OPEN ACCESS
Saudi Journal of Engineering and Technology
Abbreviated Key Title: Saudi J Eng Technol
ISSN 2415-6272 (Print) |ISSN 2415-6264 (Online)
Scholars Middle East Publishers, Dubai, United Arab Emirates
Journal homepage: https://saudijournals.com

Review Article

An Analysis of Track Effects on Storm Surge Simulation

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DOI: 10.36348/sjet.2022.v07i08.004 | **Received:** 18.08.2022 | **Accepted:** 12.09.2022 | **Published:** 18.09.2022

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Abstract

This study investigates the effects of cyclone tracks on water levels during storm surges along the coast of Bangladesh. A numerical hydrodynamical model in Cartesian coordinates has been developed, where the developed equations are solved by a semi-implicit finite difference method. The boundary fitted grid technique is employed to rectangularized the physical domain. Along the north-east corner of the model, the Meghna River fresh water discharge is taken into account. A stable tidal regime over the region of interest is generated with the help of four major tidal constituents, namely M_2 (principal lunar semi diurnal), S_2 (principal solar semi diurnal), O_1 (principal lunar diurnal) and K_1 (principal lunar diurnal) along the southern open boundary of the outermost model. This previously generated tidal regime is used as the initial state of sea in order to obtain water levels due to the nonlinear interaction of tide and surge. Numerical experiments are made with the severe storm April 1991 and some hypothetical storm tracks. The simulated results with the real track are found to be in a good agreement with some observed and some reported data. The water levels are found to be greatly influenced by the hypothetical cyclone tracks.

Keywords: Cyclone tracks, boundary fitted grid technique, Storm surge, Bay of Bengal.

1. INTRODUCTION

Cyclone is an influx of sea water pushed ashore by the strong winds in a storm. Tropical cyclones (TC) along with associated surges often cause great demolition along the Bangladesh coast. Tropical cyclones frequently hit the Meghna estuary region on Bangladesh's coast (TCs). Excessive bending of the coast line, offshore islands, shallow bathymetry, and huge discharge through the Meghna and other rivers are amongst factors that can exasperate the effect of storm surge in the Meghna estuarine region (see Roy, 1995). Therefore, a fruitful storm surge model is highly desirable for the coastal region of Bangladesh. A large extent of numerical models has developed for the prediction of storm surge, tide, and their interaction effect on storm associated surges in the Bay of Bengal (BOB), especially along the Bangladesh coast by several researchers. Some worth mentioning works are due to Das (1972), Flierl and Robinson (1972), Das *et al*., (1974), Johns and Ali (1980), Dube *et al*., (1985), Das' pioneering work in 1972 aimed at simulating cyclones with the linear tide and surge interactions, whereas it would always interact with tide nonlinearly. In the study of Das *et al*., (1974), the island and coastal boundaries were approximated by stair step method depending on grid resolution. The fine grid resolution was not considered in this study. The study of Johns and Ali (1980) directed with uncertainties of very fine grid resolution. But there remains a possibility of different result with the real situation for ignoring the real complexities of the coast of the mentioned region. But the problem was solved by Roy (1995) through using a nested grid technique whereas the model was capable of incorporating only the Meghna River estuarine region. The study due to Roy *et al*., (2004) was limited to incorporate tide and surge linearly. The problem was solved with a number of investigations conducted by Paul (2012a, 2012b, 2013, 2016, 2018a, 2018b). Also, some alternative investigations identifying the funnel shape of the coast of Bangladesh are investigated for the region of interest. Among all interrelated features, it also needs to know the direction of a cyclone movement so that the residents of potentially affected regions can be warned well ahead of time, may be this is the way to reduce damage to life and property. But among many analyses on storm surge influencing factors, the analyses due to tracks have paid a little attention. The study of Salek and Yasuda (1996) showed that the surge height waned as the cyclone track removed southward along the Chittagong coast.

Besides, according to Azam *et al*., (2004), change in track orientation creates difference on surge heights at the eastern coast although relatively higher effect was found in the western coast. From above, as far exists, it is seen that different authors have developed different parameterization schemes but most of these schemes have certain limitations and the analyses with regard to track of a TC is especially mentionable. From the prior discussion, we believe that the water level may be changed due to cyclone track effect on cyclone-induced storm surge. Thus, the present work is moved forward with the analyses of the TC tracks.

2. MATHEMATICAL FORMULATION

2.1. Basic equations

Our study investigated water levels due to storm surge based on the following vertically integrated shallow water equations (Debsarma, 2009; Paul *et al*., 2014):

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

$$\frac{\partial\tilde{u}}{\partial t}+\frac{\partial}{\partial x}(u\tilde{u})+\frac{\partial}{\partial y}(v\tilde{u})-f\tilde{v}=-g(\zeta+h)\frac{\partial\zeta}{\partial x}+\frac{T_x}{\rho}-c_f\tilde{u}\frac{(u^2+v^2)^{\frac{1}{2}}}{(\zeta+h)}, \qquad (2)$$

$$\frac{\partial\tilde{v}}{\partial t}+\frac{\partial}{\partial x}(u\tilde{v})+\frac{\partial}{\partial y}(v\tilde{v})+f\tilde{u}=-g(\zeta+h)\frac{\partial\zeta}{\partial y}+\frac{T_y}{\rho}-c_f\tilde{v}\frac{(u^2+v^2)^{\frac{1}{2}}}{(\zeta+h)}, \qquad (3)$$

Where u and v are the depth averaged velocity components in the directions of x and y, axes, respectively; t represents the time; ρ designates the sea water density, which is considered to be homogeneous and incompressible; $f=2\Omega\, sin\phi$ is the Coriolis parameter, where Ω is the angular speed of the earth rotation and ϕ signifies the latitude of the place of interest; g signifies the acceleration due to gravity and $(\tilde{u},\tilde{v})=(\zeta+h)(u,v)$.

In the study, surface stresses are parameterized by the conventional quadratic law:

$$T_x=\rho_a C_D u_a({u_a}^2+{v_a}^2)^{\frac{1}{2}} \text{ and } T_y=\rho_a C_D v_a({u_a}^2+{v_a}^2)^{\frac{1}{2}} \qquad (4)$$

Where C_D represents the surface drag coefficient. In our study, we have used $C_D=0.0028$, which is found to be used by Das (1972); ρ_a presents the air density; and u_a, v_a denote the velocity components of the surface winds along the x and y axes, respectively.

