Simulation of Tropical Cyclone YAAS and its Associated Storm Surge over the Bay of Bengal using NWP Models

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Abstract

An attempt has been made to simulate landfall, track and storm surge of the tropical cyclone Yaas that formed over the Bay of Bengal in May 2021 using Weather Research and Forecasting (WRF) model and Meteorological Research Institute (MRI) model. The WRF model was run on a single domain of 10 km horizontal resolution using Kessler scheme for microphysics, Yonsei University (YSU) scheme for planetary boundary layer parametrization, Rapid Radiative Transfer Model (RRTM) for long wave radiation, Dudhia scheme for short wave radiation and Kain-Fritsch scheme for cumulus parameterization. The model was run for 144, 120, 96, 72 and 48 hours using NCEP GFS six hourly data as initial and lateral boundary conditions. The WRF model performance has been evaluated by analyzing mean sea level pressure, wind pattern, temperature, relative humidity and track pattern. The MRI model was run for 48 hours and it's performance has been evaluated by predicting storm surge height and analyzing mean sea level pressure and wind pattern for the cyclone. The lowest position error was found 43 km and the lowest time error was found 02 hours. Results obtained from both models show reasonably good agreement with the observations. The analysis shows that the reduced lead time of the model run leads to better system predictability with minimum uncertainty. Finally, these results show the advantage of using theWRF model and MRI model for the prediction of tropical cyclones and associated storm surges over the Bay of Bengal.

Key words: Tropical Cyclone, WRF model, MRI model, Storm Surge

1. Introduction

Tropical cyclones are intense low-pressure systems that originate in the tropics and are one of the most destructive weather phenomena on the earth, with severe societal and economic consequences. These occur over the Bay of Bengal during the pre-monsoon (March to May) and post-monsoon (October to November) seasons causing deaths and extensive property damage. The Bay of Bengal ('BOB') region of the northern Indian Ocean (NIO) is known as having a high potential for cyclogenesis, with an average of three to four storms each year. Despite a lower rate of tropical cyclone development in the BoB, a combination of characteristics, such as shallow bathymetry, low-lying and flat coastal topography, and a large population density in neighboring countries, frequently result in severe impacts when TCs make landfall [1].

The main causes of damage from landfalling cyclones are three: rain, powerful winds, and storm surges. Storm surges caused by severe tropical cyclones are by far the most destructive. Death and destruction are directly caused by the high winds that are characteristic of tropical storms over a big surface of water. These winds induce seawater to pile up on the coast if it is bounded by a shallow basin, resulting in sudden inundation and flooding of coastal regions [2]. Storm surges in this region have also had far-reaching consequences that go beyond the high fatality toll. Storm surges, for example, cause losses in the agriculture sector, which is already seeing a decrease in rice cultivation due to increasing soil salinity caused by sea-level rise [3]. Over the previous three decades, TC prediction and forecasting have greatly improved as a result of enhanced observations, particularly from the satellite and rudder, as well as advancements in dynamical models. Utilizing high resolution models has greatly enhanced the treatment of model governing equations and, consequently, cyclone study. But a few studies have been conducted on tropical cyclones and the storm surges that generated in the BoB in recent years.

Pattanayak and Mohanty did a comparative study on performance of WRF and MM5 models for simulating TCs in IO. The results indicate that the WRF model performs better than the MM5 model in predicting the track and intensity of TCs [4]. Mallik et al. (2015) has simulated cyclone 'Viyaru' and associated storm surge using WRF model and the model was run for 24, 48, 72, 96 hours using FNL initial and boundary conditions. Comparing the simulated model track to the observed BMD track, it was obtained that the model has simulated the track well. The MRI model also generated the storm surges and highest tide of Viyaru's landfall time and compared the results to the BMD's and

BIWTA's anticipated and maximum tide and storm surges data. Additionally, the model has simulated the highest tide and surges caused by 'Viyaru' 24 hours before landfall [5].

Ali et al. (2018) studied the storm surge induced by cyclone 'Aila' using Japan Meteorological Agency (JMA) storm surge model and IIT-D (India Institute of Technology-Delhi) storm surge model. Weather Research and Forecasting (WRF) model-simulated data and IMD-estimated data are provided as the input for both models. The results from both models are compared with recorded data. Additionally, the changes in simulation output between two distinct input files are studied. Using both IMD estimated data and WRF model-simulated data, the IIT-D storm surge model simulates maximum surge heights of approximately 3 meters. Using WRF model-simulated data, the JMA model simulates a maximum surge height of 2 m, whereas using IMD-estimated data, the maximum surge height is 2.5 m. The highest surge recorded for cyclone 'Aila' was 3 meters. Therefore, the predicted maximum storm surge height by the IIT-D model corresponds well with the recorded highest surge height [6]. Sarkar et al. (2019) simulated intensity, structure and track of 'Amphan' using WRF-ARW Model. The model's simulation of the storm's intensity and path was compared to the best available IMD track data. The WRF model showed that the strength of the cyclone in terms of Maximum Sustained Wind (MSW) speed and MSLP was 243 kph and 905 hPa, whereas the observed MSW and MSLP were around 242 kph and 920 hPa [7]. A study on TC 'Roanu' was done by Mallik et al. (2020) where the minimum central pressure, track and maximum wind speed are predicted by WRF model and also the storm surge using MRI model [8].

In this study, Advanced Research WRF (ARW) meso-scale model is used to simulate the track and landfall of the cyclone Yaas that crossed Odisha coast on 26 May, 2021. Another simulation is also performed using MRI storm surge model for the storm surge event. The aim of this thesis work is to evaluate the ability of the WRF-ARW model in simulating the track and landfall of the cyclonic storm Yaas over the BoB, as well as to study the predictability of the associated storm surge using the MRI storm surge model.

