Coastal Trapping and Funneling Effects on Storm Surges in the Meghna Estuary in Relation to Cyclones Hitting Noakhali–Cox’s Bazar Coast of Bangladesh

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ABSTRACT

Studies are described that use a fine-resolution numerical model and incorporate the islands and detailed bottom topography of the Meghna estuary. They show that depending on the characteristics of the atmospheric cyclone and the astronomical tide, storm surges can be coastal trapped in the Meghna estuary and propagate like edge waves along the coastline causing widespread devastation and enormous loss of life and property. The funneling effect of the narrowing estuary acts strongly on the pressure response and predominantly in the region north of Sandwip Island. The combination of coastal trapping and the funneling effect results in the widespread nature of the surges in the Meghna estuary. The widespread nature of the surges is directly proportional to the wind inflow angle and to the radius of maximum cyclonic wind, but inversely proportional to the angle of crossing of the cyclone as made with the coastline. The cyclone striking the Noakhali–Chittagong coast produces more widespread surges than does a cyclone striking the Chittagong–Cox’s Bazar coast. A rapidly moving cyclone drives the surges toward the northern coast. If a cyclone strikes during the ebb tide phase, then nonlinear tide–surge interaction also generates separate surges far to the west in the Khepupara region.

1. Introduction

In earlier studies of storm surges in the Bay of Bengal, the impact on the Meghna estuary and islands was not treated with due importance. Murty et al. (1986) recommended that the bottom topographic details should be incorporated in the storm surge models of the Meghna estuary and stated that, “To represent in detail the real complexities would require very high resolution.” Yamashita (1993) simulated the 1991 cyclone without considering the “Swatch-of-No-Ground (SNG),” which is a deep ocean gully near the coast (Fig. 1). As-Salek and Yasuda (1995) reported that SNG affects tidal propagation and line discharges. Flather (1994) developed a model with a 10-km grid, regarding that he maintained “The basic model-grid should also be refined, perhaps by a factor of three in the NE of the bay.” Large differences in surge peaks from two adjacent areas necessitate finer grid spacing in the estuary (As-Salek and Yasuda 1995). The present study selects a (1/120)⁶ (0.83 km) resolution model (As-Salek 1994), which takes into consideration the islands as well as topographic features of the bay, two-dimensional treatment for the Meghna River with real bottom topography, and the actual river bed to 35 km from the mouth of the river. The validity of the model was verified (As-Salek 1994; As-Salek and Yasuda 1995) with the observed data of the Bangladesh Department of Hydrography (1991) and with those of the Surface Water Modelling Center (1991). The present study uses a model with additional coastline resolution and more tidal components in the open boundary condition.

In any effort aimed to prevent colossal damages, it is vitally necessary to predict the nature of the storm surges developing in the Meghna estuary. Uncertainty in the resultant surge relative to the standard level of warning issued was identified by the United Nation’s Centre for Regional Development (Hoque 1991) and also by a Japanese team (Katsura et al. 1992) as one of the main reasons behind the colossal loss of life during the 1991 cyclone. For the same signal level number 10 (expressing the greatest danger) issued by the Bangladesh Meteorological Department, the resultant surges were different on separate occasions. Hoque (1991, p. 83) maintained that “For those who had experienced previous cyclones in the area, previous signal 10 storm warnings were associated with some flooding at a level not much above normal; thus, special behavior was not required.” The same was restated by Takahashi (1991, p. 103) indicating the urgent need for studying the causes for the widespread surges. Based on past observations and also from published data (e.g., Murty et al. 1986; Khalil 1992), the same surge level (produced near landfall) showed a localized nature on one occasion and widespread nature on another. Thus, it is extremely im-
important to know when, and under what circumstances, the surges will be confined locally and when they will propagate a long distance.

Again, the triangular shape of the bay indicates the possible occurrence of the funneling effect. But where, when, and how this funneling effect becomes more active, the nature of its contribution to the surge development, and the factors involved in the above two phenomena have not been investigated so far.

The present study investigates the emergence of the widespread storm surges for various cyclone characteristics and the role of the astronomical tide in determining its widespread nature. The study examines cyclones that strike the coast from Noakhali to Cox’s Bazar in Bangladesh. These cyclones are considered most dangerous based on their frequency (Karmakar 1992) and the extent of devastation (Murty et al. 1986). The cyclone that struck Bangladesh, on 29–30 April 1991, is taken as representative, and experiments were performed by changing individual cyclone characteristics within the ranges selected by scientific judgment based on published references and evaluating the effect of those changes to the whole system. The present study found that the surges in the Meghna estuary can be coastal trapped and can propagate as edge waves. The funneling effect particularly amplifies the pressure response and that again predominantly to the north of Sandwip. Coastal trapping and then the propagation of the storm surges along the coastline have been found to be the main factors behind the widespread surges in the Meghna estuary.