Now following Jelesnianski (1965) the circulatory wind field is generated for the region, which is given by:

$$V_a=V_0\sqrt{\left({r_a}/{R}\right)^3} \text{ for all } r_a\le R \text{ and } V_a=V_0\sqrt{\left({R}/{r_a}\right)^3}, \text{ for } r_a>R \qquad (5)$$

Where V_0 represents the MSWS at the radial distance (u_a,v_a) of the wind field are developed from V_a given by Eq. (5). It is of important to mention here that the parameters included in Eq. (5), namely R and V_0 are available during any storm along the region of interest at the Bangladesh Meteorological Department (BMD).

2.2. Boundary conditions

In our model domain two types of boundaries namely closed and open boundaries have been used. Considering (Paul *et al*., 2016), we set the following radiation boundary conditions:

West BC:

$$v+\left(\frac{g}{h}\right)^{\frac{1}{2}}\zeta=0 \qquad (6)$$

East BC:

$$v-\left(\frac{g}{h}\right)^{\frac{1}{2}}\zeta=0 \qquad (7)$$

South BC:

$$u-\left(\frac{g}{h}\right)^{\frac{1}{2}}\zeta=-2\left(\frac{g}{h}\right)^{\frac{1}{2}}\sum_{i=1}^{4}a_i\, sin\left(\frac{2\pi}{T_i}+\phi_i\right) \qquad (8)$$

Where a_i and ϕ_i signifies the amplitude, phase of the constituent of interest, respectively, and T_i presents the period.

Meghna river discharge is considered along the north east corner of the open boundary of the very inner model. At this open boundary segment, the x-component of velocity can be written as (Roy, 1995)

$$u_b=u+\frac{Q}{(\zeta+h)\,B} \qquad (9)$$

Where Q is the fresh Meghna River water discharge in m^3s^{-1} and B is the river breadth in m.

3. NUMERICAL PROCEDURES

3.1 Boundary-Fitted Grids

It is natural to use Cartesian grids for flow within a rectangular or a square domain, and cylindrical or spherical grids for cylindrical or spherical grids, respectively. It is possible to generate conformal or orthogonal grids for relatively simple geometry, but for most estuarine and coastal applications the coastal geometry is usually quite complex so that conformal or orthogonal grids may not be suitable. Conventionally, non-orthogonal grids for estuarine and coastal applications have been generated by solving partial differential equations-e.g., Sheng (1989) employed Poisson equations, and Bao *et al*., (2000) used an elliptic coordinate transformation equation satisfying some characteristics of curvilinear grids via a variational method. In this article, we use general curvilinear or boundary fitted non-orthogonal grids to represent the model boundaries accurately in the numerical scheme, but they are generated in a different way. Our approach is based on the idea of Johns *et al.* (1981), who represented the curvilinear boundary of the East Coast of India by a function, and on the idea of Roy (1999) in representing the islands by a general function. For the formulation of the model a system of rectangular Cartesian coordinates is used in which the origin, O, is the mean sea level (average level of sea surface). OX, OY, OZ are directed towards the south, the east and vertically upwards, respectively. The displaced position of the free surface is given by $z = \zeta(x, y, t)$ and the position of sea floor is given by $= -h(x, y)$, respectively. The northern coastal boundary of Bangladesh and the southern open boundary are given by $x = b_1(y)$ and $x = b_2(y)$, respectively. The western and eastern coastal boundaries are at $y = 0$ and $y = L$, respectively. This configuration is shown in Fig 1.

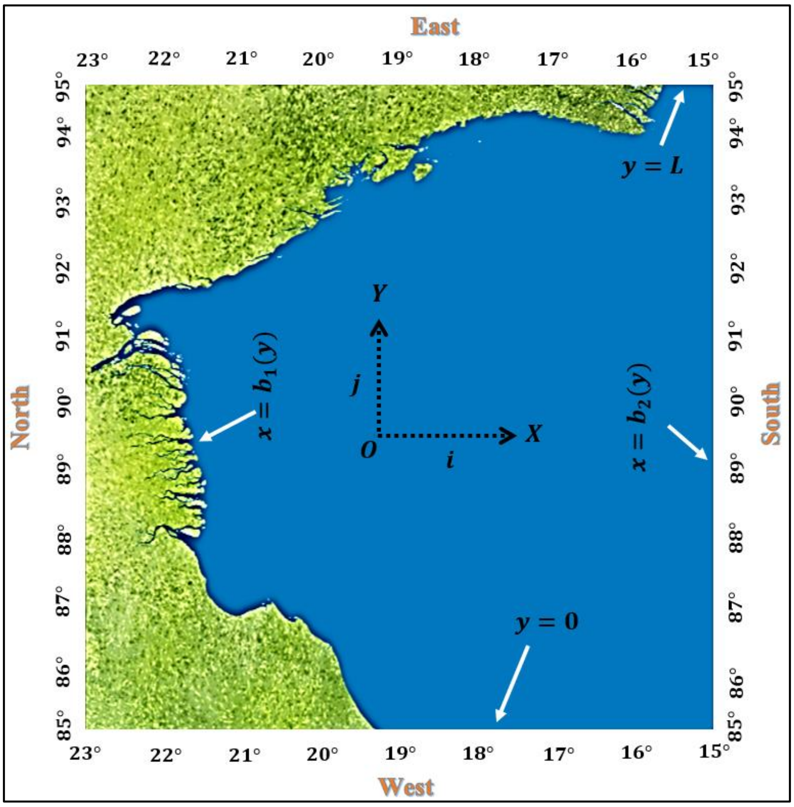


Fig 1: Boundaries of the analysis area

It may be seen in the Fig. 1 that the southern open boundary $x = b_2(y)$ is taken as a straight line but it can be considered as a curve also. Also, it is to be noted that, the functions are not defined by explicit expressions, rather they are defined in tabular form. The boundary-fitted grids are generated through the following generalized functions:

The system of gridlines along $x = b_1(y)$ and $x = b_2(y)$ are given by the generalized function

$$x = \frac{\{(m-q)b_1(y) + q\, b_2(y)\}}{m} \quad \ldots\ldots (10)$$

Where m and q are constants and $0 \leq q \leq m$.

The system of gridlines along $y = 0$ and $y = L$ are given by the generalized function

$$y = \frac{\{(l-p).0 + p\, L\}}{l} = 0 \quad \ldots\ldots (11)$$

Where l and p are constants and $0 \leq p \leq l$.