2. Experimental Set up, Data used and Methodology

The extensive menu of options for physical process schemes and numeric configuration in WRF model reflect a history of community input, making it a powerful Numerical Weather Prediction (NWP) tool. Version 4.3.3 of WRF ARW has been used for the simulation of TC Yaas in this study. The model was run for 144, 120, 96, 72 and 48 hours based on the initial condition of 0000 UTC of 21, 22, 23, 24 and 25 May, 2021. The configuration of WRF model for the present study is shown in the table below.

Table 1: WRF model configuration

Number of domain	1
Horizontal grid distance	10 km
Number of grid points	$212 \times 212 \times 38$
Map projection	Mercator
Microphysics	Kessler scheme
PBL parametrization	Yonsei University Scheme
Cumulus parametrization	Kain-Fritsch scheme
Land surface model	Unified NOAH scheme
Surface layer physics	Revised MM5 Scheme
Short wave radiation	Dudhia scheme
Long wave radiation	RRTM scheme

Meteorological Research Institute (MRI) model created at Japan Meteorological Agency (JMA) has been used to simulate the storm surge associated with cyclone Yaas. This model predicts storm surges by taking into account two main factors: wind setup and inverse barometer effect. Cyclone Yaas simulation operations in the MRI model start at 1200 UTC on May 24, 2021 and the model remained operational for the next 48 hours, concluding the simulation on May 26 at 1200 UTC. Configuration of this model is shown in the table-2.

6 hourly NCEP-GFS operational global analysis and forecast data on (0.25° by 0.25°) grids are used as the initial and lateral boundary conditions for WRF model run. BMD retrieved three hourly Global Spectral Model (GSM) surface data for 48 hours from the Japan Meteorological Agency (JMA) WIS server with a resolution of 0.25 degrees. This data was supplied by Bangladesh Meteorological Department (BMD) for the selected cyclone "Yaas" (2021) to

simulate the storm surge event. Simulated output from both models has been visualized using Grid Analysis and Display System (GrADS). The observed track data of India Meteorological Department (IMD) were used to compare the model simulated track.

Table 2: MRI model configuration

Model Setting	3
Grid	nx= 241, ny= 256
Lat/Lon	Lat_n=27.00, Lat_s=18.50, Lon_e= 94.00, Lon_w= 86.00
Index	3
p_ref	1000.0
in_und	1
wl_based	10
Intide	0
Tide_base	1.5
Tidal Perturbation	600

3. Results and Discussion

3.1 Analysis of Mean Sea Level Pressure (MSLP)

The formation of low-pressure area is an important condition for possible weather disturbances which may intensify into tropical cyclone when the favorable conditions prevail. The model derived MSLP (hPa) of the cyclone 'Yaas' valid for (at the time of model simulated landfall) 2200 UTC of 24th May, 1300 UTC of 25th May, 1700 UTC of 25th May, 0100 UTC of 26th May and 0800 UTC of 26th May, 2021 based on the initial conditions of 0000 UTC of 21st May, 0000 UTC of 22nd May, 0000 UTC of 23rd May and 0000 UTC of 24th May and 0000 UTC of 25th May, 2021 has been presented in Figure 1 (a - e) respectively.

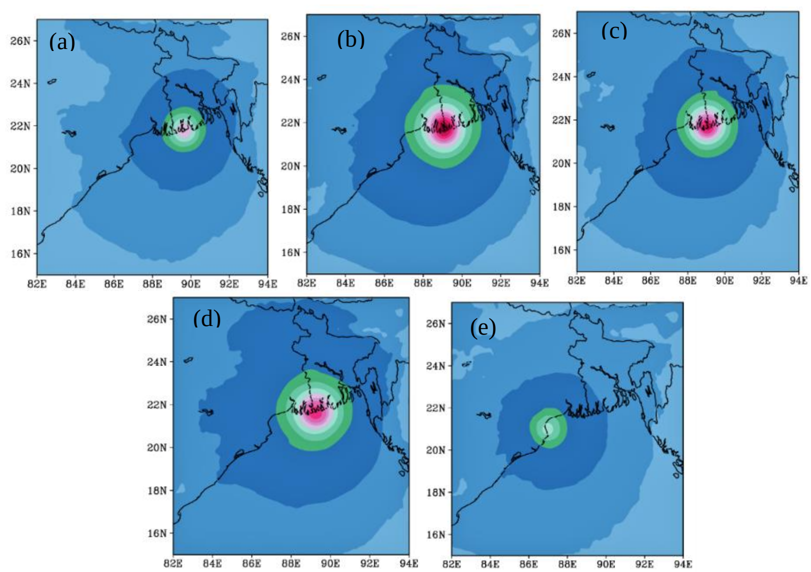

Figure 1: The WRF model simulated MSLP (hPa) valid for (a) 2200 UTC of 24th May (b) 1200 UTC of 25th May (c) 1700 UTC of 25th May (d) 0100 UTC of 26th May (e) 0300 UTC of 26th May respectively.

The center of the system at the time of landfall is located at 21.77°N & 89.66°E; 21.68°N & 89.08°E; 21.77°N & 89.08°E; 21.59°N & 89.27°E and 20.96°N & 86.94°E respectively based on 144, 120, 96, 72 and 48 hours advanced model run. From the WRF model-simulated pressure study, it is found that a low pressure area forms over the southeast BoB and moves northwestward. The model simulated MSLP gradually decreases over time, reaching a nadir before landfall, and then increases. Based on the initial conditions of the model run, the simulated central pressure at the time of landfall is 966 hPa, 957 hPa, 955 hPa, 958 hPa and 974 hPa respectively. The model-simulated MSLP analysis shows that the system's center, landfall position, and minimum MSLP are slightly different for various initial conditions. In addition, it is found that the isobar has a well organized circular arrangement around the system's center.

