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Development of a Regional Numerical Tidal Forecast Model Along the Coast of Bangladesh and Its Associated Tidal Height Estimation

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Abstract

A two-dimensional shallow water equation in the Cartesian coordinate model considered as regional model is developed to estimate the tide along the coast of Bangladesh. The model equation is discretized by the Finite Difference Method (FDM). This model has been developed by using NAO.99b tide model. In our model, the coastal boundaries, islands, and some small rivers are approximated by an exact stair step representation and solved by a conditional stable semi-Implicit Finite Difference Technique in a Structured Arakawa C-Grid system. Ignoring the wind stress has created stable tidal conditions along the southern open boundary of the ocean which is the astronomical M2 and NAO.99b component. The desired results are obtained after running the model for a fixed period of time at least 3 days for the steady state. The model results give a reasonable agreement with the observed data. The root means square error of the mean also shows good reasonable agreement.

Key words: Bangladesh, Coastal forecast, Finite difference method (FDM), Numerical modelling, Tidal forecast

1. Introduction

The periodic rise and fall of sea level due to gravitational forces outside the Earth (especially due to the Moon) are called tides. Together these two are called tides. The waves created in the ocean due to tides are called Tidal Waves. The rise of the water level when the tide moves towards the coast is called High Tide Water and the fall of the water level when the tide moves towards the sea is called the Low Tide Water. Every 6.13 hours, tides occur. That is, tides occur twice a day. The tides created by the maximum gravitational force of the Moon at the point where the Earth is closest to the Moon during its rotation are called main tides or lunar tides. Both revolve around a fixed centre of mass. The distance between this centre of mass and the centre of the Moon is less than the distance between the centres of the Earth and the Moon. Due to the strong gravitational force of the moon, strong main tides occur.

Earth revolves around its pole once in 23 hours 56 minutes 48 seconds. If there was no orbital motion of the moon, i.e. if the moon was stationary, the main tides would occur at the same specific time at a specific place on the Earth's surface. But the Moon takes $27\frac{1}{3}$ days to go around the Earth once. That is, every day ($360° + 27\frac{1}{3}$ days) $13°10'14.63''$ angular distance is covered. Consequently, 52 m 41 seconds is covered from that particular place in one day ($13°10'14.63'' = 13.17073 \times 4$ m). That is why the earth 24 hours 49 minutes 29 seconds after

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the occurrence of major tide at a place (23 hours 56 minutes 48 seconds + 52 minutes 41 seconds) the major tide will occur again at that particular place. The time difference between major tide and minor tide will be 12 hours 24 minutes 44.5 seconds. Alternatively, for a tide and an ebb the time interval will be 6 hours 12 minutes 22.25 seconds. The effect of tidal water is more towards the coast. 29% of our country's population lives in coastal areas [1], many of whom depend on marine resources. For example, a fish dry farmer, a salt farmer, a fisherman, and a sailor. And, everyone is dependent on tidal water. As much as tidal water benefits us, it also creates problems for us. Normal human movement is disrupted by low-lying floods, sometime tide may influence the coastal area with inundation [2]–[4], so accurate tidal data is very important. Tide may help nature various way like Intertidal organisms can be strongly influenced by tides, such as gamete release by seaweed [5], oxygen conductivity [6], habitat selection by animals [7]–[9], animal hatching [10]. Various marine scientists have studied this topic, among them notable researchers [11]–[17]. A significant aspect of their research is that they measured the tides through the interaction of storms and tides. Some have modelled this interaction in a non-linear manner. However, the issue of tides is a magnitude of God's creation that has many scientific explanations. For this we want to develop a numerical model that measures the exact height of tidal water. So, we modified and improved the storm model like other researchers and developed the model only to measure the height of the tide.

In this study, we used a two-dimensional shallow water equation to generate tidal numerical simulation results. Basically, we look at the interaction of our developed model and NAO.99b tide model [18] to insert tidal data on the southern open boundary. We believe that the results obtained in our study may acceptable. In the next sections, the details of the subject matter of the research are discussed in stages.

2. Data Material and Methods

2.1. Study area

Bangladesh is a sovereign country in South Asia whose official name is the People's Republic of Bangladesh. Bangladesh is bordered by India to the west, north, and east, Myanmar to the southeast, and the Bay of Bengal to the south. Our research focuses on the coastal region.