2. The model

The numerical model used here to simulate the astronomical tide and storm surges is based on the vertically integrated Navier–Stokes equations of mass and momentum conservation incorporating the assumption of hydrostatic pressure. The continuity equation is

$$\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0. \tag{1}$$

The momentum equations in the $x$ direction and $y$ direction are

$$\frac{\partial M}{\partial t} + U\frac{\partial M}{\partial x} + V\frac{\partial M}{\partial y}$$

$$= -gd\left(\frac{\partial \eta}{\partial x} + \frac{1}{\rho g} \frac{\partial P}{\partial x}\right) + \frac{1}{\rho} (\tau_{xx} - \tau_{yy})$$

$$- \frac{1}{\rho} \left(\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y}\right) + fN \tag{2}$$

$$\frac{\partial N}{\partial t} + U\frac{\partial N}{\partial x} + V\frac{\partial N}{\partial y}$$

$$= -gd\left(\frac{\partial \eta}{\partial y} + \frac{1}{\rho g} \frac{\partial P}{\partial y}\right) + \frac{1}{\rho} (\tau_{yy} - \tau_{xx})$$

$$- \frac{1}{\rho} \left(\frac{\partial \tau_{xx}}{\partial y} + \frac{\partial \tau_{yy}}{\partial x}\right) - fM, \tag{3}$$

in which $t$ is the time, $x$ and $y$ the horizontal coordinates directed east and north respectively, $d$ the total depth.
of water, \( \eta \) the water surface elevation due to the tide and storm surge relative to the still water level, \( P_s \) the atmospheric pressure on the sea surface, \( \rho \) (\( = 1.03 \times 10^3 \) kg m\(^{-3} \)) the sea water density, \( g \) the gravitational acceleration; \( f = 2\omega \sin \psi \) with \( f \)-plane approximation) the Coriolis parameter, \( \omega \) (\( = 7.29 \times 10^{-5} \) rad s\(^{-1} \)) the angular speed of the rotation of the earth, \( \psi \) the latitude, and \( \tau_{x}, \tau_{y}, \tau_{xx}, \tau_{yy} \) the internal shear stresses. Here \( \tau_{xx}, \tau_{yy} \) are the surface wind stresses and \( \tau_{xx}, \tau_{yy} \) the bottom friction stresses expressed as

\[
\tau_{xx} = \rho_a g^2 W_x (W_x^2 + W_y^2)^{1/2},
\]
\[
\tau_{yy} = \rho_a g^2 W_y (W_x^2 + W_y^2)^{1/2},
\]
\[
\tau_{xx} = \rho C_f U (U^2 + V^2)^{1/2},
\]
\[
\tau_{yy} = \rho C_f V (U^2 + V^2)^{1/2},
\]

where \( W_x \) and \( W_y \) are effective wind speed in the \( x \) and \( y \) directions, \( C_f \) the bottom friction coefficient (\( = 0.001 \sim 0.00048 \)) and \( g^2 = 0.0026 \) the surface drag coefficient. Katsura et al. (1992, p. 83) reported that there is “no hydrodynamical roughness,” that is, low hydrodynamical roughness associated with flooding in the coastal zones of the Meghna estuary. This claim has been confirmed in the present study by the lower value of the calibrated \( C_f \). Further, \( U \) and \( V \) are components of the depth-mean current in the \( x \) and \( y \) directions, respectively. The line discharges \( M \) and \( N \) in the \( x \) and \( y \) direction are \( M = (h + \eta)U \) and \( N = (h + \eta)V \), where \( h \) is the still water depth.

Fujita’s cyclone model (Wadachi 1970) is used here. Assuming concentric circular isobars of pressure, \( P_s(r, t) \), the atmospheric pressure field on the sea surface is expressed by

\[
P_s(r, t) = P_w - \frac{P_0(t)}{\left(1 + (r/r_0)^2 \right)^{1/2}},
\]

in which \( r = (X^2 + Y^2)^{1/2} \) is the distance from the center of the cyclone \((x, y)\) to the point \((x, y)\), \( X = x - x_s, Y = y - y_s, P_w \) the peripheral pressure, \( P_0(t) \) the central pressure dependent on time, and \( r_0 \) the radius of maximum cyclostropic wind. Under the assumption of a non-anomalous flow of air, the gradient wind speed at sea surface in the \( x \) and \( y \) directions, \( G_x \) and \( G_y \), are expressed as

\[
G_x = -(Y \cos \theta + X \sin \theta) \times \left\{ \left[ \frac{f^2}{4} + \frac{\rho}{\rho_a} g P_0 \left( \frac{r_0}{r_0^2 + r^2} \right)^{1/2} \right] - \frac{f}{2} \right\},
\]
\[
G_y = (X \cos \theta - Y \sin \theta) \times \left\{ \left[ \frac{f^2}{4} + \frac{\rho}{\rho_a} g P_0 \left( \frac{r_0}{r_0^2 + r^2} \right)^{1/2} \right] - \frac{f}{2} \right\},
\]

where \( \theta \) is the angle of inclination of the wind with respect to the isobars and \( \rho_a \) (\( = 0.00129 \times 10^3 \) kg m\(^{-3} \)) is the density of air. Here \( F_x \) and \( F_y \) are the translational speeds of the wind field in the \( x \) and \( y \) directions respectively, expressed as

\[
F_x = V_x \exp(-r/n r_i),
\]
\[
F_y = V_y \exp(-r/n r_i),
\]

where \( V_x \) and \( V_y \) are translational speeds of the cyclone and \( r_i \) the initial storm size = \( 5 \times 10^3 \) m. As a result, \( W_x \) and \( W_y \) are formulated by

\[
W_x = C_1 F_x + C_2 G_x,
\]
\[
W_y = C_1 F_y + C_2 G_y,
\]

where \( C_1 \) and \( C_2 \) (\( C_1 = C_2 \) and considered to be 0.95 during landfall) express the reducing effect of the rough sea surface and or land surface on the gradient wind velocity and translational velocity of the cyclone, respectively.

The model domain is bounded by 89°E and 21°N, extends to the coastline, and incorporates the Swatch-of-No-Ground (Fig. 1) and the worst affected islands (Fig. 2). Kumar (1983) compared the response of a shelf model with that of a version extending farther offshore to deep water and obtained little difference in results. Discretizing Eqs. (1), (2), and (3) by the Crank–Nicholson Scheme (Crank and Nicholson 1947), a two-point finite-difference implicit scheme is developed by using the central difference approximation in space for most terms and upwind approximation for the advective acceleration term (details in As-Salek 1994). The ADI method is employed to solve the scheme. The model is stable for the Courant number \( \left( g^{1/2} h^{1/2} \Delta t/\Delta s \right) \leq 1.165 \), in which \( \Delta t \) is the computational time step (\( = 40 \) s) and \( \Delta s \) is the grid spacing.

