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Numerical Modelling of Storm Surge in the Head Bay of Bengal Using Location Specific Model

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Abstract. The head Bay of Bengal region, which covers part of Orissa and west Bengal in India as well as Bangladesh, is one of the most vulnerable regions of extreme sea levels associated with severe tropical cyclones which cause extensive damage. There has been extensive loss of life and property due to extreme events in this region. Shallow nature of the Bay, presence of Ganga-Brahmaputra-Meghna deltaic system and high tidal range are responsible for storm surges in this region. In view of this a location specific fine resolution numerical model is developed for the simulation of storm surges. To represent most of the islands and rivers in this region a 3-km grid resolution is adopted. Several numerical experiments are carried out to compute the storm surges using the wind stress forcings representative of 1974, 1985, 1988, 1989, 1991, 1994 and 1999 cyclones, which crossed this region. The model computed surges are in good agreement with the available observations/estimates.

Key words: head Bay of Bengal, tropical cyclone, numerical model, storm surges

The coastal stretch covering the northern Orissa, West Bengal, Bangladesh and northern part of Myanmar is frequently hit by tropical cyclones causing heavy loss of life and property. The most affected region along the coastal belt is the Meghna estuary in Bangladesh. The November 1970 and April 1991 cyclonic storms caused extensive damage to life and property (Table I). Recently, Dube *et al.* (1997) reviewed the storm surge problem in the Bay of Bengal and attributed several reasons for the devastating effects of extreme sea levels in this region. The main factors contributing to disastrous surges in Bangladesh may be summarized as (Ali, 1979).

(a) shallow coastal water,
(b) convergence of the bay,
(c) high astronomical tides,
(d) thickly populated low-lying islands,
(e) favourable cyclone track, and
(f) innumerable number of inlets including world's largest river system (Ganga-Brahmaputra-Meghna)

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Table I. List of storm surges for Bangladesh (1970–2000)

No.	Date	Location	Damage
1	2-7 May, 1970	Cox's Bazar, Bangladesh	Up to 5 m surge
2	18–23 October, 1970	Chandpur, Bangladesh	4.7 m surge. 300 deaths
3	8–13 November, 1970	Between Noakhali and Chittagong, Bangladesh	3–10 m surge, 300,000 deaths, 280,000 cattle killed, 440,000 houses destroyed, 18,000 boats destroyed. Unofficial estimation of deaths more than 500,000
4	8 May, 1971	Khulna to Chittagong and offshore islands, Bangladesh	2.4–4.2 m surge. Other information not available
	28–30 September, 1971	Chandpur, Bangladesh	Surge plus tide of 5 m
5	5–6 November, 1971	Chittagong, Bangladesh	Water levels up to 5.5 m
6	5–9 December, 1973	Patuakhali coast and offshore islands, Bangladesh	Peak water level 6.2 m. Peak surge 4.5 m. 183 deaths
7	13–15 August, 1974	Khulna, Bangladesh	6.7 m surge
8	24–28 November, 1974	Chittagong, Bangladesh	3.0–5.1 m surge. 20 deaths, 50 injured, 280 persons missing, 1,000 cattle killed, 2,300 house destroyed
9	4–8 June, 1975	Chittagong, Bangladesh	Peak surge 4.0 m, 50 deaths
10	24–28 June, 1975	Bangladesh	Tide and surge 4.8 m
11	7–11 November, 1975	Barisal, Noakhali, Bangladesh	Maximum surge 3.1 m
12	15–21 October, 1976	Meghna Estuary, Bangladesh	Tide plus surge 5.0 m at Comapaniganj
13	20 November, 1976	Chittagong, Bangladesh	1.0 m surge. 2.1 m tide
14	9–13 May, 1977	Noakhali, Bangladesh	0.6 m surge. 0.7 m tide
15	6–10 December, 1981	Khulna, Bangladesh	2–4.5 m surge 72 deaths and 200 deaths in India.
16	14–15 October, 1983	Chittagong coast near the Feni River, Bangladesh	43 deaths. Substantial damage
17	5–9 November, 1983	Chittagong, Cox's Bazar, Bangladesh	1.5 m surge, 300 deaths. Substantial damage
18	20–25 May, 1985	Cox's Bazar, Chittagong, Sandwip, Bangladesh	4.55 m surge. 11,069 deaths. 94,000 houses destroyed

