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Simulation of Track and Landfall of Tropical Cyclone Viyaru and Its Associated Strom Surges Using NWP Models

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Abstract Simulation of track and landfall of the tropical cyclone Viyaru that formed over the southern Bay of Bengal during 11-16 May 2013 has been carried out using Weather Research and Forecasting (WRF) and MRI model. The WRF model was run in a single domain of 9 km horizontal resolution using KF cumulus parameterization schemes, WSM6 micro physics and YSU planetary boundary layer scheme. The model was run for 24, 48, 72 and 96 hrs using NCEP FNL initial and lateral boundary condition. The model has successfully predicted the tracks, re-curvature, areas and time of landfall of the selected tropical cyclone Viyaru. Even in the 96 hrs predictions the model has successfully predicted with reasonable accuracy. The lowest position error was found only 56 km and lowest time error was found 01 hour. The results clearly demonstrate that the track prediction error increases as the forecast hours increases except 24 hrs simulation. However, these results show the advantage of using WRF model with high resolution in prediction of the selected tropical cyclone Viyaru over the Bay of Bengal. Model simulated track was compared with that of BMD observed track and found that the model has captured the track in reasonably well. The storm surges and maximum tide was also simulated by MRI model at the time of landfall of Viyaru and compared with the BMD's and Inland Waterways Transport Authority's (BIWTA) estimated storm surges and maximum tide data. It is found that the model has also simulated the storm surges and maximum tide due to Viyaru in 24-hrs advance of landfall time.

Keywords: *track, landfall, storm surge, WRF model, MRI model*

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1. Introduction

Tropical cyclones (TC) are one of the most intense weather hazards of all meteorological phenomena that form over the tropical oceans/seas. These occur during the pre-monsoon (March – May), post-monsoon (October – November) seasons over Bay of Bengal. Every year, they cause considerable loss of lives and do immense damage to property. Strong winds, heavy and torrential rains, and the cumulative effect of storm surges are the three major elements of tropical cyclone disaster. Huge loss of life and property is mainly caused due to storm surges. Bangladesh accepts about 40% of the impact of total storm surges in the World. The Bay of Bengal and the Arabian Sea is the basin where TCs do the most damage due to the combined effects of meteorological forcing, high astronomical tide, shallow bathymetry and funneling shape of the Bay. The development of tropical cyclone over the Bay of Bengal is accounts for about 7% of the global annual total number of tropical cyclones [16]. These meteorological hazards, which formed during the period, October through December are highly devastating nature and causes loss of life and property damage, especially when they cross the coastal states of India and Bangladesh [9]. Thus any accurate prediction of the Bay of Bengal cyclones is of great importance to avoid/reduce the loss of life and damages to property. There are several studies relating to tropical cyclone/hurricane simulations. Surface fluxes of latent and sensible heat play a vital role in the development and maintenance of tropical cyclones [6]. The favourable conditions for the formation of tropical cyclone have been known for some time and it requires a pre-existing disturbance of sufficient amplitude such that air-sea interaction can occur [16,22,28]. Later Anthes and Chang [3] showed the sensitivity of Planetary Boundary Layer (PBL) parameterization in the simulation of hurricanes. Next, there have been considerable improvements in the field of prediction by numerical models during last two decades. High-resolution limited area models as well as global models are now being extensively used by most of the leading operational Numerical Weather Prediction (NWP) centres of the world. Performance of a numerical model in tropical cyclone forecast depends on how good the convection is parameterized in the model. Cumulus convection, surface fluxes of heat, moisture, momentum, vertical mixing in the PBL, radiative heating and cooling also play important roles in the development of tropical cyclones [4]. These consist of a series of practically necessary, but by no means sufficient, constraints on SST, environmental shear (weak), presence of ambient cyclonic vorticity and large-scale divergence aloft [14].

Track forecasting has been a challenging task for meteorologists over the last few decades in spite of the rapid development of numerical weather prediction techniques. There had been numerous studies on track forecasting using several models such as QLM, MM5, FSU GSM & NRSM, GFDL, BMRC, etc. over the Bay of Bengal and other basins as well. However, In India, development of objective techniques for forecasting track of TCs began in 1972 [31] by using a computer oriented half persistence and half climatology technique. Singh and Saha [32] used case studies for forecasting movement of TCs by adopting a primitive equation barotropic model. In recent years, Mohanty and Gupta [23], and Gupta and Bansal [17] have used multi-level primitive equation models with parameterization of physical processes. QLM has also been implemented in IMD for operational track forecast up to 72 h in the year 2000. Prasad and Rama Rao [27] have evaluated the QLM and its performance is found to be even better. In Bangladesh, Prasad [24,25,26] has studied the cyclone track prediction experiments in some historical cases of tropical cyclones formed over the Bay of Bengal with a QLM. The structure and movement of Cyclonic Storms over the North Indian Ocean simulated by WRF-ARW model carried out by Basnayake *et. al.,* [5]. The cyclonic disturbances in the north Indian Ocean move predominantly along westerly /northwesterly direction. However, some cyclonic disturbances re-curve from an initial northwesterly direction to a northerly direction (often after reaching 15–20°N latitude) and finally towards northeasterly direction [19]. The detailed review of the synoptic and thermodynamic characteristics to predict the movement and intensification/decay of the cyclonic storm has been discussed by Krishna Rao [21]. A review of the dynamic characteristics of the movement and intensification is given by Mohanty and Gupta [23]. The motion of TC is the result of a complex interaction between a number of internal and external influences. Environmental steering is typically the most prominent external influence on a Cyclonic Storm, accounting for as much as 70–90% of the motion. Theoretical studies have shown that in the absence of environmental steering, Cyclonic Storms move poleward and westward due to the internal influences [7,13]. The dominant influence on movement is the large-scale environmental steering. These tracks of movement are mainly due to the normal upper airflow pattern prevailing in the cyclone period. However, many forces act on the cyclonic disturbance and consequently its motion is never along a smooth path. There is also non-linear interaction between the cyclonic disturbance and the basic current in which it is embedded. Hence, the movement of the storm depends on many factors including synoptic, thermodynamic and dynamical factors. Analysis by Srinivasan and Ramamurthy [35] found that the position of the ridge line at 200 hPa is seen to govern the movement to a large extent. They have seen that when the centre is north of the ridge line but within 3° of it, in the majority of the cases a dominant easterly component of motion appears, whereas when the storm reaches beyond 3° north of the ridge line, it gets a definite eastward motion.

In these regions several studies have also been undertaken for storm surge simulation using different NWP models. Ali [1] studied storm surges and sea level rise in the Bay of Bengal. Ali *et. al.* [2] investigated the river discharge, storm surges and tidal interaction in the Meghna river mouth in Bangladesh; and back water effect of tides and storm surges on fresh water discharge through the Meghna estuary. Dube *et. al.* [10,11,12,34] and Das *et. al.* [8] have developed numerical models to observe the dynamic effect of curving coasts and the direction of motion of the storm relative to the coast on the location of the peak surge. Sinha *et.al.* [12,33] developed numerical model to simulate storm surges and sea level rise in the Indian coasts adjacent to the Bay of Bengal and the Arabian Sea.

