

Simulation of Cyclone Roanu Induced Storm Surge along Bangladesh Coast Using WRF-MRI Coupled Model

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Abstract

Tropical cyclone induced storm surge events have the potential to cause devastating damage to coastal communities who are living in low lying coast like Bangladesh. The magnitude of storm surge impacts climaxes the need for increased accuracy, location specific, real-time forecasting and predictability of storm surge. In this study, meteorological forcing configurations of four different initial conditions used for the simulation of storm surge induced by cyclone Mora, and ultimately support the improvement of storm surge forecasts for Bangladesh coast. The Weather Research and Forecasting (WRF) model is coupled to the JMA-MRI (Japan Meteorological Agency-Meteorological Research Institute) Storm Surge Model to determine water elevations. The Cyclonic Storm Roanu was first detected as a low pressure area over southwest Bay of Bengal off Sri Lanka coast in the evening of 14th May 2016. The Cyclonic Storm Roanu followed a unique track, moving very close to Sri Lanka and east coast of India, it recurved northeastwards and crossed Bangladesh coast to the north of Chittagong around 1000 UTC of 21st May 2016. The objective of this study was to conduct retrospective simulations using the Advanced Research Weather Research and Forecast (WRF-ARW) model in an effort to reconstruct the cyclone's surface wind field and mean sea level pressure field for simulation of storm surge generated by tropical cyclone Roanu.

Keywords: storm surge; cyclones; JMA-MRI; WRF; atmospheric forcing

Introduction:

Storm surges are extremely serious hazards along low lying Bangladesh coast. Bangladesh is extremely vulnerable to tropical cyclone induced storm surge due to its geographical location, low elevated and densely populated coastal areas. The damage and destruction from landfalling cyclones occur mainly due to three factors: torrential rain, strong winds, and storm surges. Almost all the loss of lives and most of the damage of costal infrastructures and crops occur from a tropical cyclone are attributable to the tropical cyclone induced storm surge [1]. Thus, forecast accuracy, predictability, real-time monitoring and location specific warning of storm surges are of great interest for decision makers, coastal volunteers and coastal peoples.

Atmospheric forcing is the main driver of storm surge generated by tropical cyclones [2,3]. In storm surge prediction models, atmospheric forcing is provided in the form of Mean Sea Level Pressure (MSLP) and near-surface wind fields from various sources and configurations. These can include the parametric vortex models, wind reanalysis products and three dimensional (3D) atmospheric models. The parametric vortex model includes the parameters-tropical cyclone location (latitude and longitude), minimum central pressure (Estimated Central Pressure -ECP), maximum wind velocity (V_{max}) and radius of maximum winds (R_{max}). These parameters are available from the forecast advisories issued by National Meteorological Services (NMSs) every 3 or 6 hours throughout the tropical cyclone's lifetime. The availability of these tropical cyclone parameters and the computational efficiency of parametric vortex models can be used for timely storm surge forecasts. For that reason, parametric vortex models are suitable for real-time forecasting of storm surge generated by tropical cyclone. However, vortex models are a simplification of the tropical cyclone wind field and fail to capture important dynamic processes such as weakening and distortion of the tropical cyclone wind field after interaction with topography during the time of landfalling [4].

There has been some work already done to study the use of the WRF model to drive different storm surge models for purposes of providing an improved storm surge prediction system. WRF model has a number of advantages over steady state and objective analysis approaches. The model simulates the evolution of atmospheric systems including tropical cyclones using full physics. It employs a range of physics options to account for cloud microphysics, atmospheric radiation processes, planetary boundary layer and surface layer processes, and parameterization of sub-grid scale moist convection. These capabilities allow WRF to simulate far field winds, spiral rainband structures, and supergradient flow in the inner core region [5].

The state-of-the-art Advanced Research WRF (ARW) model is one among the widely used mesoscale models for weather predictions over the Indian region and indeed globally. Since 2007, the ARW model has been used for real-time TC forecasting over the NIO basin [6,7]. The Weather Research and Forecasting (WRF) model is coupled to the ADvanced CIRCulation Model (ADCIRC) to determine water elevations and results show that atmospheric forcing in the form of full wind and pressure field from a high-resolution atmospheric model simulation prove reliable for storm surge forecasting [4].

Mallik et al. used the Weather Research and Forecast Model (WRF) model and Meteorological Research Institute (MRI) model to simulate the landfall and storm surge of Cyclone Viyaru [8]. Storm surges due to Typhoon Haishen was accurately simulated by coupling the mesoscale meteorological model (WRF) and the storm surge model (GeoClaw) [9]. The surface wind and mean sea level pressure predictions from mesoscale atmospheric models such as the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5) and the Weather Research and Forecasting (WRF) Model have been used to drive the storm surge models [10,11,12,13,14,15,16]. Most of these models were run in hindcast mode.

This paper is organized as follows. Section 2 describes the Weather Research and Forecast Model (WRF) model and JMA-MRI storm surge model. Section 3 presents the synoptic history of tropical cyclone Mora. Section 4 shows the Data and Methodology, and section 5 6 presents results and discussion. Section 6 presents conclusions of this study.