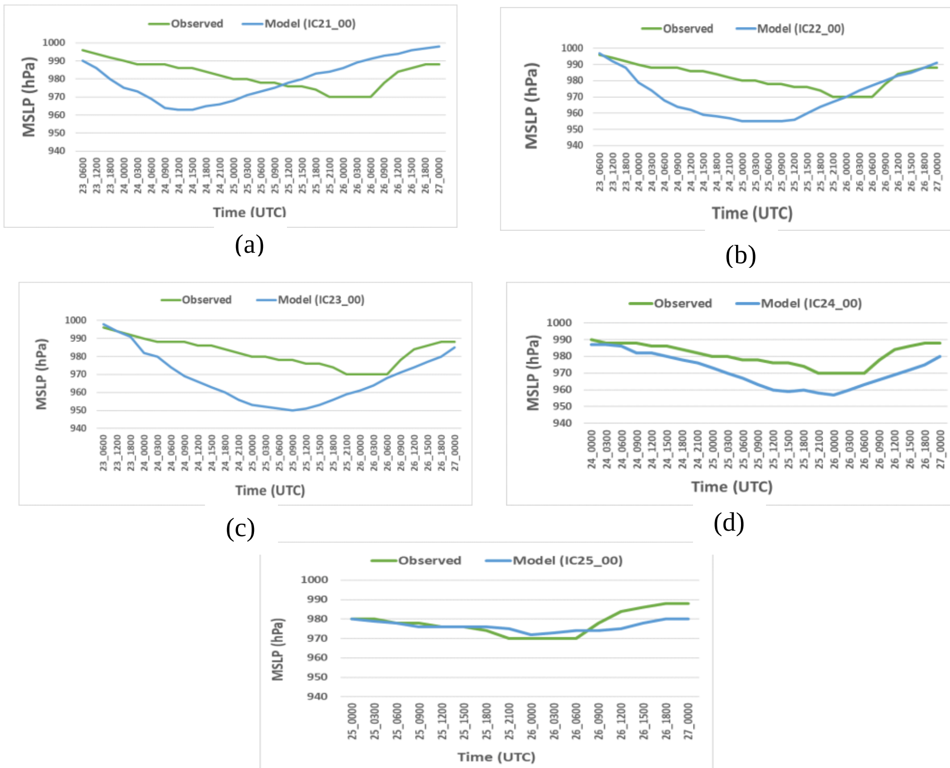

Figure 2: Comparison of model simulated MCP with the (e) ›r (a) 144 hours run (b)120 hours run (c) 96 hours run (d) 72 hours run (e) 48 hours run respectively.

Figure 2 (a-e) shows the comparison of the simulated Minimum Central Pressure (MCP) and Estimated Central Pressure (ECP) and the predicted model results exhibit a similar pattern to the observed results provided by IMD [9]. However, the simulated model pressure decreases more rapidly than the observed pressure and itis underestimated than that of the observed. These comparisons indicate that the model has predicted the MSLP distribution quite well, but with some biases.

3.2 Analysis of Wind at 850 hPa Level

The horizontal distributions of wind flow (ms^{-1}) at 850 hPa level of Tropical Storm Yaas valid for (model-simulated landfall time) 2200 UTC of 24thMay, 1300 UTC of 25th May, 1700 UTC of 25th May, 0100 UTC of 26th May and 0800 UTC of 26th May, 2021 based on the initial conditions of 0000 UTC of 21st May, 0000 UTC of 22nd May, 0000 UTC of 23rd May, 0000 UTC of 24th May and 0000 UTC of 25th May, 2021 are shown in figure 3.

At an altitude of 850 hPa, the maximum wind speed is approximately (55 - 65) $ms^{-1}$for 144 hours, (65 - 70) ms^{-1} for 120 hours, (70 - 65) ms^{-1} for 96 hours, (65 - 70) ms^{-1} for 72 hours and (50 - 60) ms^{-1} for a 48-hour advanced model run. It is also clear that the surface wind distribution is well-organized and that the system has concentrated into a powerful one. At this altitude, the wind pattern is cyclonic.

At 850 hPa pressure level, the WRF model simulated analysis shows that strong cyclonic circulation is present in every stage of wind distribution, which is indicative of wind inflow at lower levels. The distribution also depicts a well organized calm region in the eye of the system where the wind speed is less than 20 ms−1 and several bands of wind are observed around the center. The strongest wind speed is found at different eyewall regions for both levels.

At landfall time, the TC experiences high wind speed (45 − 55 ms−1) at the right forwarding sector. For each of the 144, 120, 96, 72, and 48-hour model runs, the wind speed is maximum when the TC lay over BoB (before landfall) but when it approaches the coast, it loses intensity. It has significance because casualities depend highly on wind speed and also wind is an essential factor for storm surges associated with TCs. After landfall, the wind speed reduces and TC becomes weak by giving precipitation.