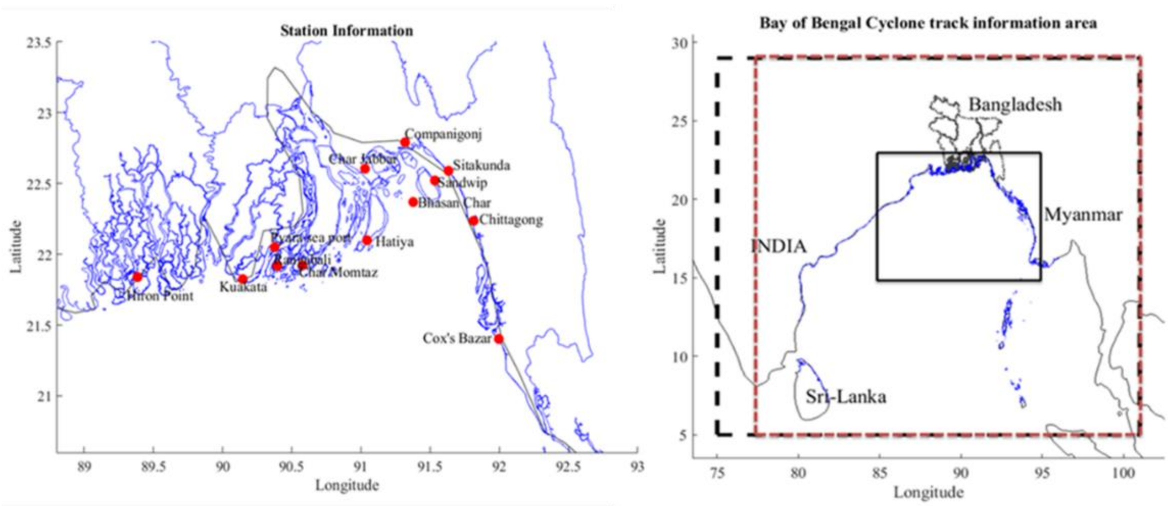

Figure 1. Study area with tidal locations

Bangladesh, the world's most tropical cyclone affected country is situated at the northern tip of the Bay of Bengal in between 88 to 92-degree East longitude and 20 to 26-degree North latitude. It is bordered on the west, north, and east by India, on the southeast by Myanmar, on the south by the Bay of Bengal. There are 7 hundred rivers, including tributaries flowing over all of Bangladesh. This study focuses on the offshore islands, but the special concentration on Hatiya, Sandwip, Monpura, Char Piya and so on.

2.2. Model equation

Considering any atmospheric or oceanic phenomenon, if the horizontal length scale is much larger than the vertical scale, the *z*-component of the momentum equation may be approximated by the hydrostatic equation. Moreover, if the density variation in all directions is negligible, the continuity equation reduces to the non-divergence of velocity. With these shallow water approximations and neglecting the molecular viscosity, the basic set of shallow water equations [11] is given by

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} - fv = -\frac{1}{\rho}\frac{\partial p}{\partial x} \tag{1}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} + fu = -\frac{1}{\rho}\frac{\partial p}{\partial y} \tag{2}$$

$$\frac{\partial p}{\partial z} = -\rho g \tag{3}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{4}$$

where u, v, w are the instantaneous components of velocity in the directions of x, y, and z respectively; t is the time; p is the pressure; ρ the density of the sea water supposed homogenous and incompressible; $f = 2\Omega \sin\varphi$ the Coriolis parameter, Ω is the angular speed of the Earth rotation and φ is the latitude of the place of interest; g the acceleration due to gravity. After applying average procedure, vertical integration process simplifies the equation we may get the basic shallow water model equation as

$$\frac{\partial \zeta}{\partial t} + \frac{\partial \tilde{u}}{\partial x} + \frac{\partial \tilde{v}}{\partial y} = 0 \tag{5}$$

$$\frac{\partial \tilde{u}}{\partial t} + \frac{\partial (u\tilde{u})}{\partial x} + \frac{\partial (v\tilde{u})}{\partial y} - f\tilde{v} = -g(\zeta + h)\frac{\partial \zeta}{\partial x} + \frac{T_x}{\rho} - \frac{C_f\,\check{u}\sqrt{(u^2+v^2)}}{\zeta+h} \tag{6}$$

$$\frac{\partial \tilde{v}}{\partial t} + \frac{\partial (u\tilde{v})}{\partial x} + \frac{\partial (v\tilde{v})}{\partial y} + f\tilde{u} = -g(\zeta + h)\frac{\partial \zeta}{\partial x} + \frac{T_y}{\rho} - \frac{C_f\,\check{v}\sqrt{(u^2+v^2)}}{\zeta+h} \tag{7}$$

where $(\tilde{u}, \tilde{v}) = (\zeta + h)(u, v)$ (8)

In the above equations, u and v in the bottom stress terms have been replaced in order to solve the equations numerically in a semi-implicit manner.