Note that, Eq. (10) reduces to $x = b_1(y)$ and $x = b_2(y)$ for $q = 0$ and $q = m$, respectively. Similarly, Eq. (11) reduces to $y = 0$ and $y = L$ for $p = 0$ and $p = l$, respectively. By proper choice of q, m , p , and l we can generate the boundary-fitted curvilinear grid lines. Curvilinear boundaries of typical domain and the curvilinear grid system are shown in Fig 2a. It may be noted that one of the boundaries is taken as straight line. In fact, it can be a curved line also. The corresponding boundaries and the rectangular grid system after the transformation are shown in Fig 2b.

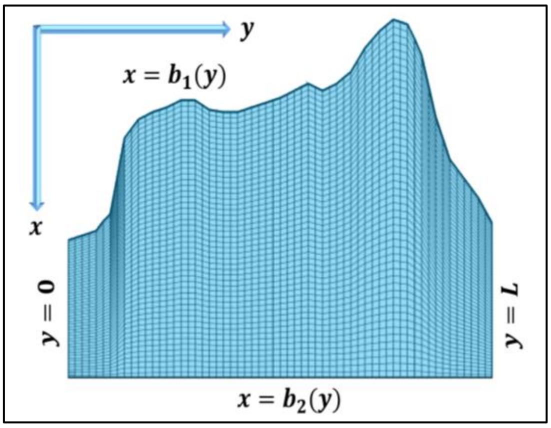


Fig 2a: Curvilinear grid system

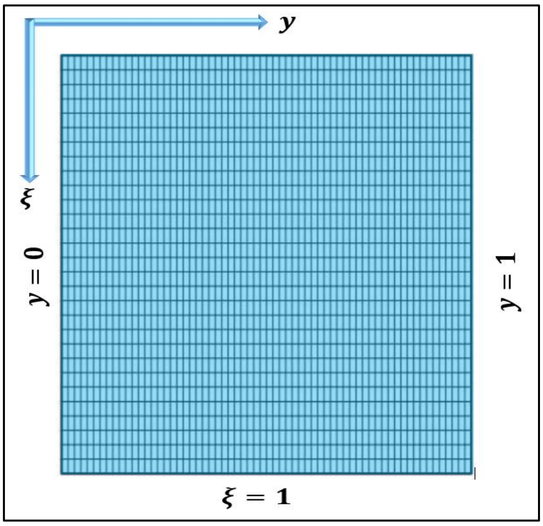


Fig 2b: Rectangular grid system in the transformed domain

3.2 Coordinate Transformation

Reid *et al.*, (1977) considered conformal mapping in storm surge work for curvilinear representation of coastal boundaries. But this treatment is of a different nature and is more similar to that reported by Jelesnianski (1976). To facilitate the numerical treatment of irregular boundaries, we introduce a coordinate transformation, similar to that in Johns et al. (1981), which is based upon a new set of independent variables ξ, y and t .

Where

$$\xi = \frac{x - b_1(y)}{b(y)} \quad \ldots\ldots (12)$$

Where $b(y) = b_2(y) - b_1(y)$.

These transforms the physical curvilinear domain into the following rectangular one

$$0 \le \xi \le 1, 0 \le y \le L.$$

Also, the generalized functions given by Eqs. (10) and (11) transforms to

$$\xi = \frac{q}{m}, \quad \ldots\ldots (13)$$

$$y = \frac{p}{l} \; . \quad \ldots\ldots (14)$$

Thus, the western and the eastern boundaries correspond to $\xi = 0$ and $\xi = 1$, respectively.

3.3 Boundary-Fitted Grids Model

The full Bay model covers an analysis area from 05°N to 23°N and 80°E to 100°E. The Head of the Bay of Bengal model is a coastal zone model that covers an analysis area from 18°N to 23°N and 85°E to 95°E. The model has the fixed eastern boundary at about 250 km from the east coast of India at $x = b_2(y)$. The treatment of the coastal boundaries involves a procedure leading to a realistic curvilinear representation of both the western and the eastern sides of the Bay of Bengal. The model also incorporates the increased resolution adjacent to the coastline. The analysis area of the Head of the Bay of Bengal model is shown in the Fig 1.

Taking ξ, y, t as the new independent co-ordinates, Eqs. (1-3) may be written as:

$$\frac{\partial}{\partial t}(b\zeta) + \frac{\partial}{\partial \xi}[bHU] + \frac{\partial}{\partial y}(bHv) = 0, \quad \ldots\ldots (15)$$

$$\frac{\partial \tilde{u}}{\partial t} + \frac{\partial}{\partial \xi}(U\tilde{u}) + \frac{\partial}{\partial y}(v\tilde{u}) - f\tilde{v} = -g(\zeta + h)\frac{\partial \zeta}{\partial \xi} + \frac{bF_s}{\rho} - \frac{c_f \tilde{u}}{(\zeta + h)}(u^2 + v^2)^{\frac{1}{2}}, \quad \ldots\ldots (16)$$

$$\frac{\partial \tilde{v}}{\partial t} + \frac{\partial}{\partial \xi}(U\tilde{v}) + \frac{\partial}{\partial y}(v\tilde{v}) + f\tilde{u} = -g(\zeta + h)\left[b\frac{\partial \zeta}{\partial y} - \left(\frac{\partial b_1}{\partial y} + \xi\frac{\partial b}{\partial y}\right)\frac{\partial \zeta}{\partial \xi}\right] \quad \ldots\ldots (17)$$
$$+ \frac{bG_s}{\rho} - \frac{c_f \tilde{v}}{(\zeta + h)}(u^2 + v^2)^{\frac{1}{2}}.$$

Where, $\tilde{u} = Hbu, \tilde{v} = Hbv, H = \zeta + h$ and ……... (18)

$$U = u\frac{\partial \xi}{\partial x} + v\frac{\partial \xi}{\partial y} = \frac{1}{b(y)}\left[u - \left(\frac{\partial b_1}{\partial y} + \xi\frac{\partial b}{\partial y}\right)v\right] \; . \ldots\ldots (19)$$

From Eqs. (6) - (8), it can be seen that the transformed boundary conditions are:

Radiation condition at the southern boundary

$$bU - \left(\frac{g}{h}\right)^{\frac{1}{2}}\zeta = -2\left(\frac{g}{h}\right)^{\frac{1}{2}} \sum_{i=1}^{4} a_i \sin\left(\frac{2\pi}{T_i} + \phi_i\right) \text{ at}$$
$$\xi = 1 \quad \ldots\ldots (20)$$