2. Model description

The present work is an application of the state-of-art models such as WRF-ARW and JMA-MRI storm surge model integrated together to understand the performance of storm surge prediction for the Tropical cyclone Roanu (May 2016) over Bay of Bengal. The following section details with a brief description of these models:

2.1. WRF-ARW model

The WRF model was used to simulate the meteorological field of Tropical Cyclone Roanu. The state-of-the-art Weather Research and Forecast (WRF ARW version 4.2) is a fully compressible, non-hydrostatic mesoscale model with hydrostatic option which uses terrain following hybrid sigma-pressure vertical coordinates and staggered Arakawa-C grid developed by the National Center for Atmospheric Research (NCAR) [17]. This advanced model incorporates accurate numerics, higher order mass conservation characteristics, and advanced physical parameterizations. The prognostic variables include three-dimensional (3-D) wind perturbation quantities of pressure, potential temperature, geopotential, surface pressure, turbulent kinetic energy and scalars. The vertical coordinates are terrain following hydrostatic pressure, and the horizontal grid discretization is Arakawa-C staggered grid. In addition, the WRF model has found wide applications in variety of problems that resolves physical processes with varied spatial scale resolutions. It uses a third order Runge-Kutta time integration scheme. The model has several options for spatial discretization, diffusion, nesting, and lateral boundary conditions. The model physics accounts for cloud micro-physics, surface layer physics, land surface model, boundary layer, long, and short-wave radiation components. The computational settings of WRF model shown in table-1.

Table 1: Computational settings for WRF

Dynamics	Non hydrostatic
Data	NCEP GFS
Interval (h)	6
Grid size	$(215 \times 215) \times 36$
Horizontal Resolution	9kmX9km
Map projection	lat-lon
Horizontal grid system	Arakawa-C grid
Integration time step	30 s
Vertical coordinates	Terrain-following sigma co-ordinate system with 36 vertical levels
Time integration scheme	Third order Runge-Kutta scheme
Spatial differencing scheme	Sixth order center differencing
Microphysics	WSM 3-class scheme
Short wave radiation	Dudhia scheme
Long wave radiation	RRTM
PBL scheme	YSU PBL scheme
Cu-physics	New Kain-Fritsch

It initializes with available large-scale analyses of meteorological parameters and includes an option for advanced data assimilation procedures. There are number of options available in model to represent the sub-grid scale

physical processes for convection, explicit microphysics, atmospheric radiation, boundary layer turbulence, and surface temperature/moisture. The Table 1 provides an overview of the schemes used in the present study. More details on the mathematical governing equations are available in the NCAR technical note.

2.2 JMA-MRI storm surge Model

JMA-MRI storm surge model was technologically advanced at Meteorological Research Institute (MRI), JMA, based on Princeton Ocean Model [18]. The storm surge model is based on vertically integrated two-dimensional ocean model. The governing equations are usual momentum equation and continuity equation. This model considers two main mechanisms of storm surges, 1) inverse barometer effect and 2) wind set-up. For calculation of water level, astronomical tides can be included with several options. Only simple surge calculation without astronomical tide, as being calculated in the previous versions, fixed or time varied (unique) tide in whole computational domain, and input of tidal components are available.

The new version takes into account the wet and dry process for inundation approximation [19]. The model assumes tidal level as a constant parameter adding surges with a linear relation. Visualization of tidal components at some grid point is also an option. The results from the model output can be sent to various local meteorological stations that issue warnings of storm surge to their respective zones of responsibility. The information regarding the period and level of water of probable maximum surges are included in the warnings in the concerned area. This model can work in any regions of the world with suitable set of bathymetry data and meteorological imposing fields [20].

Other influences, such as ocean waves, the effects of stratification, and river flows, which may also affect to storm surges, are not considered in this model. Wave setup can be estimated by wave predicted values independently. Simple storm surge simulation, without inundation can be set as one option, in that time the boundary condition at land/sea margins are assumed as fixed rigid walls.

The storm surge models need meteorological condition on surface winds and sea level pressures. This model refers two types of meteorological input. The one is parametric model and the other is predicted data from a Numerical Weather Prediction (NWP) Model.

The model can run with NWP output. The users need to get NWP predicted data. Necessary data are sea level pressures and surface (10 m) winds. Before a storm surge model calculation, NWP data must be edited for storm surge model domain and grid resolution. Description of JMA MRI storm surge model summarized in the table-2.

Storm surge forcing

Meteorological input data are prepared, the model calculates balanced water level (to air pressures) and wind (and bottom stress) forcing.