2.3. Model setup

2.3.1. Setup boundary conditions

In addition to meeting surface and bottom conditions, appropriate conditions along the lateral boundaries of the sea area under consideration must be met at all times, so we may consider the boundary conditions on three sides. One side is an open sea and the rest of them are coast. Considering some marine dynamics, a radiation type of boundary condition is generally applied. This may help the external forces to access openly. So, the major boundary conditions are as follows.

At the west boundary: $v + \left(\frac{g}{h}\right)^{\frac{1}{2}} \zeta = 0$ (9)

At the east boundary: $v - \left(\frac{g}{h}\right)^{\frac{1}{2}} \zeta = 0$ (10)

At the south boundary: $u - \left(\frac{g}{h}\right)^{\frac{1}{2}} \zeta = -2\left(\frac{g}{h}\right)^{\frac{1}{2}} a \sin \sin \left(\frac{2\pi t}{T} + \varphi\right)$ (11)

2.3.2. Setup nested scheme

We find that the model area is large enough to properly include island boundaries and coastlines in our numerical scheme, so we think the mesh size should be very small. We see several problems with small mesh sizes, which are practical problems that have been observed in many studies [19]. The problems are;

i. The number of grid points in small mesh fields is greatly increased which requires large storage facilities in computer memory which cannot be computed with small laboratory computers.
ii. Stability of the time step in the mathematical process of grid point size is required to ensure the Courant-Friedrichs-Lewy (CFL) stability criterion.

So, according to [19], the time step Δt must be related to the mesh size, Δx (or Δy), and ocean depth, h, by the relation

$$\Delta t \leq \frac{\Delta x}{\sqrt{2gh}} \quad (12)$$

Taking the above two facts into consideration, a high-resolution numerical scheme (FMS) is nested in a coarse mesh scheme (CMS) for the desired region. Further, to consider the densely populated low-lying large and small offshore islands between Barisal and Chittagong and to accurately incorporate land dynamics in the numerical model, a very fine mesh scheme (VFMS) is nested in the FMS. The grid size along the north-south direction (along the x-axis) is Δx = 15.08 km and along the east-west direction (along the y-axis) is Δy = 17.52 km. The computational xy-plane has 60×61 grid points with FMS 21^0-15^0N which covers the area between 15^0N to 23^0 N latitude and 89^0 E to 92^0 E longitude. The scheme area includes the study area and almost all offshore islands.