In this study, the high resolution Advanced Research WRF (ARW) meso-scale model adopted from NCAR and is used to simulate the track and landfall of the cyclonic storm 'Viyaru' that crossed Bangladesh coast near lat. 22.8°N and long. 91.4°E about 30 km south of Feni around 0800 UTC of 16th May 2013 with sustained maximum wind speed of about 85-95kph. Wind and storm surge are crucial factors in the determination of how much damage occurs in the coastal regions in association with any particular hurricane or tropical cyclone. In this study, another simulation is also performed using MRI storm surge model with actual cyclone track data of BMD.

The objective of the present study is to evaluate the performance of the model towards simulation of track and landfall of the cyclonic storm 'Viyaru' and its associated storm surges caused due to the selected storm.

2. Synoptic Description of Tropical Cyclone Viyaru

A depression formed over southeast Bay of Bengal at 0900 UTC of 10th May 2013 near latitude 5.0°N and longitude 92.0°E [19]. It moved northwestwards and intensified into a deep depression in the evening of the same day. Continuing its northwestward movement, it further intensified into a cyclonic storm, Viyaru in the morning of 11th May 2013. Under the influence of the anticyclonic circulation lying to the east, the cyclonic storm changed its direction of movement initially from northwesterly to northerly and then to north-northeasterly on 13th and 14th May respectively. On 15th May, it further came under the influence of the mid-latitude westerly trough running roughly along 77°E, which further helped in enhancing the north-northeastward speed of the cyclonic storm. The cyclonic storm crossed Bangladesh coast near lat.22.80°N and long. 91.40°E, about 30 km south of Feni around 0800 UTC of 16th May 2013 with a sustained maximum surface wind speed of about 85-95 kmph. After the landfall, it continued to move north-northeastwards and weakened gradually due to interaction with land surface. It weakened into a deep depression over Mizoram in the evening and into a depression over

Manipur, India around mid-night of 16th May. It further weakened into a well marked low pressure area over Nagaland, India in the early morning and moved away towards Myanmar as a low pressure area in the morning of 17th May. The satellite and radar imagery of Cyclonic Storm (CS) Viyaru is depicted in Figure 1 and Figure 2 respectively at the time of landfall.

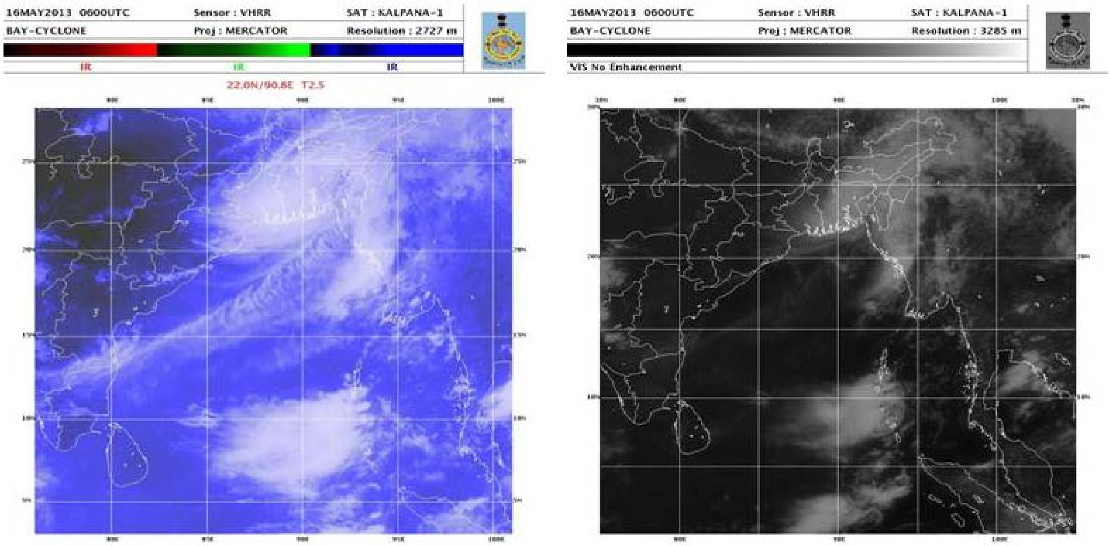

Figure 1. IR and VIS Satellite Imageries of Kalpona-1 of the cyclonic storm VIYARU at 0600 UTC on 16 May, 2013 respectively

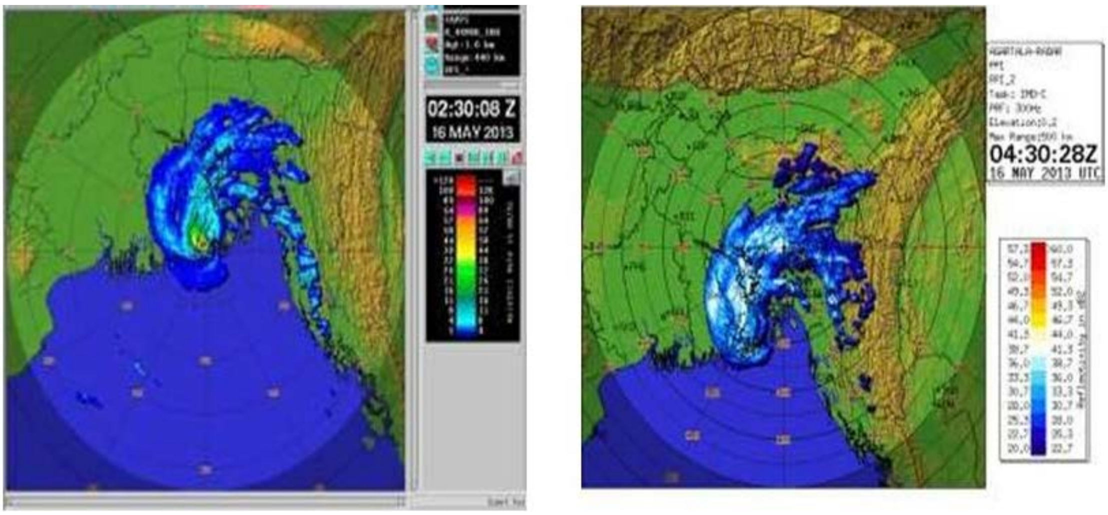

Figure 2. Radar Imageries of Khepupara and Agartala station of the cyclonic storm Viyaru at 0230 UTC and 0430 UTC on 16 May, 2013 respectively

3. Data Used, Model Experimental Setup and Methodology

The Weather Research and Forecasting (WRF) is a next generation mesoscale numerical weather forecasting community model, which has the potential to simulate meteorological phenomena ranging from meters to thousands of kilometers. There are two dynamics solvers in the WRF system: the Advanced Research WRF (ARW) solver (originally referred to as the Eulerian mass or “em”) developed primarily at NCAR, and the NMM (Nonhydrostatic Mesoscale Model) solver developed at NCEP. The ARW system consists of the ARW dynamics solver with other components of the WRF system needed to produce a simulation [30]. The ARW dynamic core of WRF model (WRF-ARW) version 3.6 has been implemented during the present study.