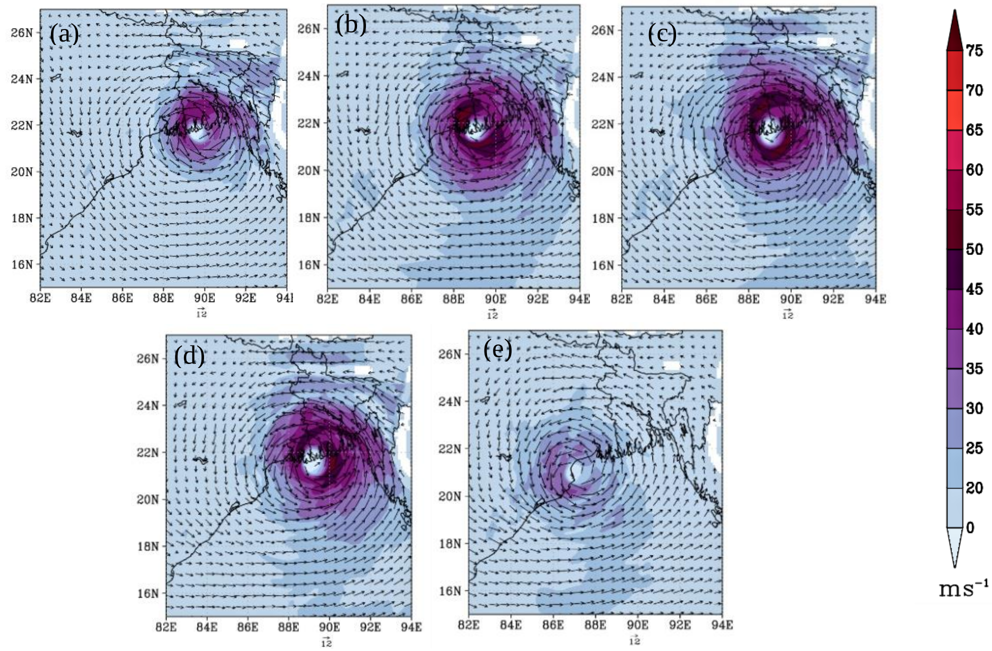

Figure 3: The WRF model simulated wind (ms^{-1}) at 850 hPa level valid for (a) 2200 UTC of 24th May (b) 1300 UTC of 25th May (c) 1700 UTC of 25th May (d) 0100 UTC of 26th May (e) 0800 UTC of 26th May respectively.

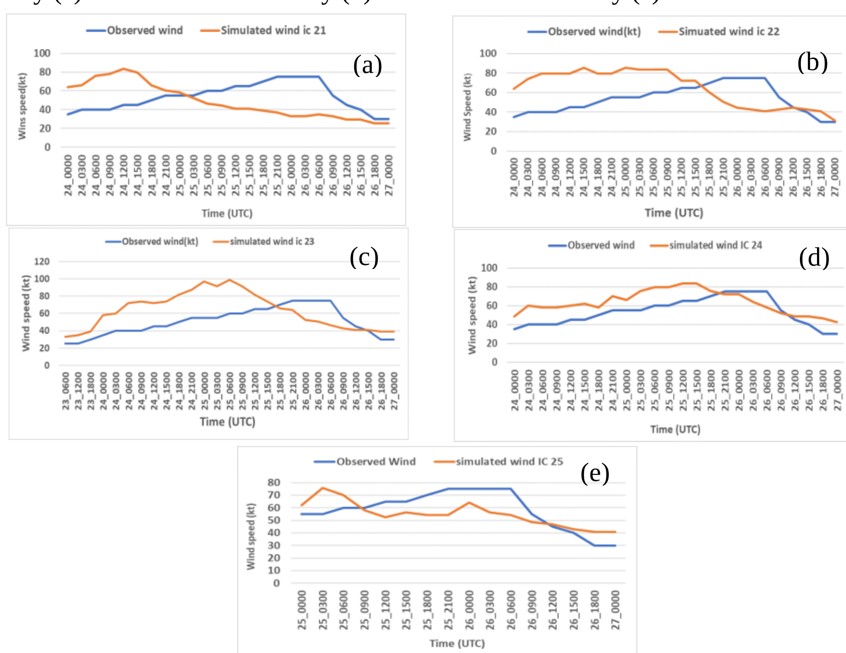

Figure 4: Comparison of model simulated wind speed (kt) with the observed speed for (a) 144 hours run (b) 120 hours run (c) 96 hours run (d) 72 hours run (e) 48 hours run respectively.

Figure 4 illustrates comparison between observed wind speed of IMD [9] and simulated wind speed (kt) for initial conditions of 0000 UTC of 21st May, 0000 UTC of 22nd May, 0000 UTC of 23rd May, 0000 UTC of 24th May and 0000 UTC of 25th May, 2021. The simulated values vary with different initial conditions and they are more or less than observed values. The WRF model has simulated wind speed well but it has some biases.

3.3 Analysis of Relative Humidity

Figure 5 (a-e) shows relative humidity for tropical storm Yaas valid for (model-simulated landfall time) 2200 UTC of 24th May, 1300 UTC of 25th May, 1700 UTCof 25th May, 0100 UTC of 26th May and 0800 UTC of 26th May, 2021 with the initial conditions of 0000 UTC of 21st May, 0000 UTC of 22nd May, 0000 UTC of 23rd May, 0000 UTC of 24th May and 0000 UTC of 25th May, 2021. From the modelanticipated RH analysis at 2 meter height, there is a strong southeasterly flow that continuously carries a massive amount of moisture with a value of roughly (80 -100) percent in the northern direction. High moisture content plays an important role in the formation of severe convective activities associated with cyclonic storms over these locations.

Figure 6 shows the comparison between the simulated relative humidity at Balasore station(Latitude 21.5° N, Longitude 86.9° E) for different conditions with observed relative humidity collected by Indian Meteorological Department [**9**]. It can be seen from the figures that WRF model simulated relative humidity underestimates the observed relative humidity measurements. When the lead time is reduced the model predicted data shows less error.

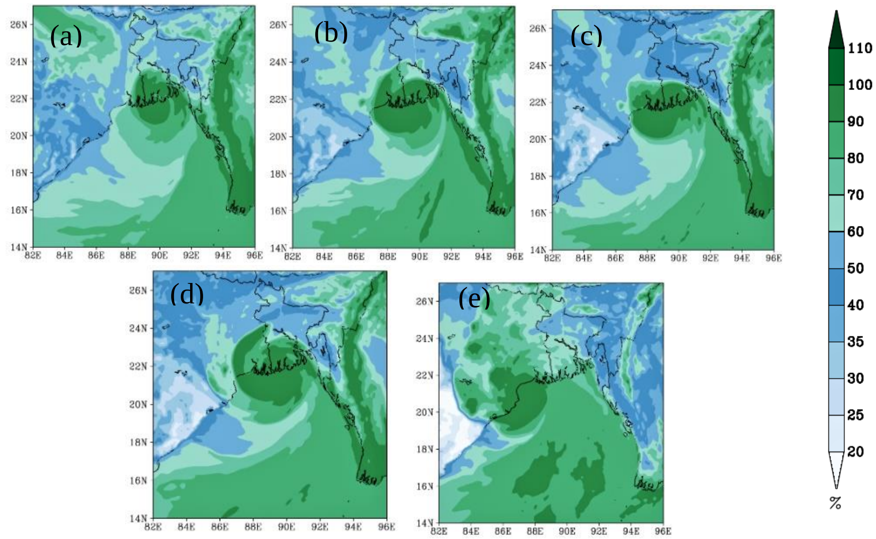

Figure 5: The WRF model simulated relative humidity (%) valid for (a) 2200 UTCof 24th May (b) 1300 UTC of 25th May (c7) 1700 UTC of 25th May (d) 0100 UTC of26th May (e) 0800 UTC of 26th May respectively.