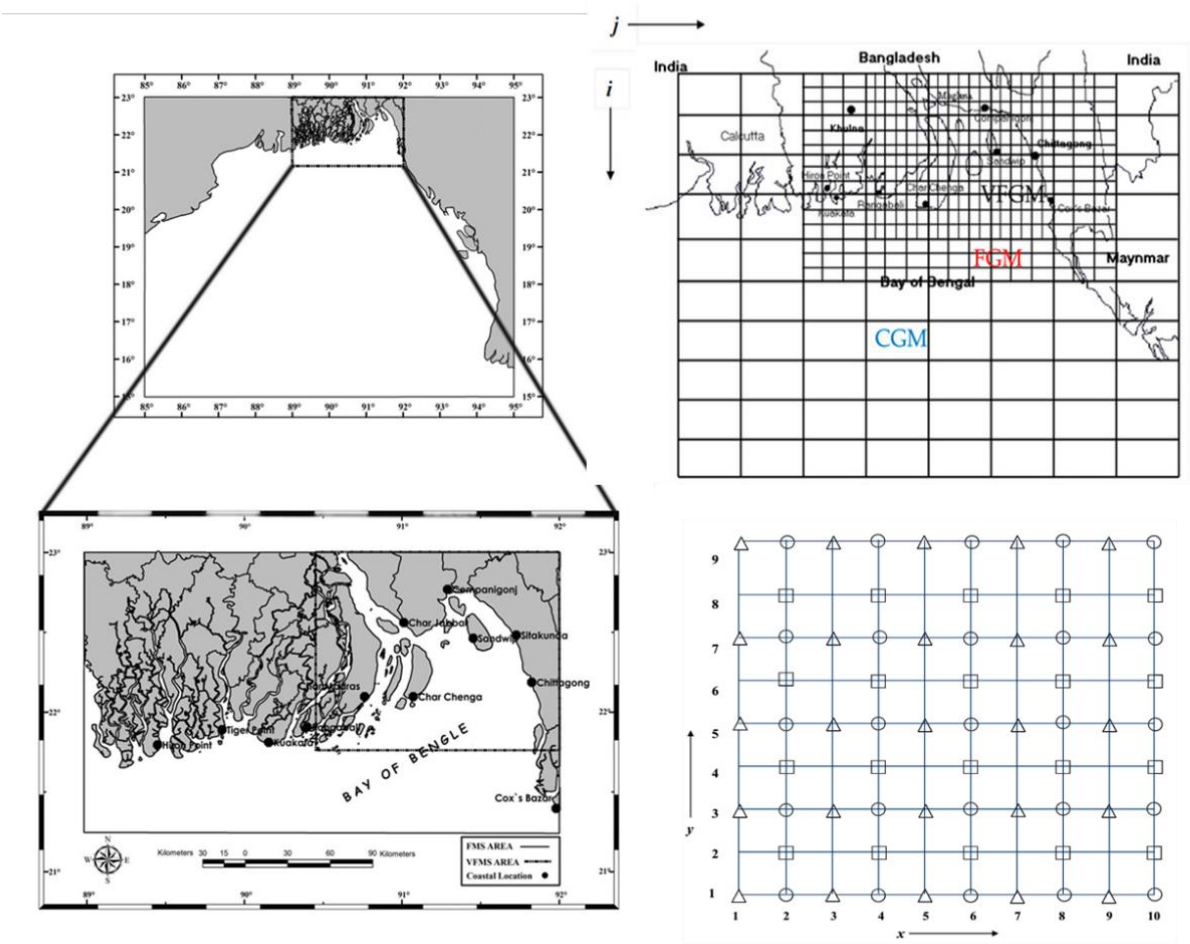

Figure 2. Numerical schemed area and gridding system

The grid size along the north-south direction (along the x-axis) is $\Delta x = 2.15$ km and along the east-west direction (along the y-axis) is $\Delta y = 3.29$ km. The computational xy-plane has 192×95 grid points. VFMS covers the area between 21.77^0 N to 23^0 N latitude and 90.40^0 E to 92^0 E longitude. The mesh size along the north-south direction (along the x-axis) is $\Delta x = 720.73$ m and along the east-west direction (along the y-axis) is $\Delta y = 1142.39$ m. The computational xy-plane has 190×145 grid points. Details of various schemes are also presented in tabular form. Table 1 shows the Domains, grid spacing, and number of computational points of different schemes. So we can say, grid is a small-scale geometric shape covering the physical domain, whose purpose is to identify discrete volumes or elements where conservation laws can be applied.

Table 1. Computational points of different schemes considering domains and their grid spacing

Scheme	Domain	Grid spacing along x axis (km)	Grid spacing along y axis (km)	Number of Computational points
CMS	15^0 -23^0 N, 85^0 - 95^0 E	15.08	17.52	60×61
FMS	21^0-15′- 23^0 N, 89^0 E to 92^0 E	2.15	3.29	192×95
VFMS	21.77^0 -23^0 N 90.40^0 - 92^0 E	0.72073	1.14239	190×145

2.3.3. Discretized form of model equation

The governing equation (5) to (7) and the boundary conditions (9) to (11) are discretized by finite-difference technique (forward in time and central in space) and are solved by conditionally stable semi-implicit methods using a staggered grid system. So, the finite-difference method is as follows

$$\zeta_{i,j}^{k+1} = \zeta_{i,j}^{k} - \Delta t[TL1 + TL2] \quad (13)$$

$$\tilde{u}_{i,j}^{k+1} = \frac{\tilde{u}_{i,j}^{k} - \Delta t(TL1+TL2+TL3) + \Delta t(TR1+TR2)}{(1+\Delta t.FR3)} \quad (14)$$

$$\tilde{v}_{i,j}^{k+1} = \frac{\tilde{v}_{i,j}^{k} - \Delta t(TL1+TL2+TL3) + \Delta t(TR1+TR2)}{(1+\Delta t.FR3)} \quad (15)$$

Consider, $\zeta_{i,j}^{k+1}$ in equation (13) is computed at i = 2, 4, 6, … , M – 2; and j = 3, 5, 7, … , N - 2; $\tilde{u}_{i,j}^{k+1}$ in equation (14) is computed at i = 3, 5, 7, … , M –1; and j = 3, 5, 7, … , N –2; and $\tilde{v}_{i,j}^{k+1}$ in equation (15) is computed at i = 2, 4, 6,....., M –2; and j = 2, 4, 6, … , N –1.

