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Development of a cylindrical polar coordinates shallow water storm surge model for the coast of Bangladesh

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Abstract The coast of Bangladesh is funnel shaped. The narrowing of the Meghna estuary along with its peculiar topography creates a funneling effect that has a large impact on surge response. In order to have an accurate estimation of surge levels, the impacts of the estuary should be treated with due importance. To represent in detail the real complexities of the estuary, a very high resolution is required, which in turn necessitates more computational cost. Considering the facts into account, a location specific vertically integrated shallow water model in cylindrical polar coordinates is developed in this study to foresee water levels associated with a storm. A one-way nested grid technique is used to incorporate coastal complicities with minimum cost. In specific, a fine mesh scheme (FMS) capable of incorporating coastal complexities with acceptable accuracy is nested into a coarse mesh scheme (CMS) covering up to 15°N latitude in the Bay of Bengal. The coastal and island boundaries are approximated through appropriate stair step representation and the model equations are solved by a conditionally stable semi-implicit finite difference technique using a structured C-grid. Numerical experiments are performed using the model to estimate water levels due to surge associated with the April 1991 and AILA, 2009 cyclones, which struck the coast of Bangladesh. Time series of tidal level is generated from an available tide table through a cubic spline interpolation method. The computed surge response is superimposed linearly with the generated time series of tidal oscillation to obtain the time series of total water levels. The model results exhibit a good agreement with observation and reported data.

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Introduction

Tropical cyclones along with associated tidal surges often cause considerable devastation along the coast of Bangladesh (Paul and Ismail 2012a). Paul et al. (2014) note that on an average 5–6 storms form in the Bay of Bengal every year, but with 80% of the global casualties. The coast of Bangladesh, located at the northern tip of the Bay of Bengal, is recognized globally as most vulnerable to cyclones and storm surges. A list of major factors behind the vulnerability can be found in Paul and Ismail (2013). But the area is insufficiently studied (Paul et al. 2016). Therefore,

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the region should be taken more in consideration so that an efficient surge forecasting model for it can be made, which in turn can help to minimize damages resulting from a tropical cyclone (TC). Considering the triangular shape of the coast of Bangladesh (see Fig. 1), Roy et al. (1999) first developed a model in cylindrical polar coordinate system, where they superimposed surge with previously generated tide for operational forecasting purposes. They ascertained that their adopted technique may be a feasible way of practical forecasting. But the study was conducted using stair step method with uniform distribution of grid lines in the radial direction without ensuring fine mesh resolution. It is pertinent to pinpoint out here that accuracy of results from a stair step model depends among others on high spatial resolution. Also, accuracy in surge prediction in a complex terrain is highly dependent on the true representation of coastal geometry (Murty et al. 1986; Rao et al. 2009), which requires a high spatial resolution. Thus, the model due to Roy et al. (1999) may not be capable of incorporating the real complexities of the coast in details (Paul and Ismail 2013). However, Rahman et al. (2013) developed the model of Roy et al. (1999) using a one-way nested numerical scheme but the investigation was limited to the estimation of water levels due to pure surge only. It is to be noted here that astronomical tide is a continuous process in the sea and it will always interact with surge (Roy 1995). Therefore, among other factors, accurate prediction of water levels depends highly on the generation of pure tidal regime over the region of interest. But the main difficulty in generating a pure tidal oscillation over the area of interest lies with the accurate estimations of amplitudes and phases of the effective tidal constituents. However, another important point to be noted here that the approximation of the coastal geometry was made manually in both the investigations of Roy et al. (1999) and Rahman et al. (2013). But a manual approximation of such a complex geometric domain can lead to inaccurate representations of the coastal and island boundaries, bottom topography, coastal stations, etc. Thus, the time series of surge response emanated through an efficient model simulation with that of the compiled tidal oscillation generated from an available tide table can be an effective and efficient way of forecasting water levels operationally.

In this communication, we intend to develop the models of Roy et al. (1999) and Rahman et al. (2013) for the prediction of water levels efficiently due to the combined effect of tide and surge along the coast of Bangladesh. Here, the main emphasis is given on the accurate incorporation of a funnel shaped complex coastal geometry and the impact of near-coastal grid resolution and the coastal geometry on the overall computation of surge profiles.

Fig. 1 The model analysis area delimiting the boundaries of the CMS and FMS
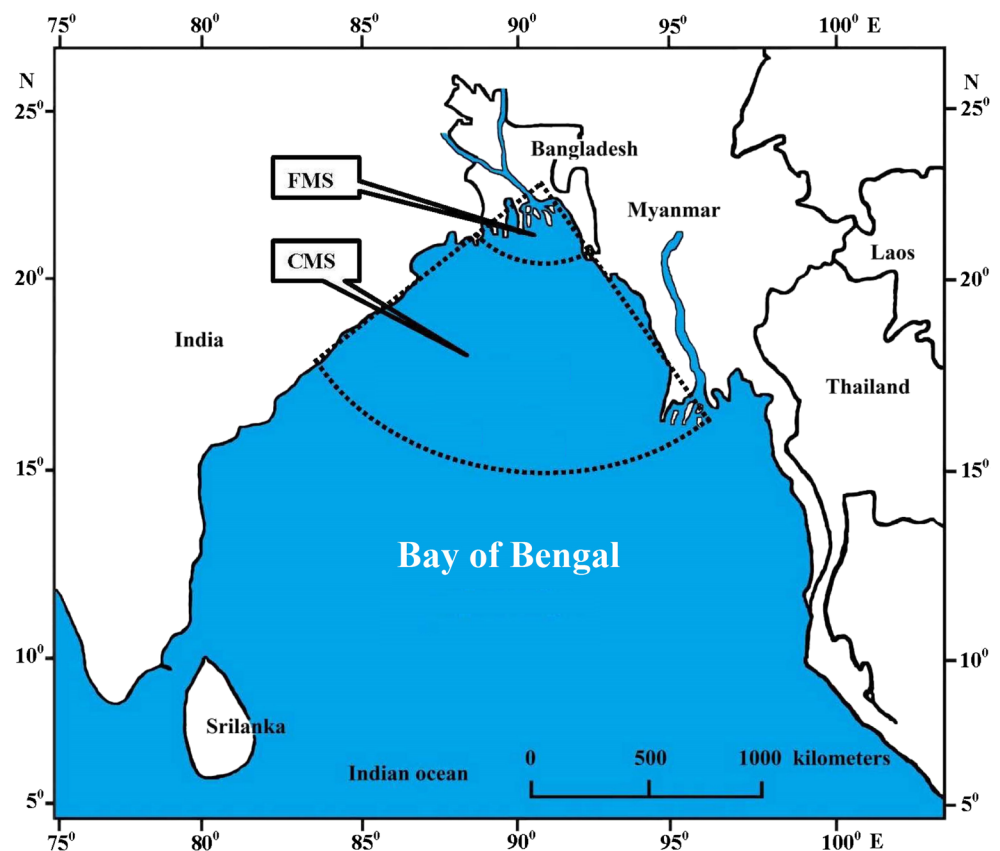
Cyclone warning system and coastal management in Bangladesh: a brief review

Cyclone warning system and preparedness

Bangladesh Meteorological Department (BMD) is the sole government organization and authority accountable for forecasting, preparing, issuing, and disseminating warnings for cyclones in Bangladesh (Paul 2009; Roy et al. 2015). After the formation of a depression in the Bay of Bengal, the storm warning center (SWC) of the BMD issues special weather bulletins to alert specially the country's coastal and island inhabitants through which a significant reduction in the loss of lives and properties can be made (Khalil 1993). The SWC issues warnings in different stages of the formation of the cyclones, namely cyclone alert stage, cyclone warning stage, cyclone disaster stage and cyclone great-danger stage. At the cyclone alert stage, an alert message is sent to cyclone preparedness programme (CPP), radio, and television when the speed of the rotating wind in a TC reaches 50 km h^{-1}. The cyclone warning stage is initiated at least 24 h before a predicted landfall when the wind speed of a TC reaches between 51–61 km h^{-1} and a message in this regard is sent to the respective authorities and media with information about the current and forecasted positions of the TC, the TC movement rate with direction, maritime ports and areas likely to be hit, forecasted surge height associated with the TC, and suggested safety measures for fishing boats (Roy et al. 2015). A cyclone disaster stage begins when the maximum wind speed of a TC exceeds 61 km h^{-1}. At this stage, an updated danger-warning message is disseminated every 30 minutes. The final stage is initiated at least 10 h before the predicted landfall (Roy et al. 2015) when the maximum sustained wind speed of a TC exceeds 89 km h^{-1}. A warning message in this regard is then usually disseminated every 15 minutes and the residents are urged to evacuate at this point. The National Disaster Management Council (NDMC), headed by the Honorable Prime Minister of Bangladesh, then formulates and reviews disaster management policies and gives directives to all concerns for disaster risk reduction, mitigation, preparedness, evacuation, response and recovery. The CPP of Bangladesh Red Crescent Society (BDRCS) with its volunteers plays a leading and vital role in disseminating the cyclone warnings among villagers via megaphones, sirens, signal lights, and cyclone warning flags (Paul 2009). The volunteers also assist coastal people in the process of evacuation, execute rescue operation, provide first aid, and assist in distributing relief goods under the supervision of the Government of Bangladesh (GOB) local adminstration. It is to be pointed out here that the SWC meteorologists prepare warning messages based on both self produced and accessed numerical model generated forecasts with weight on the former one (Roy et al. 2015). But the accessed numerical models through which the forecasts are produced are not advanced, and the SWC meteorologists do not have the necessary computational skills to modify these models for forecasting precisely new TCs (Roy et al. 2015). Also, computational resources are insufficient at the BMD for running advanced numerical models (Roy and Kovordanyi 2012). Thus, predictions by the SWC meteorologists in terms of the precise location of cyclones, landfall timing, precise estimation of surge height, etc. have often been criticized (Miyan 2005; Hossain et al. 2008). These weaknesses in the TCs forecasts need to be addressed appropriately to improve the efficacy of the existing warning system for making coastal people more practical against future TCs. Because, unnecessary evacuations following erroneous warnings are not only waste of wealth but also infallibly cause the coastal people to ignore subsequent warnings of genuine danger (White and Haas 1975). Therefore, a developed model capable of running in the existing resources at the BMD for precise forecasting of the TCs is desirable for the world's most vulnerable region.

