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Simulation of storm surge associated with cyclones land falling Bangladesh coast

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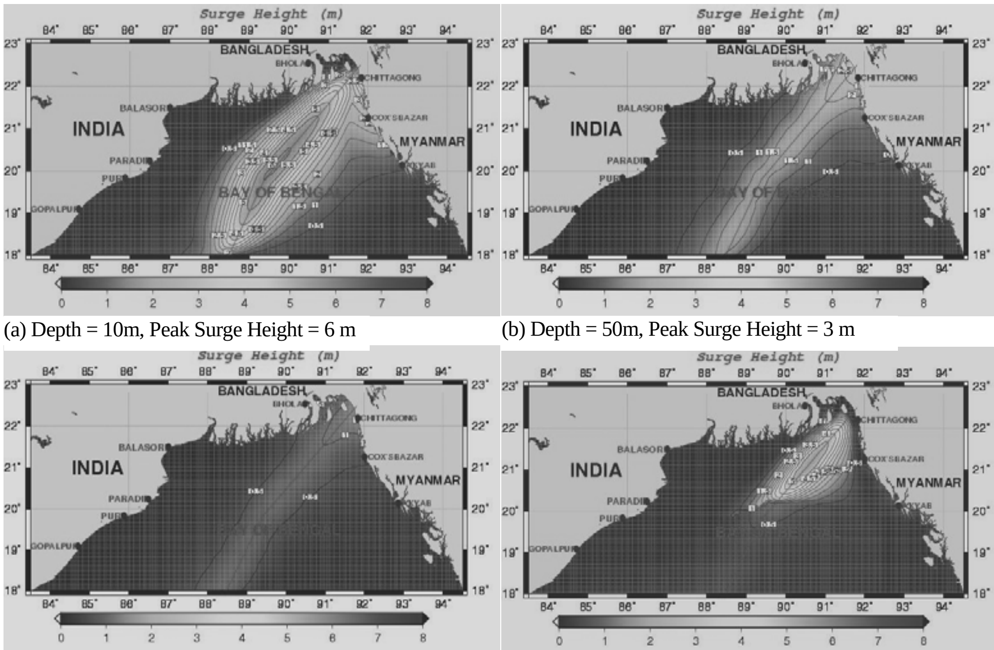
सार – इस शोध–पत्र में बंगाल की खाड़ी में भारतीय प्रौद्योगिकी संस्थान (आई. आई. टी.) के निदर्श (बंगलादेश मौसम विज्ञान विभाग में स्थापित) का उपयोग करते हुए तूफान महोर्मि परिघटना के आधारभूत लक्षणों का उल्लेख किया गया है। बंगाल की खाड़ी के उत्तरी भाग में चक्रवात के प्रवेश करने के पश्चात् तूफान महोर्मि के दृश्यलेखों को पर्याप्त करने के लिए उच्च्च विभेदन के आई.आई.टी. के निदर्श का उपयोग किया गया है। विशलेषण का यह क्षेत्र 18° उत्तर से 23° उत्तर और 83.5° पूर्व से 94.5° पूर्व तक है। इस निदर्श के लिए रॉयल एडमिरेलिटी सारणी और ई. टी. ओ. पी. ओ. 2 आकड़ा सैटों से अपेक्षित बेथेमीट्रिक आँकड़े लिये गए है। इस शोध–पत्र में तूफान महोर्मियों के विभिन्न दृश्यलेखों को विकसित किया गया और तत्पश्चात परिवर्ती इनपुट प्राचल मानों के लिए इनकी जाँच की गई। इस शोध–पत्र में थल प्रवेश बिंदु की तरफ चक्रवात के आगे बढ़ने के समय तीन प्रचंड़ चक्रवाती तूफानों के आँकड़ों का उपयोग करते हुए निर्धारित थल प्रवेश बिंदु पर महोर्मियों की समयबद्ध श्रंखलाओं की भी जाँच की गई है।

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 and ETOPO2 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



(a) Depth = 10m, Peak Surge Height = 6 m

(b) Depth = 50m, Peak Surge Height = 3 m

(c) Depth = 100m, Peak Surge Height = 1.4 m

(d) Shallow depth, Peak Surge Height = 5m

Figs. 1(a-d). Simulated surge scenarios for 10 m, 50 m, 100 m and shallow uniform depths

of coastal areas were destroyed in cyclone of 12 Nov. 1970. Thus the development of numerical storm surge prediction system is of great concern to Bangladesh and its neighborhood.

