dec./0600]	2.44[11 Dec./0600]	3 [11 Dec./0600]	
Thane (2011)	26 December/0000	96	30 [29 December/0600]	5.57[29 December/0600]	17 [29 December/0600]	28 [29 Dec./0000]
	27 December/0000	72	22 [29 December/0000]	4.69[29 December/0000]	28 [29 December/0000]	
	28December/0000	48	25 [29 December/1800]	5.00[29 December/1800]	14 [29 December/1800]	
	29 December/0000	24	16 [29 December/1800]	4.00[29 December/1800]	14 [29 December/1800]	

It is noted that for TC Madi 24 hrs predictions simulates the lowest ΔP 6 hPa and 72 hrs predictions simulated the highest ΔP 18 hPa. but 96 hrs and 48 hrs it are 15 hPa and 10 hPa respectively and for TC Thane 24 hrs prediction simulates the lowest ΔP 16 hPa and 96 hrs prediction simulates the highest ΔP 30 hPa, but 72 and 48 hrs it are 22 hPa and 25 hPa. More conclusion that for Very Severe Cyclonic Storm Madi among all simulated ΔP values, the 72 hrs predicted ΔP 18 [9 December/0000] is nearest the observed value 19 [9December/0000. For Very Severe Cyclonic Storm Thane among all simulated ΔP values, the 96 hrs predicted ΔP 30 [29 December/0600] is nearest the observed value 28 [29 December/0000]. So it is also seen that the model underestimates the intensity in terms of ΔP of tropical cyclones under consideration. Figure 3 show the time variations of model simulated and observed pressure drop. For all cases it increases with time up to the highest maturity stage of the respective cyclones and it is more or less in good agreement with the observed values.

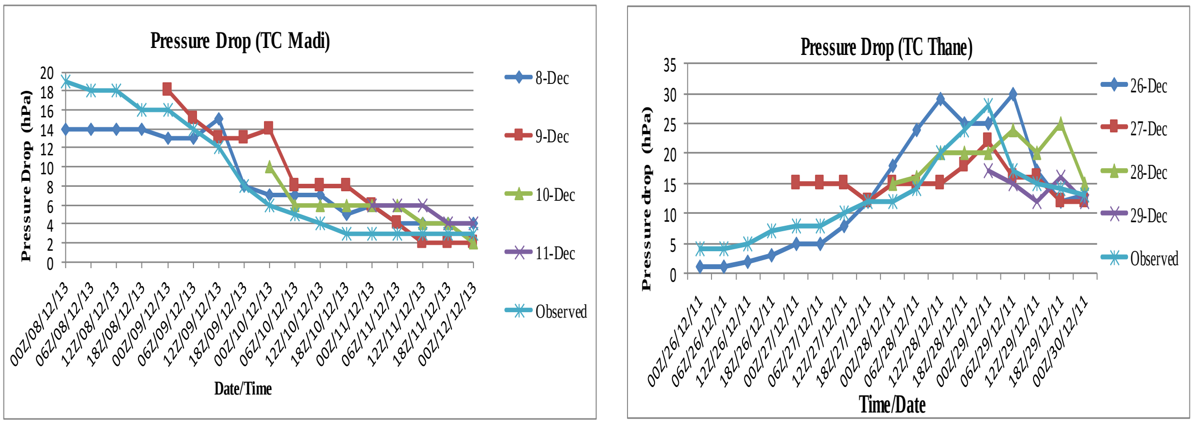


Figure 3: Model simulated and observed pressure drop with time of Very Severe Cyclonic Storm Madi and Very Severe Cyclonic Storm Thane.

3.3 Maximum Wind Speed

Maximum wind speed (MWS) is another important parameter of tropical cyclones for measuring its intensity. It is of importance as it directly devastates the affected area at the time of landfall, it is the most active driving force of generating storm surge over the area of landfall. Table 3 summarizes model and observed MWS of selected cyclone. These surface winds are taken at the standard meteorological height of 10 meter in an unobstructed exposure. In the Table 3, initial conditions are written in column 2 and the corresponding simulated highest values of MWS along with its obtaining time are written in column 4, estimated values in column 5. The observed MWS at the time of highest simulated MWS is writen in column 6. Finally, the highest observed value of MWS is written in column 7. MWS has been estimated by modified Fletcher's formula (1995) [29], $V_{max}=13.6\sqrt{\Delta p}$, [30] using modeled pressure drop (Δp). Here Δp is in hPa and V_{max} is in knots. The simulated values obtained using initial field condition.