In the similar case the discretize form of the boundary conditions are;

$$\zeta_{i,1}^{k+1} = -\zeta_{i,3}^{k+1} - 2\sqrt{\frac{h_{i,2}}{g}} V_{i,2}^{k} \quad (16)$$

$$\zeta_{i,N}^{k+1} = -\zeta_{i,N-2}^{k+1} - 2\sqrt{\frac{h_{i,N-1}}{g}} V_{i,N-1}^{k} \quad (17)$$

$$\zeta_{M,j}^{k+1} = -\zeta_{M-2,j}^{k+1} + 2\sqrt{\frac{h_{M-1,j}}{g}} U_{M-1,j}^{k} + 4a\sin\left(\frac{2\pi k\Delta t}{T} + \varphi\right) \quad (18)$$

where, i = 2, 4, 6, … , M –2; and j = 1, 3, 5, 7, … , N

2.3.4. Numerical procedure

A stable tidal regime was generated over the model domain by first applying the strongest tidal component, the semidiurnal principal lunar tide. The period of tidal oscillation is taken as 12.4 hours. It is noted here that the period of tidal oscillation in the region of interest is not exactly periodic but the average period is found to be about 12.4 hours [20]. The initial values of amplitude and phase relative to the component are determined through equation (18) along the southern open boundary of the CMS following [21]. Then using the atmospheric pressure gradient force and constants involving a component from the initial state of rest in the absence of wind pressure, a stable tidal regime was achieved after 4 tidal cycles. But the generation of a pure tidal condition depends on the exact value of a and we have followed the technique of [20] for precise specification of the values of the constant. Its initial values are taken as zero to represent a cold start and from this time, a stable tidal system develops in the analysis area. The tidal regime at the start of the model provides the initial state of the ocean at the time of the model, and after a certain period, tidal effects are obtained in coastal areas. The time step is taken as 60 seconds which ensures the Courant-Friedrichs-Lewy (CFL) criterion for the stability of the numerical schemes.

3. Results

Model results were calculated for 60 hours and presented for the last 24 hours from 1.00 UTC May 29 to 1.00 UTC May 30, 2017. However, all the information shown in the figure is given according to the local time of Bangladesh.

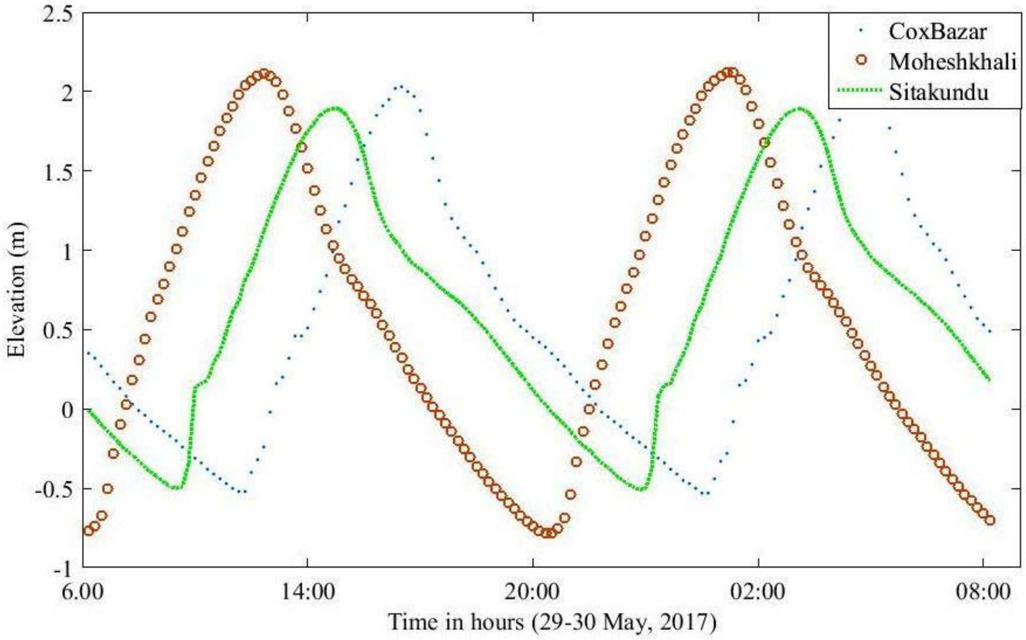

Figure 3. Simulated tide height at three different tidal stations on the east coast of Bangladesh