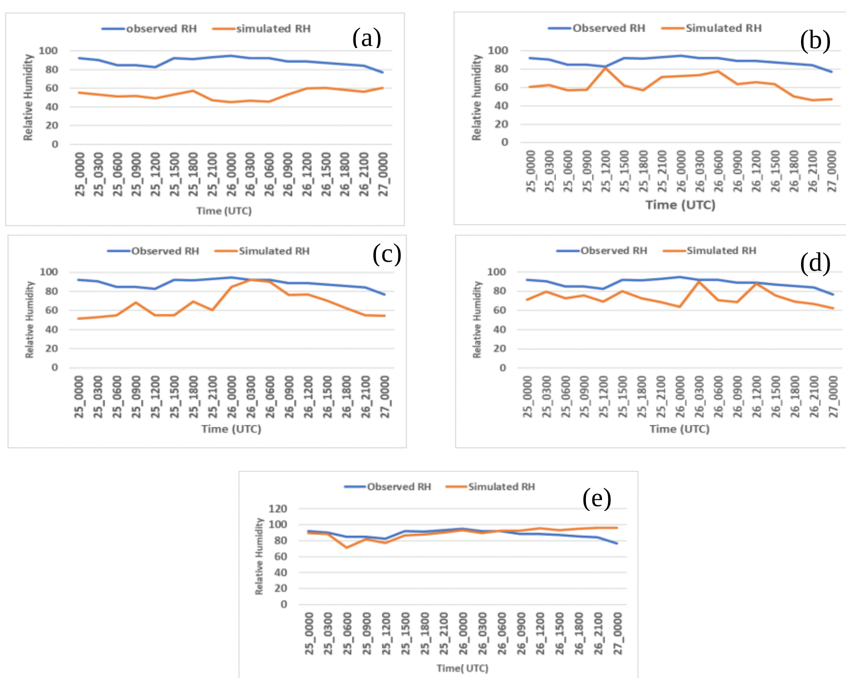

Figure 6: Comparison of model simulated relative humidity (%) with the observed relative humidity (%) at Balashore (Latitude=21.4° N, Longitude= 86.9° E) for (a) 144 hours run (b) 120 hours run (c) 96 hours run (d) 72 hours run (e) 48 hours run respectively.

3.4 Analysis of Temperature at 2 meter Height

The model simulated temperature (◦C) at 2 meter height of TC Yaas at 2200 UTC of 24th May, 1300 UTC of 25th May, 1700 UTC of 25th May, 0100 UTC of 26th May and 0800 UTC of 26th May, 2021 for 144, 120, 96, 72 and 48 hours model run are shown in figure 6.7 (a - e) respectively. According to the model-predicted temperature analysis at a height of 2 meters, the system center temperature is around (27 -30) ◦ C for 144, 120, 96, 72 and 48 hours model run. It is clear from the results that temperature starts to decrease after crossing the landfall position and decreases upto (16 - 26)◦ C. This temperature drop clearly implies that the system will not have another opportunity to regain its intensity and will eventually come to an end. The model simulated temperature analysis shows that the WRF model captured the temperature drop reasonably well.

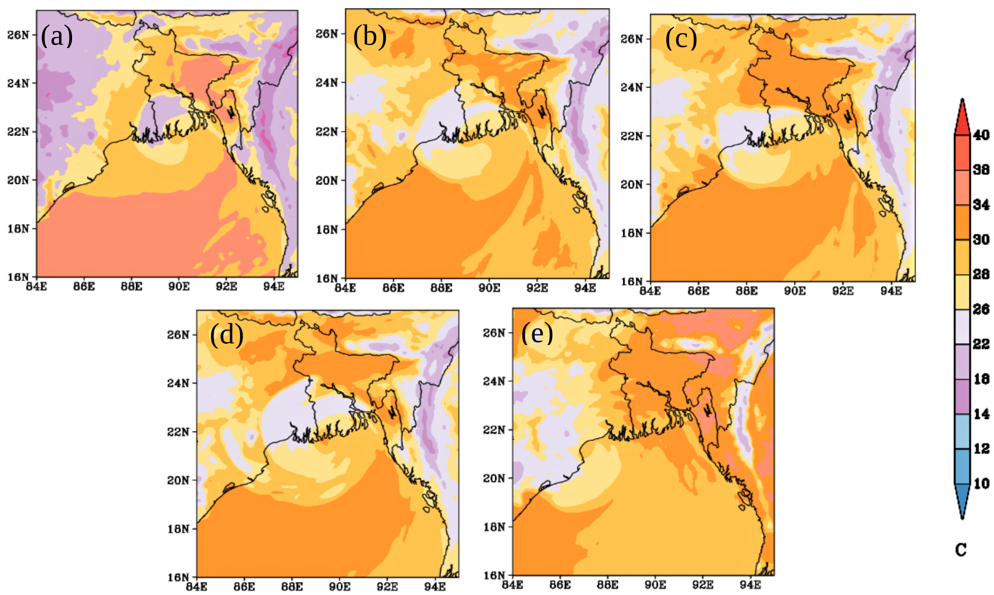

Figure 7: The WRF model simulated temperature (◦C) at 2 m height valid for (a) 2200 UTC of 24th May (b) 1300 UTC of 25th May (c) 1700 UTC of 25th May (d) 0100 UTC of 26th May (e) 0800 UTC of 26th May respectively.