Inverse barometer effect

The balanced water level to air pressure can be calculated with hydrostatic balance:

$$\frac{dP}{dz} = -\rho_w g$$

From the relation, water level rise by pressure depression (inverse barometer effect) can be expressed as

$$\delta z = -\frac{\delta P}{\rho_w g}$$

From two pressure profiles, sea level rise is expressed as

$$\delta z = \begin{cases} \frac{1}{\rho_w g} \frac{\Delta P}{\sqrt{1+(r/r_0)^2}} & \text{Fujita [21]} \\ \frac{\Delta P}{\rho_w g} \left(1 - \frac{1}{\exp(r_0/r)}\right) & \text{Schloemer [22]} \end{cases}$$

Surface and bottom stresses

The stresses are estimated with the conventional bulk scheme, expressed as follows.

surface stresses by winds

$$\boldsymbol{\tau}_a = \begin{cases} \tau_{ax} = -\rho_a C_{da} |\mathbf{V}| v_x \\ \tau_{ay} = -\rho_a C_{da} |\mathbf{V}| v_y \end{cases}$$

bottom frictions

$$\boldsymbol{\tau}_b = \begin{cases} \tau_{bx} = -\rho_w C_{db} |\mathbf{U}| u \\ \tau_{by} = -\rho_w C_{db} |\mathbf{U}| v \end{cases}$$

Where $\mathbf{V} = (v_x, v_y)$ indicates surface winds, and C_{da} , C_{db} are drag coefficients. There are many expressions on the drag coefficients; we empirically set these values as:

$$\begin{cases} C_{da} = 3.2 \times 10^{-3} \\ C_{db} = 2.5 \times 10^{-3} \end{cases}$$

Table 2: Description of JMA MRI storm surge model

Model	2-dimensional ocean model, vertically integrated
Coordinate	Lat/Lon cartesian grid (Arakawa C-Grid)
Area	8.5°N – 23.5°N, 80.0°E – 100°E
Grid resolution	3.75 km x 3.75 km
Forcing Data	WRF output 9km resolution
Pressure profile	Fujita
Visualization Tools	Grid Resolution and Display System (GrADS)
Topographic data	GEBCO 3 sec resolution

3. Synoptic History of Tropical Cyclone Roanu

The system was first detected as a low pressure area over southwest Bay of Bengal off Sri Lanka coast in the evening of 14th May 2016. Moving northeastwards, it became well marked low pressure area over southwest Bay of Bengal and adjoining Sri Lanka coast in the morning of 15th May 2016. It further moved northwestwards and lay over Sri Lanka and adjoining areas of Gulf of Mannar and southwest Bay of Bengal in the morning of 16th May 2016. Moving thereafter, north-northwestwards, it concentrated into a depression and was centered over southwest Bay of Bengal off Tamil Nadu coast in the morning of 17th May 2016. It further moved nearly northwards, intensified into a deep depression and was centred over westcentral and adjoining southwest Bay of Bengal near latitude 13.3°N and longitude 81.0°E at 0300 UTC of 18th May 2016. The system moved north-northeastwards skirting Tamil Nadu and Andhra Pradesh coast, intensified into a cyclonic storm over westcentral Bay of Bengal and was centered near latitude 15.1°N and longitude 81.4°E at 0000 UTC of 19th May 2016. The system continued to skirt along the east coast of India while moving northeastwards and intensified slightly at 0600 UTC of 19th May 2016 and then at 1800 UTC 20th May 2016. The system maintained its same intensity and crossed Bangladesh coast near north of Chattogram around 1000 UTC of 21st May 2016 as a Cyclonic Storm. After landfall, the system started weakening due to land interactions. Continuing its east-northeastward journey, the Cyclonic Storm weakened gradually. The observed track of the Cyclonic Storm Roanu is shown in Figure 1. The Cyclonic Storm Roanu followed a unique track, moving very close to Sri Lanka and east coast of India. It recurved northeastwards and crossed Bangladesh coast to the north of Chittagong. The lowest estimated central pressure (ECP) was 983 hPa with a pressure drop of 11 hPa. The Cyclonic Storm travelled a distance of about

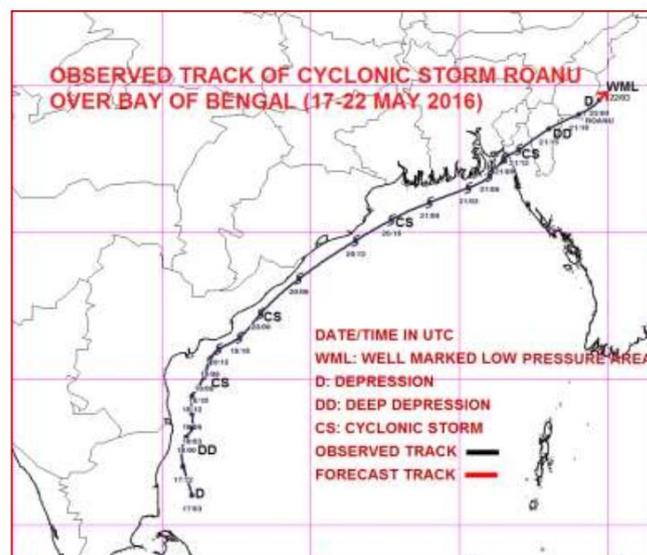


Figure-1: Observed Track of Cyclonic Storm Roanu. [23]

2300 km during its five days life period. Cyclonic Storm Roanu showed large scale diurnal variations with respect to its central cloud cover and spiral bands in terms of depth of cloud and area of coverage. While the cloud mass intensified towards early morning, it showed signs of weakening towards sunset. Cyclonic Storm Roanu did not intensify to a severe cyclone in spite of its long travel over the sea mainly due to land interactions and large-scale diurnal variations.