Coastal management

Over the last four decades with the initiation in 1960s, the GOB has constructed about 5,333 km of embankments in the coastal districts (see Paul 2009) to prevent the ingress of saline water from the sea, support agriculture and protect the lives and property of coastal residents in the course of storm surges. As in Paul (2009), the embankments have been proved to provide an effective shield during storm surges. Unfortunately, due to meager maintenance, most of the embankments are in dilapidated condition with numerous cuts or portions partially/completely eroded. After the 1966 cyclone, the GOB also initiated a coastal forestation program along the coastal zone on newly accreted land, the riverine coastal belt, and abandoned embankments to create a green belt (Paul 2009). It is of interest to note here that coastal forests not only provide protection for residents against storm surges but also act as a natural shield that reduce wind velocities (GOB 2008). However, the program was not systematically implemented and vast areas have been cleaned. Therefore, with proper coastal management having proper forecasting of the TCs, the loss of lives and property of the country's coastal residents resulting from the TCs and associated surges can be reduced.

Theoretical foundation

Vertically integrated shallow water equations

The vertically integrated linear shallow water equations in cylindrical polar coordinate system, representing the conservation

of fluid mass and momentum, can be given by (see Roy et al. 1999)

$$\frac{\partial \zeta}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}[r(\zeta + h)v_r] + \frac{1}{r}\frac{\partial}{\partial \theta}[(\zeta + h)v_\theta] = 0, \quad (1)$$

$$\frac{\partial v_r}{\partial t} - f v_\theta = -g\frac{\partial \zeta}{\partial r} + \frac{T_r}{\rho(\zeta + h)} - \frac{C_f v_r \left(v_r^2 + v_\theta^2\right)^{\frac{1}{2}}}{\zeta + h}, \quad (2)$$

$$\frac{\partial v_\theta}{\partial t} + f v_r = -\frac{g}{r}\frac{\partial \zeta}{\partial \theta} + \frac{T_\theta}{\rho(\zeta + h)} - \frac{C_f v_\theta \left(v_r^2 + v_\theta^2\right)^{\frac{1}{2}}}{\zeta + h}, \quad (3)$$

where $(v_r, v_\theta) = \int_{-h}^{\zeta}(\widetilde{v_r}, \widetilde{v_\theta})dz$.

In Eqs. 1–3, $\widetilde{v_r}$ and $\widetilde{v_\theta}$ stand for the radial and tangential components of the Reynolds averaged velocity, respectively, f denotes the Coriolis parameter; g (9.81 m s^{-2}) is the acceleration due to local gravity; ρ (1025.00 kg m^{-3}) is the sea water density, which is assumed to be constant; C_f denotes the friction coefficient at the sea bottom; $\zeta(r, \theta, t)$ and $-h(r, \theta)$ represent the displaced level of the free surface of the sea and the position of the sea bed, respectively; T_r, T_θ represent the radial and tangential components of the surface wind stress, respectively.

The components of the forcing terms in Eqs. 2 and 3 are the Coriolis force, the surface wind stress and the bottom stress. Among them, the Coriolis force can easily be generated from $f = 2\omega \sin \phi$, as the angular speed of the earth rotation ($\omega = 7.2921159 \times 10^{-5}$ rad s^{-1}) and the latitude (ϕ) of the region of interest is known. The friction force can easily be calculated with the usual value for the friction coefficient C_f. In our study, the radial and tangential components of the wind stress are derived following Roy et al. (1999) as

$$(T_r, T_\theta) = C_D \rho_a V_a^2 (-\sin \delta, \cos \delta), \quad (4)$$

where ρ_a (1.226 kg m^{-3}) is the density of air, δ is the inflow angle of the circulatory wind of the storm, and C_D is the drag coefficient, which can be given by (see Powell et al. 2003)

$$C_D \times 10^3 = \begin{cases} 1.052, & V_a \leq 6 \text{ m s}^{-1} \\ 0.638 + 0.069V_a, & 6 \leq V_a \leq 30 \text{ m s}^{-1} \\ 2.708, & V_a \geq 30 \text{ m s}^{-1}, \end{cases} \quad (5)$$

where V_a is the circulatory wind field at a height of 10 m above sea surface. It is of interest to mention here that the circulatory wind field can be generated by various empirical formulae. For the region of our choice, the most frequently used formula based on the available information at the BMD is due to Jelesnianski (1965), which is given by

$$V_a = \begin{cases} V_0 \sqrt{\left(\frac{r_a}{R}\right)^3}, & \text{for } r_a \leq R \\ V_0 \sqrt{\left(\frac{R}{r_a}\right)}, & r_a > R, \end{cases} \quad (6)$$

where V_0 is the maximum sustained wind at the radial distance R from the eye of the cyclone and r_a is any radial distance from the eye at which the wind field is to be generated.

Boundary conditions

Following Paul et al. (2016), no normal flow is chosen as the condition at the closed boundaries, the coastal and island boundaries. At the open sea boundaries, a boundary condition of radiation type, following Roy et al. (1999), is considered along the western, eastern and southern open sea boundaries, respectively, being given by

$$v_\theta + (g/h)^{1/2}\zeta = 0, \quad (7)$$

$$v_\theta - (g/h)^{1/2}\zeta = 0, \quad (8)$$

$$v_r - (g/h)^{1/2}\zeta = 0. \quad (9)$$

Application of a radiation condition at the open sea boundary of a model allows the propagation of disturbances outwards from the model domain in the form of a simple progressive wave as well as helps to eliminate transient response more quickly (Jain et al. 2007).

Numerical procedure

Set up the domain of the model and nested grid

The coast of Bangladesh is very complex in nature. To incorporate the complexities properly, a high spatial resolution is desirable in shallow water areas, which is deemed unnecessary elsewhere (Rahman et al. 2013; Paul et al. 2014). It is important to note here that the polar coordinate system itself ensures high resolution along the tangential direction near the pole and lower resolution away from it. Thus considering the pole nearer to the coastal belt, it is possible to get benefit of incorporating coastal complexities along the tangential direction in the mentioned coordinate system. In our study, the pole is considered at the point $O(22.96°N, 91.68°E)$ in the r–θ plane on the mean sea level (MSL). Along the tangential direction, uniformly distributive 45 straight lines are drawn through the pole with angle increment $\triangle \theta = 2°$. Along the radial direction, 45 circular grid lines with center at O are drawn at a uniform interval of approximately $\triangle r = 18.5$ km. Therefore, we get a scheme with 45×45 grid points excluding the pole. It is of interest to note here that all the 45 straight lines meet at the pole, for numerical convenience it is assumed that there are 45 distinct grid points at the pole. Thus there are 46×45