\( a. \) The boundary and initial conditions

Johns and Lighthill (1992) concluded that “A fixed side-wall model is appropriate in practical applications given the extra computational overheads involved with a moving coastline model.” The water level profiles (i.e., time of arrival, maximum surge, resurgence, and the duration of the surges) with flooding treatment do not qualitatively differ from those reported by Yamashita (1993, pp. 135–151) from his experiments without flooding (Fig. 6c). Thus, the fixed sideline condition is employed for the land boundary and around the islands; that is, the component of current along the outward-directed normal to the coastline is considered zero.

A radiation condition is used at the open boundary of the coarser grid model.

The coupling of the coarser and finer grid models is done according to Johns et al. (1985, 509), who maintained “... the interaction between the parent and nested models is one way. This implies that the parent model drives the nested model but the response in the nested model does not affect that in the parent model.” Here \( M, N, \) and \( \eta \) calculated by the (1/60)° resolution parent...
model (extending to the deep water offshore) are used as the boundary values of \(1/120\)° resolution coupled at 22.18°N in the shallow estuary.

Tidal levels with \(M_2\) (principal lunar), \(S_2\) (principal solar), \(O_1\) (principal lunar diurnal), and \(K_1\) (luni-solar diurnal) components at the open boundary of the coarser-grid model are taken, respectively, from part II, III, V, and IV of Schwiderski (1979; 1981a, b, c). A surge component related to the atmospheric pressure deficit derived from the hydrostatic law is introduced at the open boundary of the coarser-grid model.

The present model uses a nonlinear two-dimensional treatment for the Meghna River with real bottom topography and the actual river bed to 35 km from the mouth of the river. Thus, the present model proves to be good for incorporation of the angle of wind stress, angle of wave propagation, and angle of water current in the Meghna River.

Dube et al. (1986, 97) maintained that “The difference between the predicted maximum surge from BRM1 and BRM2 is insignificant up to a distance of about 35 km from the mouth of the river.” Observed data (Surface Water Modelling Centre 1991) shows that flow in the Meghna River is governed by the oceanic tide (rising and falling of the water level with negative and positive discharge) up to Chandpur station, located 120 km north of the river mouth. Research is needed on the simultaneous prediction of the river discharges. The present study, therefore, considers a no-flow boundary condition (i.e., just like a river with no discharge condition of “BRM2” of Dube et al. 1986; Yamashita 1993) at the upstream boundary of the Meghna River.

Initial condition is “cold start” (e.g., Flather 1994); that is, \(\eta = M = N = 0\) at time \(t = 0\).

b. The data

Bottom topographic data (Figs. 1 and 2) of the present model were compiled from various sources as quoted in Katsura et al. (1992, Fig. 4.6). The observed water level data were procured from the Bangladesh Department of Hydrography (1991) and from the Surface Water Modelling Centre (1991). In the absence of a universal datum and geoid level, these are used as suggested by Flather and Khandker (1987) to adjust the mean water level (MSL). The datum of the observed data is vertically shifted for Sandwip (-2.78 m), Teknaf (-2.08 m), Dasmunia (also known as Dasmina) (-0.88 m), Galachipa (-1.58 m), Khepupara (-1.78 m), Sundarikota (-1.38 m), Chittagong (-2.58 m), and Cox’s Bazar (-2.08 m) to adjust the MSL. This adjustment is again verified by two simulations started from 2 April 1991 and 14 April 1991, which agreed with the observed data.

Sundarikota is surrounded by the “Sundarbans” mangroves. The \(C_f\) for mangroves is calibrated as 0.001 (the highest one within the range described in section 2 above) and the concerned area is identified from the images of the Bangladesh LANDSAT Program (1977).

The tracking paths proposed by the Joint Typhoon Warning Center (1991), Bangladesh Space Research
and Remote Sensing Organization (SPARRSO), and Bangladesh Red Crescent (1991) mutually differ by about 100 km (Katsura et al. 1992; see Fig. 3 here). The tracking time series of JTWC is selected (Fig. 3 and Table 1) that agrees with the local observation of the strike of the cyclone at the time of the local peak tide.

c. Verification of the applicability of the model

First, a stable tidal regime is established in the model after forcing with the astronomical tide for 10 synoptic h. The simulation for astronomical tides is carried out for 60 synoptic h starting from 2 April 1991 and 14 April 1991 (Fig. 4). The synoptic time is chosen as a period free from the influence of storms or cyclones. On the whole, the computed astronomical tides at Teknaf, Cox’s Bazar, Sadarghat (Chittagong), Dasmunia, Galachipa, Khepupara, and Sundarikota stations all agreed well with observed values, and these stations cover almost the entire modeled coastline. The applicability of the present model is thus verified and established.

Figure 5 shows computed and observed total water levels during the 1991 cyclone. Table 2 shows the sources and status of the observed water levels. Continuous observed data for the left side of the cyclone track were procured and these are compared with the computed ones. The computed total water levels during the 1991 surge event agreed fairly well with the observed values. In the computed total water levels of Dasmunia and Galachipa (Fig. 5), the 0.2–0.7 m deficiencies from the observed values are comparable to (and, therefore, may be accounted for by) the amount of runoff (Surface Water Modelling Centre 1991) consequent to the reported rainfall (Katsura et al. 1992), which is, however, beyond the scope of the present study.