4. Data and Methodology

A coupled atmospheric-storm surge model used by coupling the mesoscale meteorological model (WRF) and the storm surge model (JMA-MRI). The coupled model was used for the accurate simulation of storm surge generated by Severe Cyclonic Storm Mora. The WRF model was used to simulate the meteorological field of Severe Cyclonic Storm Mora for 72 hours with the configuration as stated in the table-1. Single domain was used as the WRF computational domain with 9kmX9km horizontal grid resolution and 36 vertical levels using 6 hourly 0.25° resolution GFS operational data as input from National Centers for Environmental Prediction (NCEP). The forecast experiments were conducted with two different initial conditions-18UTC of 19 May and 00UTC of 20May 2016. As the JMA-MRI storm surge model only needs two meteorological inputs-wind field at 10m height and mean sea level pressure field, for that reason these two parameters separated (subset) from WRF model output by using CDO (Climate Data Operator) for better management of data. Then WRF subset data used as input to the JMA-MRI storm surge model along with the General Bathymetric Chart of the Oceans (GEBCO) bathymetry data and FES2014 Tide Model-the last version of the FES (Finite Element Solution) tide model developed in 2014-2016. For the simulation of storm surge induced by the Severe Cyclonic Storm Mora, the JMA-MRI storm surge model run for 48 hours with each set of input data. The flow diagram of whole process shown in the figure-2. The output of the storm surge model analyzed and visualized with GrADS and finally simulated storm surge compared with available reported storm surge and real time simulation of other storm surge models.

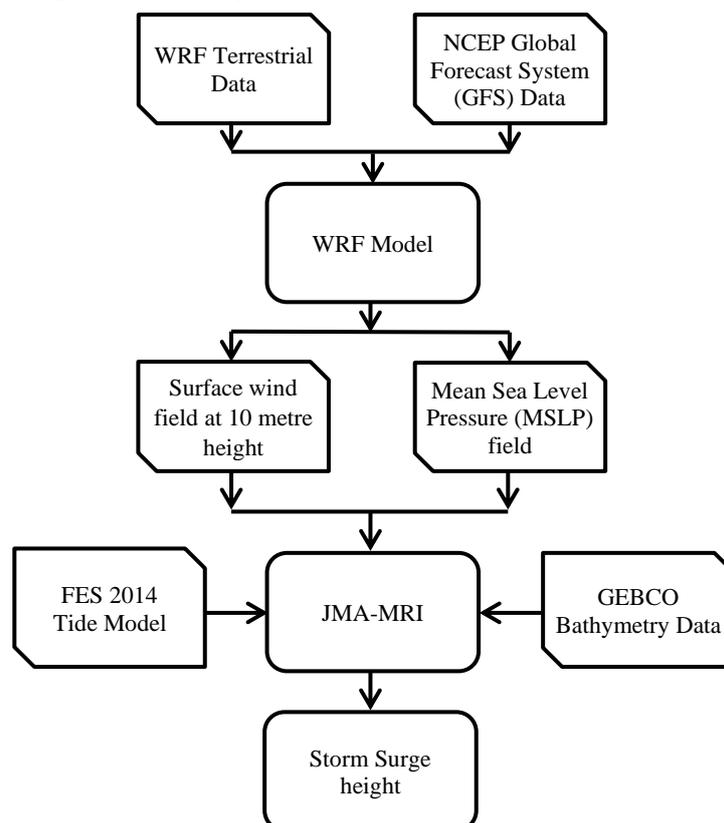


Figure-2: Flow diagram of WRF-JMA-MRI Couple Model

5. Result and Discussion

The Cyclonic Storm Roanu was simulated using initial conditions of 18 UTC, 19 May 2016. Figure-3.a shows very organized mean sea level pressure distribution of Cyclonic Storm Roanu just before landfall at 09UTC of 21 May 2016 and the lowest minimum pressure was 972 hPa. The figure-3.b Shows the 10m wind distribution of Cyclonic Storm Roanu at 09 UTC of 21 May 2016 and highest wind speed of 30m/sec found on the left side of the cyclone. Both figure show that predicted movement of the cyclone was slower than the observed when WRF model run with initial condition of 18UTC, 19 May 2016.