Table 3: Maximum wind speed (MWS) of selected tropical cyclones at the stage of highest intensity

TC	Initial Date/Time (UTC)	F/H	Simulated MWS in m/s [Date/Time]	Estimated MWS in knots [Date/Time]	Observed MWS in m/s [corresponding of simulated [Date/Time]	Full track observed MWSin m/s [Date/Time]
Madi	8 December/0000	96	50[9 Dec./1200]	98.00[9 Dec./1200]	50[9 Dec./1200]	65[9 Dec./0000]
	9 December/0000	72	55[9 Dec./0000]	107.8[9 Dec./0000]	65[9 Dec./0000]	
(2013)	10 December/0000	48	37[10 Dec./0000]	72.52[10 Dec./0000]	30[10 Dec./0000]	
	11 December/0000	24	26[11 Dec./0600]	50.96[11 Dec./0600]	25[11 Dec./0600]	
Thane (2011)	26 December/0000	96	68[29 December/0600]	133.28[29 December/0600]	75[29 December/0600]	75[29 December/1800]
	27 December/0000	72	64[29 December/0000]	125.44[29 December/0000]	70[29 December/0000]	
	28 December/0000	48	66[29 December/1800]	129.36[29 December/1800]	75[29 December/1800]	
	29 December/0000	24	60[29 December/1800]	117.60 [29 December/1800]	75[29 December/1800]	

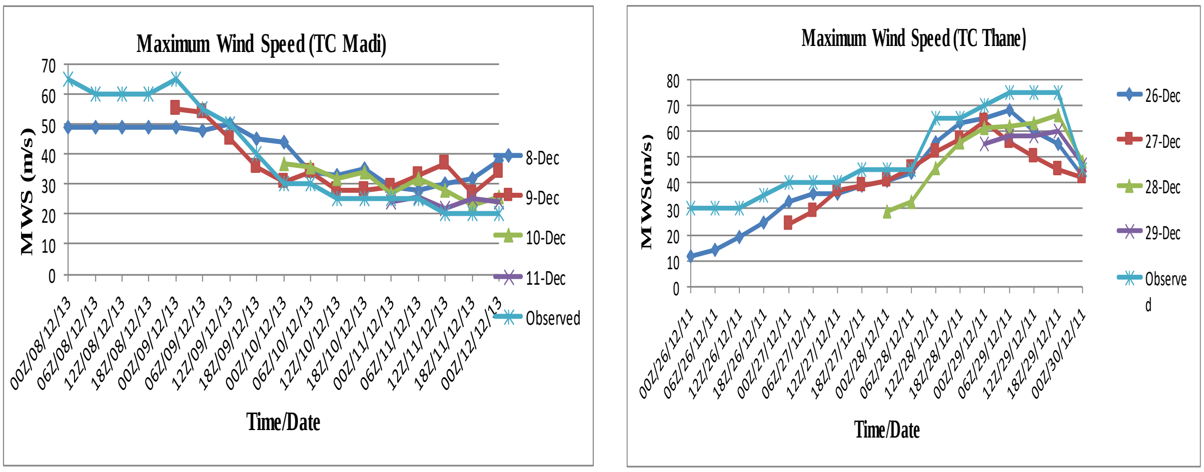


Figure 4: Model simulated and observed MSW with time of Very Severe Cyclonic Storm Madi and Very Severe Cyclonic Storm Thane

It is noted that for Very Severe Cyclonic Storm Madi 24 hrs predictions simulates the lowest MWS 26 m/s and 72 hrs prediction simulated the highest MWS 55 m/s, but 96 hrs and 48 hrs it are 50 m/s and 37 m/s respectively and for Very Severe Cyclonic Storm Thane 24 hrs prediction simulates the lowest MWS 60 m/s and 96 hrs prediction simulates the highest MWS 68 m/s, but 72 and 48 hrs it are 64m/s and 66 m/s. More conclusion for Very Severe Cyclonic Storm Madi among all simulated MWS values, the 72 hrs predicted MWS 55 [9December/0000] is nearest the observed value 65 [9December/0000] and for Very Severe Cyclonic Storm Thane among all simulated MWS values, the 96 hrs predicted MWS 68 [29 December/0600] is nearest the observed value 75 [29 December/1800]. Figure 4 show the time variations of model simulated and observed pressure drop. For all cases it increases with time up to the highest maturity stage of the respective cyclones and it is more or less in good agreement with the observed values. So it is also seen that the model underestimates the intensity in terms of MWS for all the selected tropical cyclones under consideration.

The model successfully simulates the genesis of minimum sea level pressure (MSLP), Pressure drop (Δp), maximum wind speed (MWS) and the results indicate realistic relations among parameters with different intensity of the tropical cyclone.

3.4 Tracks of VerySevere Cyclonic Storm Madi

This experiment is carried out with the initial field of 0000UTC of 7 December for capturing recurvature of the track. The prediction experiments captured well the direction of motion, recurvature and probable areas of landfall. The tracks of Madi show that the prediction experiments captured well the direction of motion and probable areas of landfall.