grid points in the computational scheme, which is referred to as CMS. Since the pole is taken on the land, no parameters will be computed there and hence there are no questions of instability in the computation. The grid increment along the tangential direction varies from zero to approximately 29 km. But the grid resolution in the radial direction is the same everywhere and considerably higher, so it is not possible to incorporate the coastal complexities with acceptable accuracy in this numerical scheme. Considering the facts into account, a one-way nested method is used in this study. Because it is simper, this approach is used in most nested ocean models (Yu and Zhang 2002). The method allows high resolutions in a desired region of interest with lower resolutions elsewhere, which in turn leads to reduce computational cost (Paul et al. 2016). In this technique, the parent scheme is integrated in time and the information along the nested boundaries of the child scheme is supplied temporally and spatially interpolating the information obtained from adjacent parent grid points. The child scheme is subsequently integrated in time with the boundary conditions obtained from the parent scheme. In this way the parent scheme influences the computations within the child scheme. However, since there is no feedback from the child to its parent, the child scheme can not influence computations within the parent scheme (Nash 2010). In our study, a child scheme referred to as fine mesh scheme (FMS) capable of incorporating the complexities of the coast is nested into the CMS (see Figs. 1, 2). The FMS extends from the pole to the 18th circular grid line of the CMS and lies between the same boundary lines of the CMS so that it can cover the coastal belt and offshore islands of our region of concern. To construct the FMS, two straight grid lines through the pole along the tangential direction have been included between every pair of successive grid lines of the CMS. Thus, there are a total of 133 grid lines in the tangential direction of the FMS having a uniform grid size of $\triangle \theta = 0.66°$. On the other hand, uniformly distributed six circular grid lines are introduced in the radial direction between every pair of consecutive circular grid lines of the CMS. So, we have a total of 120 circular grid lines in the radial direction of the FMS having a uniform grid size of $\triangle r = 02.6$ km approximately. Thus in the FMS, there are 120×133 grid points. With the grid resolutions of the FMS, the coastal and island boundaries were approximated closely and each of the targeted stations were achieved with acceptable accuracy (see Fig. 2). In our study, the approximation of the coastal and island boundaries is made through a stair step representation, which is executed with the use of a MATLAB routine using a colour image of the domain constructed through ArcGIS software. Firstly, the pole is selected at the point $O(22.96°N, 91.68°E)$, then the above mentioned grid lines are drawn through the pole on that image. It is to be noted here that the image used in

this approximation process was prepared with two colours, namely white and sky blue. White colour was used for representing land and sky blue colour was that for water. Corresponding to the colour information of the grids, a matrix was constructed composed of the digits 0 and 1 representing land and water, respectively, considering n distinct grid points at the pole, where n is the number of grid lines along the radial direction. Then applying some matrix operations, following the method of 'stair step' representation, the coastal and island boundaries are approximated. This process is applied to both the schemes. In the FMS, the grids representing the coastal stations are also identified closely using another image having a different colour for the coastal stations. After converting the resulting matrix into a figure, the obtained graphical output is shown in Fig. 2. It is aforementioned that in their investigations Roy et al. (1999) and Rahman et al. (2013) approximated coastal and island boundaries manually, whereas in our present study, the approximation procedure is made with the help of a developed Matlab program. Another important matter in a nested grid technique is the coupling of the schemes. It is to be mentioned here that the two boundaries (tangential directed) of the FMS are coincident with the eastern and southern open boundaries of the CMS and the 120th circular grid line is another boundary of the FMS which is coincident with the 18th circular line of the CMS. Thus only the results emanated from the 18th circular line of the CMS are interpolated to supply them to the grids of the 120th circular line of the FMS. In our study we have used cubic spline interpolation to interpolate the results.

The data sources and used numerical values

This study involves a number of inputs. The required meteorological inputs, namely tracking path of the storm, maximum sustained wind speed and maximum wind radius are supplied having information from the BMD. In shallow water regions, surge height is very sensitive to the depth of the ocean (Murty et al. 1986; Paul and Ismail 2013). Therefore, the bathymetric data should properly be incorporated. To specify the bathymetric data accurately to the grids discussed in "Set up the domain of the model and nested grid", the area covering Latitudes 15°–23°N and Longitudes 85°–95°E is cropped from Fig. 3, which was used in the study of Johns et al. (1985). Then using paint software, a contour is considered of that picture removing the remaining contours. Then by a MATLAB routine, a matrix of the updated picture is generated and the depth information of the existing contour is extracted to another matrix having the same dimension setting all other depths as zero. In a similar manner, different matrices are generated for each of the remaining contours. Then by the rule of matrix addition, all the depth information specified by the given
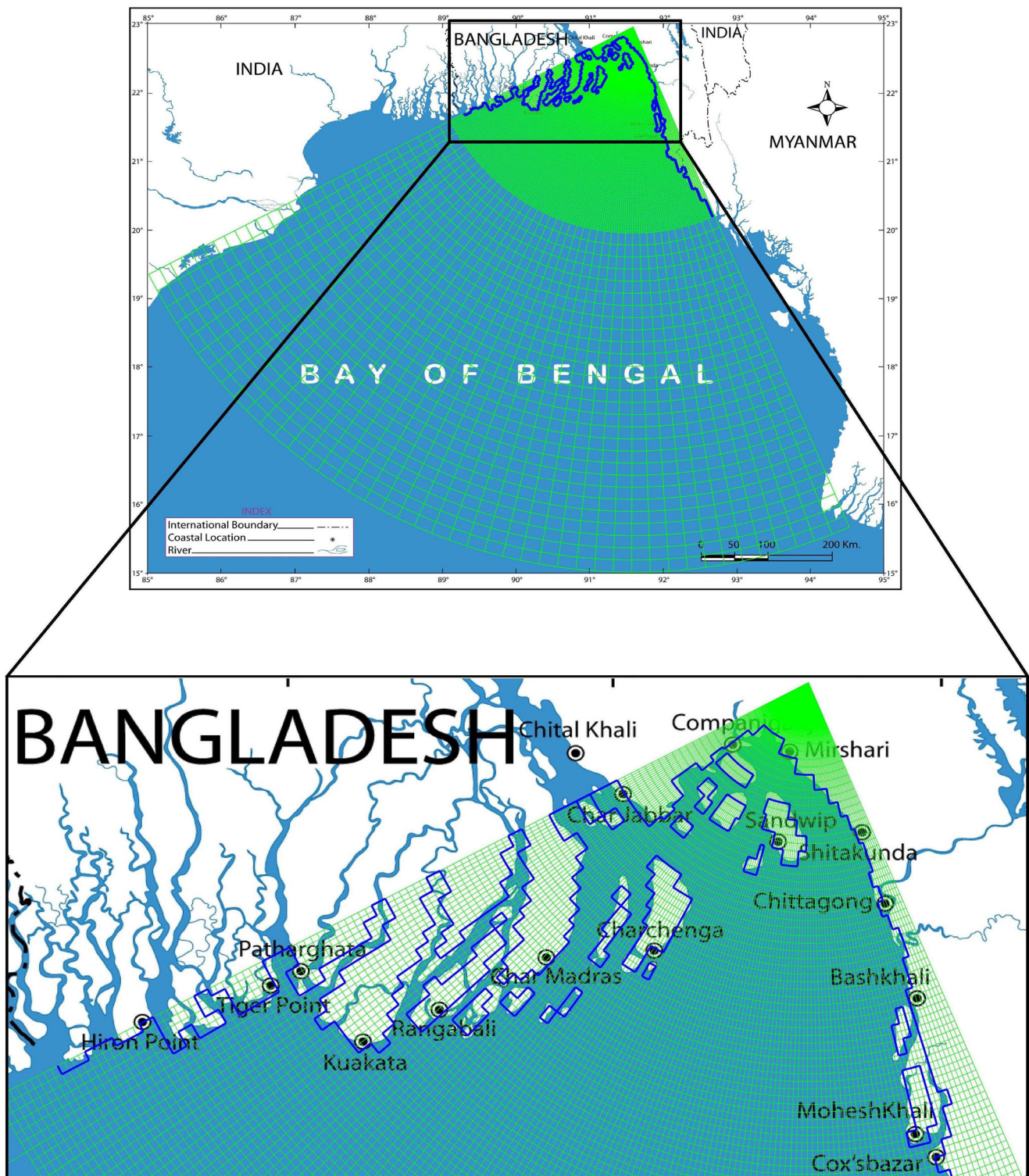
Fig. 2 The model grid for the coast of Bangladesh along with some coastal stations and the approximated coastal and island boundaries obtained through stair step representation