Western boundary

$$v + \left(\frac{g}{h}\right)^{\frac{1}{2}}\zeta = 0 \text{ at } y = 0. \quad \ldots\ldots (21)$$

Eastern boundary

$$v - \left(\frac{g}{h}\right)^{\frac{1}{2}}\zeta = 0 \text{ at } y = 1. \quad \ldots\ldots (22)$$

3.2. Numerical experiment

The numerical experiments were carried out for the cyclonic storm (CS) April 1991 with several different tracks as investigated information about the cyclone is relatively more. The transformed Eqs. (15)-(17) as well as the concerned BCs given by Eqs. (20)-(22) are solved by a conditionally stable semi-implicit

FDM (forward in time and centered in space) with the help of a structured Arakawa C-grid. C_f and C_D equal to the generally accepted value of 0.0026 and 0.0028, respectively (see Paul et al. 2016). Some parameters involved in the present study have been assumed to have their standard values, namely $g = 9.8ms^{-2}$, $\rho = 1025\text{kg}m^{-3}$, $\rho_a = 1.226\text{kg}m^{-3}$, $\Omega = 0.0174532s^{-1}$. The initial values of ζ, u and v are taken as zero to represent a cold start, such an assumption is supported by Zhang *et al.*, (2007). A time step of 10 s ensured CFL (Courant–Friedrichs–Lewy) criterion of stability.

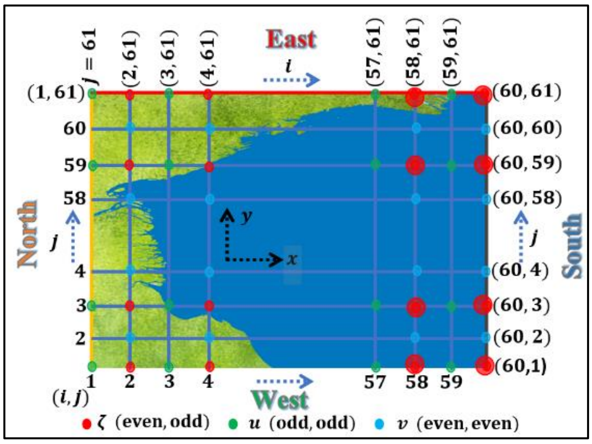


Fig 3: Discretization of the physical domain

Table 1: Time series of the CS April 1991 (Source: BMD, Paul *et al.*, 2016)

Date (1991)	Hour (UTC)	Latitude (°N)	Longitude (°E)	Central pressure (mb)	Nature of the storm
26 April	1800	11.80	87.50	996.00	Cyclonic storm
27 April	0300	12.50	87.50	996.00	Cyclonic storm
27 April	0600	13.00	87.50	996.00	Cyclonic storm
27 April	0900	13.60	87.50	990.00	Severe cyclonic storm
27 April	1800	14.50	87.50	938.00	Severe cyclonic storm with hurricane core
28 April	0600	15.80	87.70	938.00	Severe cyclonic storm with hurricane core
28 April	0800	16.50	88.00	938.00	Severe cyclonic storm with hurricane core
28 April	1800	17.60	88.30	938.00	Severe cyclonic storm with hurricane core
29 April	0600	19.80	89.40	938.00	Severe cyclonic storm with hurricane core
29 April	1200	20.80	90.40	938.00	Severe cyclonic storm with hurricane core
29 April	1800	22.00	91.40	938.00	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 radius of sustained wind: 50 km

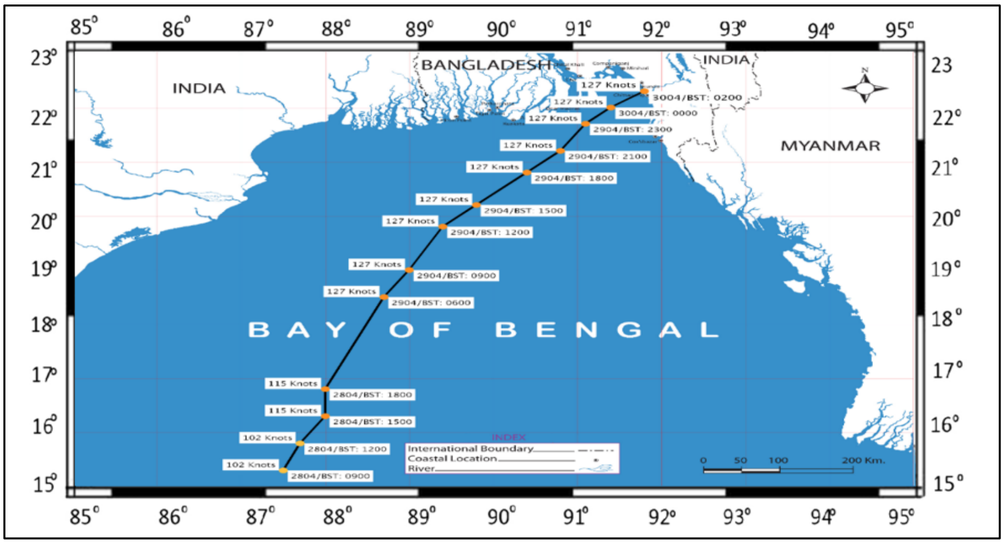


Fig 4: The track and intensity of the cyclone 1991, according to the Saffir–Simpson scale (Data source: BMD and IMD)

4. Analysis of results and model verification

The analysis of the model simulated results has been made for the CS April 1991. Our numerical results with the CS April 1991 are presented at some representative stations along the COB, namely Hiron Point, Kuakata, Patharghata, Rangabali, Tiger Point, Char Chenga, Char Jabbar, Char Madras, Companigonj, Chitalkhali, Sandwip, Bashkhali, Cox's Bazar, Chittagong, Moheshkhali, Mirshari, Shitakunda. The results were calculated for 80 h from 1800 UTC April 26 to 0200 UTC April 30, and they were presented from 0200 UTC 28 April to 0200 UTC 30 April for a better perspective. Our model simulated temporal variation of water levels with a view to surge only associated with the under taken storm at some stations are displayed in Fig 5. The results in this regard agree well with those presented in Paul (2013). Fig 6 displays our computed time variation of sea levels to the dynamical interaction of surge with tide at ten stations.