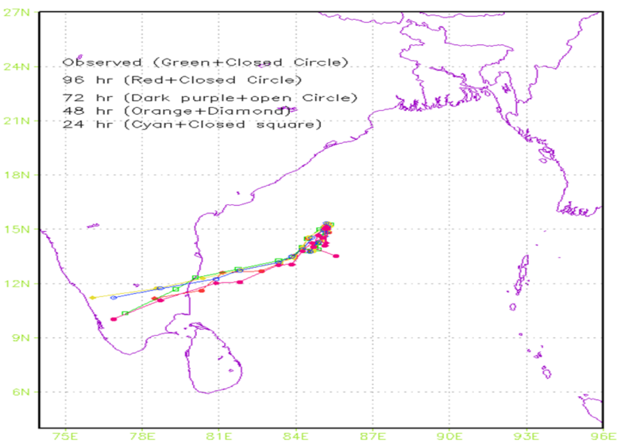


Figure 5: Model simulated trasks of Very Severe Cyclonic Storm Madi.

The forecast tracks agreed well with the observed track and indicated landfall at Tamil Nadu coast close to Vedaranyam around 1330 UTC on December 12, 2013, fairly close to the actual. It is noted from observed information that the very severe cyclonic storm Madi remained stationary near 13.7ºN/83.5ºE for some time on 12 December, 2013 and abruptly changed its direction and started to move towards the north-east. It then emerged into the Palk Strait at 1530 UTC and crossed the Tamil Nadu coast near Tondi at 1700 UTC on the same day. Colachel in Kanyakumari district of Tamil Nadu got the highest rainfall of 115 mm in 24 hours on December13. Figure 5 shows that the model forecast also captured well this recurvature towards northest after the initial northwest movement and the stationary feature of the tracks.

3.5 Tracks of Very Severe Cyclonic Storm Thane

This experiment is carried out with the initial field of 0000UTC of 26 December for capturing recurvature of the track. The prediction experiments captured well the direction of motion, recurvature and probable areas of landfall. The tracks of very severe cyclonic storm Thane show that the prediction experiments captured well the direction of motion and probable areas of landfall. The 96 hrs, 72 hrs, 48 hrs and 24 hrs forecast tracks agreed well with the observed track and indicated landfall at Tamil Nadu coast between Cuddalore and Puducherry and rapidly weakenen into a depression and fairly close to the actual. The 72 and 48 hrs predicted tracks finally deviated to northeast from the observed track.

It is noted from observed information that the very severe cyclonic storm Thane remained stationary near 12.0ºN/82.0ºE for some time on 29 December 2011 and abruptly changed its direction and started to move towards the north-east direction. Figure 6 shows that the model forecast also captured well this recurvature towards northest after the initial northwest movement and the stationary feature of the tracks. With some position and timing errors figure 5 and figure 6 demonstrate that model captured more or less realistic of track movement of cyclone

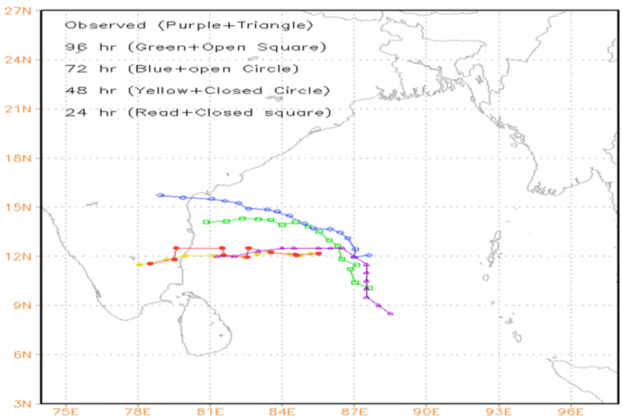


Figure 6: Model simulated trasks of very severe cyclonic storm Thane.

3.6 Landfall forecast errors

As landfall of tropical cyclones is very important to the cyclone forecasters, the landfall position and time errors are investigated for evaluating the model performances. The results are presented in Tables 4-5. It reveals that reducing the prediction hours with updated initial fields reduces the time errors.