3. Coastal trapping and funneling effect in the 1991 surge event

a. Coastal trapping and propagation

The south and east elevations of the total water levels during the 1991 surge event along with the total water level contours and cyclone characteristics for the same instance are depicted (Fig. 6a). From the south-end views (south elevations), the water level during the surge event can be recognized as decaying exponentially seaward from the coastline. In other words, the surges are coastal trapped within a Rossby radius of the coastline. In the east-end views (Fig. 6a), these coastal trapped surges are seen to propagate along the coastline. It took about 4 h for the surge to propagate from the place where it achieved its maximum (i.e., Banskhali at 0025 LST) to a place 100 km north of Banskhali (i.e., at Mirsarai at 0400 LST) in the edge wave pattern. Figure 6b provides south and east elevations of the surge component of the 1991 surge event and the contours of the surge component, the cyclone characteristics in this case remained the same as shown in Fig. 6a. To make sure that no nonlinear effects from the tidal interaction are present, this latter experiment was performed with

<table>
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<th>Date (1991)</th>
<th>Time (GT)</th>
<th>Lat (°N)</th>
<th>Long (°E)</th>
<th>( C_p ) (hPa)</th>
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<td>3</td>
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<td>19.9</td>
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no tidal forcing. Further experiments incorporating tidal forcing, that is, surge residuals from \((\text{tide} + \text{surge}) - (\text{tide only})\), show qualitatively similar results. These experiments also prove that the along coast propagation of coastal-trapped surges in the Meghna estuary is not an effect of the nonlinear coupling of tide with surge.

These results support Johns and Lighthill's (1992) finding that coastal trapping may act to produce a concentration of energy in the edge-wave pattern (in other words, some augmentation of the storm surge amplitude) as it travels along the coast.

The indication of along coast propagation of the surge...
Table 2. Sources and status of observed water levels. All are still water levels. BDH: Bangladesh Dept. of Hydrography, HWL: Highest WL during surge, K: Katsuura et al. (1992), SWMC: Surface Water Modelling Centre, WL: Total water level, *: time of HWL at Cox’s Bazar, Anwara, Chittagong and Sandwip are approx. from local opinion collected by personal visit.

<table>
<thead>
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<th>Station</th>
<th>HWL</th>
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<tr>
<td>Anwara</td>
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</tr>
<tr>
<td>Chittagong</td>
<td>K, p. 52*</td>
<td>BDH</td>
</tr>
<tr>
<td>Cox’s Bazar</td>
<td>K, p. 71*</td>
<td>BDH</td>
</tr>
<tr>
<td>Dasmunia</td>
<td>BDH</td>
<td></td>
</tr>
<tr>
<td>Galachipa</td>
<td>BDH</td>
<td>SWMC</td>
</tr>
<tr>
<td>Khepupara</td>
<td>SWMC, BDH</td>
<td>SWMC</td>
</tr>
<tr>
<td>Sandwip</td>
<td>SWMC*</td>
<td>SWMC</td>
</tr>
<tr>
<td>Sundarikota</td>
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<td></td>
</tr>
</tbody>
</table>

may also be noticed in the simulated results of the 1991 surge from Yamashita (1993), As-Salek (1994), Flather (1994), and Fig. 6. Results from these three different models provide evidence that the surge that developed during landfall of the 1991 cyclone propagated along the coast and appeared in the northern part of the estuary after about 3–4 h.

b. Nature of the funneling effect

1) BACKGROUND

The funneling effect is the amplification of the surge due to concentration of the surge energy confined by a triangularly shaped bay. It is a topographic mechanism, whose relative influence in the Meghna estuary on the surge component from the wind stress and that from the pressure deficit is unknown so far. In the vast area of the triangular bay, the location where the funneling effect is relatively strong has yet to be identified.

2) EXPERIMENT

The funneling effect on the surge component from the pressure field and that from the wind field have been studied for the 1991 cyclone by investigating the surge response for only pressure deficits (assuming wind stresses to be zero) and the surge response for only wind stress (assuming pressure deficits to be zero) and keeping other conditions unchanged. To ensure that no influence from the tidal interaction is present, this experiment has been performed without tidal forcing.

3) DISCUSSION

The peak of the pressure response arrives about 2–5 h earlier than that of the wind stress response (Fig. 7). The difference in the arrival time between the pressure

Fig. 5. Comparison of simulated total water levels at various locations during 29–30 April 1991 cyclone with the observed levels.
Fig. 6a. Top, south-end, and east-end views of the total water levels during the 1991 surge event showing the formation of an edge wave along with the funneling effect. The characteristics of the cyclone in the same time step are also shown at left. For clarity in the figures, the wind vectors are shown for every (1/7.5)° resolution.
response and the wind stress response varies from place to place due to the difference in bottom topographic influences acting on the propagation speeds of the responses from pressure and wind stress. The influence of the funnelling effect on the pressure component becomes strong when the propagated surge reaches to the north of Sandwip Island where the pressure component is amplified (Fig. 7, Fig. 8—right) due to the triangular
shape of the bay. Thus, the pressure response north of Sandwip Island is far greater than that south of the island. These results explain the field investigation report of “unexpected higher surges” (Umitsu 1991) north of Sandwip Island. Experiments including also the tidal forcing, that is, $[(\text{tide} + \text{pressure with no wind stress}) - \text{(tide only)}]$, show qualitatively similar results. These experiments further demonstrate that the amplification of the pressure response is not due to tidal coupling.