contours are taken in a single matrix. Depth information at the remaining elements of the matrix is generated using the inverse distance weighted (IDW) interpolation. A contour map of our interpolated bathymetry is shown in Fig. 4. It is to be noted here that the bathymetric data are now available in the obtained matrix at some longitudinal and latitudinal
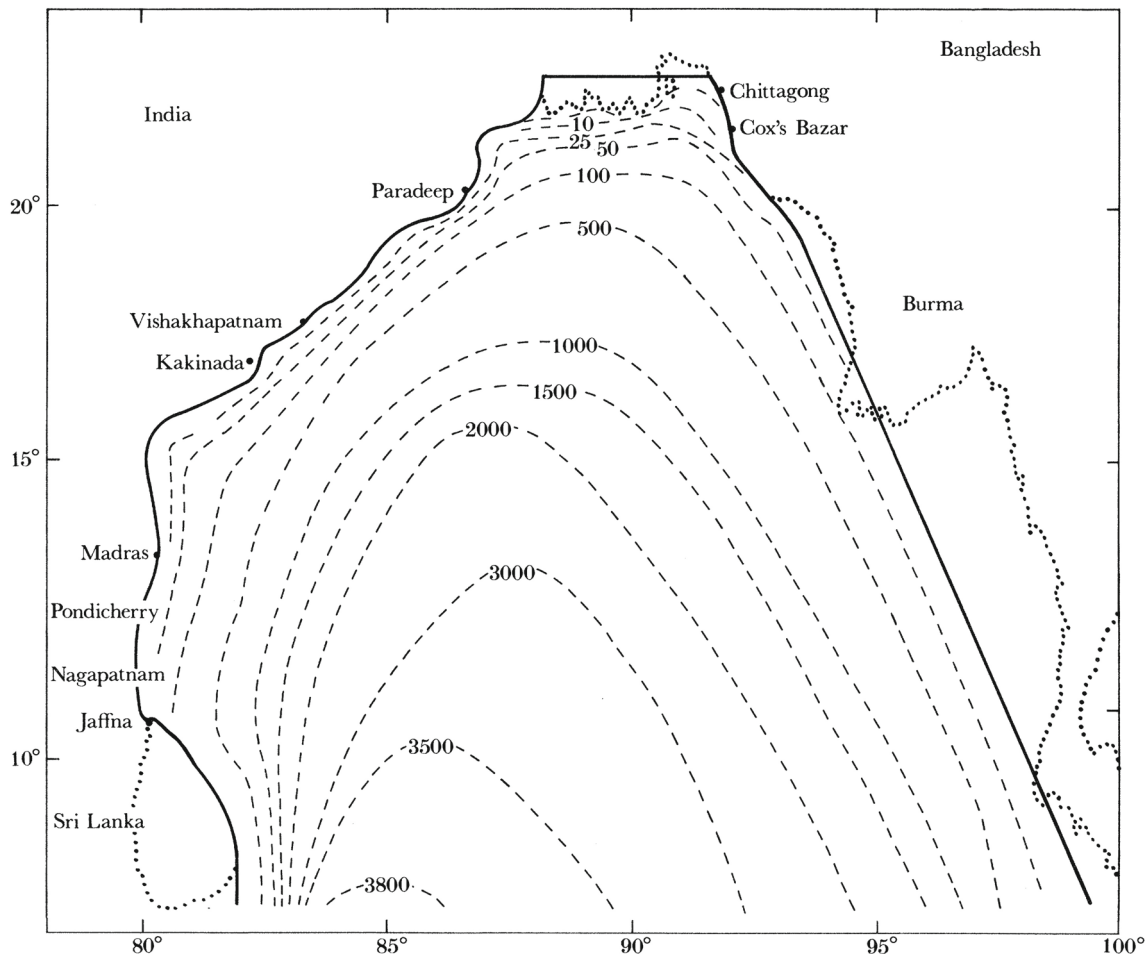
Fig. 3 The isobaths of the model bathymetry (after Johns et al. 1985) representing depth of the sea bed in meters

positions of the area of interest. The bathymetric data at each of the longitudinal and latitudinal positions of the computational grid points of the CMS and FMS are then compiled from the generated matrix using the IDW interpolation. The initial values of the parameters ζ, u and v are taken as zero to represent a cold start. A time step of 60 s is used that ensured Courant-Friedreich-Lewy (CFL) stability criterion. Following Roy et al. (1999), the value of C_f is considered uniformly throughout the domain under consideration as 0.0026. The rest of the parameters used in the study have been assumed to have their standard values.

Numerical solution of model equations

The model equations given by Eqs. 1–3 as well as the boundary conditions given by Eqs. 7–9 are discretized by finite difference (forward in time and central in space) approximation using the Arakawa C grid and the obtained equations are solved by a conditionally stable semi-implicit manner. The discretizations are made using the averaging operator in such a way that ζ, u and v are to be calculated at (even, odd), (odd, odd) and (even, even) grid points, respectively. For numerical stability, the last term on the right hand side of each of Eqs. 2 and 3 is discretized in a semi-implicit manner. For example, the last term $v_\theta \left(v_r^2 + v_\theta^2 \right)^{\frac{1}{2}}$ of Eq. 3 is discretized as $v_\theta^{t+1} \left\{ \left(v_r^t \right)^2 + \left(v_\theta^t \right)^2 \right\}^{\frac{1}{2}}$, where the superscripts t and $t + 1$ denote the values at the tth and $(t + 1)$th time levels, respectively. Along the closed boundaries, i.e., coastal and island boundaries, the normal component of the depth averaged velocity is taken as zero, and this is easily achieved through appropriate stair step representation. It is to be noted here that the schemes CMS and FMS have the same hydrodynamic equations given by Eqs. 1–3 but with different boundary conditions. The boundary conditions for the CMS are given by Eqs. 7–9 and those for the FMS are aforementioned. In the solution process of the CMS, ζ is calculated in advanced time step at all the (even, odd) grid points specified by the discretized equation of Eq. 1. Then the values of ζ at the grid
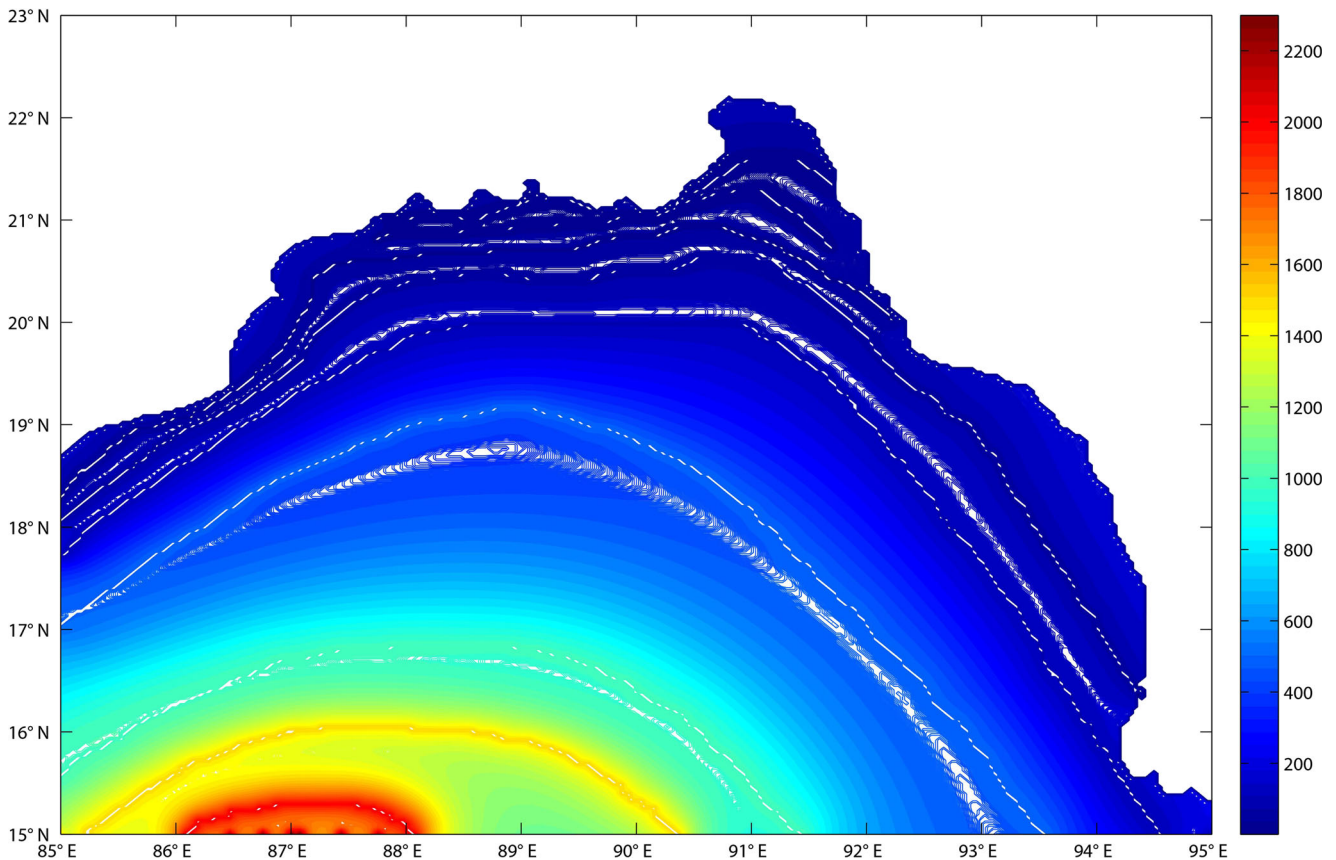
Fig. 4 Interpolated bathymetry obtained by inverse distance weighted interpolation

points of the three open boundaries are calculated from the discretized forms of Eqs. 7–9. Then a weighted average technique is taken into account to ensure the values of ζ at the remaining necessary grid points. The path for a storm is subsequently generated from the relevant procured data from the BMD. The x and y-components of the wind stress are then generated at necessary grid points using Eqs. 4–6 at each time step. Then u and v are calculated at their corresponding grid points using the discretized Eqs. 2 and 3, respectively. The similar process is continued for the FMS. The only difference here is in the boundary conditions. The details of the boundary conditions for the schemes are discussed in "Set up the domain of the model and nested grid ". Finally, from the FMS, the time series of water levels at some grid points representing coastal stations are stored and are displayed and analyzed in "Analysis of results and model validation".