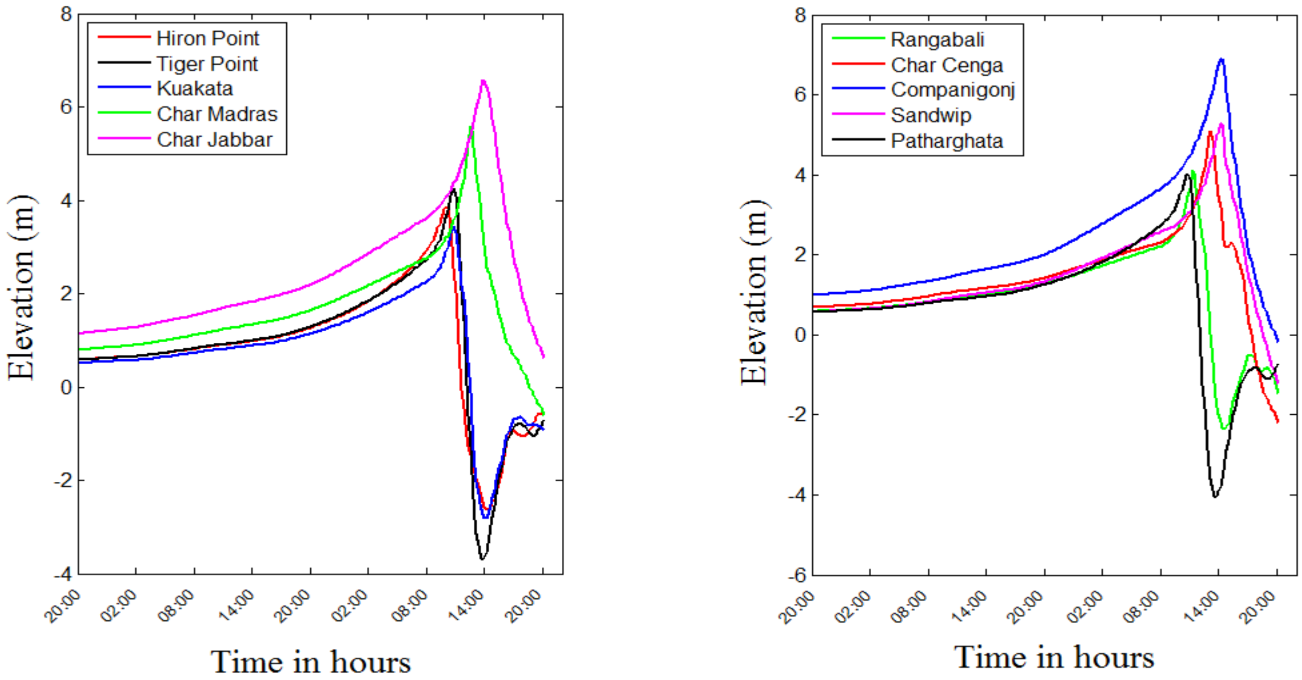


Figure 5: Our estimated water levels refer to the mean sea level (MSL) due to surge only associated with the CS April 1991 along the COB

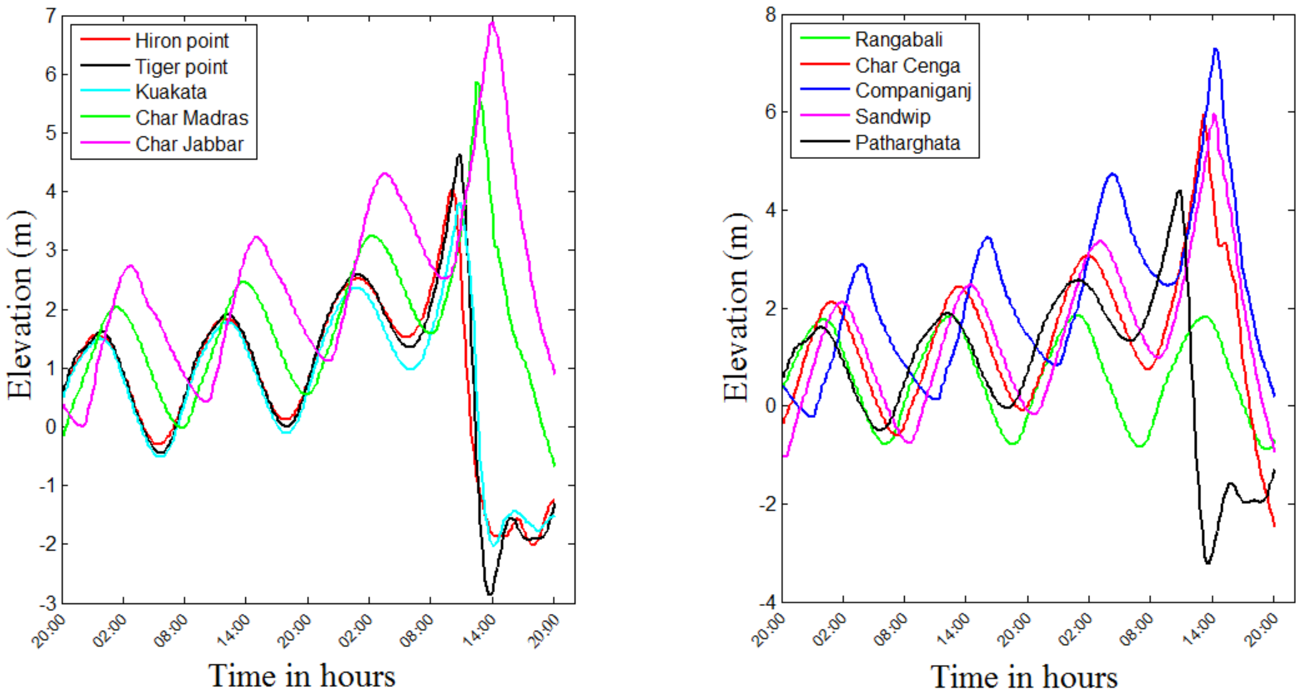


Figure 6: Time varying of water levels with refer to the MSL as a result of surge, tide and their dynamical interaction associated with the storm April 1991 along the COB

Fig 7 depicts water levels owing to tide surge interaction with observed data procured from the BIWTA at Hiron point, Chittagong and Char Chenga. However, our estimated water levels at these two stations match well with the observed data. It is to be mentioned here that the simulation was made with the input used in Paul (2013).