3.1. Data Used

The Final (FNL) Operational Model Global Tropospheric Analyses of National Centre for Environmental Prediction (NCEP) on 1.0°×1.0° grids covering the entire globe every 6-h were taken as the initial and lateral boundary condition. The 30 sec United States Geological Survey (USGS) data were used to simulate the Terrain/Topography and the 25 Categories United States Geological Survey (USGS) data were taken as vegetation/land use fields. The observed track data of Bangladesh Meteorological Department (BMD) were used to compare or validate the model simulated track. The observed position and maximum sustained wind data of BMD were also used as input for MRI Storm surge model.

3.2. Model Experimental Setup and Methodology

The experiment was performed on a single domain at 9 km horizontal resolution. The domain configuration in WRF model for the present study is shown in Figure 3. The Domain has 295×304 grid points in the west-east and north-south directions respectively. The domain was configured to have the same vertical structure of 38 unequally spaced sigma (non-dimensional pressure) levels. The physical parameterization schemes used in this study are Kain-Fritsch (new Eta) scheme for cumulus parameterization [20] and WRF Single Moment 6-class (WSM6) scheme for microphysics [18], Yonsei University (YSU) scheme for planetary boundary layer.

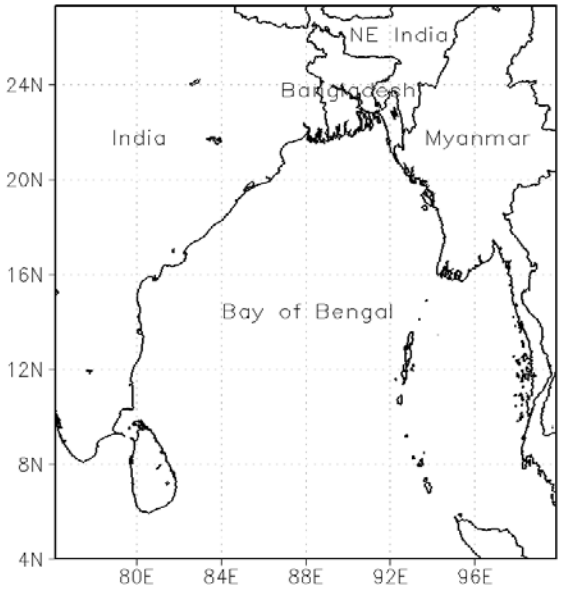

Figure 3. WRF Model Domain for the NWP study

The WRF model was run for 24, 48, 72 and 96 hours based on the initial condition of 0000 UTC of 13, 14, 15 and 16 May 2013.. On 16 May, 2013, the cyclonic storm Viyaru centered over the southeastern part of Bangladesh and recorded heavy to very heavy rainfall over different parts of Bangladesh. Bangladesh Meteorological Department (BMD) has recorded 232 mm rainfall at Khepupara, 122 mm rainfall at Patuakhali, and 95 mm rainfall at Barisal on 15 May 2013 and 58 mm rainfall at Khepupara, 123 mm rainfall at Patuakhali, and 122 mm rainfall at Barisal on 16 May 2013. The model derived synoptic situations valid for 1200 UTC (just after landfall) of 16 May 2013 are presented and analyzed in the present paper with special attention to the above stations.

4. Results and Discussion

The results and discussion of the study are outlined in the following sections.

4.1. Mean Sea Level Pressure Analysis

The formation of low pressure area is an important initial condition for possible weather disturbances which may intensify into a tropical cyclone when the favourable conditions prevail. The model derived mean sea level pressure (hPa) of the cyclone Viyaru valid at 1200 UTC of 16 May, 2013 based on the initial condition of 0000 UTC of 13, 14, 15 and 16 May 2013 are shown in Figure 4 (a-d) respectively.

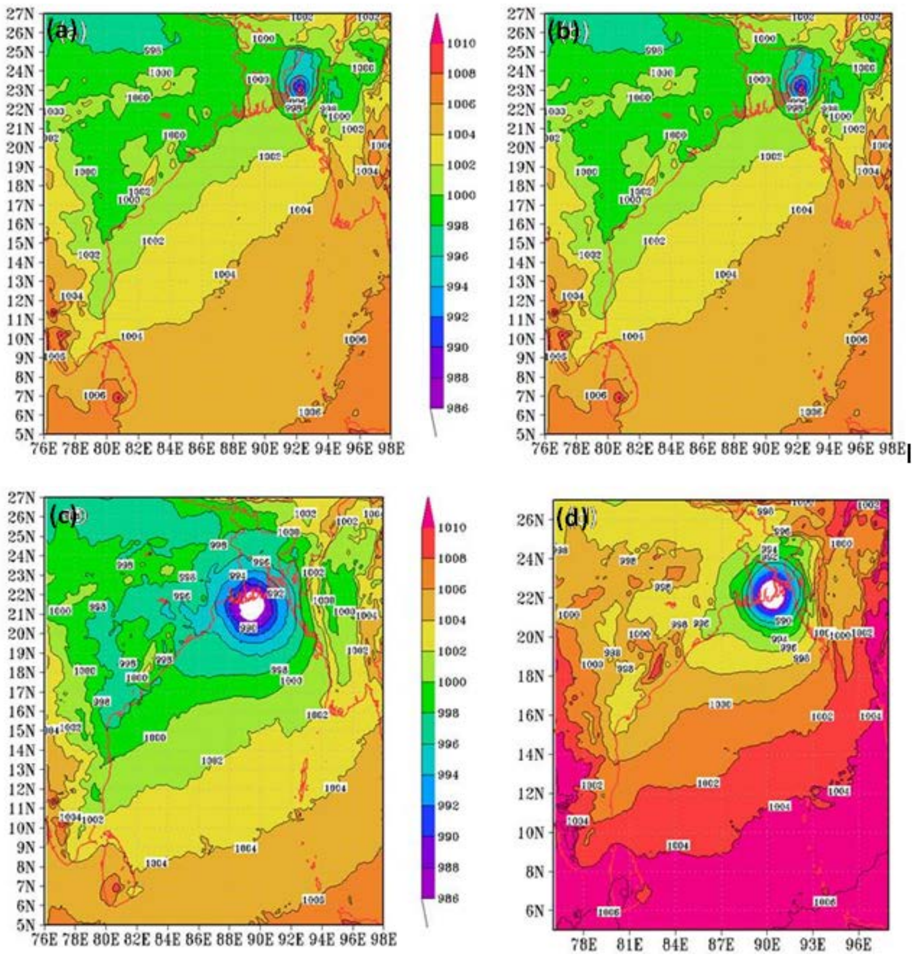

Figure 4. (a-d): The distribution of mean sea level pressure (hPa) analysis valid for 1200 UTC of 16 May, 2013 based on (a) 24-h, (b) 48-h, (c) 72-h and (d) 96-h

It is found that the centre of the cyclone at 1200 UTC on 16 May 2013 is located at 23.0^0N, 92.5^0E; 21.0^0N, 89.8^0E; 21.5^0N, 89.5^0E and 22.0^0N, 90.5^0E respectively over the southern part of Bangladesh and adjoining area based on 24, 48, 72 and 96 hours advance model run. The lowest central pressure of cyclonic storm Viyaru is about 986 hPa, at 1200 UTC, 16 May, 2013. The model simulated isobars over the North Bay of Bengal have almost southwest to northeast orientation. The mean sea level pressure over southeastern part and adjoining NE India is also low and central pressure was nearly 1000 hPa at 1200 UTC of 16 May 2013 [Figure 4 (a-d)]. The CS Viyaru over the Bay of Bengal moved rapidly towards NE direction may be due to this low pressure belt over southeastern part and adjoining NE India and the supporting westerly steering wind of 200 hPa level (Figure not shown).