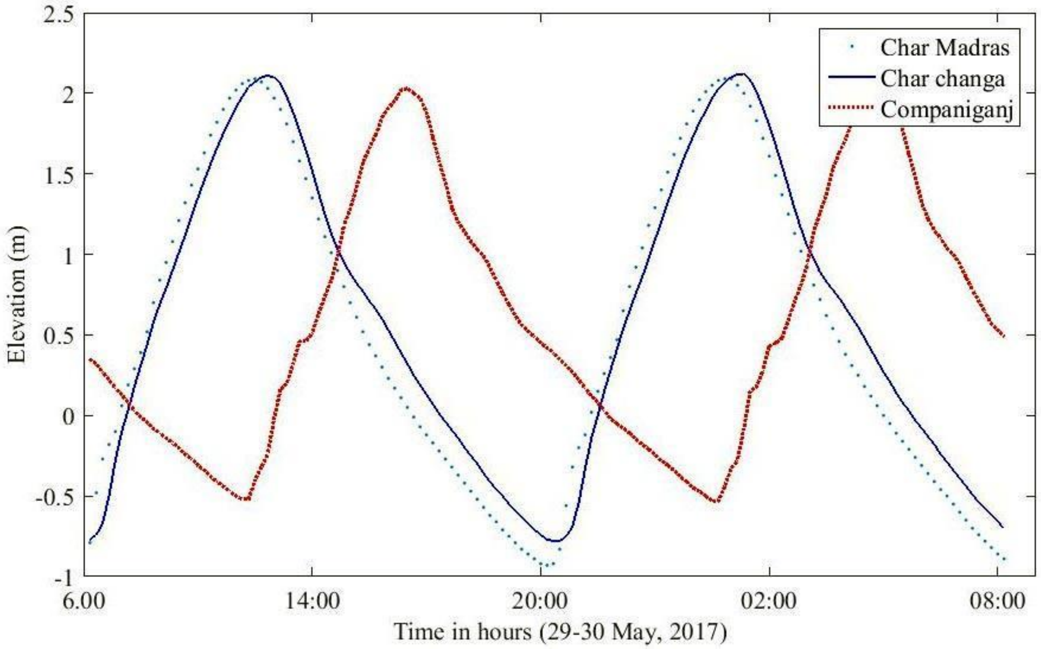

Figure 4. Simulated tide height at three different tidal stations on the middle coast of Bangladesh

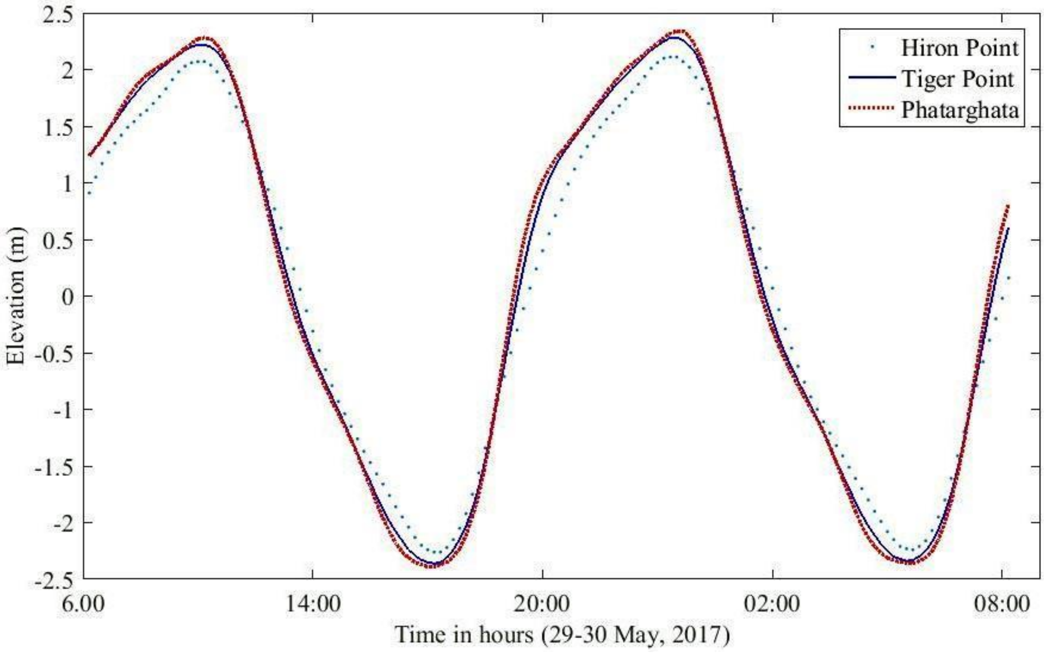

Figure 5. Simulated tide height at three different tidal stations on the west coast of Bangladesh