Table 1. Continued

No.	Date	Location	Damage
19	7–9 November, 1986	Chittagong, Bangladesh	0.61 m surge, 50 deaths. Substantial damage
20	24–30 November, 1988	Khulna coast near Raimangal river, Bangladesh	4.4 m surge. 11,683 deaths in Bangladesh, 532 deaths in India 6,000 missing. 65,000 cattle killed. 15,000 deer killed. 9 royal Bengal tigers killed. Substantial crop damage.
21	7–8 October, 1990	Barisal, Bangladesh	150 fishermen missing. Substantial damage
22	16–18 December,1990	Khulna coast, Bangladesh	4.4 m surge, 5683 deaths, 15,000 and 9 tigers killed, 65,000 cattle killed
23	25–30 April, 1991	Chittagong, Cox's Bazar, Bangladesh	6–7.6 m surge. 140,000 deaths. 70,000 cattle killed. Great damage
24	31 May–2 June, 1991	Noakhali-Patakhali, Bangladesh	2.5 m surge, 300 deaths
25	26–29 October, 1996	Sundarban coast, Bangladesh	1.52–2.12 m surge, 9 deaths, 2,000 fishermen missing, 15,000 cattle killed, 10,000 houses damaged
26	15–20 May, 1997	Chittogong, Bangladesh	4.55 m surge, 155 deaths
27	24–27 September,1997	Noakhali-Chittagong coast, Bangladesh	3.03–4.55 m surge at Bhoala, 1.52–2.12 m surge at Barguna, 2.42–3.03 m surge at Galachipa, 67 deaths. At Khagrachhari, 16 villages and a part of the district town went under 1.82–2.42 m surge
28	4–9 November 1997	Bangladesh coast	3.0 m surge, Substantial damage
29	17–21 May 1998	Bangladesh coast	16 deaths

Table II. List of storm surges along West Bengal coast of India (1737–2000)

No.	Date	Location	Damage
1	7–12 October, 1737	Mouth of Hoogly River, West Bengal, India	12 m surge (probably includes tide and wind waves). Surge penetrated 100 km inland through the Hoogly River. 300,000 deaths in India and Bangladesh (could be a slight exaggeration)
2	21 May, 1833	Sagar Island/24 Paraganas, West Bangal, India	3 m surge. 50,000 deaths. 100,000 cattle lost
3	October, 1854	Mouth of Hoogly River, West Bangal, India	Up to 12 m water level increase near Calcutta and environs. 50,000 deaths
4	2–5 October, 1864	Near Contai, West Bengal, India	Up to 12 m surge. Flooded up to 13 km on either side of the Hoogly River. 80,000 deaths.
5	1 November, 1867	East of Calcutta, West Bengal, India	1.8 m surge. Damage at Port Canning. 13 m surge at Hatia, Bhola Islands
6	13–16, October, 1874	Mouth of Hoogly, West Bengal, India	3,049 deaths
7	21–26, September, 1887	Calcutta, West Bengal, India	No estimation of deaths.
8	18–29, September, 1916	West Bengal coast, India	Extensive damage, No estimation of deaths
9	14–16 October, 1942	Contai, West Bengal, India	5 m surge at Midnapore (64 km upstream in Hoogly River) 15,000 deaths
10	29 May–1 June, 1956	Near Calcutta, West Bengal, India	Inundation in Midnapore District. Damage to agriculture due to saline water intrusion
11	13–20 August, 1974	Contai, West Bengal, India	3 m surge. Inundation of low-lying areas of Digha and Juneput. 7 deaths
12	11 September, 1976	Contai, West Bengal, India	2.5 m surge. 1.4 m tide. 40 deaths.