The triangular coastal geometry amplifies the pressure response more than it amplifies the edge-trapped wind stress response. This is because of the qualitative nature of pressure and wind response in the Meghna estuary (Fig. 8). The wind response propagates toward the north in a narrow strip and is edge-trapped in nature (Fig. 8, left) but the pressure response proceeds toward the north in a widespread band (Fig. 8, right) extending from the eastern coastline to almost the western coastline (i.e., up to the coastline of Bhola Island). Thus, in the northern area of Sandwip Island the pressure response experiences the convergence of the coastlines and amplifies more than the wind response does. Proudman (1955) showed that convergence of the coastlines leads to the amplification of surges. The east–west length of the shelf north of Sandwip Island is less than the radius of deformation of a surge component and this makes the funneling effect of that zone much stronger than that in other areas. While encompassing Sandwip Island the pressure component from the east of the island meets with the pressure component from the west of the island, and the combined surge is further intensified due to the funneling effect. Thus, the pressure response am-
Fig. 6c. Propagation of surge residual of 1991 surge event in Yamashita’s (1993) model, in which the computations with flooding also show similar propagation pattern of edge waves. Thin lines are for total water level without flooding treatment and thick lines for total water level with hypothetical flooding treatment. Left figures are for total water levels and right figures for surge residuals only (reproduced from Yamashita 1993).

plifies suddenly in the area north of the Sandwip Island, which in turn intensifies the funneling effect.

c. Current patterns also support the coastal trapped phenomenon

The conceptual diagram provided by Cutchin and Smith (1973) for the case of a coastal trapped wave (Fig. 9a) shows that the current vectors are in the direction of the wave propagation near the coastline and in the opposite direction of the wave propagation in the offshore areas. The line discharges during the 1991 cyclone (Fig. 9b) also show that for some hours (especially during the propagation of the surge) the vectors are in the direction of the wave propagation near the Chittagong coastline and in the opposite direction in the offshore areas. The circulation found for only the surge component, that is, without any tidal forcing, shows a qualitatively similar current pattern. Johns and Lighthill (1992) maintained that “Particles of water move in horizontal circles with radii largest at the shoreline and decreasing exponentially with distance from it.” The current pattern of the 1991 storm surge indicates its coastal trapped characteristics. Similar edge wave patterns in the horizontal circulation can also be identified in the figures provided by Yamashita (1993), As-Salek (1994), and Flather (1994). Adams and Buchwald (1969) maintained that the alongshore component of the wind stress can generate sufficient vorticity to explain many of the important features of the coastal-trapped waves. A good in-depth treatment of various coastal-trapped waves is given by Wang and Mooers (1976). In a recent study, Tang and Grimshaw (1995) maintained that cyclonic vorticity favors generation of coastal-trapped shelf waves.

d. Confirmation from observed data

Hoque (1991) gives a description of the 1991 surge as “The storm surge completely submerged the islands of Sonadia, Moheshkhali, Matarbari, Ujantia, Koriardia, Kutubdia, and Sandwip. It also severely affected the
western parts of Cox’s Bazar, Chakaria, Banskhali, Anwar, and Sitakund Upazilas, the islands of Hatia and Monpura, and the mainland chars of Feni and Noakhali districts. Heavy damage was also reported from Patuakhali, Bholo, and Barguna districts from the lateral waves created by the main storm surge.” The widespread surge and the lateral waves, that is, resurgences observed in places far away from the origin of generation (Hoque 1991), also supports the edge wave nature of the 1991 surge event.

The widespread nature of the surge can be recognized inFig. 10a (from Katsura et al. 1992) by the levels of observed flooding in the areas far from the point of landfall of the 1991 surge. Figure 10b (from Matsuda 1991) shows the Upazila (=Thana)-wise ratio of the number of deaths to the worst affected population. Katsura et al. (1992) maintained that “The number of deaths caused by the storm surge accounts for more than 95% of the total lives lost.” Thus, the fact of so many human lives lost in this vast area and the huge destruction of property can only be explained by the widespread nature of the 1991 surge. The affected area covers a narrow but long strip of about 200 km along the coastline, and it may be considered to have been caused by a propagating edge wave. The computed maximum water levels (Fig. 10c) for the 1991 surge event indicate the same widespread nature as the observed data (Figs. 10a and 10b).

4. Investigation into factors responsible for coastal-trapped widespread surges

The cyclone that struck Bangladesh on 29 April 1991 is taken as a model cyclone for this investigation. Ex-
Experiments are performed by changing (within the ranges based on published references) one by one the characteristic parameters of that representative cyclone, keeping the other parameters unchanged and evaluating the effect of that change on the whole system.

**a. Central pressure**

The time series of the central pressure of the model cyclone (refer to Table 1) was changed by ±20 hPa and ±10 hPa. Pressure affects the wind stress in Eqs. (9), (10), and (11) but the effect is proportional in nature. The decrease in central pressure amplifies the total water levels resulting from surge amplitude, as Fig. 11a shows. The pressure response is modified by the funneling effect and by the local bottom topography (Figs. 7, 8). The effect and modification of the pressure response have already been discussed in the preceding section.

A decrease in central pressure results in an increase of offshore wind stress on the left-hand side of the cyclone’s track. The effect should be a lowering of the maximum water levels in the northern estuary with a decrease in pressure. The interesting fact here is that with a decrease in central pressure, the maximum total water levels increase in the northernmost part of the estuary, which is clearly due to the coastal trapping and funneling effect.

**b. Inflow angle**

The inflow angle varies with the distance from the cyclone center (Overland 1975), with time, and also with the size of the cyclone (Jelesnianski 1965). The observed inflow angles (Katsura et al. 1992) sometimes measures about 80° from the isobars for the 1991 cyclone. Experiments have been done for θ = 0°, θ = 22°, θ = 44° (model case), and θ = 60° in Eqs. (10) and (11).