Numerical storm surge prediction models have been developed for several coastal regions of the world by different workers. Chittibabu (1999) developed storm surge prediction models for the Bay of Bengal and the Arabian Sea. Das *et al.,* (1983), Dube *et al.,* (1981, 1982, 1985, 1986), Dube and Rao (1989, 1991) have developed several numerical models to simulate surge associated with cyclones hitting east and west coast of India and Bangladesh. Dube *et al*., (1981, 1982) also studied in detail the effect of coastal geometry and wind stress forcing on storm surges. Flather and Khandekar (1993), Flather (1994), Henry *et al.,* (1997), Roy (1995), Roy and Hussain (2001) developed several models to simulate the surges associated with several severe cyclonic storms hitting the coast of Bangladesh. Sinha *et al.,* (1984, 1997) developed numerical model to simulate storm surges and sea level rise in the Indian coasts adjacent to the Bay of Bengal and the Arabian sea. Debsarma (2003) visualized the May 1997 storm surge by using High Resolution IIT model.

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

$$\frac{\partial \zeta}{\partial t} + \frac{\partial \tilde{u}}{\partial x} + \frac{\partial \tilde{v}}{\partial y} = 0 \tag{1}$$

$$\frac{\partial \tilde{u}}{\partial t} + \frac{\partial}{\partial x}(u\tilde{u}) + \frac{\partial}{\partial y}(v\tilde{u}) - f\tilde{v} = -g(\zeta + h)\frac{\partial \zeta}{\partial x} - \frac{1}{\rho}(\zeta + h)\frac{\partial p_a}{\partial x} + \frac{F_s}{\rho} - \frac{c_f \tilde{u}}{(\zeta + h)}(u^2 + v^2)^{1/2} \tag{2}$$

$$\frac{\partial \tilde{v}}{\partial t}+\frac{\partial}{\partial x}(u\tilde{v})+\frac{\partial}{\partial y}(v\tilde{v})+f\tilde{u}$$
$$=-g(\zeta+h)\frac{\partial \zeta}{\partial y}-\frac{1}{\rho}(\zeta+h)\frac{\partial p_a}{\partial y}+\frac{G_s}{\rho}$$
$$-\frac{c_f\tilde{v}}{(\zeta+h)}(u^2+v^2)^{1/2} \quad (3)$$

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 Corioli'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.*,

$$u\cos\alpha + v\sin\alpha = 0 \quad \text{for all } t\geq 0 \quad (4)$$

where α 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

$$u\cos\alpha + v\sin\alpha + \left(\frac{g}{h}\right)^{1/2}\zeta = 0 \quad (5)$$

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),

$$V = \begin{cases} V_m (r/R)^{3/2} & \text{for all } r < R \\ V_m (r/R)^{1/2} & \text{for all } r \geq R \end{cases} \quad (6)$$

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

$$\begin{cases} F_s = \rho_a\, C_D\, u_a\, (u_a^2+v_a^2)^{1/2} \\ G_s = \rho_a\, C_D\, v_a\, (u_a^2+v_a^2)^{1/2} \end{cases} \quad (7)$$

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

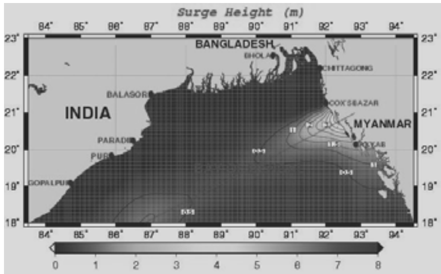
2.4. *Formulation of the model*

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).

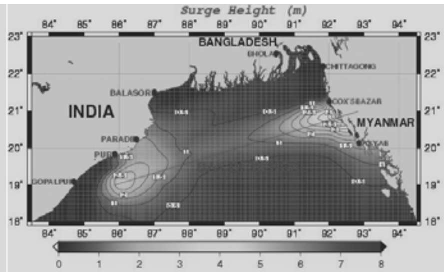
3. Results and discussion

3.1. *Effect of bathymetry on storm surge amplitude*

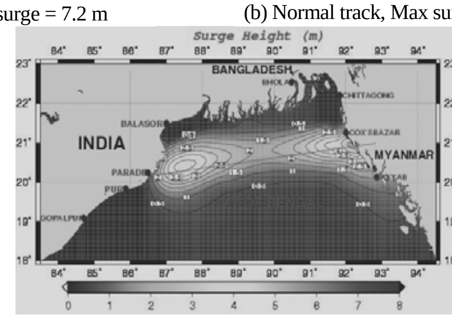
In order to study the effect of bathymetry on storm surge amplitude the model was run for four different uniform depths which are 10 m, 50 m and 100 m. The simulated surge heights were 6 m, 3 m and 1.4 m for these uniform depths respectively. Thus it is seen that surge height decreases by increasing 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 5m as shown in Fig. 1(d).