Figure 8: Comparison of model simulated temperature (◦C) at 2 meter height with the observed temperature at Balashore station (Latitude=21.4 ◦ N, Longitude= 86.9 ◦ E) for (a) 144 hours run (b) 120 hours run (c) 96 hours run (d) 72 hours run (e) 48 hours run respectively.

The comparison between WRF model simulated temperature (°C) with IMD observed temperature at Balasore station (Latitude 21.5°N, Longitude 86.9°E) at different times has been shown figure 6.8 (a - e) for 144, 120, 96, 72 and 48 hours model run respectively. It is clear from the figures that the model predicted temperature overestimates the observed temperature. From the model simulated temperature analysis it can be concluded that the WRF model is able to simulate the temperature distribution reasonably well though it has considerable errors.

3.5 Cone of Uncertainty

The cone of uncertainty for cyclone Yaas has been shown in figure-9 based on 24th May, 2021. The probable landfall zone can be predicted in the cone. It is seen that the BMD observed track of cyclone Yaas lies completely inside the cone of uncertainty and landfall position varies upto 299 km to the right and 243 km to the left from the observed track. It has significance because before the landfall it is necessary to take precautionary measurements in the probable landfall region.

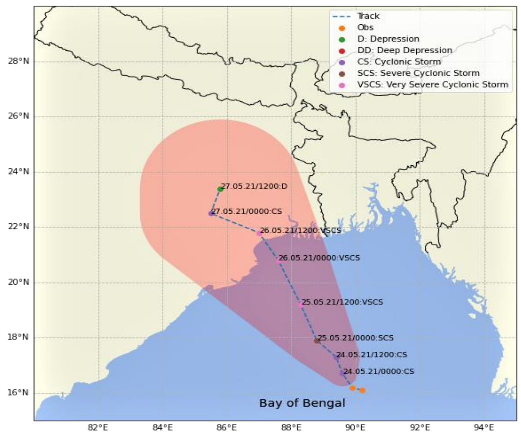

Figure 9: Cone of Uncertainty for cyclone Yaas

3.7 Track of Cyclone Yaas

The simulated track and observed track of IMD for tropical cyclone 'Yaas' with theinitial condition of 0000 UTC of 21st, 22nd, 23rd, 24th, 25th May, 2021 have been showed in figure10(a-e) respectively. The figures clearly illustrate

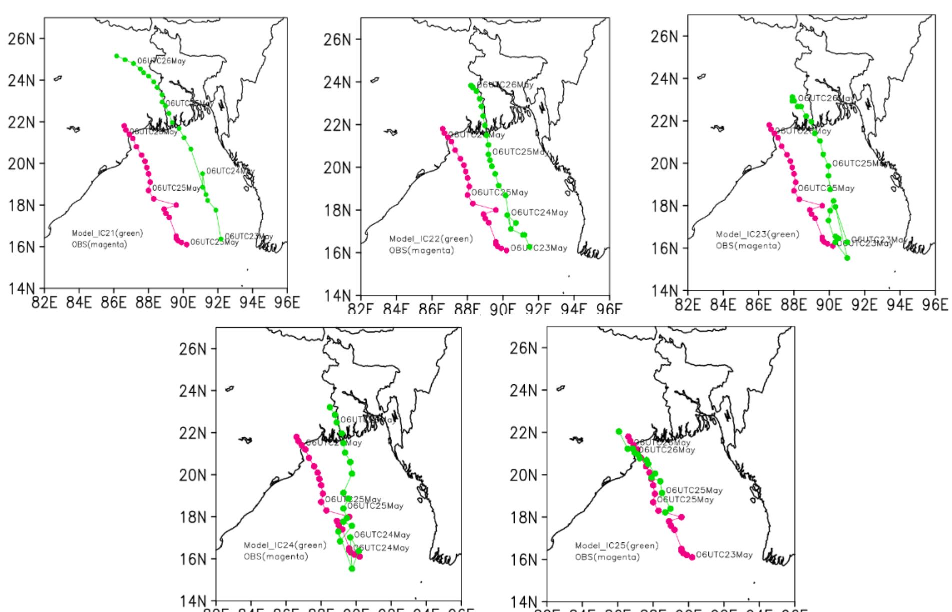

Figure 10: The 144, 120, 96, 72 and 48 hours model simulated track (green) and observed track (magenta) beginning from (a) 0000 UTC of 21st May to 0000 UTC of 27th May (b) 0000 UTC of 22nd May to 0000 UTC of 27th May (c) 0000 UTC of 23rd May to 0000 UTC of 27th May (d) 0000 UTC of 24th May to 0000 UTC of 27th May respectively (e) 0000 UTC of 25th May to 0000 UTC of 27th May respectively.

that the model simulated track has a almost parallel pattern with the observed track. The model is capable of predicting the northwest movement of the system for each of the 144, 120, 96, 72, and 48-hour model runs, as shown by the observed track. These two tracks are not initially close to each other, but they are found to be close to each other near the time of landfall.

The signature of predicted track based on 0000 UTC of 21st May and 0000 UTC of 22nd May is similar to the observed track in direction but shows error in landfall position. The simulated path of the TC Yaas based on 23rd May and 24th May are relatively better than 144 and 120 hours track prediction. The track based on 25th May is very close to the observed track. In this case, the position and time is much closer to the observed result than any other simulation.

Figures illustrate that the model captured the track of the disturbance with some timing and position errors. These figures also indicate that landfall accuracy improvesas lead time decreases. This shows the benefit of using WRF model with a high resolution to anticipate the formation of CS over the BoB. However, nested domainmodel runs with a high resolution give better results. Based on the above discussion,it appears that the WRF model has a high potential for forecasting the position andtime of landfall of TCS over the BoB with considerable uncertainty.