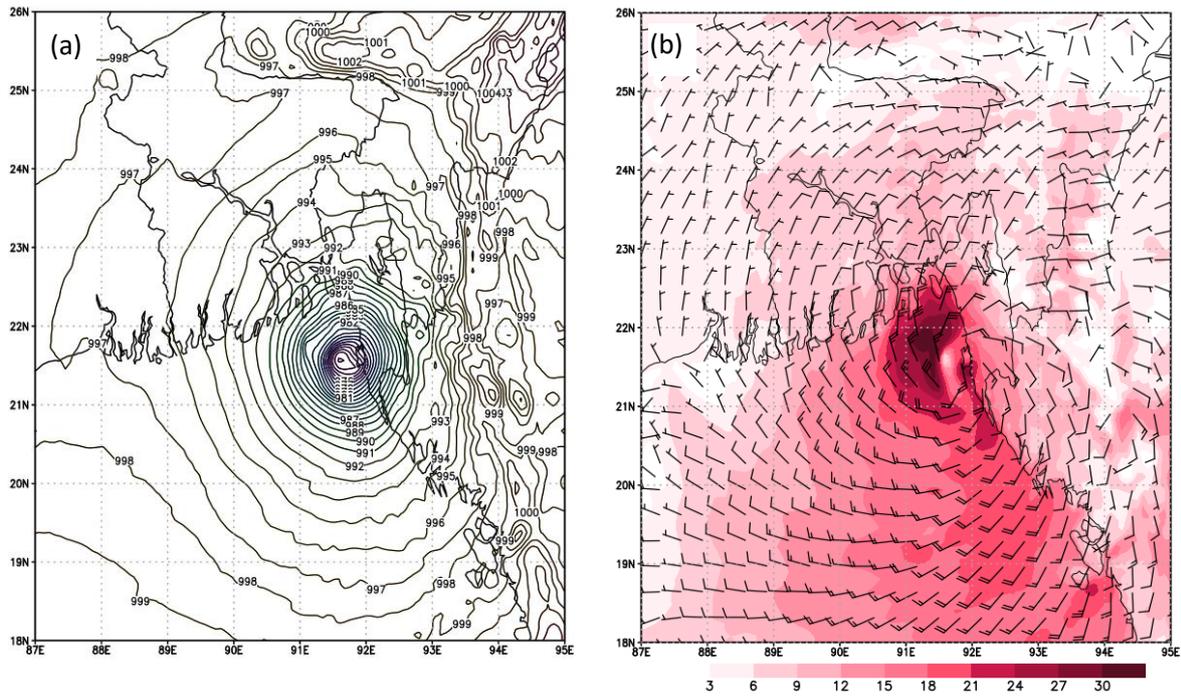


Figure-3(a-b): WRF predicted mean sea level pressure (in hPa) field (a) and wind field (b) at 09UTC of 21 May 2016 with the initial condition of 18UTC of 19 May 2016.

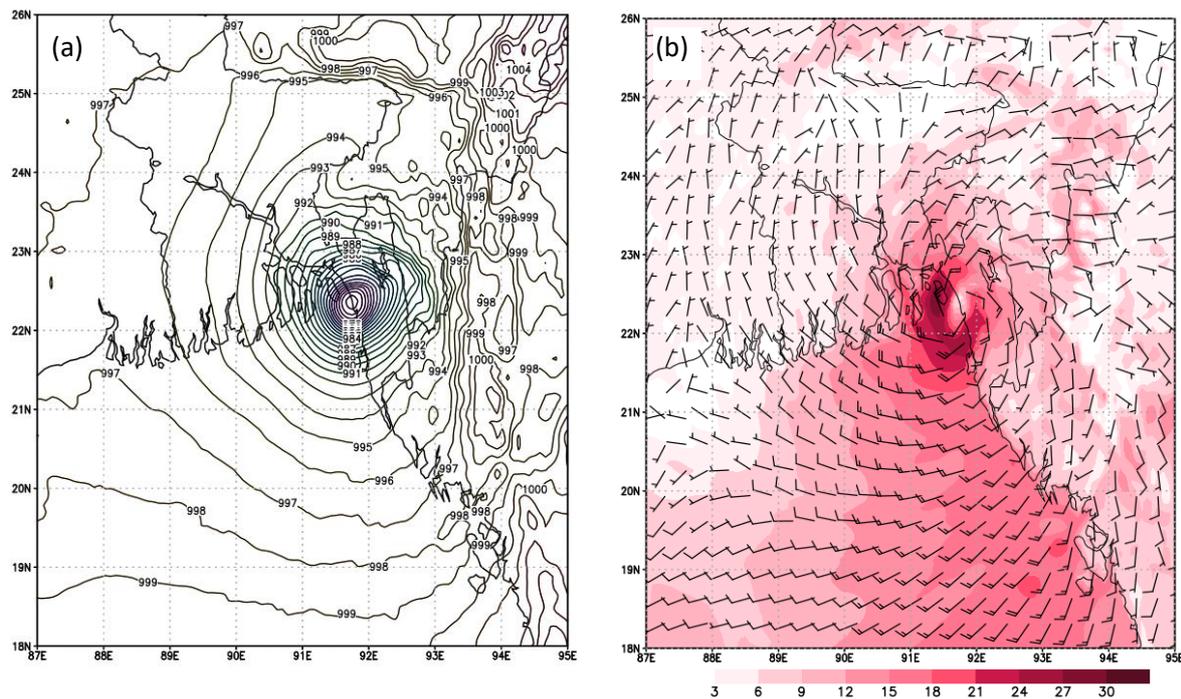


Figure-4(a-b): WRF predicted mean sea level pressure (in hPa) field (a) and wind field (b) at 12UTC of 21 May 2016 with the initial condition of 00UTC of 20 May 2016.