Generation of tidal oscillation

The astronomical tide is a continuous process in the sea, the surges due to TCs always interact with the astronomical tide (Roy et al. 1999). Thus, the pure tidal oscillations provide the initial state of the sea (Sinha et al. 2008) and

hence to obtain the total sea-surface elevation due to tide and surge, it is required to generate the initial sea-state condition. Application of the tidal constituents M_2 (principal lunar), S_2 (principal solar), O_1 (principal lunar diurnal), and K_1 (lunisolar diurnal) along the southern open boundary of the parent model may yield an accurate tidal regime along the region of interest (Paul et al. 2016). To make the work simple, some studies, namely Roy (1995), Paul and Ismail (2012b, 2013), Paul et al. (2014) were conducted in Cartesian coordinates generating tidal oscillation with applying only the M_2 tide along the southern open boundary of the parent model. It is important to note here that M_2 is the dominating tidal constituent over the region of interest (Paul et al. 2016). But, the main problem in generating a pure tidal oscillation in the polar coordinate shallow water model is that the grid points of the open sea boundary are laid at different latitudes and hence the amplitude and phase of a constituent will be different in different latitudinal positions. Thus, it is very difficult to generate an accurate tidal oscillation through the model simulation within the model domain with the use of the mentioned four constituents or even only with the M_2 tidal constituent in the simplification case. Another remarkable problem is the variation of tidal amplitude in the spring-neap cycle (Roy et al. 1999). Furthermore,
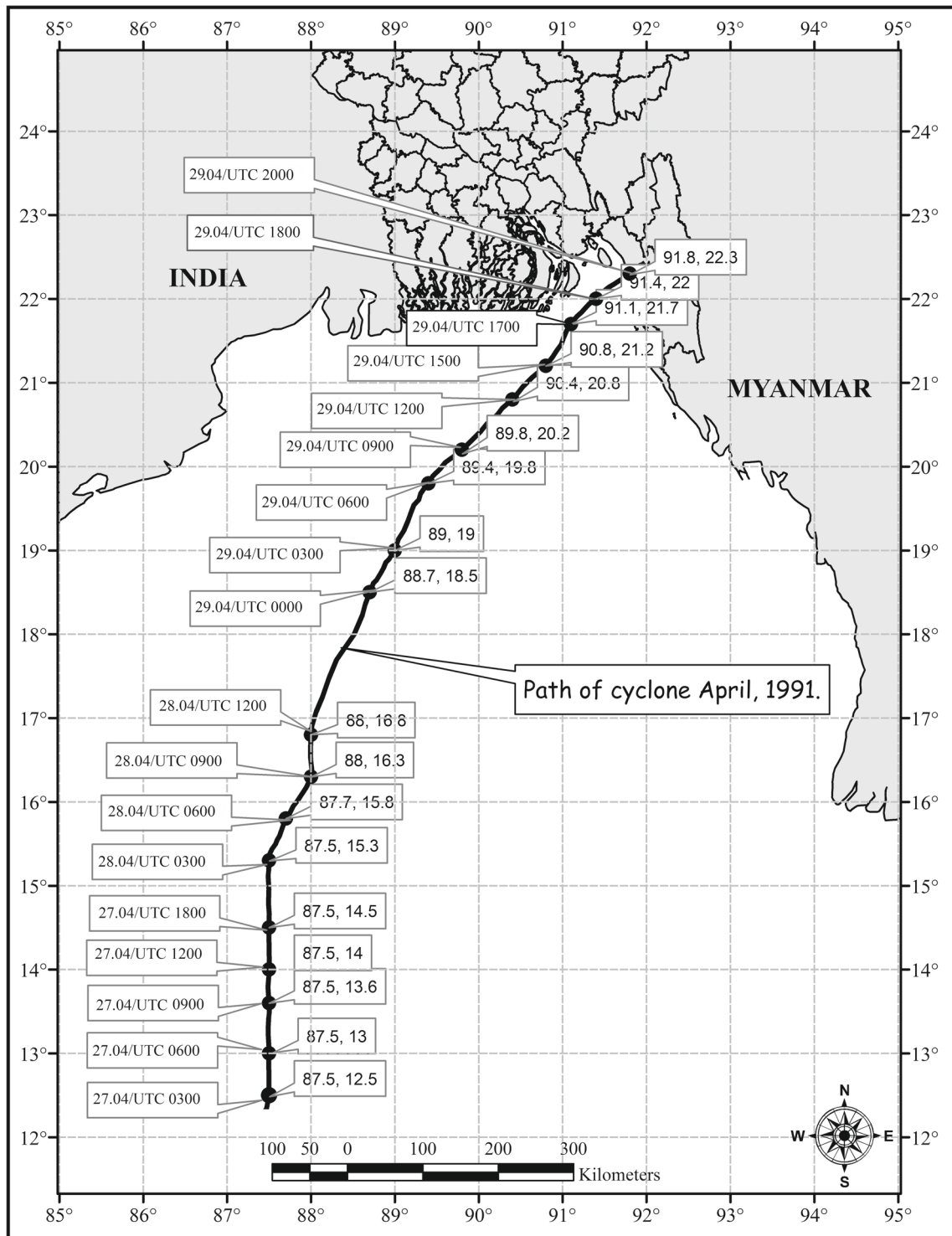
Fig. 5 Path of the cyclone April 1991 (Data source: BMD)

for the nonlinear interaction of tide and surge, an actual tidal oscillation has to be generated for each storm period, which is always difficult and time consuming. Because of the above facts, it is not feasible to develop a dynamical tide-surge interaction model for operational forecasting purposes

(Roy et al. 1999). A different way to overcome this situation is to superimpose linearly the time series of surge response obtained through the model simulation with that of the tidal oscillation generated from a station's available tide table. As hourly tidal data are available at some coastal stations

Table 1 Time variation history of the cyclone April 1991 (Source: BMD, Talukder et al. 1992)

Date	Hour (UTC)	Latitude (°N)	Longitude (°E)	Nature of the storm
26 April	1800	11.80	87.50	Cyclonic storm
27 April	0300	12.50	87.50	Cyclonic storm
27 April	0600	13.00	87.50	Cyclonic storm
27 April	0900	13.60	87.50	Severe cyclonic storm
27 April	1800	14.50	87.50	Severe cyclonic storm with hurricane core
28 April	0600	15.80	87.70	Severe cyclonic storm with hurricane core
28 April	0800	16.50	88.00	Severe cyclonic storm with hurricane core
28 April	1800	17.60	88.30	Severe cyclonic storm with hurricane core
29 April	0600	19.80	88.40	Severe cyclonic storm with hurricane core
29 April	1200	20.80	90.40	Severe cyclonic storm with hurricane core
29 April	1800	22.00	91.40	Severe cyclonic storm with hurricane core
29 April	2000	22.30	91.80	Crossing the coast near Chittagong
30 April	0000	23.00	92.40	Crossed the Bangladesh coast
30 April	0200	23.50	92.80	–

Maximum wind speed: 234 km h^{-1}, maximum sustained wind radius: 50 km

of Bangladesh, a time variation of tidal information can be generated through a cubic spline interpolation method. Since the tidal information is authentic and the cubic spline interpolation is a fast, efficient and stable method, we think that the process will yield more effective results with less computational cost.

Model experiments

The numerical experiments are performed to simulate the surges generated by April 1991 and AILA, 2009 cyclones. The cyclone April 1991 was chosen because of its severity as well as availability of reported data. Another reason is its path. The storm passed nearby the Meghna mouth, which is the region of concern. On the other hand, the recent severe cyclonic storm AILA was chosen due to the possibility of having more observed data. A synoptic history of each of the TCs is presented in "Storm April 1991" and "Storm AILA, 2009", which is important for storm surge modeling, analysis of model simulated results and model validation.

