Simulation of storm surge associated with cyclones land falling Bangladesh coast

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ABSTRACT. This paper describes the basic features of storm surge phenomena using Indian Institute of Technology (IIT) model (installed at Bangladesh Meteorological Department) for the Bay of Bengal. To capture the storm surge scenarios, after the entrance of the cyclone into the northern part of the Bay of Bengal, high resolution IIT model has been used. The analysis area is from 18° N to 23° N and 83.5° E to 94.5° E. Bathymetric data required for the model has been taken from Royal Admiralty Table andETOPO2 dataset. In this paper, various scenarios of storm surges are developed and then investigated for varying input parameter values. This paper also examines the time-series of surges at the fixed landfall point by using the data of three severe cyclonic storms when the cyclone approaches the landfall point.

Key words – Storm surge, ETOPO2 dataset, Sea surface, Staggered grid system.

1. Introduction

Bangladesh, situated at the northern tip of the Bay of Bengal, is frequently visited by natural disasters such as tropical cyclones, storm surges, floods, droughts and tornadoes. Of these, tropical cyclone originating in the Bay of Bengal and associated storm surges are the most disastrous. When the tropical cyclones pass over the continental shelf, there is a sudden rise in the sea level due to pressure gradients and very strong surface winds. This abnormal rise in sea level, which reaches a maximum on the coast, normally at the time of the landfall of the cyclone is called storm surge. Both tropical storms and the associated surges cause tremendous devastation when they cross the coast and therefore, the destruction caused by storm surges is of serious concern along the Bangladesh coastline. About 60% of all deaths due to storm surges have occurred in the low-lying coastal areas of the countries bordering the Bay of Bengal and the Arabian Sea (Dube et al., 1997). According to Frank and Hossain (1971) about 90% of marine fishermen suffered casualties and about 65% of total annual fishing capacity
Figs. 1(a-d). Simulated surge scenarios for 10 m, 50 m, 100 m and shallow uniform depths

In the present study, using IIT model a number of experiments is performed to provide full-insight of the storm surge phenomena. Analysis on the time series of surge at a point near land fall for three cyclones was also studied in order to evaluate the storm surge model.

2. Storm Surge Model

2.1. Basic equation

The details about the formulation and development of model equations are given by Johns et al., (1981). Final predictive equations as developed by the authors are

\[
\begin{align*}
\frac{\partial \zeta}{\partial t} + \frac{\partial \tilde{u}}{\partial x} + \frac{\partial \tilde{v}}{\partial y} &= 0 \\
\frac{\partial \tilde{u}}{\partial t} + \frac{\partial \tilde{u}}{\partial x} (\tilde{u} - \tilde{v}) + \frac{\partial \tilde{v}}{\partial y} - f \tilde{v} &= -g(\zeta + h) \frac{\partial \zeta}{\partial x} - \frac{1}{\rho} (\zeta + h) \frac{\partial p_a}{\partial x} + \frac{F_x}{\rho} \\
&- \frac{c_f \tilde{u}}{(\zeta + h)} (u^2 + v^2)^{1/2}
\end{align*}
\]
\[
\frac{\partial \tilde{v}}{\partial t} + \frac{\partial}{\partial x}(u \tilde{v}) + \frac{\partial}{\partial y}(v \tilde{v}) + f \tilde{u} = -g(\zeta + h) \frac{\partial}{\partial y} \left( \frac{1}{\rho} (\zeta + h) \frac{\partial p_a}{\partial y} + G_s \right) - \frac{c_f}{(\zeta + h)} \left( u^2 + v^2 \right)^{1/2}
\]

where \( \tilde{u} = (\zeta + h) u \) and \( \tilde{v} = (\zeta + h) v \) are prognostic variables, and \( c_f \) is an empirical bottom friction coefficient. The forcing terms in these three equations are Coriolis’s terms, the inverted barometric effect i.e., \( \frac{\partial p_a}{\partial x} \) and \( \frac{\partial p_a}{\partial y} \) due to fall in atmospheric pressure and the component of wind stress \( (F_s, G_s) \).

### 2.2. Boundary condition

The only boundary condition needed in the vertically integrated system is that the normal transport vanishes at the coast i.e.,

\[
u \cos \alpha + v \sin \alpha = 0 \quad \text{for all } t \geq 0
\]

where \( \alpha \) denotes the inclination of the outward directed normal to the \( x \)-axis.