There are about 29 events of severe storm surges (more than 1 m) in Bangladesh during the period 1970–2000. The frequency of tropical cyclones in the Bay of Bengal and the Arabian Sea is not high, even though the coastal regions of India, Bangladesh and Myanmar suffer most in terms of loss of life and property caused by the surges. There can be little doubt that the number of casualties would have been considerably lower if the surge could have been predicted, say, 24 hours in advance allowing effective warnings in the threatened area. The prediction, must, of course, be accurate enough so that one can distinguish between the dangerous surges and the surges that cause little harm, as people cannot be evacuated from exposed areas for every approaching storm. Some success has been achieved in predicting storm surges by computer oriented numerical models. The purpose of the present paper is to describe a numerical storm surge prediction model for the head bay region. Several studies have been undertaken for the storm surge simulation in this region (Johns and Ali , 1980; Murty, 1984; Dube *et al.*, 1985a; Murty *et al.*, 1986; Sinha *et al.*, 1986; Dube *et al.*, 1997; Roy, 1999 and Roy *et al.*, 1999). As there are large number of islands and river inlets in the Ganga-Meghna-Bhrahmaputra deltaic system there is a need to develop a high-resolution model to represent the coast line accurately in this region. To achieve this objective we have taken a grid resolution of 3 km in the present study. Using stair step boundaries and this grid resolution we are able to represent most of the islands, rivers and irregular coastal terrain. The analysis region of the model with stair step boundary representation is shown in Figure 1. We have carried out several numerical experiments using the wind stress forcings representative of 1974, 1985, 1988, 1989, 1991, 1994 and 1999 cyclones, which crossed this region.

1. Basic Equations

For the formulation of the model a system of rectangular Cartesian coordinates is used. Origin 'O' is within the equilibrium level of the sea surface, Ox points towards the east, Oy points towards the north and Oz is directed vertically upwards.

The depth-averaged form of the predictive equations for this model may be written as (Dube *et al.*, 1985b)

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

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

$$\frac{\partial \tilde{v}}{\partial t} + \frac{\partial}{\partial x}(u\tilde{v}) + \frac{\partial}{\partial y}(v\tilde{v}) + f\tilde{u} \;=\; -g(\zeta + h)\frac{\partial \zeta}{\partial y} + \frac{G_s}{\rho}$$