Storm April 1991

The cyclone was first detected as a depression on 23 April 1991 in the satellite picture taken at the Space Research and Remote Sensing Organization (SPARRSO) from NOAA-II and GMS-4 satellites (Khalil 1993). At 0300 Universal Time Coordinated (UTC) of 25 April, the depression was located at latitude 10°N and longitude 89°E, which thereby intensified into a deep depression at 1200 UTC near 11.5°N and 88.5°E and turned into a cyclonic storm at 1800 UTC in the same day with the maximum sustained wind speed 18–24 m s^{-1} having a central pressure of 996 mb. The

system retained this intensity till 0900 UTC 27 April when it was found to have developed into a severe cyclonic storm with the maximum wind speed 25–32 m s^{-1} having 990 mb as the central pressure. On the same day at 1800 UTC, the system intensified into a severe cyclonic storm near 14.5°N and 87.5°E. It further intensified into a severe cyclonic storm with a hurricane core near 15.5°N and 87.5°E at 0300 UTC 28 April that had wind speeds of more than 36 m s^{-1}. From about this time, it started moving in a northeasterly direction towards the Meghna estuary and finally crossed the Bangladesh coast a little north of Chittagong at Companiganj of Noakhali Coast (Paul and Ismail 2013) at about 2000 UTC 29 April (at about 0200 Bangladesh Standard Time on 30 April). The maximum wind speed observed at Sandwip was 65 m s^{-1}. The central pressure of the cyclone was as low as 938 mb, as measured by the Chittagong port authority of Bangladesh and the estimated maximum pressure drop was about 60 mb (Talukder et al. 1992). The track of the April 1991 cyclone is shown in Fig. 5, whereas Table 1 presents details of the time variation history of the storm.

Storm AILA, 2009

The storm AILA hit the south western coastal districts of Bangladesh on 25 May 2009, killing 190 people, affecting more than 3.9 million people across the 11 coastal districts disrupting their livelihoods and destroying infrastructure (see Paul et al. 2016). According to BMD estimates, a low formed over Southwest Bay and adjoining area at 1200 UTC of 21 May 2009, moved northwards and intensified into a well marked low over Southwest Bay and adjoining West Central Bay at 0300 UTC of 23 May 2009. At 0900 UTC of 23 May the system again intensified into a
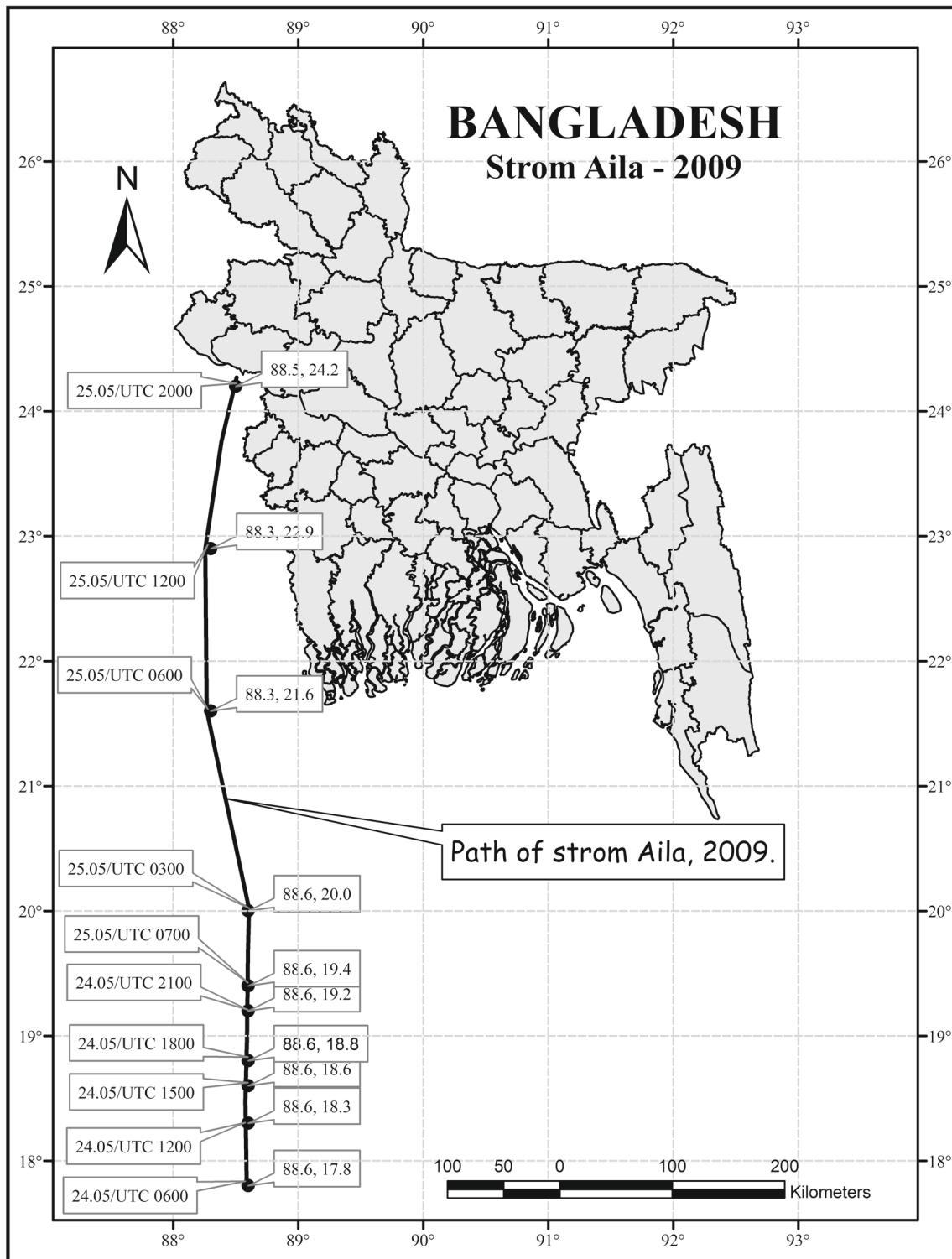
Fig. 6 Track of the cyclone AILA, 2009 (Source: BMD). The track is generated with the help of ArcGIS software

depression and moved northwards and after 2100 UTC of the same day the system changed its direction of movement and moved north-northeastwards and intensified further into a deep depression. Then the system moved northwards into Northwest Bay and adjoining west central Bay, intensified

into a cyclonic storm AILA at 1200 UTC of 24 May 2009. At about about 0800 UTC of 25 May, the system started to cross West Bengal-Khulna (Bangladesh) coast near Sagar Island of India and then moved continuously northwards. At about 1200 UTC, the central position of the system

Table 2 Time series for the positions and nature of the storm AILA, 2009 (Data source: BMD)

Date	Hour (UTC)	Latitude (°N)	Longitude (°E)	Nature of the storm
23 May	0900	16.00	88.00	Depression
23 May	1500	16.50	88.00	Depression
24 May	0000	17.20	88.30	Depression
24 May	0600	17.80	88.60	Deep depression
24 May	0900	17.80	88.60	Deep depression
24 May	1200	18.30	88.60	Cyclonic storm
24 May	1800	18.80	88.60	Cyclonic storm
24 May	2100	19.20	88.60	Cyclonic storm
25 May	0000	19.40	88.60	Cyclonic storm
25 May	0300	20.00	88.60	Cyclonic storm
25 May	0600	21.60	88.30	Cyclonic storm
25 May	1200	22.90	88.30	Cyclonic storm
25 May	2000	24.20	88.30	Cyclonic storm

Maximum wind speed: 120 km h^{-1}, maximum sustained wind radius: 54 km

positioned over Kolkata (India) and adjoining areas of India and Bangladesh but the remaining part of AILA was still crossing the coast. During next 03–04 h the system completed its crossing the coast and lay centred at West Bengal and adjoining western parts of Bangladesh. The track of the storm AILA generated through ArcGIS software with the data from the BMD is shown in Fig. 6, where the time series for the positions and the nature of the cyclone are presented in Table 2 for better understanding.

Analysis of results and model validation

For the purpose of model validation and analysis of model simulated results, we present them for both the chosen storms at some stations along the coast of Bangladesh, Khalil (1993) predicted 4–9 m. The time variation tidal information at a station is mandatory to foresee sea-surface elevation due to the superposition of tide and surge. On the other hand, observed water level data are required for model validation. Unfortunately, observed data are available only at a few number of stations during a stormy period at some sources, e.g., Bangladesh Inland Water Transport Authority (BIWTA). For the mentioned fact, our computed water levels due to the superposition of tide and surge are shown at those stations where the observed data are available.