The main difficulty in validating the model is the lack of accurate water level data. It may be noted here that the Bangladesh Inland Water Transport Authority (BIWTA) collects the water level at some station every hour.

In this research we have improved a storm model and tried to estimate the tidal height from it. Figure 3 to Figure 5 shows the simulated tide height along the coast of Bangladesh in the different tide stations. These figure shows the simulated tide height in different tidal stations near the coast of Bangladesh. Basically, we have prepared our model considering the duration of a storm to run. For the simulation of tide within the Bay of Bengal, we considered the severe cyclone Mora, which hit the Bangladesh coast in 2017. However, when we run the model, we turn off the dynamics of a storm. After that, we run the model only for tides estimation. From the data obtained after running the model, we can see that the difference in tidal height in the coastal region of Bangladesh is very small, which is about 0.8 to 1 meter. However, in some areas, the tidal height is about 3 meters. However, we see a maximum of 2.5 to 2.8 meter's height of tide wave in the area of interest. However, to empirically compare these results, we collect observational data to compare with simulation data. After that, we compare both the observed data and simulated data. These comparative results and their rational analysis are given in the below discussion section.

4. Discussion

In this study, we developed a model to measure tide along the coast of Bangladesh. From this study, it is found that the height of the tide is 2 to 3 meters' maximum along the region of interest. Our developed model is primarily used to measure the storm surge in this region [22]. After that, we developed it for tide estimation. We use storm data as input to the model but only the storm start time is considered when running the model. Because we run our model for 3 days and start collecting data after 30 hours. For the first 30 hours, the model takes to get used or to be stable. We use the value of a commonly used tidal constituent at the southern boundary. After 30 to 48 hours of running the model, we start getting accurate data which is shown in the figure below.