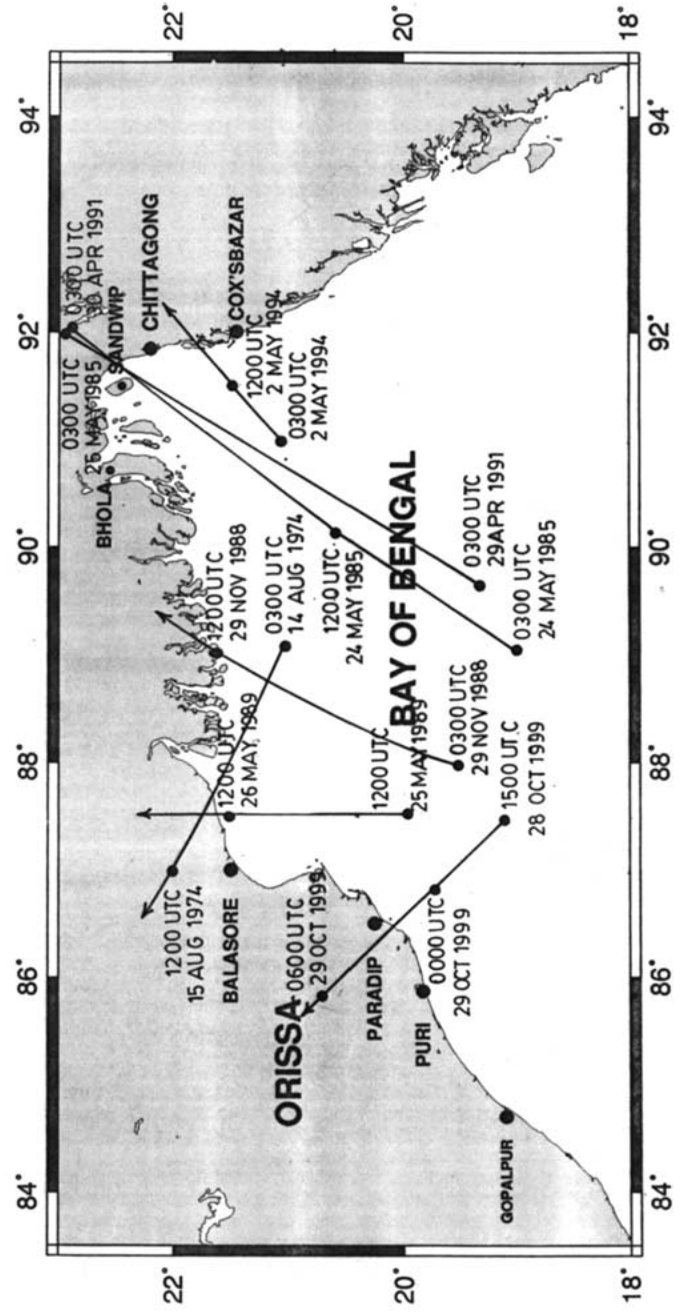

Figure 1. Analysis region.

$$-\frac{c_f \tilde{v}}{(\zeta + h)}(u^2 + v^2)^{\frac{1}{2}}, \tag{3}$$

where $\tilde{u} = (\zeta + h)u$ and $\tilde{v} = (\zeta + h)v$; u, v, averaged component of velocity in the direction of x, y respectively; ζ, sea surface elevation above mean water level; h, water depth; t, time; ρ, density of the sea water; f, Coriolis parameter, $f = 2\omega \sin\phi$; g, acceleration due to gravity; F_S, G_S; x and y components of surface wind stress; c_f, bottom friction coefficient (2.6×10^{-3}).

A conventional quadratic law parameterizes the surface stresses as follows

$$(F_s, G_s) = c_d \rho_a (u_a^2 + v_a^2)^{\frac{1}{2}} (u_a, v_a),$$

where $c_d = 2.8 \times 10^{-3}$ is the surface drag coefficient, ρ_a is density of the air and u_a, v_a are the x and y components of the surface wind.

2. Boundary Conditions

The boundary and initial conditions take the form

$$\tilde{u} = 0 \text{ at meridional boundaries} \quad \tilde{v} = 0 \text{ along latitudinal boundaries} \tag{4}$$

and

$$\zeta = u = v = 0 \text{ for } t = 0.$$

At the southern open sea boundary a radiation type of condition (Heaps, 1973) is applied which leads to

$$v + \left(\frac{g}{h}\right)^{\frac{1}{2}} \zeta = 0 \quad \text{at } y = 0 \tag{5}$$

The finite difference formulation and complete numerical treatment of the above equations (1)–(5) can be found in Dube *et al.* (1985b) .

3. Numerical Experimentation

The model has been used to compute the maximum surge associated with the cyclones that struck head bay region during 1974, 1985, 1988, 1989, 1991, 1994 and 1999. The idealised wind stress forcing for driving the model has been computed by using the following empirical formulae given by Jelesnianski (1972)

$$V = V_{\max}\left[\frac{2Rr}{R^2 + r^2}\right], \tag{6}$$

where R is the radius of the maximum wind and $V_{\max}$ is the maximum wind at R, while r is the radial distance from the centre of the cyclone. A time step of

Table III.

Name of the cyclone	V_{max} (m/s)	R (km)
1974 Contai cyclone	40	20
1985 Chittagong cyclone	42	30
1988 Khulna cyclone	45	30
1989 Balasore cyclone	45	30
1991 Chittagong cyclone	65	40
1994 Teknaf cyclone	50	30
1999 Paradip cyclone	75	40

2 minutes was found to be consistent with the computational stability. The input parameters for the above mentioned storms are given in the Table III.