3.8 Landfall Forecast Errors

The landfall position and time errors of Tropical Cyclone "Yaas" are investigated to evaluate the WRF model's performance. The model simulated track for cyclone Yaas is in the right side of the observed track with mean landfall position errors of 304, 239, 240, 258 and 43 kilometers for 144, 120, 96, 72 and 48 hours advanced run respectively. The respective mean time errors are 32 hours, 19 hours, 13 hours, 5 hours and 2 hours. The 48 hours prediction shows lowest position and time errors than that of 72, 96, 120, 144 hrs predictions for the selected cyclone. It is clear from the results that reducing lead time will improve accuracy of landfall position and time. The results are summarized in the Table 3.

Table 3: Mean landfall position and time errors for cyclone Yaas

Base Date/Time (UTC)	Forecast hours	Landfall Forecast		Actual Landfall		Error	
		Position Lat/Lon	Date/Time (UTC)	Position Lat/Lon	Date/Time (UTC)	Distance(km)	Time(hrs)
21/0000	144	21.77/89.66	24May/2200	21.35/86.95	16May/0600	304	32E
22/0000	120	21.68/89.08	25May/1300	21.35/86.95	16May/0600	239	19E
23/0000	96	21.77/89.08	25May/1700	21.35/86.95	16May/0600	240	13E
24/0000	72	21.59/89.27	26May/0100	21.35/86.95	16May/0600	258	5E
25/0000	48	20.96/86.94	26May/0800	21.35/86.95	16May/0600	43	2D

3.9 Analysis of Storm Surge Height

Cyclone Yaas simulation operations in the MRI model start at 1200 UTC on May 24, 2021. Using GSM data, the model remained operational for the next 48 hours, concluding the simulation on May 26 at 1200 UTC. This event's simulation of the storm surge shows the path of the cyclone approaching the coastline and landfall. The height of the

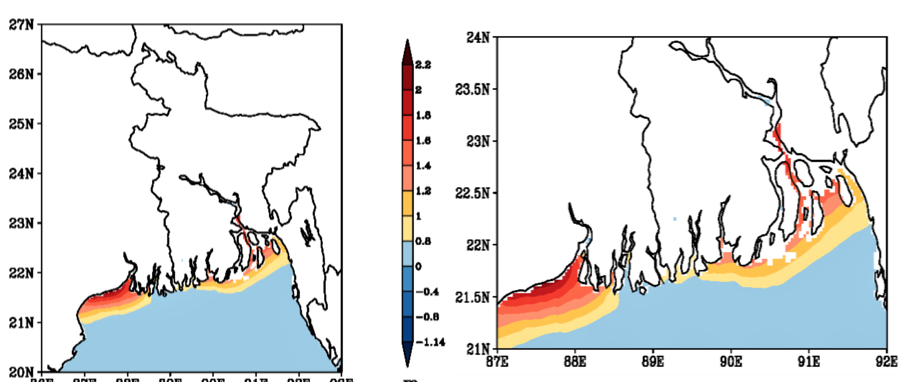

Figure 11: Model simulated maximum storm surge height (meter) of Cyclone Yaas at 0600 UTC of 26 May (landfall time) over wide area and zoomed area

storm surge was comparatively lower on the 25th of May, but it steadily increased on the 26th of May. The storm surge at the time of landfall of cyclone Yaas has been shown in the figure 11. The regions that attain high surge heights after landfall show negative surge heights before the landfall. It is found from the results that the cyclone shows surge height of 1.8-2.2 meter in various areas of Bay of Bengal and coastal areas of Bangladesh and India during 04:00-09:00 UTC of 26th May. Cyclone Yaas shows maximum simulated surge height 2-2.2 meter on 26th May in coastal regions of India. Simulated results are in good agreement with the estimated storm surge height of IMD (1-2 m) [9]. The MRI model simulated MSLP (hPa), zonal wind and meridional wind (m/s) for cyclone Yaas shown in figure-12 and figure-13 respectively. From the the figures it is found that the MRI model simulated mean sea level pressure field, zonal wind and meridional wind very well.