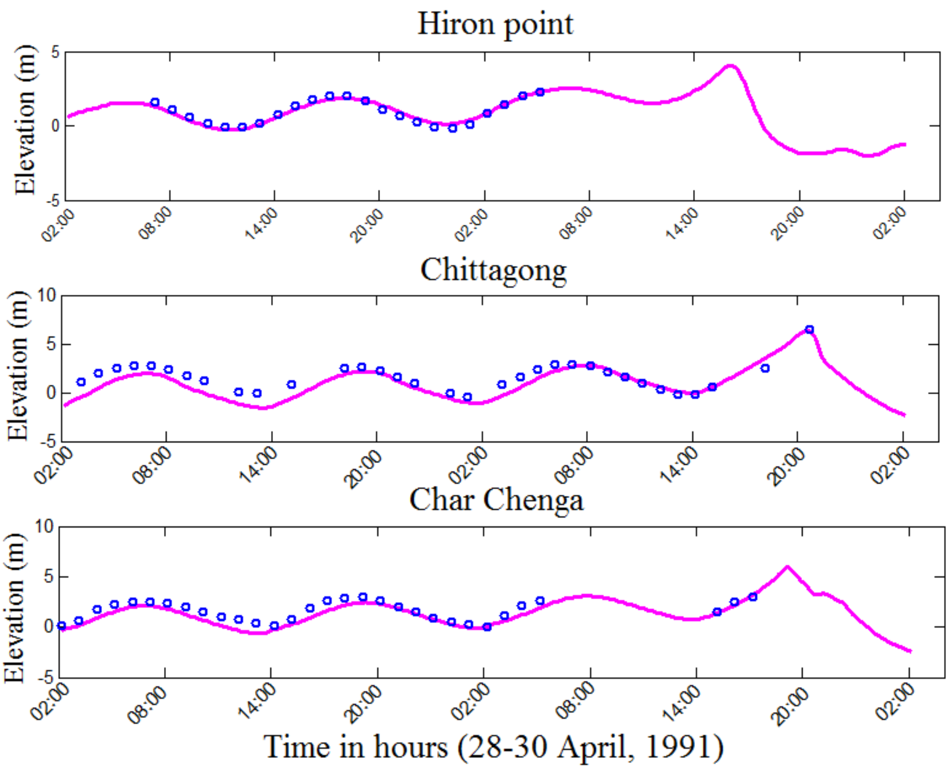


Figure 7: Comparison of the model simulated outputs with the observed data. Here the MSLs were adjusted following the study due to Paul and Ismail (2013)

5. Effects of tracks on water levels

In this study, we have considered several tracks namely, T_1, T_2, T_3, T_4. The tracks are presented through Figs 8-11. The figures are made with our developed MATLAB routine choosing the mentioned hypothetical tracks. The following figures shows water levels owing to tide-surge interaction with the consideration of the chosen storm tracks.