4. Results and Discussions

4.1. 1974 CONTAI CYCLONE

A deep depression was formed on the morning of 13 August with its centre at 03:00 UTC near 21.5°N and 90°E. The depression intensified into a cyclonic storm on the morning of 14th when it was centred near 21.2°N and 89.5°E. Moving slowly west northwest, this storm became severe on the morning of 15th with its centre near Sagar Island and crossed west Bengal coast near Contai that noon. The track of the cyclone in the analysis region is shown in Figure 1. India Meteorological Department (IMD) estimated maximum winds of 40 m/s and a radius of maximum wind of 25 km at landfall using satellite, radar and surface observation analysis.

The model is integrated ahead in time up to 48 hours with a maximum wind speed of 40 m/sec and the radius of maximum wind of 25 km. The maximum peak surge contours are shown in Figure 2. A maximum surge of about 3.4 m is computed which is shown in the figure. The regions around Sagar island and adjoining areas in Bangladesh are inundated by tidal waves of 2.5–3.5 m.

4.2. 1985 CHITTAGONG CYCLONE

A depression developed over the central bay on 22 May centered at 03:00 UTC near 15.5°N and 88°E. Remaining stationary it intensified into a cyclonic storm by evening. Then it moved north northwestwards until the morning of the 23rd and again lay quasi stationary at 16.5°N, 87.5°E for 9 hours. Thereafter it took north northeasterly course and intensified into a severe cyclonic storm by the evening of 24th, crossed Bangladesh coast near Hatia in the early hours of 25th. The maximum wind speed associated with this cyclone is 154 km/h (83 knots). The model is

