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Further Development of Forecasting Model for Storm Surge Hazard along the Coast of Bangladesh

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Abstract In this study, numerical prediction of surge associated with a storm is made through finite difference method accurately incorporating the coastal complexities along the coast of Bangladesh. In incorporating the coastal complexities with a considerable accuracy, (1/120)° grid resolution is used. To incorporate river dynamics, the fresh water discharge through the Meghna River is taken into account. Simulated results by the study are found to be in good agreement with the available observations and reported data. For better forecasting, estimation of flooding is of importance, which is responsible for most death. Thus, the main objective of this paper is to develop an effective numerical model that will help to reduce the death during storm surges along the coastal area of Bangladesh.

Keywords: *tropical cyclone, numerical model, storm surge, Bangladesh, coastal flooding*

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1. Introduction

Geographically, Bangladesh is located at the interface of two different geographical locations, such as, the Himalayas and Khasi-Jaintia hills to the north, and the Bay of Bengal (BOB) and the North Indian Ocean to the south. This peculiar geographical position brings not only life giving monsoons but also catastrophic natural disasters, such as flood, drought, earthquake, storm surge, etc. [1,2,3]. The country has three distinct coastal plains, namely, (i) the Ganges Tidal Plain, also known as the Western Region; (ii) the Chittagong plain, also known as the Eastern Region; and (iii) the Meghna Deltaic Plain or the Central Region in between the above two. Among the plains, the Meghna Deltaic one is world most vulnerable for storm surges, which is at the confluence of the Ganges, Brahmaputra and Meghna rivers (commonly known as the GBM river system). It is known that about 5-6 storms form over the BOB region but with about 80% of global casualties [4], where the coast of Bangladesh, especially Meghna Deltaic plain is mostly affected. For making understand the ferocity of these storm surges along this region, Table 1 with the losses have been included.

From Table 1, one can make out the losses made by the tropical storm and associated surges over the years and its impact on the socioeconomic sectors, which make an appeal to the research community for the development of a proper storm surge prediction model for the region executable in the existing system of the country. Developments in predicting cyclones and issuing early warnings to the public have become essential as both coastal populations and the incidence of life-threatening storms. Several investigations have been made in this region in order to develop a proper warning system [5-17]. Also, various practices have already been ensued, and many lives have been protected by the progresses in disaster guessing, evacuation and emergency shelter systems [18,19]. It is known that Bangladesh Meteorological Department has a warning system based on a numerical model brought from IIT, India, that can predict the landfall time, sea level rise storm track in a certain accuracy. But sometimes the prediction made by Bangladesh Meteorological Department (BMD) meteorologist is questionable [20]. Also, inundation area associated with a storm surge is another big issue, which has been paid a little attention. Thus it is required to introduce a new model for better understanding of expected motive in storm surge activities.

Table 1. Landfall locations and loss of life due to storm surges (data sources: Debsarma [4], and NASA website)

Year	Location of landfall	Human death
1970	Bangladesh	500,000
1897	Bangladesh	175,000
1991	Bangladesh	140,000
1876	Bangladesh	100,000
1822	Bangladesh	40,000
1965	Bangladesh	19,279
1963	Bangladesh	11,520
1961	Bangladesh	11,468
1977	India	10,000
1960	Bangladesh	5,149
2007	Bangladesh	3,376
2009	India	275
2016	Bangladesh	24

2. Materials

2.1. Model Equations

The vertically integrated SWEs for the dynamical process in the sea can be given by [13]

$$\frac{\partial \zeta}{\partial t}+\frac{\partial \tilde{u}}{\partial x}+\frac{\partial \tilde{v}}{\partial y}=0, \quad (1)$$

$$\frac{\partial \tilde{u}}{\partial t}+\frac{\partial (u\tilde{u})}{\partial x}+\frac{\partial (v\tilde{u})}{\partial y}-f\tilde{v} = -gD\frac{\partial \zeta}{\partial x}+\frac{T_x}{\rho}-\frac{c_f\tilde{u}(u^2+v^2)^{1/2}}{D}, \quad (2)$$

$$\frac{\partial \tilde{v}}{\partial t}+\frac{\partial (u\tilde{v})}{\partial x}+\frac{\partial (v\tilde{v})}{\partial y}+f\tilde{u} = -gD\frac{\partial \zeta}{\partial y}+\frac{T_y}{\rho}-\frac{c_f\tilde{v}(u^2+v^2)^{1/2}}{D}, \quad (3)$$

where $(\tilde{u},\tilde{v})=D(u,v)$.

In Eqs. (1)-(3), x and y represent the coordinate axes directed towards the south and east, respectively, with the reference point (23° N, 85° E) on the mean sea level at the north-west corner of the study domain; u and v stand for representing the Reynolds average velocity components along the x and y axes, respectively; -h(x,y) and $\zeta(x,y,t)$ stand for denoting the undisturbed water depth and the elevation of the free surface at any point over the time t about the undisturbed surface level, respectively, so that the total depth of the water column $D=h+\zeta$; $f=2\Omega\sin\phi$ represents the Coriolis parameter, where Ω is the angular speed of the earth rotation and ϕ is the latitude of the place of interest; g is the acceleration due to local gravity; ρ represents the sea water density; C_f is the friction coefficient; T_x and T_y designate the components of wind stress acting on the water surface along the x and y axes, respectively.