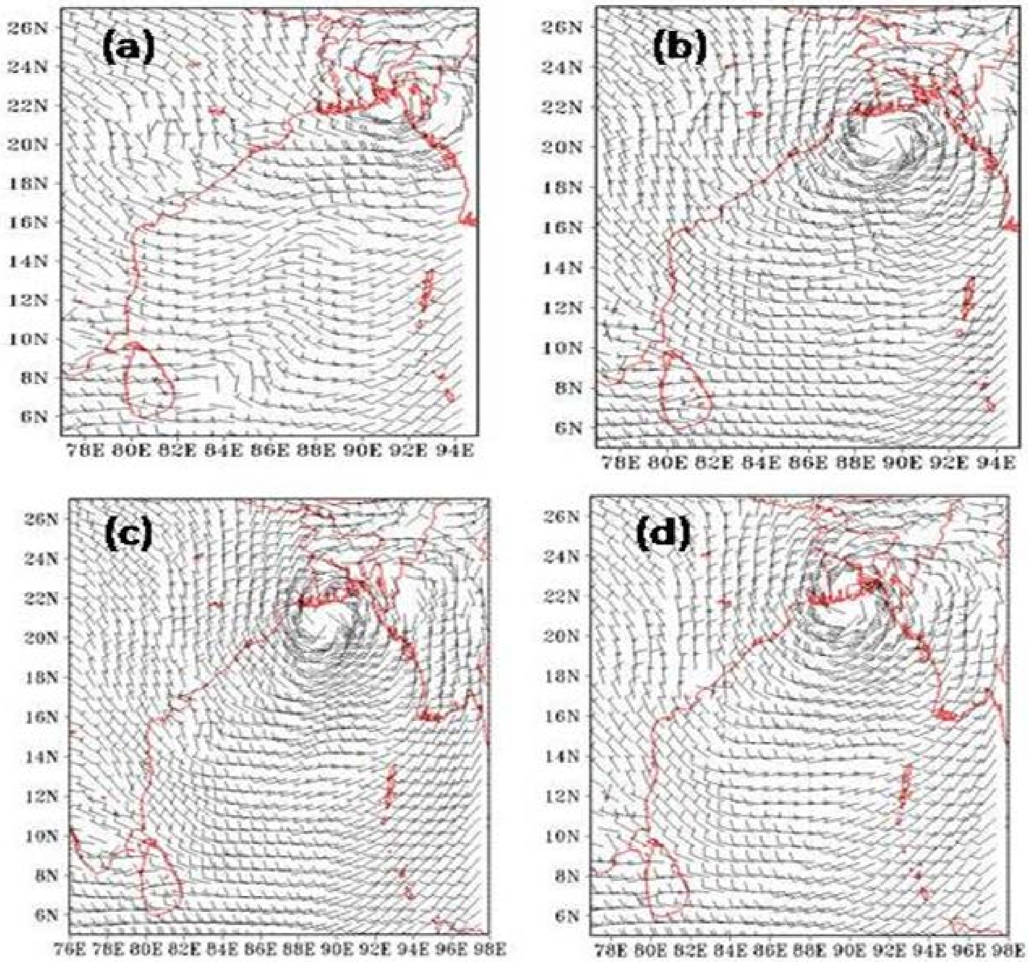

Figure 5(a-d)). The distribution of wind flow analysis valid for 0900 UTC of 16 May 2013 at 850 hPa level, based on (a) 24-h, (b) 48-h, (c) 72-h and (d) 96-h

4.2. Wind Flow Analysis

The distribution of 850 hPa level wind flow (ms^{-1}) valid for 0900UTC of 16 May 2013 is presented in Figure 5(a-d). It is found that a cyclonic circulation lies over the coast of southern part of Bangladesh and adjoining area having its centre at 22.0^0N, 91.4^0E, at 21.0^0N, 89.4^0E, at 20.8^0N, 88.8^0E and at 22.0^0N, 90.4^0E in 850 hPa level wind based on (a) 24-h, (b) 48-h (c) 72-h (d) 96-h which was also observed almost same at mean sea level pressure analysis [Figure 4 (a-d)]. The prominent feature is a strong southwesterly flow transporting high magnitude of moisture from the vast area of the Bay of Bengal towards the southern and central part of Bangladesh at 0900 UTC of 16 May 2013. The southwesterly is prevailed over the North Bay of Bengal and southern part of Bangladesh up to 500 hPa [Fig. is not included]. The area of convergence (i.e., zone of high convective activity) observed over Patuakhali, Khepupara and Barisal i.e., northern sector of the centre of Viyaru.

4.3. Vertical Wind Shear Analysis

The WRF model simulated vertical wind shear (ms^{-1}) of the u component of wind between 500hPa and 850 hPa level (u500- u850) valid for 0900 UTC of 16 May 2013 is presented in Figure 6(a-d) based on the initial condition of 0000 UTC of 13, 14, 15 and 16 May 2013. It is found that the atmosphere of Patuakhali, Khepupara, Barisal and neighbourhood where very heavy rainfall observed were characterized by the strong vertical wind shear. A core of strong vertical wind shear of the order of 15-25 ms-1 is observed over Patuakhali, Khepupara, Barisal and neighbourhood. In the centre and vicinity of the Viyaru, the vertical wind shear is found minimum (-5 to 5 ms^{-1}) which indicates the intensification of the cyclonic storm Viyaru. These wind shear help to develop intense and short lived multi cell thunderstorms over these coastal regions of Bangladesh being combined with the southerly flow gives very heavy rainfall.