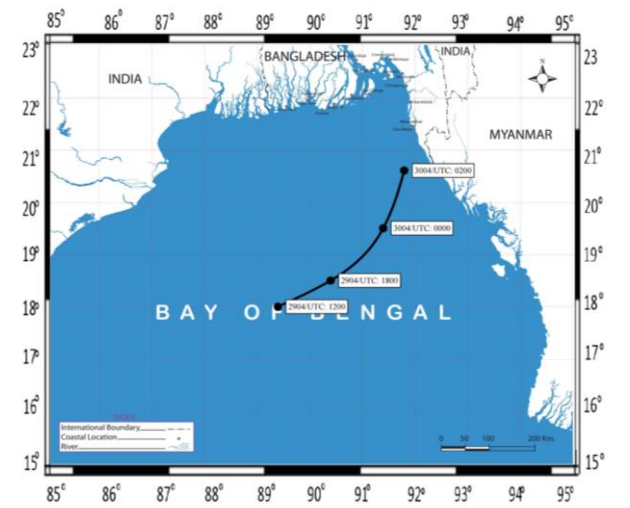


Fig 8: T1

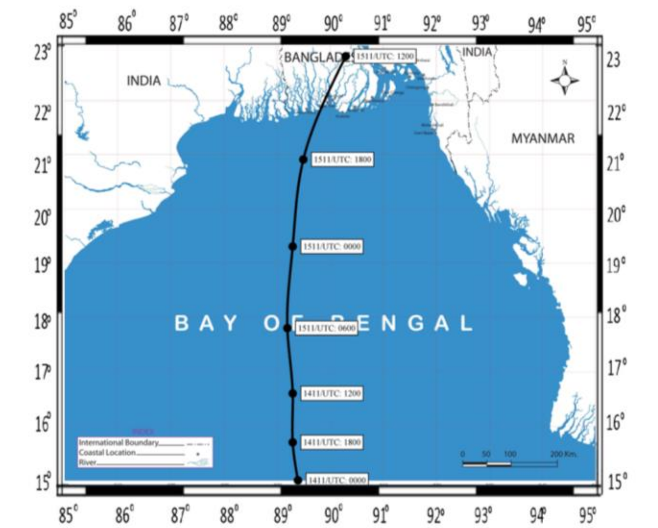


Fig 9: T2

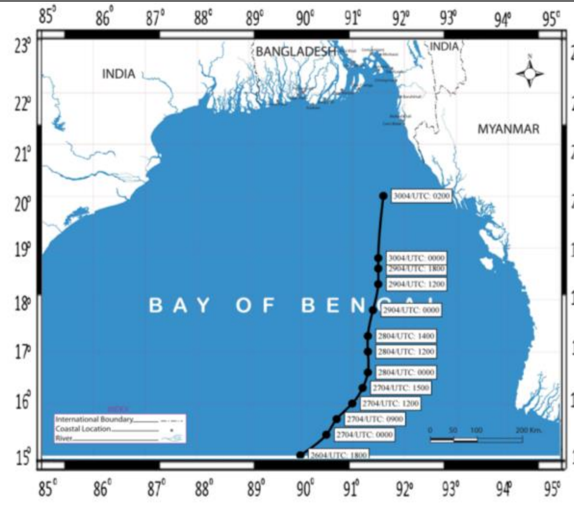


Fig 10: T3

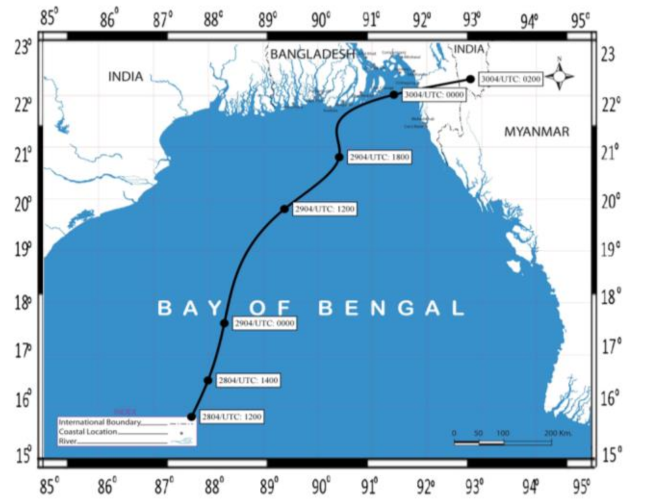
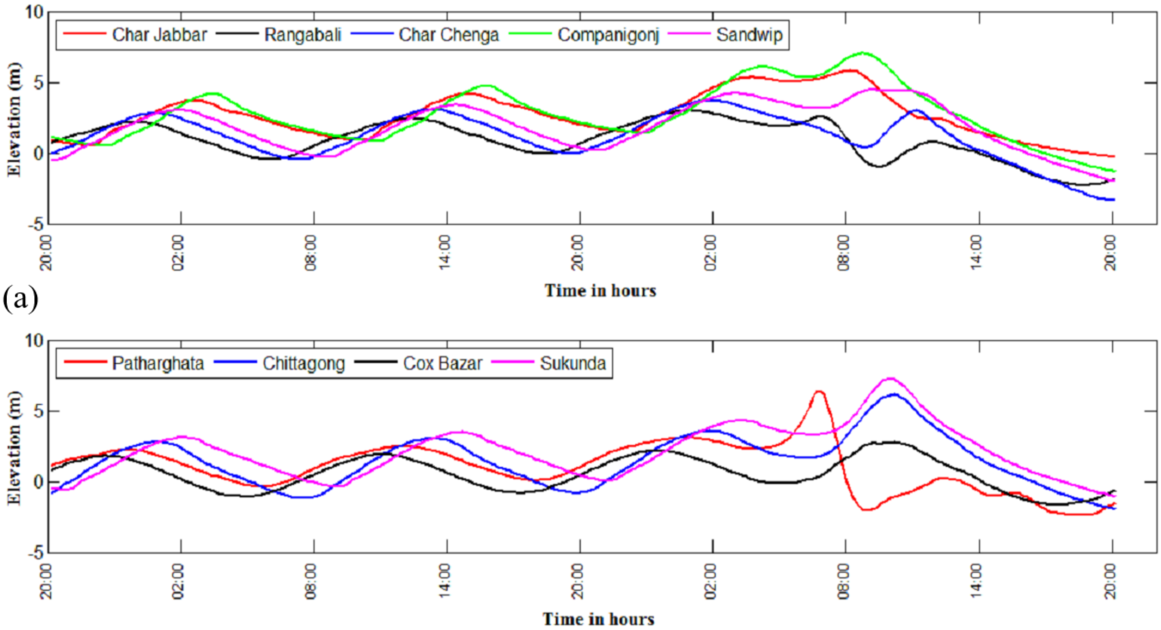
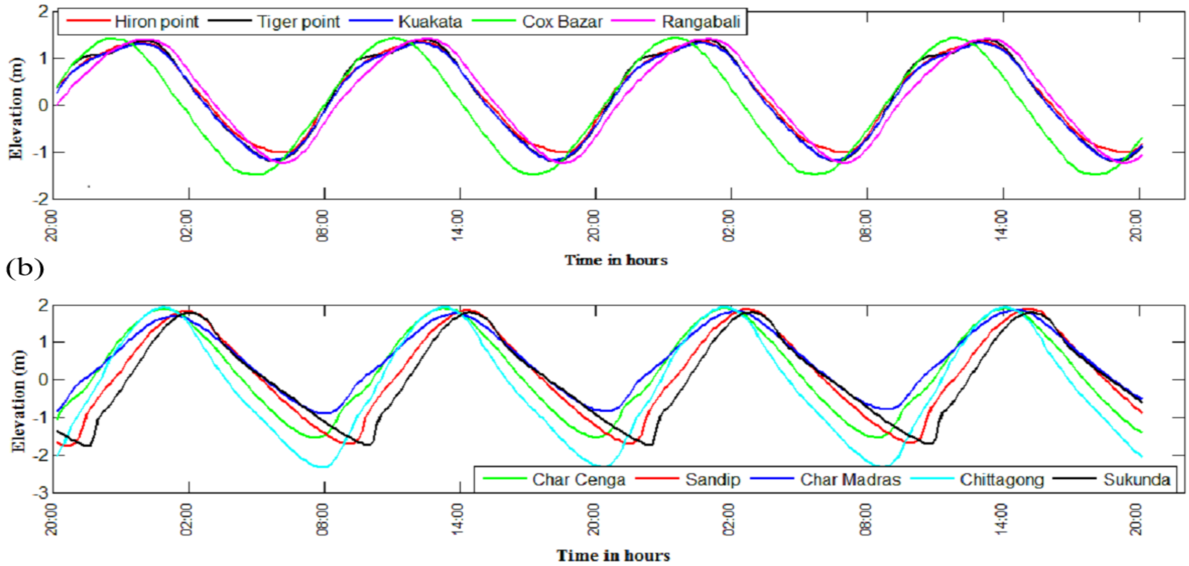


Fig 11: T4



(a)



(b)