Results for the storm April 1991

For the storm April 1991, the results were calculated for 80 h and were presented for the last 2 days from 0200 UTC of 28 April to 0200 UTC of 30 April. Our computed time series of water levels due to pure surge (in the absence of astronomical tide) associated with the storm April 1991 at some coastal stations are depicted in Fig. 7 (left panel). The maximum surge levels associated with the storm April 1991 resulted from our simulation can be found to range from 2.91–7.15 m with 5.15 m at Chittagong. Based on a report from the BMD, the peak surge level at Chittagong was 5.5 m and there was 3.5–6.1 m high surge along the coast of Bangladesh. It is of interest to note here that surge is not found switched off in the nature and it is very difficult to find observed pure surge data. Thus we compared the results due to pure surge with the corresponding results obtained in some investigations. Roy et al. (1999) estimated 0.70 m (Hiron Point)–5.45 m high storm surge in different coastal areas of Bangladesh, Khalil (1993) predicted 4–9 m high storm surge along this area, whereas Paul and Ismail (2012b) simulated it to be 2.69–6.98 m. Thus the results came out through our model simulation due to surge associated with the storm April 1991 compare well with some reported data and observed peak surge value at Chittagong. Fig. 8 depicts our computed water levels due to pure surge, tide, their superposition and observed data during the mentioned period of the storm April 1991 at Hiron Point, Char Changa (Hatiya) and Chittagong. The reason behind the choice of the stations is aforementioned. It is inferred from Fig. 8 that the results obtained through our model simulation due to the superposition of tide and surge agree fairly well with the observed data from the BIWTA and with the ones presented in Roy et al. (1999) (see Fig. 8). From Fig. 8, it is also seen that a peak water level of 6.69 m was occurred at Chittagong at 2000 UTC, whereas Roy et al. (1999) found it to be 6.8 m. Based on a report from the BMD, the peak water level of 6.53 m at Chittagong occurred at 2000 UTC of 30 April. Thus our simulated results at Chittagong are in agreement with the sequence and the data mentioned above. The peak water level due to the superposition of tide and surge by our model came out to be 3.66 m at Hiron Point, which strongly deviates the result (1.98) obtained in Roy et al. (1999). This may be due to the fact that the study of Roy et al. (1999) was conducted without ensuring a spatial high resolution.

Results for the storm AILA, 2009

For the storm AILA, the results were computed for 59 h (from 0900 UTC 23 May to 2000 UTC 25 May) and in each case they were presented for the last 48 h from 2000 UTC 23 May to 2000 UTC 25 May 2009 at some coastal and island locations of Bangladesh. Through comparison of observed and model computed water levels is also not possible in the case of the storm AILA in a similar reason stated for the storm April 1991. Figure 7 (right panel)

Fig. 7 Simulated water levels
with respect to the MSL due to
surge (in the absence of
astronomical tide) associated
with the storms April 1991 and
AILA, 2009 at four coastal
stations; the left panel for the
storm April 1991 and the right
panel for the storm AILA, 2009
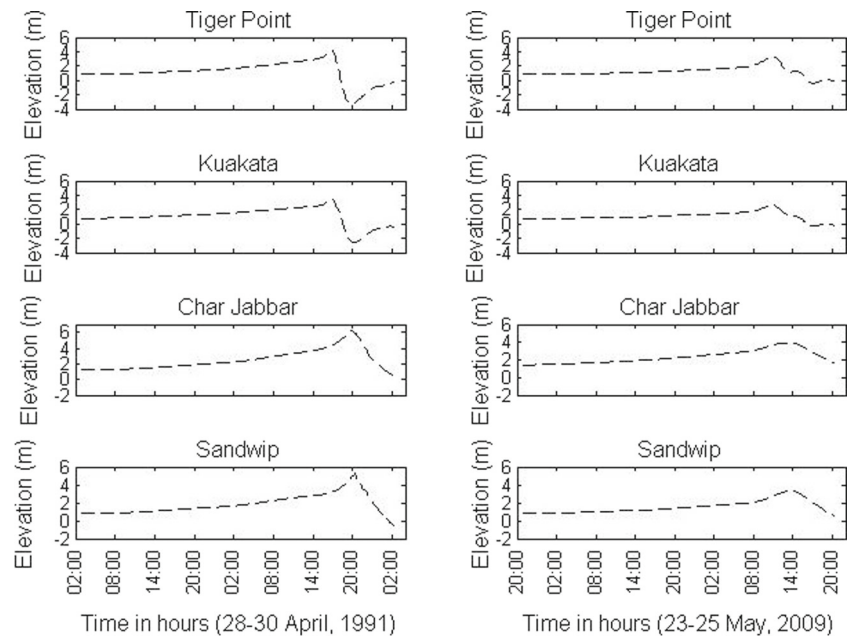
depicts our model simulated time series of water levels
due to surge only associated with the storm AILA at some
stations along the coast of Banglaesh. The maximum surge
levels resulted from our simulation were found to be 1.07–
4.58 m with 2.48 m at Hiron Point (Sundarban, Khulna).
NASA's Goddard Space Flight centre reported a storm surge
of 3.05–3.96 m high along the western Bangladesh coastline
while land fall occurred. Again based on a report from the
Indian Meteorological Department, there was about 2–3 m

surge above the astronomical tide over the West Bengal and
adjoining Bangladesh coasts. Roy et al. (1999) referred a
maximum storm surge of about 2 m over the Sundarbans
area. Thus our computed water levels due to surge associ-
ated with the storm AILA are found to be in a reasonable
agreement with the reported and some observed data. Fig. 9
depicts our model simulated time series of water levels
due to surge, tide, their superposition and observed data at
Hiron point, Char Changa and Chittagong. It can be inferred