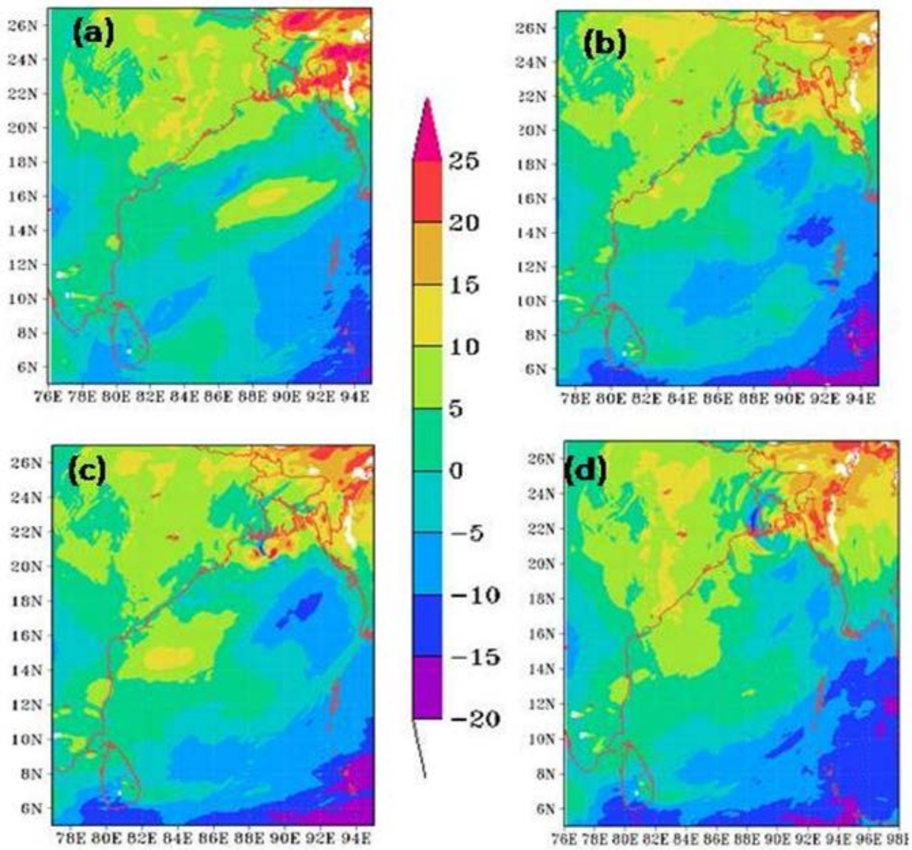

Figure 6 (a-d). The distribution of vertical wind shear (ms-1) of the u component of wind between the 500 hPa and 850 hPa level (u500- u850)valid for 0900 UTC of 16 May 2013 based on (a) 24-h, (b) 48-h, (c) 72-h and (d) 96-h

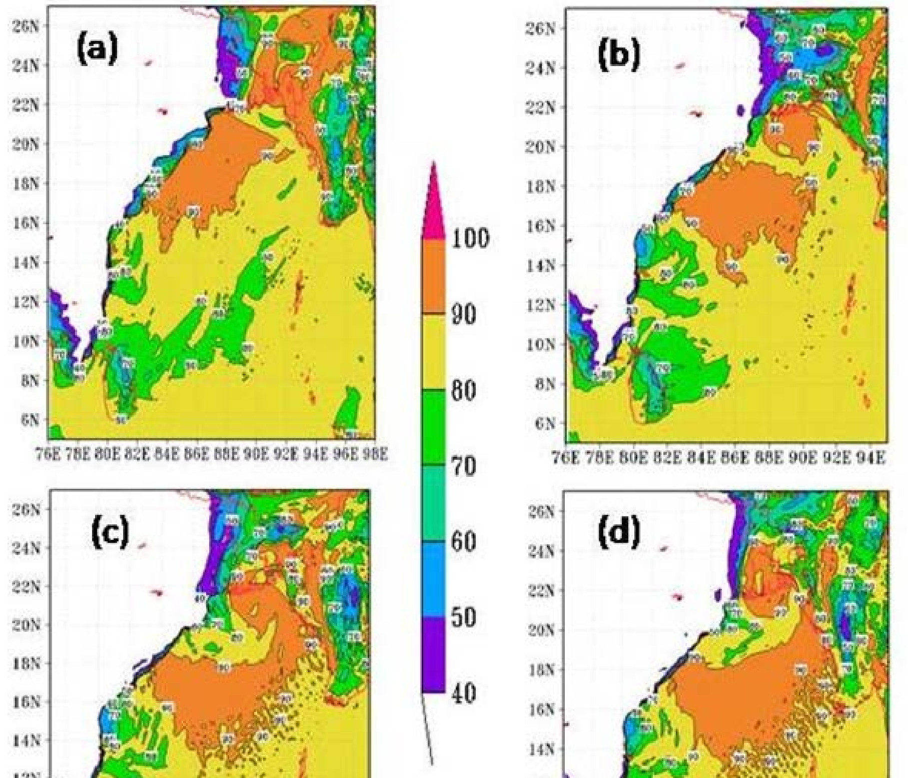

Figure 7(a-d). The distribution of relative humidity at 850 hPa level valid for 0900 UTC of 16 May 2013 based on (a) 24-h, (b) 48-h, (c) 72-h and (d) 96-h with the initial condition of 0000 UTC of 16, 15, 14 and 13 May 2013 respectively

4.4. Horizontal and Vertical Profile of Relative Humidity

The high relative humidity (more than 80%) is an important environmental parameter associated with cloud and rain formation. Moreover, clouds are unlikely to form with dry air resulting in clear skies. The relative humidity at 850 hPa level and its vertical cross section along 22.5°N valid for 0900 UTC of 16 May 2013 is presented in Figure 7 (a-d) and Figure 8 (e-h) based on the initial condition of 0000 UTC of 13, 14, 15 and 16 May 2013. From Figure 7 (a-d), it is found that the strong southwesterly flow transports plentiful of moisture of the order of 80-100% to the plain of central and southern part of Bangladesh and adjoining area from the Bay of Bengal at 0900 UTC of 16 May, 2013. The contents of high magnitude of moisture play an important role for the formation of the severe convective activities associated with the cyclonic storm over this region. The vertical cross-section of relative humidity analysis along the 22.5°N valid for 0900 UTC of 16 May, 2013 is shown in Figure 8 (e-h). It is found that the relative humidity of the order of 85-100% vertically extended up to 400 hPa level.