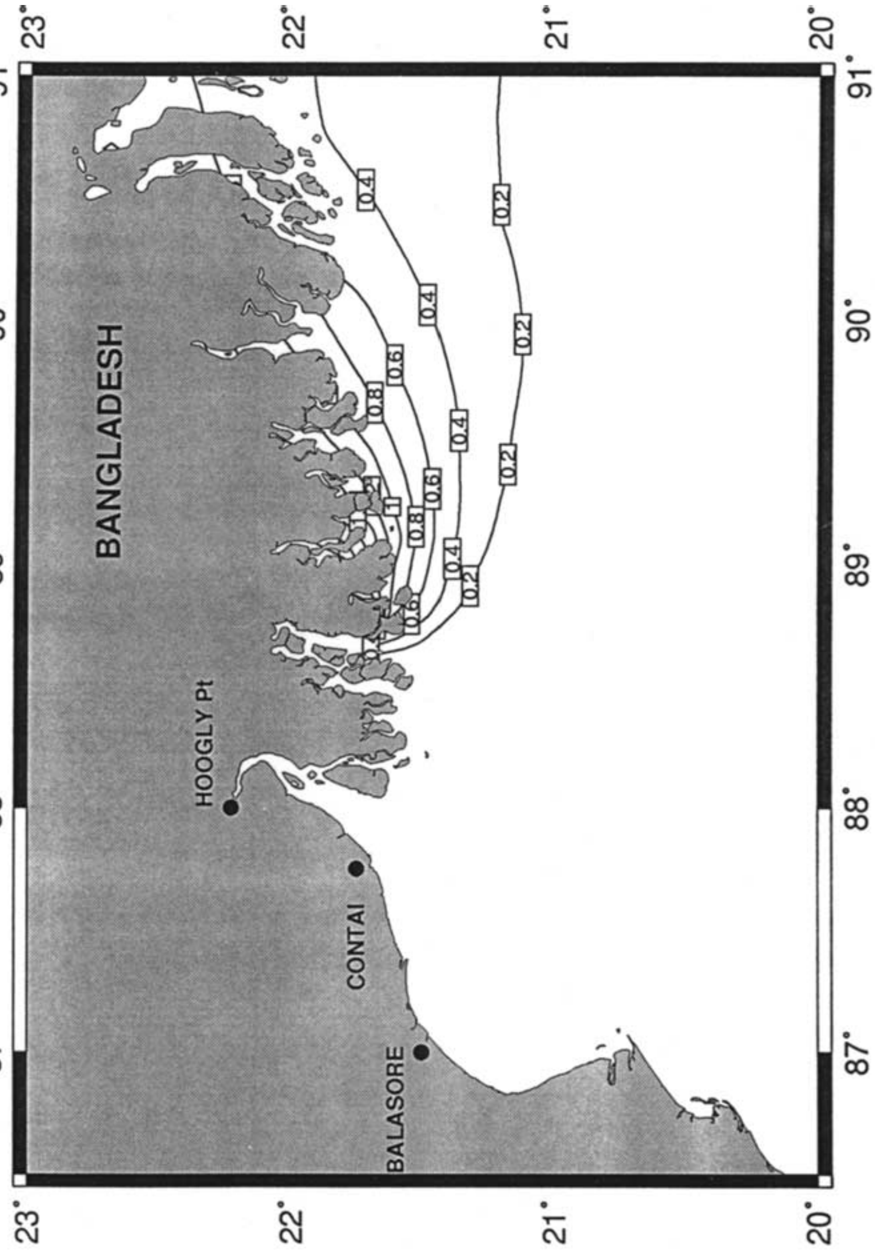

Figure 2. Peak surge contours (m) associated with 1974 Contai cyclone.

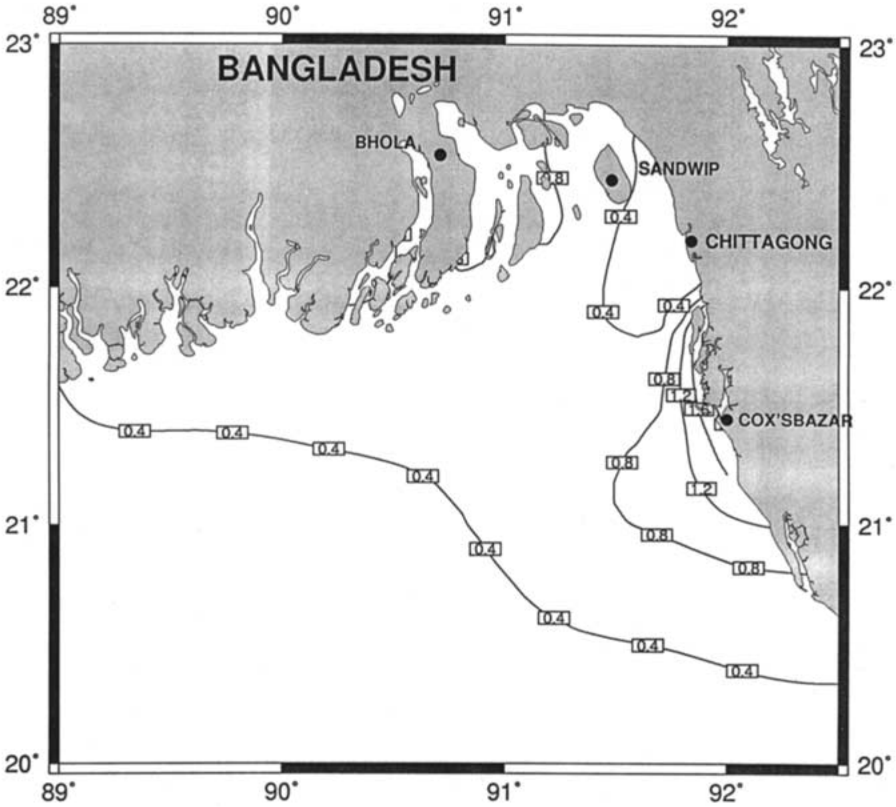

Figure 3. Peak surge contours (m) associated with 1985 Chittagong cyclone.

integrated with a maximum wind speed of 42 m s^{-1} and with a radius of maximum wind of 30 km.