(a) Southerly track, Max surge = 7.2 m

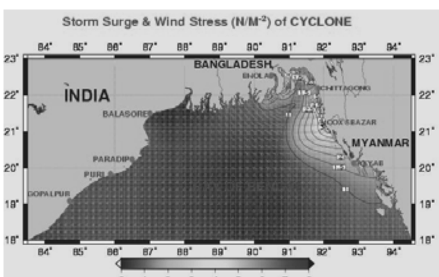


(b) Normal track, Max surge = 7.95 m

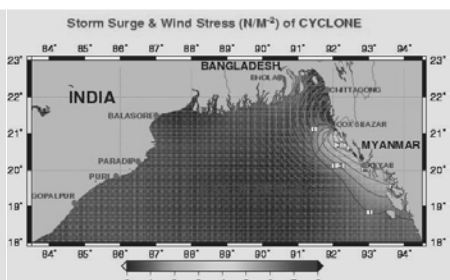


(c) Northerly track, Max surge = 7.96 m

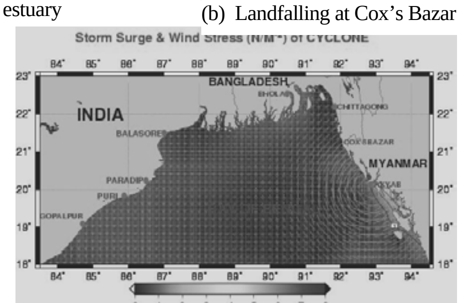
Figs. 2(a-c). Storm surge scenarios for different track but of same landfall point



(a) Landfalling near Meghna estuary



(b) Landfalling at Cox's Bazar

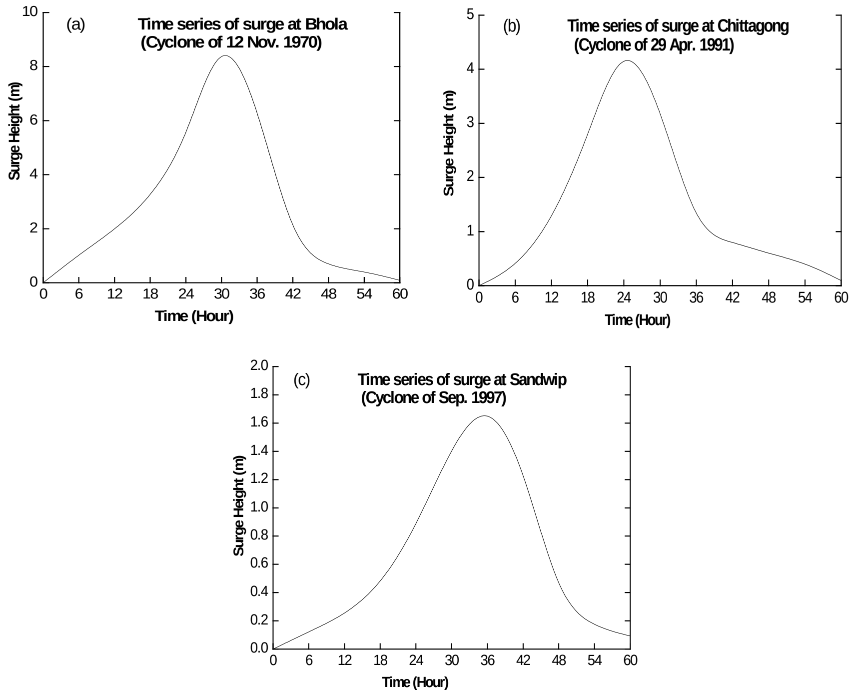


(c) Landfalling near Akyab

Figs. 3 (a-c). Storm surge scenarios for different directions of a cyclone but of same intensity

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



Figs. 4(a-c). Time series of surges at (a) Bhola (b) Chittagong and (c) Sandwip

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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