The Cyclonic Storm Roanu was also simulated using initial conditions of 00UTC, 20May 2016. Figure-4.a shows very organized mean sea level pressure distribution of Cyclonic Storm Roanu during landfall at 12UTC of 21 May 2016 and the lowest minimum pressure was 988 hPa. The figure-4.b Shows the 10m wind distribution of Cyclonic Storm Roanu at 12 UTC of 21 May 2016 and highest wind speed of 30m/sec found on the left side of the cyclone. Both figure show that predicted movement of the cyclone was slightly slower than the observed but faster than when WRF model run with initial condition of 18UTC, 19 May 2016. Figures 4(a) and 4(b) also show that landfall time and location were very close to observed when model run with initial condition of 00UTC of 20 May 2016.

(a)

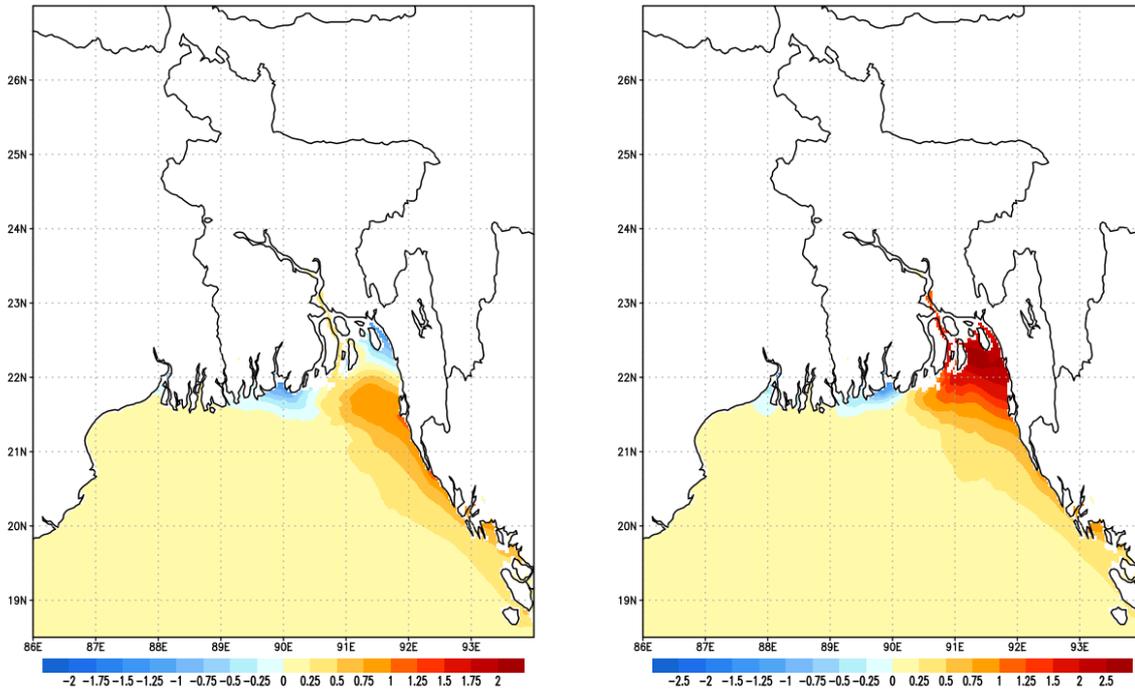


Figure-5(a-b): JMA-MRI predicted storm surge height in meter (a) at 09UTC of 21 May 2016 with the initial condition of 18UTC of 19 May 2016 and (b) at 12UTC of 21 May 2016 with the initial condition of 00UTC of 20 May 2016

Storm surge induced by Cyclonic Storm Roanu simulated by using JMA-MRI storm surge model with input data from WRF model output of 18UTC, 19 May 2016. From the figure-5.a, it is found that the peak storm surge of about 2m was along Cox’s Bazar coast which is right side of the cyclone track Roanu but much south of actual landfall position.

Storm surge induced by Cyclonic Storm Roanu also simulated by using JMA-MRI storm surge model with input data from WRF model output of 00UTC, 20 May 2016. From the figure-5.b, it is found that the peak storm surge of about 3m was along Chattogram coast which is also right side of the cyclone track Roanu and very close to actual landfall position.

For both cases, the negative storm surge found left side of the cyclone track which is realistic.