At the open-sea boundary, a radiation type of condition, Heaps (1973), may be applied which leads to

\[
u \cos \alpha + v \sin \alpha + \left( \frac{\rho g}{h} \right)^{1/2} \zeta = 0
\]

### 2.3. Determination of forcing functions

The surge is generated by an idealized cyclone of constant strength, tracking across the analysis area with constant speed. In view of the strong associated winds and consequently high values of the wind stress forcing, the forcing due to barometric changes \( \left( i.e., \frac{\partial p_a}{\partial x} \text{ and } \frac{\partial p_a}{\partial y} \right) \) may be neglected in the surge prediction models. The wind field is generated by various empirical formulae. For the Bay of Bengal region most frequently used formula is due to Jelesnianski (1965),

\[
V' = \left\{ \begin{array}{ll}
V_m (r/R)^{3/2} & \text{for all } r < R \\
V_m (r/R)^{1/2} & \text{for all } r \geq R
\end{array} \right.
\]

where \( V_m = C(\Delta P)^{1/2} \), the maximum wind at the distance of radius of maximum sustained wind \( R \).

With the surface winds estimated one can proceed to the computation of the stress at the sea surface. The surface stress is computed by the conventional quadratic law as

\[
\begin{align*}
F_s &= \rho_a C_D u_a (u_a^2 + v_a^2)^{1/2} \\
G_s &= \rho_a C_D v_a (u_a^2 + v_a^2)^{1/2}
\end{align*}
\]

where \( u_a \) and \( v_a \) are the \( x \) and \( y \) components of surface winds, \( C_D \) is the drag co-efficient.

### 2.4. Formulation of the model

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 (Johns et al., 1981).

### 3. Results and discussion

#### 3.1. Effect of bathymetry on storm surge amplitude

In order to study the effect of bathymetry on storm surge amplitude the model was run for four different uniform depths which are 10 m, 50 m and 100 m. The simulated surge heights were 6 m, 3 m and 1.4 m for these uniform depths respectively. Thus it is seen that surge height decreases by increasing depth. Figs. 1(a-c) depict the simulated surge scenarios for 10 m, 50 m, and 100 m uniform depths. In another experiment we computed the surge by taking shallow coastal water and actual depth of the basin elsewhere. The computed surge in this case was 5 m as shown in Fig. 1(d).
3.2. Effect of cyclone landfall angle on storm surge

The cyclones of similar intensity generate surges of different amplitudes depending upon the angle of landfall at a particular location. To analyze the result, the model was run with idealized cyclones land falling from different angles in a basin of uniform depth. The same landfall point was used in three cases. Figs. 2 (a-c) depicts the storm surge scenarios for different tracks. Simulated storm
surge heights were found to be 7.2 m, 7.95 m and 7.96 m in the case of southerly, normal and northerly tracks respectively.

3.3. Impact of cyclone of same intensity land falling at different locations

It is experienced that the cyclones of same intensity land falling at various locations in the same basin generates surges of varying amplitude. To analyze this, the three experiments were performed for different tracks of same intensity of cyclone. The model was run with same starting position at 17.5° N and 90.0° E for three experiments. The model was integrated for 24 hours for all cases. The speed of wind and the radius of maximum winds were 55 ms\(^{-1}\) and 74 km respectively. Figs. 3(a–c) depict the storm surge scenarios for three different landfall points. In Fig. 3(a), the landfall point was Meghna Estuary (22.7° N and 92.0° E) and peak surge was 6.2 m. In this case some surges occurred on the left side of the track due to the conical (so called funneling) effect of coastal geometry. In Fig. 3 (b), the landfall point was Cox’s Bazar (21.5° N and 92.8° E) and peak surge was 5.5 m. In Fig. 3 (c), the landfall point was near Akyab (20.0° N and 93.5° E) and peak surge was 4 m that occurred close to the landfall point.

3.4. Analysis on the time series of surge at a point near landfall

Time series of surges due to cyclone of 12 November 1970 is shown in Fig. 4(a). In this case the landfall position was taken at latitude 22.7° N and longitude 90.6° E (Bhola coast). It may be seen from the Figure that storm surge height increases with time \(i.e.,\) with the approach of cyclone towards the coast. After 30 hours the storm surge height was found highest it occurred when the cyclone crossed the landfall point. After crossing the coast (landfall point), it is seen that the surge height decreases. Fig. 4 (b) depicts the time series of surges due to cyclone of 29 April 1991 and it is seen that the peak surge occurred after 24 hours. In this case the landfall point was taken at latitude 22.7° N and longitude 91.4° E (Chittagong). Fig. 4(c) depicts the time series of surges for the cyclone of September 1997. In this case, the landfall point was taken at Sandwip with position 22.8° N and 91.5° E where maximum surge occurred after 36 hours.
4. Conclusion

In this study, IIT model has been used effectively for simulating the storm surge along the coast of Bangladesh. Model incorporates detailed oceanographic, meteorological and geomorphologic data of the head Bay of Bengal. Since storm surge is sensitive to bathymetric data on the continental shelf, it is expected that IIT model will perform better once very high resolution bathymetry is incorporated.

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