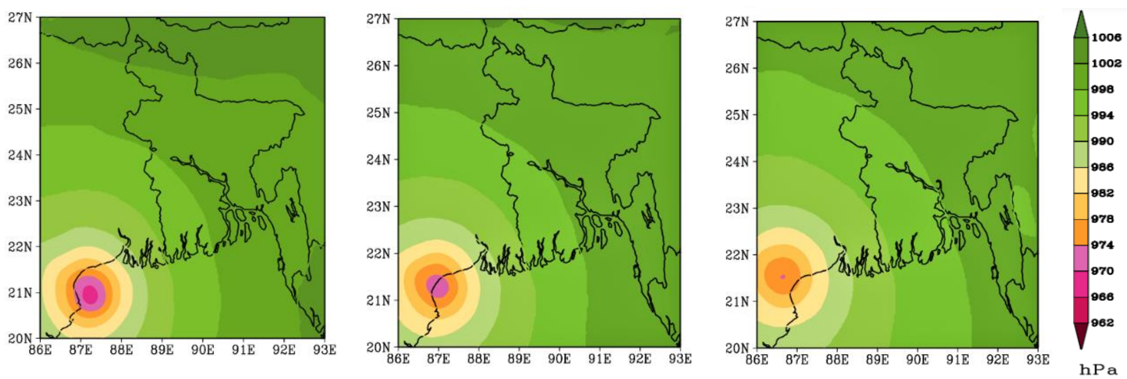

Figure-12: zonal wind and meridional wind (m/s) for cyclone Yaas

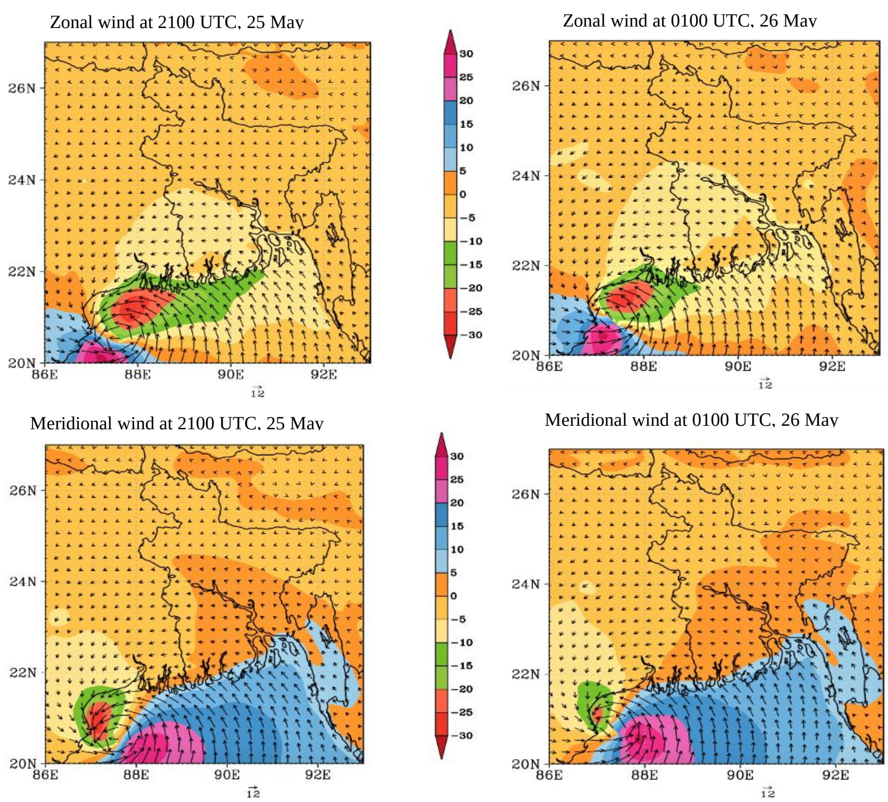

Figure 13: MRI model simulated zonal wind and meridional wind (m/s) for cyclone Yaas

In all of the above figures well organized cyclonic wind fields can be seen. The wind's movement shows a circular motion of the wind from the sea to the land, indicating the movement of a cyclonic storm.

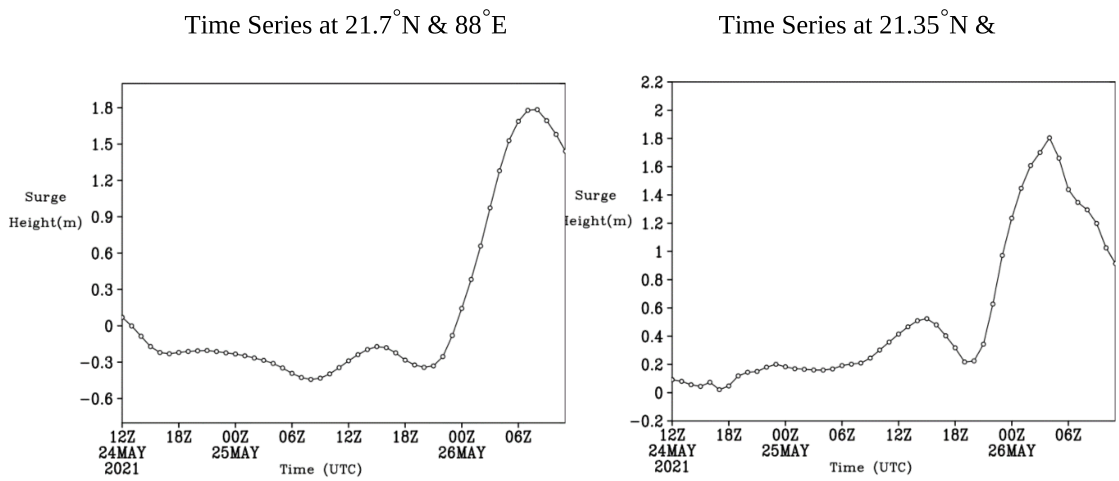

Figure 14: Time series of simulated storm surge for cyclone Yaas using GSM data at 21.7◦N & 88◦E and 21.35◦N & 87◦E respectively.

4. Conclusion

On the basis of the study, the following conclusions are drawn:

1. The WRF model simulated central pressure for cyclone Yaas is different with different initial conditions. At the time of landfall, simulated central pressure is 966 hPa, 957 hPa, 955 hPa, 958 hPa and 974 hPa for 144, 120, 96, 72 and 48 hours model run respectively and Estimated Central Pressure (ECP) of IMD is 970 hPa, i.e. model has underestimated the pressure.

2. The magnitude of maximum wind varies with different initial conditions and is more or less in magnitude than that of observed maximum wind of IMD.

3. The WRF model predicted the re-curvature and probable landfall areas and time of cyclone Yaas quite well. The model also shows that with updated initial fields, landfall accuracy increases as prediction time reduces.

4. Track forecasting position errors for cyclone Yaas were found to be 304 km for 144 hours, 239 km for 120 hours, 240 km for 96 hours, 258 km for 72 hours, and 43 km for 48 hours. For simulations of 144, 120, 96, 72 and 48 hours, the time errors were 32 hours, 19 hours, 13 hours, 5 hours and 02 hours respectively. The smallest position error was determined to be 43 km, and the smallest time error was found to be 02 hours.

5. The estimated storm surge height of IMD (1-2 m) associated with cyclone Yaas is in good agreement with the storm surge height simulated by MRI storm surge model.

Overall the study shows that the selected WRF model can be adopted for real time forecasting of track and landfall by doing more case studies. The simulation with data assimilation will improve the track forecast and minimize the landfall errors. Also, the MRI model used here is capable of simulating storm surge events that occur in the coastal region of Bangladesh. These models can be applied as tools for further upcoming cyclone forecasting.

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