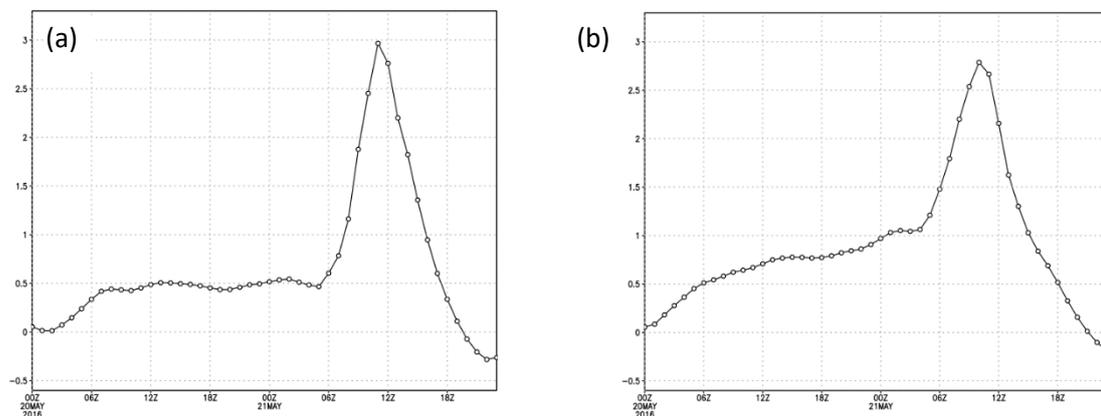


Figure-6(a-b): JMA-MRI storm model computed peak surge envelope along the Chattogram coast (lat.22.3°N and long. 91.3°E) and east coast Hatiya at lat 22.2°N and long. 91.8°E.

Figure 6 (a) shows the JMA-MRI storm model computed peak surge envelope with initial condition of 00UTC of 20 May 2016 along the Chattogram coast (lat.22.3°N and long. 91.3°E). It can be seen that a maximum surge of about 3.0m occurred close to the landfall point. The east coast of Hatiya also affected by storm surge and more than 2.7m storm surge predicted by JMA-MRI storm surge model at lat 22.2°N and long. 91.8°E (figure-6.b).

6. Conclusion:

The study reports on the performance evaluation of WRF-ARW winds on computed storm surge using the JMA-MRI storm surge model for tropical cyclone Mora that made landfall along Bangladesh coast. A comprehensive analysis covers the role of different initial conditions in the final determination of total water level elevation and resultant storm surge.

The 72 hours forecast of cyclone Roanu by WRF-ARW shows reasonable accuracy in terms of cyclone track and intensity. For the small domain model simulated initial and landfall position of the cyclone looks very close to the observed one when the WRF model run with the initial condition of 00UTC, 20th May 2016. The model results simulated in the present study are in good agreement with available reports/estimates.

This study showcased a coupled model for the numerical simulation of storm surge over the Bay of Bengal and examined the accuracy of the results for the super cyclonic storm Roanu. WRF ARW model could forecast the mean sea level pressure field and wind field at 10m well. Since the application of WRF model for the Bay of Bengal cyclones is new, further modification of this model is possible, which is expected to give a more accurate input for the prediction of tropical cyclone induced storm surge. More experiments with domain size, initial and boundary conditions as well as application of moving nest and vortex initialization technique can be helpful for the further improvement of the model.

The WRF wind and pressure fields can be used to drive a storm surge model such as the Japan Meteorological Agency-Meteorological Research Institute (JMA-MRI) model as part of a storm surge prediction and analysis. WRF output may represent a potential source of data for storm surge prediction and analysis especially for regions with limited or no observational data like Bay of Bengal.

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References:

- [1] Dube, S. K., Jain, I., Rao, A. D., & Murty, T. S. (2009). Storm surge modelling for the Bay of Bengal and Arabian Sea. *Natural Hazards*, 51(1), 3–27. doi:10.1007/s11069-009-9397-9.
- [2] Dietrich, J.; Muhammad, A.; Curcic, M.; Fathi, A.; Dawson, C.; Chen, S.; Luettich, R., Jr. Sensitivity of storm surge predictions to atmospheric forcing during hurricane ISAAC. *J. Waterw. Port Coast. Ocean Eng.* **2017**, 144, 04017035.
- [3] Lakshmi, D.D.; Murty, P.; Bhaskaran, P.K.; Sahoo, B.; Kumar, T.S.; Sheno, S.; Srikanth, A. Performance of WRF-ARW winds on computed storm surge using hydrodynamic model for Phailin and Hudhud Cyclones. *Ocean Eng.* **2017**, 131, 135–148.
- [4] Ramos Valle, A., Curchitser, E., Bruyere, C., & Fossell, K. (2018). Simulating Storm Surge Impacts with a Coupled Atmosphere-Inundation Model with Varying Meteorological Forcing. *Journal of Marine Science and Engineering*, 6(2), 35. doi:10.3390/jmse6020035
- [5] Mattocks, C.A.; Forbes, C.; Jedlovec, G.; Case, J.; LaFontaine, F. Adaptation of the advanced hurricane WRF for driving a storm surge prediction model. In *Proceedings of the 29th Conference on Hurricanes and Tropical Meteorology*, Tucson, AZ, USA, 10–14 May 2010.
- [6] Osuri, K. K., Mohanty, U. C., Routray, A., Kulkarni, M. A. and Mohapatra, M., “Sensitivity of physical parameterization schemes of WRF model for the simulation of Indian seas tropical cyclones”, *Nat. Hazards*, 63, 3, 1337-1359, 2012.
- [7] Osuri, K. K., Mohanty, U. C., Routray, A., Mohapatra, M. and Niyogi, D., “Real-time Track Prediction of Tropical Cyclones over the North Indian Ocean using the ARW model”, *J. Appl. Meteorol. Climatol.*, 52, 11, 2476-2492 2013.
- [8] Mallik, M. A. K., Ahsan, M. N., and Chowdhury, M. A. M., (2015) Simulation of Track and Landfall of Tropical Cyclone Viyaru and Its Associated Storm Surges Using NWP Models. *American Journal of Marine Science*, 3(1):11-21. doi: 10.12691/marine-3-2-1.
- [9] Toyoda, M., Fukui, N., Miyashita, T., Shimura, T., & Mori, N. (2022). Uncertainty of storm surge forecast using integrated atmospheric and storm surge model: a case study on Typhoon Haishen 2020. *Coastal Engineering Journal*, 64(1), 135–150. <https://doi.org/10.1080/21664250.2021.1997506>.