In the BOB region, the surface stresses are parameterized using a conventional quadratic law [21], which leads to

$$(T_x,T_y)=\rho_a C_D(u_a^2+v_a^2)^{1/2}(u_a,v_a) \quad (4)$$

In Eq. (4), C_D is the surface drag coefficient having a value of $C_D=0.0028$, which is found to be used by most modelers [5]; ρ_a represents the air density; and u_a,v_a are the velocity components of the surface wind along the axes, respectively. For generating wind field, we used the formula due to Jelesnianski [21] being given by

$$V_a=\begin{cases} V_0\sqrt{\left(\frac{r_a}{R}\right)^3} & \text{for all } r_a<R, \\ V_0\sqrt{\left(\frac{R}{r_a}\right)^3} & \text{for all } r_a>R, \end{cases} \quad (5)$$

In the above equation, V_0 is the maximum sustained wind speed and R is the corresponding radial distance measured from the eye of the storm; r_a is the radial distance at which the wind field is to be generated. It is to be noted here that the meteorological information required in generating the wind field by the formula mentioned above are available in BMD.

2.2. Boundary Conditions

The normal components of the depth averaged velocity component is set to zero for closed boundaries whereas radiation boundary conditions are prescribed for open boundaries for the BOB region due to the unavailability of suitable information where the boundaries are set. It is to be noted here that zero boundary conditions at the closed boundaries are not suitable for flood models. However, the following open boundary conditions are used in our study [11,12]:

the west boundary:

$$v+\sqrt{\frac{g}{h}}\xi=0, \quad (6)$$

the east boundary:

$$v-\sqrt{\frac{g}{h}}\xi=0, \quad (7)$$

the south boundary:

$$u-\sqrt{\frac{g}{h}}\xi=-2a\sqrt{\frac{g}{h}}\sin\left(\frac{2\pi t}{T}+\varphi\right), \quad (8)$$

where a and φ stand for the amplitude and phase, respectively, of the tidal constituent of interest, and T denotes its period.

Along the northern boundary of the model, Meghna river is considered between longitudes 90.46° E and 90.61° E and following Paul et al. [14], the river discharge is taken into account by the formula

$$u_b=u+\frac{Q}{(h+\xi)}, \quad (9)$$

where Q is the fresh water discharge through the river, and B is the breath of the river which is approximately 16 km in width at the mentioned position.

3. Methodology

The vertically integrated SWEs can be solved by forward in time and centre in space finite difference method with the help of well-known Arakawa C grid. In this regard, domain is rectangularzed with (1/120)° grid resolution by stair step algorithm. Then the governing equations are discretized using the C-grid. Then, firstly, ζ is computed from the discretized form of Eq. (1) at the (even, odd) grid points. Discretized forms of Eqs. (6)-(9) are then used to update ζ at the grid points on the model boundaries. Weighted average procedure is taken into account to obtain ζ at the remaining points representing water. The wind and pressure fields are subsequently generated with the help of Eqs. (4) and (5), respectively. Discretized form of Eq. (2) is then taken care into account to solve for u component of velocity. Lastly, discretized form of Eq. (3) is solved for y component of velocity. Discretized forms of Eqs. (1)-(3) are available in [4,11]. The process mentioned above is maintained for a specified storm with a chosen period.

4. Results

Here the simulation of the storm surge associated with the storm AILA for the specified time (59 h: 0900 UTC 23 May - 2000 UTC 25 May) is shown in Figure 1 with the observed data from the BMD at three stations. Other such results are overlooked. The reason behind the choice of the three stations is the availability of observed data. However, it is seen that model simulated data agree well with observed data. The model thus can predict water level with a considerable accuracy with observed data, which can be regarded as a storm surge prediction model with proper refinement that can be used for issuing warning on real time basis. But work is still needed to be done, especially estimation of inundation area with which a considerable amount of loss can be reduced.

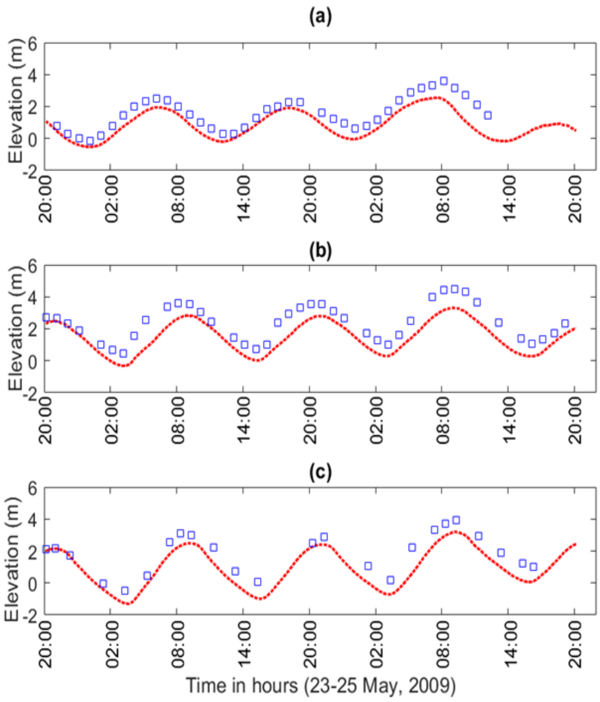

Figure 1. Computed temporal variation of total water levels with refer to the mean sea level simulated by the study with observed data from the BMD; **(a)** at Hiron Point, **(b)** at Char Chenga, and **(c)** at Chittagong. In each of the figures, *a dotted red curve* represents our computed temporal variation of total water levels due to the interaction of tide and surge and *a square with blue color* represents an observed data (whenever available)

5. Conclusions

In this research work, we executed a good resolution surge model to estimate water level elevations at some stations along the coast of Bangladesh. The model results are found to be in a reasonable agreement with the observed data from the BMD. On the basis of the output as simulated by the study, an operational forecasting model can be designed with some refinements, from which an inundation area could be estimated properly as is need for practical forecasting.

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