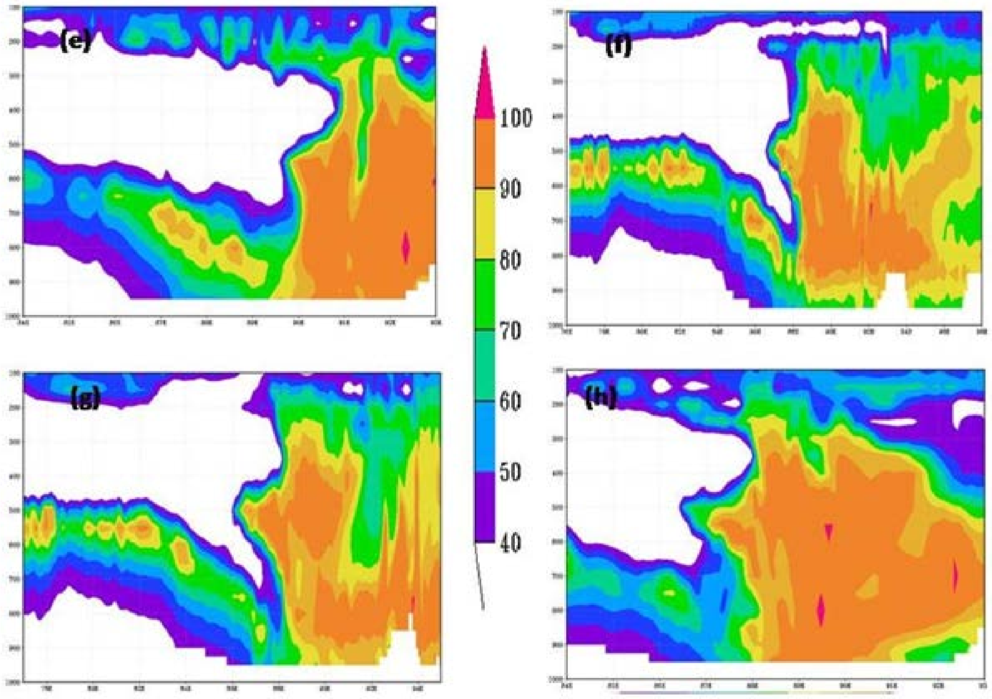

Figure 8 (e-h). Vertical cross section of relative humidity along 22.5^{0}N (position of landfall) valid for 0900 UTC of 16 May 2013 based on (e) 24-h, (f) 48-h, (g) 72-h and (h) 96-h

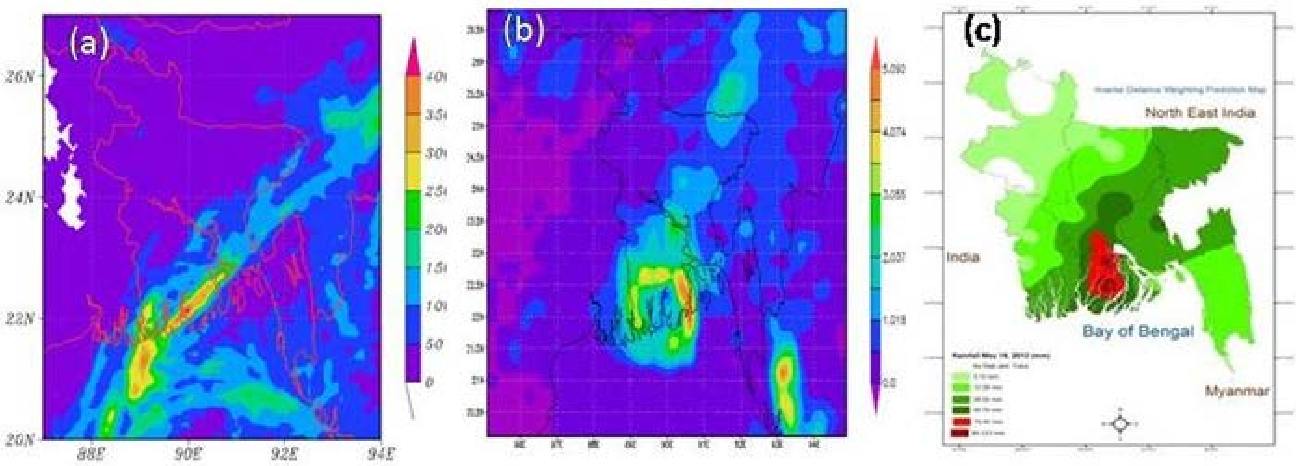

Figure 9 (a-c). The spatial distribution of 24-h model simulated rainfall (a), 24-h TRMM rainfall (b) and 24-h BMD observed rainfall (c) valid for 0000 UTC of 17 May 2013

4.5. Rainfall Analysis

The spatial distribution of model simulated 24-h accumulated rainfall on 16 May 2013 is given in Figure 9(a). The model simulated rainfall has been compared with the TRMM 3B42V7 in Figure 9(b) and BMD rain gauge observed rainfall in Figure 9(c) which are shown in Figure 9(a-c). The model simulated rainfall indicates that high values of rainfall is found over Khepupara, Patuakhali, Barisal and adjoining areas on 16 May 2013 agreeing well with observations produced by BMD rain gauges [Figure 9(b)]. TRMM distribution shows large spatial variability between north and south of Bangladesh. The distribution of BMD observed data shows good rainfall over the belt of southern and central part of Bangladesh, but low rainfall over the rest part of the country. It is found that model simulated rainfall over the country overestimates the rainfall compared to that of TRMM and underestimates the BMD observed rainfall though the pattern is almost similar. However, the WRF model not only captured the location of the heavy rainfall area over Khepupara, Patuakhali, Barisal and adjoining areas but also in many other places providing a picture of spatial variability. Thus it is expected that the model would have generated the realistic rainfall throughout the country. It is to mention in this regards that the network of rain-gauge stations of Bangladesh is not dense enough to capture the realistic picture of mesoscale processes unless one or more stations are located on the passage of convective systems. So far the TRMM data is concerned, it was found by Islam and Uyeda that TRMM underestimates the rainfall in this region. Thus, the WRF model-simulated rainfall seems to be more or less realistic both for quantitative assessment of rainfall and geographical distribution.

4.6. Translational Wind Speed of the Selected Viyaru

To study the track of the selected CS Viyaru the WRF model was run for 24, 48, 72 and 96 hrs before the landfall time. The observed average translational speed is calculated for respective model forecast hour (24, 48, 72 and 96 hrs) and also for full observed track. Model predicted 3-hourly average translational speed of the selected CS Viyaru along with the corresponding observed speed is given in Figure 10. It is found that the model simulated translational speed of Viyaru is below as compared with the actual speed of the system except landfall time. However, model simulated translational speed of Viyaru is more or less realistic up to 96 hrs. In general, the simulated results demonstrate that the translational speed of the system increases as it intensifies and moves towards the landfall position.