- [10] Lin, N., J. A. Smith, G. Villarini, T. P. Marchok and M. L. Baeck, 2010: Modeling extreme rainfall, winds, and surge from Hurricane Isabel (2003). *Wea. Forecasting*, 25, 1342–1361, doi:10.1175/2010WAF2222349.1.
- [11] Zhong, L., M. Li and D.-L. Zhang, 2010: How do uncertainties in hurricane model forecasts affect storm surge predictions in a semi-enclosed bay?, *Estuarine Coastal Shelf Sci.*, 90, 61–72, doi:10.1016/j.ecss.2010.07.001.
- [12] Di Liberto, T., B. Colle, N. Georgas, A. Blumberg, and A. Taylor, 2011: Verification of a multimodel storm surge ensemble around New York City and Long Island for the cool season. *Wea. Forecasting*, 26, 922–939, doi:10.1175/WAF-D-10-05055.1.
- [13] Chen, C. and Coauthors, 2013: Extratropical storm inundation testbed: Intermodel comparisons in Scituate, Massachusetts. *J. Geophys. Res. Oceans*, 118, 5054–5073, doi:10.1002/jgrc.20397.
- [14] Georgas, N., P. Orton, A. Blumberg, L. Cohen, D. Zarrilli, and L. Yin, 2014: The impact of tidal phase on Hurricane Sandy's flooding around New York City and Long Island Sound. *J. Extreme Events*, 1, 1450006, doi:10.1142/S2345737614500067.
- [15] Wang, H. V., J. D. Loftis, Z. Liu, D. Forrest, and J. Zhang, 2014: The storm surge and sub-grid inundation modeling in New York City during Hurricane Sandy. *J. Mar. Sci. Eng.*, 2, 226–246, doi:10.3390/jmse2010226.
- [16] Zambon, J. B., R. He, and J. C. Warner, 2014: Tropical to extratropical: Marine environmental changes associated with Superstorm Sandy prior to its landfall. *Geophys. Res. Lett.*, 41, 8935–8943, doi:10.1002/2014GL061357.
- [17] Skamarock, W.C., Klemp, J.B., Dudhia, J., Gill, D.O., Barker, D.M., Wang, W., Powers, J.G., 2005. A Description of the Advanced Research WRF version 2. NCAR Tech. Note NCAR/ TN-4681STR, pp. 88.
- [18] Blumberg, A.F., Mellor, G.L., 1987: A description of a three-dimensional coastal ocean circulation model. In *Three-dimensional Coastal Ocean Model*, N.S. Heaps, Ed., *Coastal. Estuar. Sci.*, 4, 1-6.
- [19] Hasegawa, H., Kohno N., and Itoh M., (2015) Development of storm surge model in Japan Meteorological Agency. Office of Marine prediction, JMA.
- [20] Higaki, M., Hironori, H., and Futoshi N. (1998) Outline of the Storm Surge Prediction Model at the Japan Meteorological Agency. 25-38.
- [21] Fujita, T., 1952: Pressure Distribution Within Typhoon. *Geophys. Mag.*, 23, 437 – 451.
- [22] Schloemer, R. W., 1954: Analysis and synthesis of hurricane wind patterns over Lake Okechobee, Florida. *Hydrometeorology Rep.* 31, Dept. of Commerce, Washington, DC, 49 pp.
- [23] Cyclonic Storm, 'Roanu' over the Bay of Bengal (17-22 May 2016): A Report, India Meteorological Department, 2016.
https://rsmcnewdelhi.imd.gov.in/download.php?path=uploads/report/26/26_b99261_Roanu.pdf