Fig. 8 Computed water levels
with respect to the MSL due to
tide, surge, the superposition of
tide and surge associated with
the storm April 1991 at three
coastal stations. The observed
water level data obtained from
the BIWTA for the chosen
period (0200 UTC of 28th April
to 0200 UTC of 30th April) of
displaying results are also
presented in the figure. In each
case a dotted red curve
represents the configuration for
surge, a black solid curve
represents that for tide, a green
solid curve represents that for the
superposition of tide and surge
and a circle that for an observed
data, whenever available, in the
mentioned period; **a** Hiron
Point, **b** Char Changa (Hatiya)
and **c** Chittagong
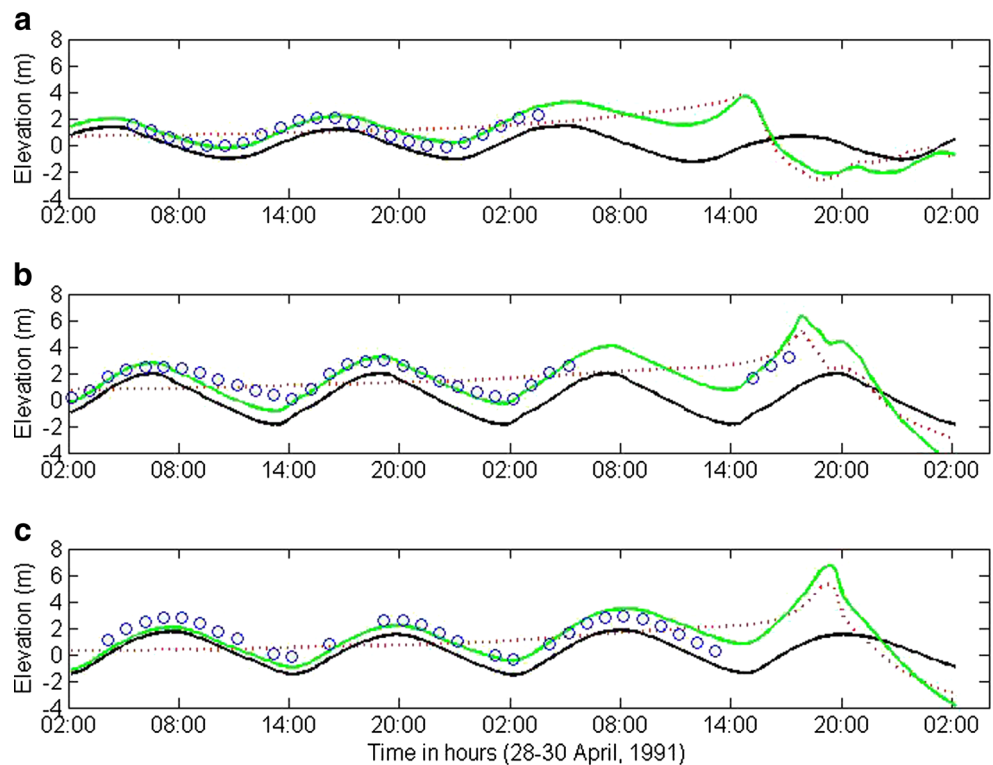
Fig. 9 Computed water levels with respect to the MSL due to tide, surge, the superposition of tide and surge associated with the storm AILA 1991 at three coastal stations. The observed water level data obtained from the BIWTA for the chosen period (2000 UTC of 23rd May to 2000 UTC of 25th May) of displaying results are also presented in the figure. In each case a dotted red curve represents the configuration for surge, a black solid curve represents that for tide, a green solid curve represents that for the superposition of tide and surge and a circle that for an observed data, whenever available, in the mentioned period; **a** Hiron Point, **b** Char Changa (Hatiya) and **c** Chittagong
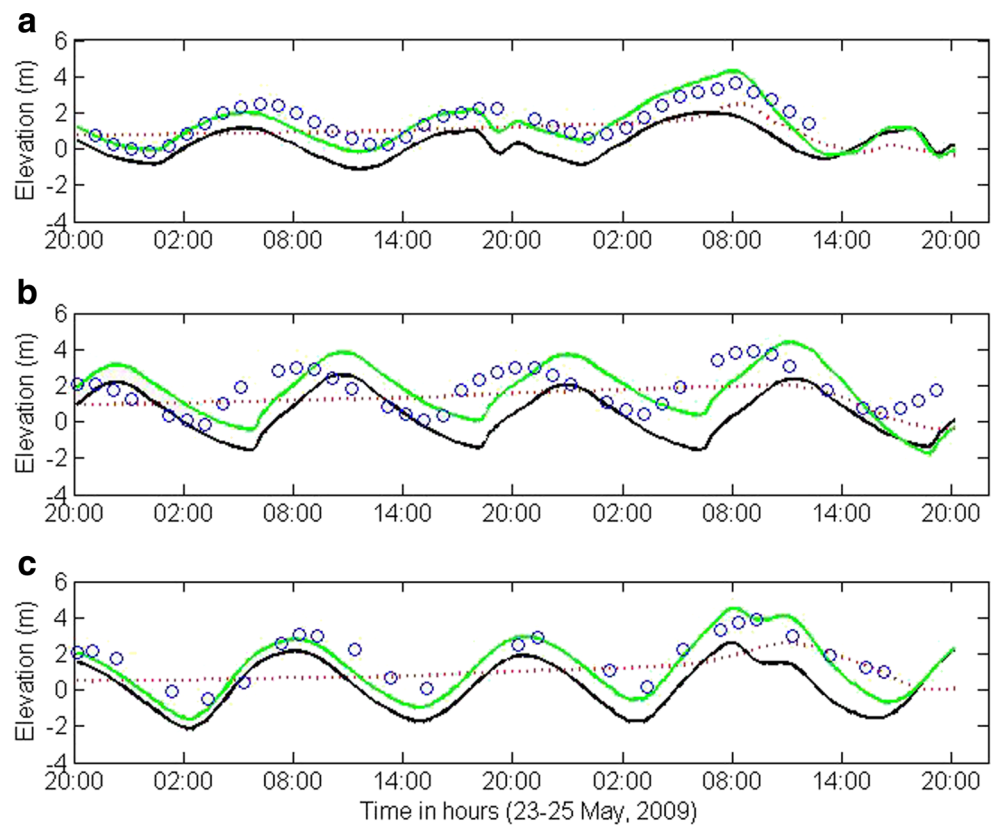
from Fig. 9 that our time series of simulated results are in good agreement with the observed data obtained from the BIWTA. The peak water levels due to the superposition of the tide surge simulated by the model came out to be 4.3 m, 4.37 m and 4.5 m at Hiron Point (Sundarban, Khulna), Char Changa and Chittagong, respectively. According to Roy et al. (2009), the peak water level at the time of landfall was 4–5 m. Based on a report from the BMD, the storm AILA started to cross the West Bengal Khulna coast near Sagar island in India nearly 0800 UTC of 25 May and made landfall between 0800 to 0900 UTC of 25 May over Bangladesh coast (Khulna) when the local astronomical tide was at peak. Our simulated result justifies well (see Fig. 9a) the landfall time. Also by a report from the BMD, at about 1200 UTC the central position of the system positioned over Kolkata (India) and adjoining areas of India and Bangladesh. Thus, our computed water levels due to surge and superposition of tide and surge (see Fig. 9) are in agreement with the sequence of events and data mentioned above. It can be seen from Fig. 9 that the maximum water levels due to surge and the superposition of tide and surge at each location increase with time as the storm approaches the coast and finally there is a recession. This is as to be expected because of increasing intensity of the wind while approaching the coast. The beginning of recession at the coastal locations delays with the increase in their east longitudes. Early recessions of water levels at the western costal

locations are observed from the figures (see Figs. 8, 9), which are as to be expected. A similar analysis can also be made for the storm April 1991. The analysis is found to be consistent with those made in Roy et al. (1999), Paul and Ismail (2013), Rahman et al. (2013) and Paul et al. (2014).

Model efficiency test

To test the efficiency of the model, the root mean square error (RMSE) has been estimated between observed and computed overall water levels due to the superposition of tide and surge with reference to both the storms. Also, to show the relative importance of offshore islands and grid resolution, the corresponding RMSE values have also been evaluated. The RMSE values of the results obtained in the study of Roy et al. (1999) for the superposition of tide and surge refer to the storm April 1991 are also presented in Table 3. It can be inferred from Table 3 that our model results are reasonable and found to be better (with respect to the RMSE values) in comparison with the compiled results obtained from the figure used in the study of Roy et al. (1999). It can also be observed from Table 3 that the factors, namely offshore islands and grid resolution have contribution on water levels and those cannot be ignored in developing an optimal operational forecasting model for the region of interest, as such a model would enable the coastal

Table 3 Estimated root mean square errors in meter

Storm	Coastal station	The present study	The study due to Roy et al.	Without islands	Without FMS
April 1991	Chittagong	0.73	0.67	0.89	0.87
	Char Chenga	0.65	0.78	0.68	0.64
	Hiron Point	0.32	0.49	0.37	0.36
AILA, 2009	Chittagong	0.82	–	1.00	1.00
	Char Chenga	1.38	–	1.40	1.39
	Hiron Point	0.52	–	0.59	0.59

authorities for appropriate planning for disaster reduction in the event of any severe cyclone.

Some mitigative measures against storm surges

The main contribution of the present study is to estimate water levels efficiently and use it for operational forecasting purposes along the coast of Bangladesh. It is to be noted here that cyclones and associated surges, although not fully preventable, can at least be made less harmful and the suffering they inflict can considerably be reduced by taking action on time (Khalil 1992), which highly depends on proper forecasting of these TCs. Accurate forecast of the TCs and concerned warning system can be treated as an important low-cost measure to minimize losses (Khalil 1992). For taking long term mitigative measures against the TCs, many national and international agencies are involved since 1950. Embankment system is one of them as is aforementioned. To protect the coast as well as to prevent sea water from overrunning the land, a major embankment system was constructed in the 1960's and 1970's (Khalil 1992). Even such prohibitively expensive structures might not be able to withstand the full force of impact from the incoming surge (Murty and EI-Sabh 1992). Proper cultivation of deep rooted shrub type vegetation along the shoreline may be able to partially dissipate the energy of storm surges (Murty and EI-Sabh 1992). In addition to that, more research should be conducted to understand the viability of artificially planted surge forests as effective coastal defenses. Such a surge forest will not only provide some esthetic value, but may have other beneficial effects (Murty and EI-Sabh 1992). It is of interest to note here that in southwestern coast of Bangladesh, the world's largest mangrove forest, Sunderbans, served as a buffer, reducing the effects of cyclone Sidr (Paul 2009). However, due to greenhouse warming, the storm surge amplitudes in near future could be greater than that of the present time. Keeping the idea in mind, based on proper estimation of maximum surge, construction of cyclone shelters should be encouraged.

Concluding remarks with future opining

In this study, we have developed a one-way nested model in cylindrical polar coordinates that ensures finer resolution near the coast than that of the deep sea along both radial and tangential directions. The developed model is found to be suitable for incorporating the complexities of the coast with considerable accuracy. The computed water levels due to the superposition of tide and surge are found to be in good agreement with the observed data and with the results obtained by other studies with different approaches. Moreover, the model can be found to be efficient to compute surge in the head Bay of Bengal with less computational cost (central processing unit time 1 m 23 s, surge only). Therefore, this study can be appropriate for the funnel shaped coast of Bangladesh for the precise forecasting of surge amplitude at a specific location, which in turn may be used for any funnel-shaped estuary with a complex geometry. Because, the polar coordinate system automatically ensures finer resolution along tangential direction near the pole. Thus, by setting the pole suitably at a point where an improved grid resolution is required, a uniform grid size can be generated in the tangential direction by a set of radial lines through the pole. As a result the arc distance between any two successive radial lines will be decreased towards the pole and will be increased away from the pole and an uneven grid resolution will be achieved in the tangential direction in spite of using uniform grid size. However, water levels as predicted by the present study can be used for issuing proper forecasting from time to time, which in turn can lead to provide proper warnings to users and to CPP volunteers who can assist local population in the evacuation process and to execute rescue operations. The conclusions of this study have implications towards building short and long-term planning for disaster risk reduction along the world's most vulnerable region. Development has yet to be done taking into account the river dynamics and the inverse barometric effect. Finally, our intention is to develop the model for practical purposes along the coast of Bangladesh.

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