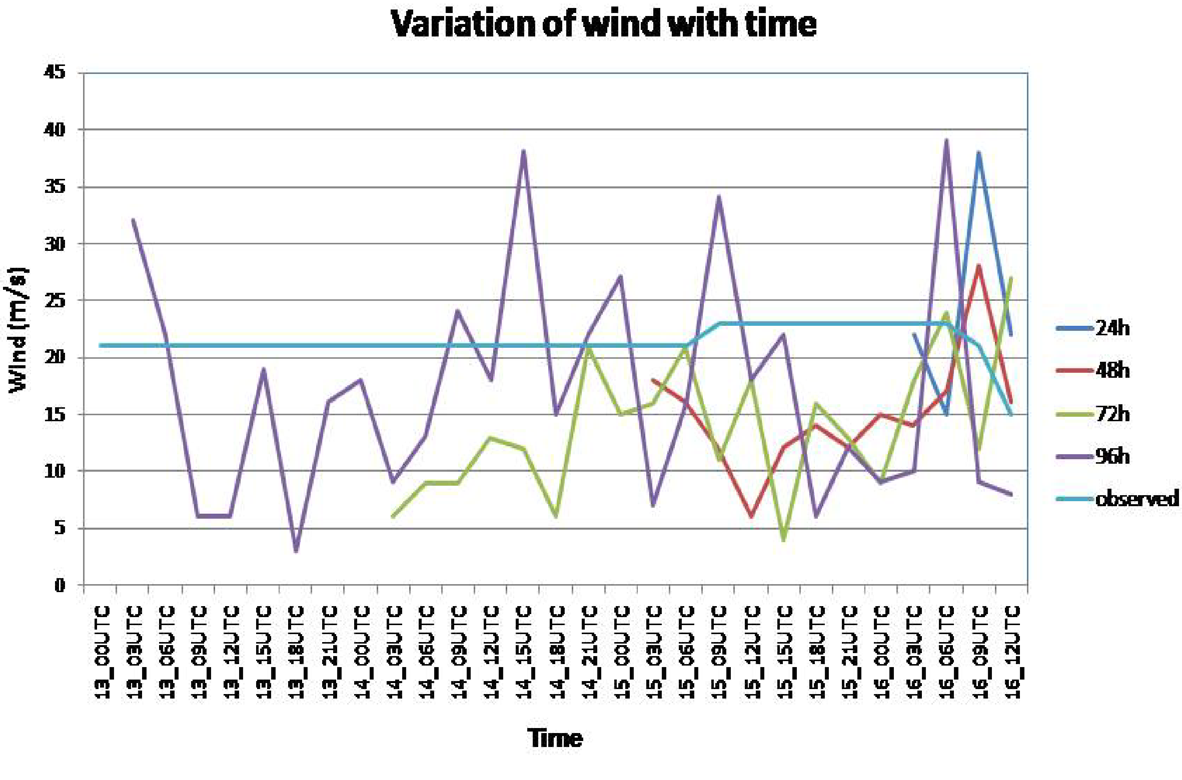

Figure 10. Comparison of 3-hourly simulated and observed maximum wind based on 24-h, 48-h, 72-h and 96-h with the initial condition of 0000 UTC of 16, 15, 14 and 13 May 2013

4.7. Track Forecast of the Selected CS Viyaru

Figure 11(a-d) shows the 24, 48, 72 and 96 hrs model predicted tracks of the CS Viyaru (green) beginning from 0000 UTC of 16 May 2013, 0000 UTC of 15 May 2013, 0000 UTC of 14 May 2013 and 0000 UTC of 13 May 2013 respectively along with corresponding IMD observed tracks (red). To draw the track of the disturbance the centre position of the system is taken at different interval. The model simulated tracks of Viyaru show that the model prediction experiments captured well the direction of motion, re-curvature and probable areas of landfall as compared with that of observed Figure 11 (a-d).

However, the 24 predicted track deviated east and 48 hrs forecast tracks agreed well with the observed track and indicated landfall at Bangladesh coast near Feni fairly close to the actual [Figure 11 (a-b)]. The 72hrs predicted track initially deviated to west, and then re-curve and move towards the northeast following the observed track. However the model predicted landfall point match with that of observed in reasonably well [Figure 11(c)]. The 96 hrs predicted track initially deviated to east from the observed track and landfall points [Figure 11 (d)]. Figures demonstrate that model captured more or less realistic track of the disturbance with some position and timing errors. These figures also show that the landfall accuracy increases as the prediction time decreases with the updated initial fields.

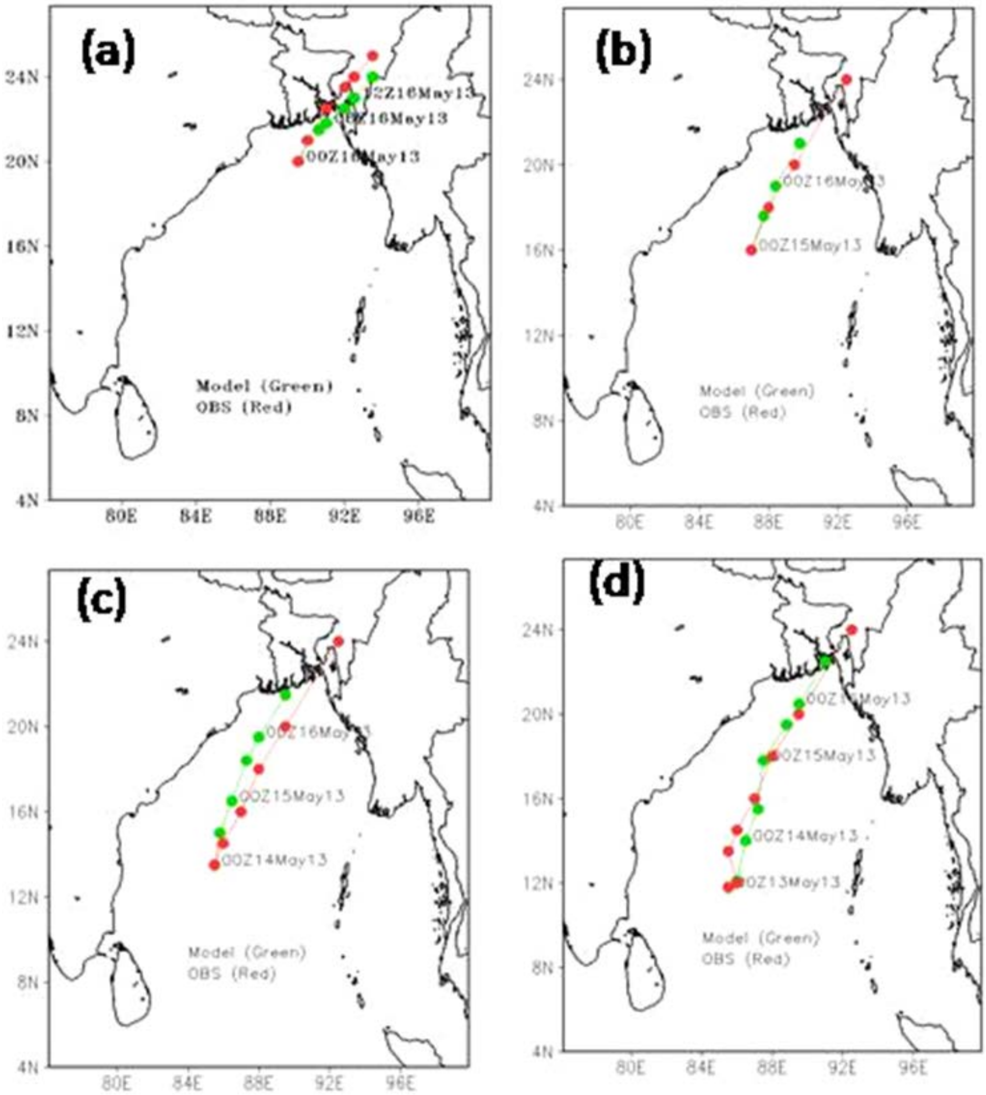

Figure 11(a-d): Model simulated (green) and observed (red) track of the CS Viyaru for (a) 24hrs forecast beginning from 0000 UTC of 16 May 2013, (b) 48hrs forecast beginning from 0000 UTC of 15 May 2013, (c) 72hrs forecast beginning from 0000 UTC of 14 May 2013 and (d) 96hrs forecast beginning from 0000 UTC of 13 May 2013