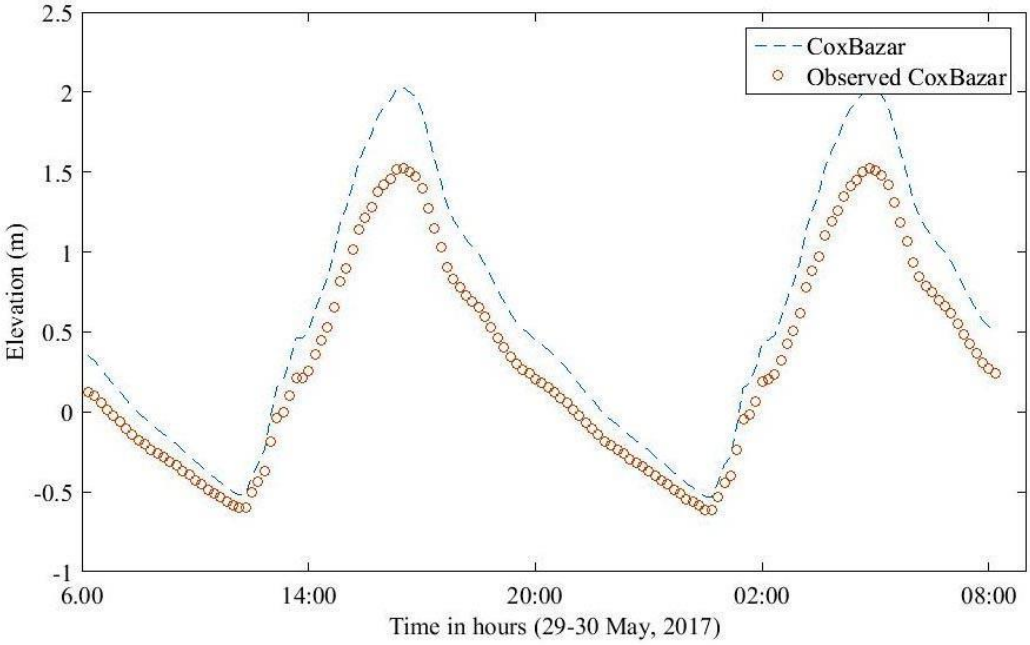

Figure 6. Simulation and observed data comparison at Cox Bazar tide station

Figures (6) to (7) depict the tide at 2 locations, namely Hiron Point, and Cox Bazar. The simulated results of the tide fairly agree with the BIWTA observed data. We can see from Figures 6 and 7 that there is a good agreement between the observational data and our simulation data. But to get this good fit, the data should be taken at 10-minute intervals like the simulation data, which was not in the observational data. Observational data included tide times and the maximum and minimum tide heights. Therefore, we compare these values with the simulation data by weighted average interpolation over the data at 10 min intervals. Now we find that the tidal height difference in the Cox's Bazar region of the eastern coast of Bangladesh is 2 meters and the observed tidal height ranges from -0.5 to 2.30 meters. However, note that the tidal time obtained from our simulations and the observed tides during high and low tides shows good consistency.

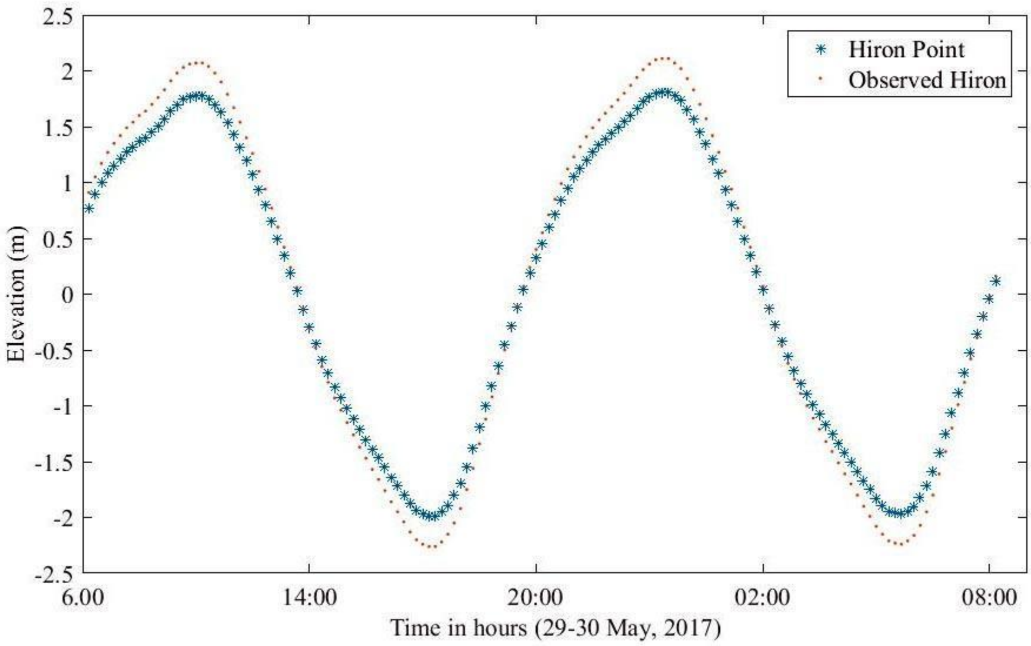

Figure 7. Simulation and observed data comparison at Hiron Point tide station

From a similar point of view, we can see the height of the tide at Heron Point in Khulna, on the western coast of Bangladesh, the height of the tide in this area is almost similar to the tide of Cox's Bazar. However, one thing is observed that the difference in the height of the highest and lowest tides is greater at Khulna's Hiron Point than at Cox's Bazar. We also find that observational data at Heron Point agree better than the Cox's Bazar region. Statistically speaking, the correlation of observations at Heron Point is much better than at Cox's Bazar. However, in both regions there is positive correlation of simulation data with observational data.

5. Conclusion

In this study, numerical experiments with a doubly nested numerical model were conducted using data from tropical cyclone Mora which hit the southwestern coastal region of Bangladesh to quantify the tidal height in the southwestern coastal region. The model is able to accurately incorporate coastlines and island boundaries with considerable accuracy and is also capable of accurately measuring tidal heights. To accurately measure tidal height, the nested numerical scheme ensures a very fine mesh near the coast and a coarse mesh away from the coast. Although we could not integrate all the input data correctly due to various environmental problems, our results were found to be satisfactory. Proper incorporation of oceanographic, meteorological and geographic information is necessary to improve model accuracy. However, our improved model is capable of accurate measurement of tidal height.

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Conflict Interest

The authors declare no competing financial or personal interests that may appear and influence the work reported in this paper.

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