The wind field with a greater inflow angle produces widespread surges (and the total water levels increase) (Fig. 11b) even at the left of the cyclone track (e.g., at Mirsarai) and at places far west from the strike point (e.g., in Khepupara). The ratio between the onshore winds (particularly its alongshore component) and offshore winds greatly increases with the increase of inflow angle. The momentum transfer from the wind to the water surface is proportional to the square of the wind speed and is stronger in shallow water. Thus, in the northern shallow zone of the Meghna estuary, the influence of the inflow angle is very strong. If the inflow angle is changed from 0° to 44°, the tangential component of stress is reduced in the ratio of 1:(cos44°)², that is, 1:0.517 but the normal component increases in the ratio of 0:(sin44°)², that is, 0:0.482. These normal components play a major role in generating and propagating storm surges in the Meghna estuary; this agrees with the findings of Adams and Buchwald (1969), who showed that the alongshore component of the wind stress can produce sufficient vorticity to generate the coastal trapped waves.

The nature of the coastal trapped surges is more sensitive to the inflow angles than it is to the pressure deficit. Though the generation of the edge wave is theoretically related to both the wind stress response and the pressure response, the influence of the wind stress in the generation of coastal trapped surges is found to be more than that of the pressure field.

**c. Radius of maximum cyclonic wind**

The radii of maximum cyclonic wind were assumed to be 30 km by Das et al. (1974) for the 1970 cyclone, 280 km by Johns and Ali (1980) for an idealized cyclone, and 60 km by Katsura et al. (1992) for the 1991 cyclone. While the model cyclone has a radius of 63 km, experiments have been performed for \( r_0 = 31.5 \text{ km} \) to \( r_0 = 126 \text{ km} \) in Eqs. (9), (10), and (11).

The cyclones with larger \( r_0 \) produce widespread surges and the total water level increases (Fig. 11c), but this
spreading is more to the right side of the cyclone’s track (compare with Fig. 11b, which shows that cyclones with a larger inflow angle generate surges to the left of the cyclone’s track). For larger diameter cyclones, the onshore winds to the right of the cyclone become effective in a wider area, but the resultant surges are still seen to spread toward the northernmost part of the estuary. Though the surge to the left side of cyclone track is expected to be reduced due to an increase in offshore wind in that area, the surges arriving from the south have increased it.

An increase of radius decreases the pressure profile gradient and shifts the position of the maximum wind speed away from the center of the cyclone. These two factors may lead to a reducing effect on the height of storm surges, but the increase in diameter strongly influences the development of surges in the northern shallow Meghna estuary. In this respect, surges in the shallow Meghna estuary show exactly the same surge behavior as speculated by Murty et al. (1986) for north of the Bay of Bengal. For larger diameter cyclones, weaker winds but with larger area and longer fetch act strongly in the northernmost part of the Meghna estuary to produce coastal-trapped surges.

d. Translation speed of cyclone

Experiments are performed for changes in the translation speed of a cyclone, (a) faster and (b) slower than the model cyclone. To ensure that the same astronomical tide as prevails during the model cyclone is considered, the time of landfall for the cyclone is kept the same as that of the model cyclone by shifting the starting time of the model cyclone by shifting the starting time of the translation speed of the model cyclone (Fig. 11d). The widespread nature of the surges in the case of a faster moving cyclone can be explained by edge wave theory, which implies an augmentation of the edge waves with an increase in the cyclone center’s translation speed.

e. Propagation path of a cyclone

The time series of a cyclone’s position (shown in Table 1) have been shifted uniformly to a northern latitude (i.e., toward the Chittagong–Noakhali coast) and also to a southern latitude (i.e., toward the Chittagong–Cox’s Bazar coast). The distance has been selected as 10, 20, 50, and 100 km in the north–south direction from the model cyclone’s path for each case, keeping other conditions unchanged.

If a cyclone crosses the Noakhali–Chittagong coast, the surges become more widespread than those under a cyclone crossing the Chittagong–Cox’s Bazar coast. The shallow water depth in the northernmost part of the estuary allows the wind stresses to act strongly. Also, when the cyclone crosses a point within the Noakhali–Chittagong coast, the wind to the right of the cyclone center has more opportunity to act on the shallow water to produce coastal trapped surges. In the 1970 cyclone with lowest central pressure 940 hPa (Murty et al. 1986) striking Noakhali, the death toll reached as high as 350,000, whereas in the 1991 cyclone (with the same lowest central pressure, i.e., 940 hPa, but this time striking Chittagong) the death toll was much lower at 140,000 persons. Though a similar situation of peak tide prevailed in both the cases, the propagation path differed. This difference explains, at least partly, the difference in the severity of the 1970 and 1991 cyclones, as reflected in different death tolls for these two events.

When the cyclone crosses a point along the Chittagong–Cox’s Bazar coast, though the surge to the left side of the cyclone track is expected to be reduced due to an increase in offshore wind in the northernmost part of the estuary, the surges arriving from the south increase the water level there.

f. Angle of coastline crossing

The coastline of southeastern Bangladesh (from Noakhali to Teknaf) is roughly oriented about 25°–30° anticlockwise from north–south. Analysis of the paths of past cyclones shows that the cyclones striking the region usually cross this coastline at an angle within the range of 30°–90°. The angle of crossing has been changed to 30°, 60° (the case for model cyclone), and 90° clockwise from the coastline and accordingly the propagation path has been shifted. The point and time of landfall and other conditions have been kept the same as those of the model cyclone.