4.8. Landfall Forecast Errors

The landfall position and time errors are investigated for evaluating the model performances. The results are presented in Table 1. The table shows that 24 hrs predictions exhibit low landfall position errors whereas 48, 72 and 96 hrs predictions have comparatively high landfall position errors. There are variations in the landfall time errors. The 24 hrs predictions show 1hr landfall time error. The position errors of the Viyaru in track forecasting were found to be 56 km for 24 hrs, 222 km for 48 hrs, 222 km for 72 hrs and 157 km for 96 hrs of predictions. The landfall time error was relatively higher in different forecast times (Table 1). It was mainly due to the fact that the cyclonic storm, Viyaru moved very fast on the day of landfall which could not be predicted by most of the numerical weather prediction models. The respective time errors were 2hrs, 04 hrs, 07hr and 01 hr delay for simulation of 96, 72, 48, and 24 hrs respectively. The lowest position error was found only 56 km and lowest time error was found 01 hour.

Table 1. Landfall point and time error of the CS Viyaru

Base Date/Time (UTC)	Forecast Hours	Landfall Forecast		Actual Landfall		Error	
		Position (Lat °N/Lon °E)	Date/Time (UTC)	Position (Lat °N/ Lon °E)	Date/Time (UTC)	Distance (km)	Time (hrs)
13/0000	96	21.8/90.4	16May/1000	22.8/91.4	16May/0800	157	02D
14/0000	72	21.6/89.8	16May/1200	-do-	-do-	222	04D
15/0000	48	21.6/89.8	16May/1500	-do-	-do-	222	07D
16/0000	24	22.5/91.8	16May/0900	-do-	-do-	56	01D

Note: D indicates forecast landfall time is delay to actual landfall time.

The results clearly demonstrate that the track prediction error is not periodic in nature. Moreover, the model was able to forecast successfully the tracks of the disturbance up to 96 hrs. This shows the advantage of using WRF model with high resolution for the predictions of CS formed over the Bay of Bengal. However, use of higher model resolution is expected to provide better results.

It appears from the above discussion that the WRF model has high potential to forecast position and time of landfall of the CS over the Bay of Bengal with the certain amount of uncertainty. However, further studies on sensitivity experiments with model resolution, boundary layer formulation, model physics and cumulus parameterization schemes on track prediction are required for proper tuning of the model to improve the prediction accuracy and reduce landfall error. The errors of distance and time are also shown in Table 1.

5. Storm Surge due to Cyclone Viyaru

A maximum storm surge and maximum tide of about 1-2 meter is simulated due to cyclonic storm Viyaru by MRI model based on the 6-hourly initial condition of the observed position and maximum sustained wind data of BMD at 0000 UTC, 0600 UTC, 1200 UTC, 1800 UTC of 15 May 2013 and 0000 UTC of 16 May 2013 . The data set is given in Table 2.

Table 2. Data of storm surge simulation of the CS Viyaru

Date	Pcenter (hPa)	Lon (°E)	Lat (°N)	Ro (km)	Pfar (hPa)
13051500	996	86.50	14.90	30	1012
13051506	996	87.30	16.50	30	1012
13051512	990	87.70	17.50	30	1012
13051518	990	88.50	18.50	30	1012
13051600	990	89.00	19.50	30	1012

The simulated maximum storm surge and maximum tide is shown in the Figure 12(a) and 12(b) respectively. The maximum surge height due to cyclone 'Viyaru' was 2 meters in southern coastal region of Bangladesh reported by local media. Thus the model simulated surge is almost same as observed surge. The astronomical tide at the landfall time of the cyclonic storm Viyaru was 3 meters is also reported by the tide gauge of Bangladesh Inland Waterways Transport Authority (BIWTA). Tide is actually storm surge plus astronomical tide height. So, the measured tide at the crossing time of Cyclone Viyaru is 3 metres which is in good agreement with the MRI storm surge model output.

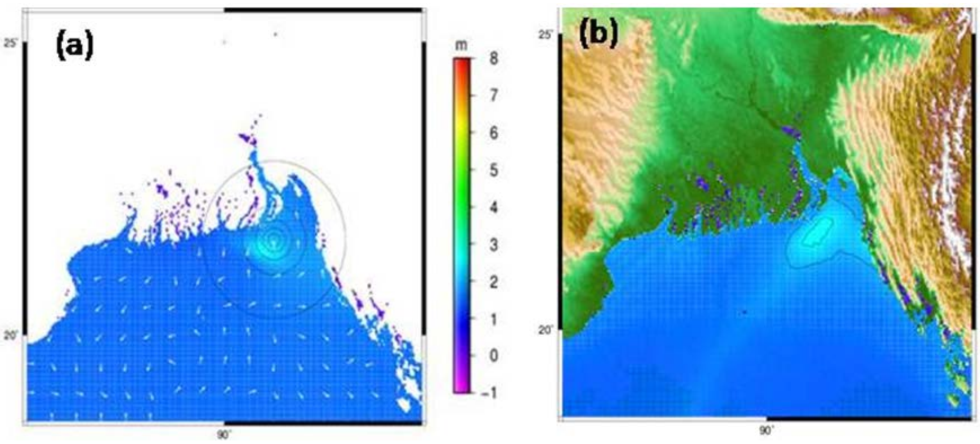

Figure 12. Storm surge (a) and maximum tide (b) valid at 0000 UTC on 16 May 2013 simulated by MRI model

6. Conclusion

On the basis of the above discussion, the following conclusions are drawn:

1. Minimum central sea level pressure are different with different initial conditions.
2. The magnitude of maximum winds with different initial conditions is close to each other but more or less than observed maximum wind.
3. The model simulated translational speed of Viyaru is more or less realistic up to 96 hrs. The simulated results demonstrate that in general the translational speed of the system increases as it intensifies and moves towards the landfall position.
4. The model has successfully predicted the tracks, re-curvature and probable areas and time of landfall of Viyaru with reasonable accuracy even in the 96 hrs prediction. The model also shows that the landfall accuracy increases as the prediction time decreases with the updated initial fields.
5. The position errors of Viyaru in track forecasting were found to be 56 km for 24 hrs, 222 km for 48 hrs, 222 km for 72 hrs and 157 km for 96 hrs of predictions. The respective time errors were 2 hrs, 04 hrs, 07 hrs and 01 hr delay for simulation of 96, 72, 48, and 24 hrs respectively. The lowest position error was found only 56 km and lowest time error was found 01 hour.
6. 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.
7. The storm surge and maximum tide is in good agreement with MRI storm surge model.

Finally, it may be concluded that the WRF model is able to simulate the track and landfall of the selected cyclone Viyaru. The model can be adopted for real time forecasting of track and landfall by doing more case studies. The simulation with data assimilation will be improved the track forecast and minimize the landfall errors.

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