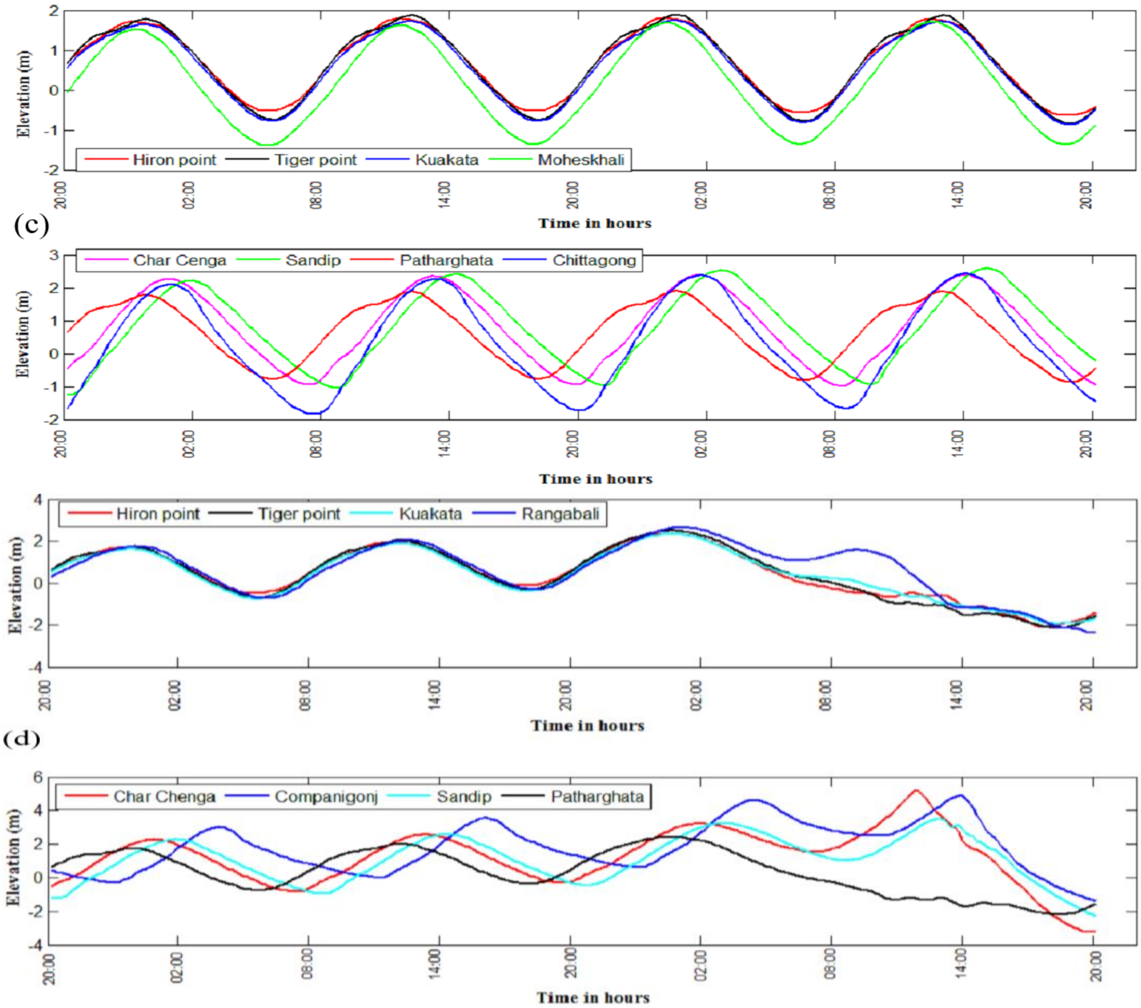


Fig 12: (a), (b), (c), (d) represents time variation of peak water levels due to tide-surge interaction at some locations along the COB with refer to the hypothetical tracks T_1, T_2, T_3 and T_4

To get a better understanding on water levels due to tide surge interaction calculated from the aforementioned tracks, a bar diagram is attached below:

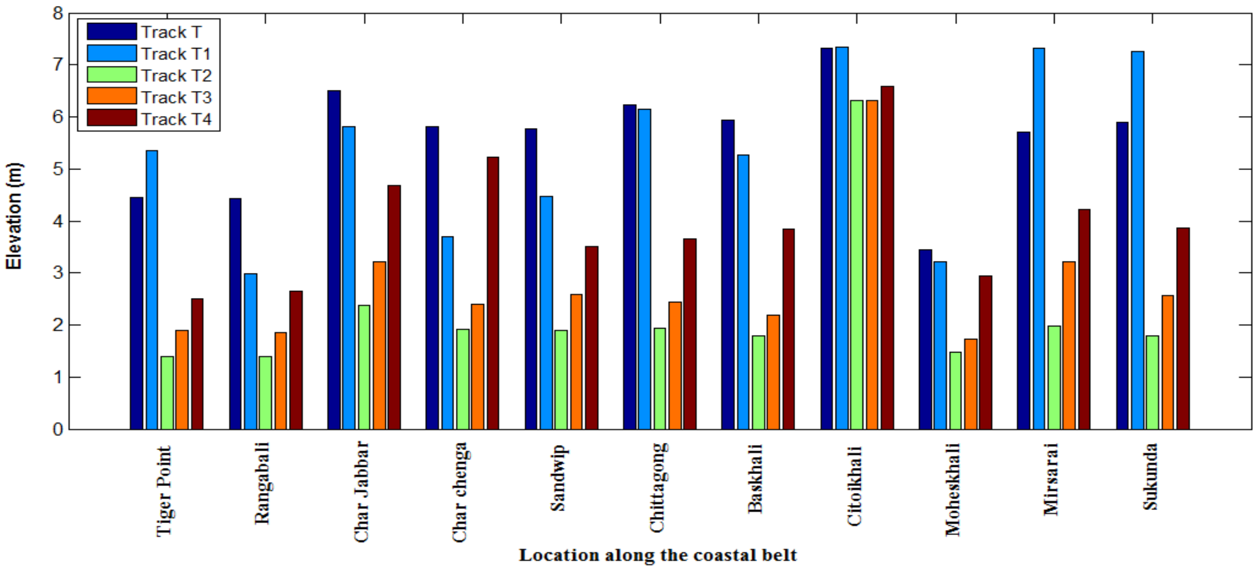


Fig 13: Peak water levels due to tide-surge interaction with refer to the four hypothetical tracks (T_1, T_2, T_3 T_4) along with the base track (T)

From the geographical representation, we observe that due to change in tracks, the elevations of water levels owing to the interaction of tide and surge greatly differ. That is water levels due to the dynamical interaction of surge with tide for the hypothetical tracks vary in heights over the real track in spite of having the same cyclonic inputs.

6. CONCLUSION

In this study, the effects of tracks on water levels associated with a storm are investigated. Water levels are seemed to be influenced by the tracks for the area of interest besides the other surge influencing factors. On the basis of the study, it can be concluded that for the prediction of optimal elevation of sea surface along the coast of Bangladesh, the surge levels influencing factors should accurately be taken into account. Therefore, in getting better results on storm surge simulation, cyclone tracks must be predicted in a better way

Conflict of interest: The authors declare that there is no conflict of interest concerning the publication of the paper.

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