Cyclones with a smaller angle of crossing produce widespread surges in the northern zone like Mirsarai and shift the location of the maximum total water level from the Banskhali region to the northern Anwara region (Figs. 10b and 11f). The shift in the location of the maximum water level with the angle of crossing of the cyclones in the Meghna estuary supports the findings of Jelesnianski (1967).

In the northern part of the Meghna estuary, the water level rises with the smaller angles of crossing because with the decrease in the angle of crossing, the time and space available for the cyclone to act on the shallow waters there are greater (see the coastline in Fig. 2).
A larger angle of crossing thus reduces the energy input and also the alongcoast velocity of the cyclone’s translation, which theoretically influences the edge wave generation.

g. Role of the astronomical tide

The model cyclone struck the Chittagong coast just when the local astronomical tidal peak was at its maximum. Keeping all other conditions the same as in the case of the model cyclone, the time of landfall has been shifted (lagging and leading, from the peak of the astronomical tide of Chittagong) by 1, 3, and 6 h.

In areas far from the point of landfall (e.g., in Khepupara), the cyclone that strikes at 3 h lag produces larger surges in Khepupara (Fig. 11g, left) than those produced due to the cyclone that strikes at 3 h lead (Fig. 11g, right). Again, the cyclone that strikes at lead 3 h spreads surges along the coastline. Similarly, in areas far from the point of landfall, the cyclone that strikes at 6 h lag produces larger surges in Khepupara (Fig. 11h, left) than does the cyclone that strikes at 6 h lead (Fig. 11h, right).

The Meghna estuary is shallow and the relative change of the water depth due to the high range of the astronomical tide is comparatively large. In other words, the nonlinear interaction between tide and storm surge is also prominent in the Meghna estuary. The generated edge wave, being coupled with the tide, tends to propagate or spread depending on the local tidal phase.

If the cyclones strike during the rising tidal phase, the surges spread along the coast. If cyclones strike during the falling tidal phases, then nonlinear tide–surge interaction also produces the surges in the Khepupara region.

5. Propagation of the entrapped surge after the cyclone strikes

a. Experiment

After the cyclone strikes the coast, the wind stress weakens but is still able to produce a surge. It is nec-

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**Fig. 9b.** Circulation in the northern part of Meghna estuary during alongcoast propagation of the 1991 surge shows pattern similar to that depicted in Fig. 9a. For clarity in the figures, the line discharge vectors are shown for every (1/40)° resolution.
necessary to clarify whether this prolonged wind action after the strike or the surge nature is responsible for the propagation of the surges. Thus, the surge nature has been investigated by stopping the cyclone just after the strike.

b. Discussion

The surges propagate along the coastline even after the cyclone is stopped (Figs. 12a and 12b). For the surges to the right of the cyclone’s track (i.e., in the southern areas like Anwara, Banskhali, and Cox’s Bazar) the falling limb sharply decreases. But the surge signature gradually exhibits resurgences (which are indicated by an upward arrow) as surge propagates toward the northern areas like Sandwip and arrives at Mirsarai around 0400 LST (which is almost the same time for the 1991 surge). After the cyclone is stopped, the wind stress and pressure deficit do not act. A decrease in the surges compared to the surges of the 1991 surge event is noted. The surge still propagates toward the northern zone. The arrival time of the in-
The distribution of observed data (reproduced from Matsuda 1991) shows the Upazila (since renamed Thana)-wise ratio of the number of deaths to the worst-affected population. (In the figure read “Banskhali” for “Banshkhali” and “Legend” for “Legent.”)

Fig. 10c. Distribution of maximum water levels in the 1991 cyclone as computed by the present model. (KTB: Kutubdia Island; CXB: Cox’s Bazar; KHP: Khepupara).

The propagation speed of the cyclone with a northward propagating tide.

Furthermore, the propagation speed of a linear long wave is given by \((\frac{g}{h})^{1/2}\) and thus the speed becomes slower as the wave approaches the coast in the Meghna estuary. In the Meghna estuary, most cyclones gradually gain speed as they approach the coast, thereby reducing the probability of coupling between the cyclone and a northward propagating tide. Also, in a mean water depth of 29–30 m, the propagation speed of the astronomical tide is \(60.7 \text{ km h}^{-1}\) from \((\frac{g}{h})^{1/2}\) and that of the 1991 cyclone was about \(23.0 \text{ km h}^{-1}\) (JTWC, and Table 1). Moreover, in a mean water depth of 3 m, the propagation speed of the tide is about \(19.4 \text{ km h}^{-1}\) and that of the 1991 cyclone was \(38.1 \text{ km h}^{-1}\). The propagation speed of the 1991 cyclone was accelerating and that of the astronomical tidal peak was decelerating while approaching the coast. The propagation speed was increased to 166% for the cyclone and it was decreased by 68% for the astronomical tide within about 3 h. The speed of the accelerating cyclone and that of the decelerating tide can never be equal long enough to excite coupling between the cyclone and the northward propagating astronomical tide.

Before the cyclone strikes, if the propagation speed of a surge reaches the cyclone’s alongshore speed, the surge travels like a forced coastal trapped wave (e.g., like forced coastal trapped surges as described by Fan dry et al. 1984) and after landfall, if the cyclone is not forcing, the surge travels like a coastal trapped wave with no wind forcing. In both cases, however, the surge is coastal trapped. Kraus and Businger (1994, p. 274) maintained that, “Depending on the coastal configuration, the traveling surges can have the character of shelf waves, Kelvin waves, or, most commonly, hybrid, intermediate forms.”