Table 4: Landfall point and time errors during very severe cyclonic storm Madi

Base Date/Time (UTC)	Forecast Hours	Landfall Forecast		Actual Landfall		Errors	
		Position Lat^{O}N/Lon^{O}E	Date/Time (UTC)	Position Lat^{O}N/Lon^{O}E	Date/Time (UTC)	Distance (km)	Time (hrs)
9/0000	96	11.2/79.9	12/1600	11.1/80.7	12/0900	89 nw	7 D
10/0000	72	11.2/79.8	12/0300	-do-	-do-	99 nw	6 E
11/0000	48	12.1/79.6	12/0300	-do-	-do-	163 nw	6 E
12/0000	24	12.1/80.9	12/0600	-do-	-do-	112 ne	3 E

*D: Delay and E: Early

Table 5: Landfall position and time errors during very severe cyclonic storm Thane

Base Date/Time (UTC)	Forecast Hours	Landfall Forecast		Actual Landfall		Errors	
		Position Lat^{O}N/Lon^{O}E	Date/Time (UTC)	Position Lat^{O}N/Lon^{O}E	Date/Time (UTC)	Distance (km)	Time (hrs)
26/0000	96	12.1/81.00	29/1200	11.8/81.1	29/2100	187 nw	9 E
27/0000	72	12.8/80.00	29/1600	-do-	-do-	110 nw	5 E
28/0000	48	12.9/80.10	29/1800	-do-	-do-	163 nw	3 E
29/0000	24	12.6/80.9	29/2300	-do-	-do-	91 nw	2 D

*D: Delay and E: Early

3.7 Errors in Track Forecasting

Forecast verification has been carried out in the present study by computing the position error- the geographical distance between the predicted location of the tropical cyclones and the verifying position at the valid hour. The position error of a tropical cyclone is an essential indicator for researchers to understand the model performance. It helps to properly tune the model by conducting sensitivity experiments before applying for real time prediction. It is worth noting that the mean position errors is calculated considering all the forecasted points for the period ranging from 24 hrs to 96 hrs throughout the passage of cyclone till the landfall.

Table 6: Mean landfall position and time errors of selected tropical cyclones

Forecast predictions	Mean Landfall Distance Errors (km)	Mean Landfall Time Errors (hrs)
96 hrs	138.0	8.0
72 hrs	104.5	5.5
48 hrs	163.0	4.5
24 hrs	101.5	2.5

The mean landfall position and time errors of selected cyclones are calculated considering only the magnitude. In table 6 the mean landfall position errors for 96 hrs, 72 hrs, 48 hrs and 24 hrs are 138 km, 104.5 km, 163 km, and 101.5 km respectively and respective mean time errors are 8.0 hrs, 5.5 hrs, 4.5 hrs, and 2.5 hrs. The 24 hrs and 48 hrs predictions show low landfall time errors than that of 72 hrs and 96 hrs predictions. Mean position errors in track prediction of some previous studies. Mathur and Ruess [22], in an evaluation of the QLM's forecast track guidance in NMC Washington during the period 1998-90 reported mean forecast errors in the range of 180-190 km for 24 hrs, 300-370 km for 48 hrs, and 400-540 km for 72 hrs forecasts. Rao and Prasad [31] have reported mean position errors of around 167 km for 24 hrs, 367 km for 48 hrs and 433 km for 72 hrs forecasts in respect of the QLM experiments carried out earlier. Goerss [25] has reported mean position errors in track prediction with GFDL of about 142 km for 24 hrs, 246 km for 48 hrs and 364 km for 72 hrs predictions. After making cyclone track prediction experiments with QLM at 40 km horizontal resolution for nine cyclonic storms developing during the period 1997-2000, Prasad [12] have reported the mean position errors of about 122 km for 24 hrs, 256 km for 48 hrs and 286 km for 72 hrs predictions. Though this level of forecast errors in quite large, particularly in the higher forecast range, from the point of view of dependability of WRF guidance for operational cyclone track prediction. It appears from the above discussion that the WRF model is high potential to forecast position and time of landfall of Bay of Bengal cyclones with the certain amount of uncertainty.

4. Conclussions

One of the outstanding findings of the study is that the model has successfully predicted the probable areas of the selected tropical cyclones with high accuracy predictions. It may finally be concluded that the WRF model used in the present study with high resolution has high potential to predict the evolution and tracks of the tropical cyclones of the Bay of Bengal. The WRF model successfully simulates the evolution process and more or less realistic intensification of tracks movement. In some cases the model underestimated the intensity of the cyclonic system. The model results indicate that the longer range prediction provides better intensity forecasting. The model generates a realistic genesis and tracks movement of the tropical cyclones with high spatial details without use of any idealized vortex in the initial. This has been possible due to the higher spatial resolution of the regional model. However, there are scopes for further studies on sensitivity experiments with proper combination of physical and dynamical options along with appropriate sub-grid scale parameterization schemes for proper tuning of the model to improve the prediction and reduce the forecast errors. Horizontal and vertical grid resolutions preferably with nesting options are other important model features to be tested to improve the model performance. The Bay of Bengal is a data sparse region, improvement of the meteorological network through deployment of fixed and floating data collection buoys over the Bay of Bengal will improve the initial field and thus the performance of the model will also improve.

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