As a surge is traveling toward the northern part of the estuary, the gradual prominence of resurgences, which clearly indicate the coastal trapped nature of the
Fig. 11. Widespread nature (i.e., coastal trapping + funneling effects) of the surges in the shallow estuary depends on particular cyclone characteristics and local astronomical tide. The figures show the maximum water levels in the Meghna estuary and are compiled from some representative model runs: (a) Left panel relates to the cyclone with central pressure 20 hPa up from model cyclone, and the right panel relates to the cyclone with central pressure 20 hPa down from model cyclone. (b) Left panel relates to the cyclone with inflow angle 22°, and the right one to the model cyclone with inflow angle 60°. (c) Left panel relates to the cyclone with radius of maximum cyclonic wind as half of model cyclone’s. Right panel is for the case of the cyclone with radius of maximum cyclonic wind as double of model cyclone’s.
Fig. 11. (Continued) (d) Left panel is for the cyclone with translational speed as half of that of the model cyclone, and the right panel for the cyclone with the translational speed double of model cyclone's. (e) Left panel is for the case of the cyclone whose propagation path is shifted by 100 km south of model cyclone's path. Right panel is for the case of the cyclone whose propagation path is shifted by 100 km north from model cyclone's path. (f) Left figure relates to the cyclone that crosses at 90° with the coastline, and right figure relates to the cyclone that crosses at 30° with the coastline. (g) Left panel is for the case of the cyclone striking 3 h lagging after model cyclone, and right panel is for the case of the cyclone striking 3 h leading before the model cyclone. (h) Left panel is for the case of the cyclone striking 6 h lagging after model cyclone, and the right panel is for the case of the cyclone striking 6 h leading before model cyclone. (KTB: Kutubdia island; CXB: Cox's Bazar; KHP: Khepupara).
surges (Munk et al. 1956), has been noticed. Resurgences of the surges in the northern zone of the Meghna estuary are also displayed in Yamashita (1993) and Flather (1994). The formation of resurgences in the models supports Hoque’s (1991) report. These resurgences have been found even after cyclone stalling and in the propagation of the surge component without the tide (i.e., by subtracting the tide from the total water level). These experiments also demonstrate that the mechanism for the coastal trapping of the surges in the Meghna estuary does not depend on tidal coupling.

Buchwald and Adams (1968) maintained, “There is a negative group velocity for a range of wavelengths, indicating that energy can propagate in the opposite sense in some regions,” which is what happened in the case when the cyclone stalled just after the landfall. A relatively small portion of the surge (from the place where the highest surges developed) propagated toward southern Cox’s Bazar (downward arrow in Fig. 12b), which is a property of coastal-trapped waves as discussed by Buchwald and Adams (1968). On the other hand, the possibility of an increase in surge height due to surges originating farther south of Cox’s Bazar would only support the coastal trapped nature of surges.

Further, as has been shown in the preceding section, strong nonlinearity exists between the coastal-trapped surge component and tides, and modification of the coastal trapped surge is influenced by local bottom topographic characteristics.

6. Summary of results and conclusions
a. Coastal trapped nature of the 1991 surge

The 1991 surge (i) was coastal trapped with edge-wave characteristics, (ii) was influenced by the funneling effect in the zone to the north of Sandwip Island, and (iii) was widespread along the coast.

b. Coastal trapping and funneling effect

The present study suggests that surges may propagate as edge waves, and the “funneling effect” enhances, in particular, the effect of low atmospheric pressure associated with a cyclone. In the case of the Meghna estuary, the funneling effect acts strongly in the area to the north of Sandwip Island.

c. Generation of widespread surges

The combination of coastal trapping and funneling effects results in that widespread nature of the surges in the Meghna estuary, and the surge is proportional to the inflow angle and to the radius of the maximum cyclonic wind, but inversely proportional to the coastline.
crossing angle of the cyclones. A rapidly moving cyclone spreads the surges toward the northern estuary. The pressure response contributes to the widespread nature of the surge by amplification through the funneling effect. The cyclones striking the Chittagong–Noakhali coast produce more widespread surges than do the cyclones striking the Chittagong–Cox’s Bazar coast.

Though the generation of the edge wave is theoretically related to the wind stress response and also to the pressure response, the influence of the wind inflow angles on the generation of coastal trapped surges is more than that of the pressure field. The wind stress components normal to the isobars play a major role in generating coastal-trapped surges in the Meghna estuary.

d. Propagation of trapped surges

The trapped surge continues its propagation even when the cyclone is no longer forced by wind stress. Before the landfall of the cyclone, when the propagation speed of the surge almost reaches that of the cyclone’s alongshore speed, the surge travels as a wind-forced coastal trapped wave, and after the landfall, when the cyclone is not forcing, it travels as a coastal-trapped wave. However, in both the cases the surge is coastal trapped. The gradual prominence of resurgence in the surge signature, as it propagates toward the northern zone, clearly indicates the coastal-trapped nature of surges in the Meghna estuary.

e. Role of astronomical tide

The spreading natures of trapped surges, as developed during rising and falling tidal phases, are different and distinctive by the surges that produced in the western Khepupara region for the latter case. In both the cases, the surge produced near the landfall remains edge bounded with the wave-variance maxima at the shoreline. The alongcoast propagation of edge-bounded surges in the Meghna estuary and the amplification of the pressure response, are not the effects from nonlinear coupling of the tide with surge.

The present study provides information about the coastal trapping and funneling effects in the Meghna estuary and makes it possible to ascertain the nature and characteristics of an impending surge and to foresee if a cyclone will produce widespread surge, so as to make it possible to issue timely and appropriate warning forecasts about surges.

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Fig. 12c. Pattern of flow showing persistence of edge wave nature even when the cyclone is stopped just after landfall. The figures are from the experiments described in Fig. 12a. Both the experiments, with and without tidal forcing, show qualitatively similar edge wave pattern.


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