A maximum surge of about 3 m is computed which is shown in Figure 3. The computed surge values at Chittagong and Cox's Bazar are 1.8 m and 2.2 m, respectively. Roy *et al*. (1999) reported astronomical tide at this location as 1 m at the time of landfall. Thus the total water level at Chittagong is about 2.8 m, which is close to the observations reported by Roy *et al*. (1999).

4.3. 1988 KHULNA CYCLONE

The system intensified into a cyclonic storm in the morning of 25 November and became severe cyclonic storm around 06:00 UTC of that day. From the morning of the 26th onwards the storm moved in a northerly direction and headed for west Bengal–Bangladesh coast. During its northerly course it further intensified into a severe cyclonic storm with a core of hurricane winds on the morning of the 27th. It crossed west Bengal-Bangladesh coast around 12:00 UTC of the 29th and weakened over northern parts of Bangladesh by the evening of the 30th. The system was one of the severe storms that affected Indian coast as well. The fury of the hurricane was felt over south and north of 24 Paraganas district in west Bengal and the coastal districts of Bangladesh. Height of water level in Roy Mongal river rose to 4 m from the normal tide. At Goasba in Sagar Island, the water level of the river Bidyadhari rose by about 2.4 m above normal tide (Das *et al*., 1990). The track of the cyclone is shown in Figure 1. The IMD estimated the lowest central pressure of the cyclone to be 942 hPa and the maximum sustained winds of 150–200 km/h. As per the post storm survey reports storm surges of 3–4 m above the astronomical tide level affected the region to the right of the track of the cyclone.

Numerical experiments are carried with a maximum wind speed of 45 m s^{-1} and with a radius of maximum wind of 30 km. A maximum surge of about 7.8 m is computed in the Roy Mongal estuary, which is shown in Figure 4.

4.4. 1989 BALASORE CYCLONE

A depression developed over the east central bay and neighborhood on 23rd morning. Initially, the system followed a northerly course and then a northwesterly course and intensified into a cyclonic storm in the morning of 24th. It moved westwards and further intensified into a severe cyclonic storm over the northwest bay on 25th evening. Afterwards, it took a northerly course and became a severe cyclonic storm with a core of hurricane winds by the next morning off north Orissa coast. It crossed north Orissa-west Bengal coast about 40 km NE of Balasore around 15:00 UTC of 26th. Tidal waves of 3–6 m height were observed in the coastal areas of Balasore, Midnapore and 24 Paragana districts. Maximum tide level of 5.7 m was observed at the southern end of Sagar Island. Maximum estimated winds associated with this cyclone were 90 knots.

The numerical experiment is carried out with a maximum wind speed of 45 m s^{-1} and with a radius of maximum winds of 30 km. A maximum surge of 5 m is computed in the Hooghly estuary, which is depicted in Figure 5. At Sagar and Contai the peak surge values are 2.4 m and 3.4 m, respectively. The west Bengal coast from Contai to Hooghly estuary is affected by surges between 3–5 m, which are in good agreement with the reported observations (Gupta *et al*., 1991)

4.5. 1991 CHITTAGONG CYCLONE

Detected as a low pressure area over the southeast bay and adjoining Andaman Sea on the morning of April 23, it developed into a depression near 10°N and 89°E at 03:00 UTC on April 25. It became a cyclonic storm near 12.5°N and 87.5°E at 03:00 UTC on April 27, intensified into a severe cyclonic storm near 14.5°N and 87.5°E at 18:00 UTC on the same day. It further intensified into a severe cyclonic storm with a core of hurricane winds near 15.5°N and 87.5°E at 03:00 UTC on April 28. The cyclone crossed Bangladesh coast a little north of Chittagong at 20:00 UTC on April 29. This cyclone is one of the worst killer cyclones in human

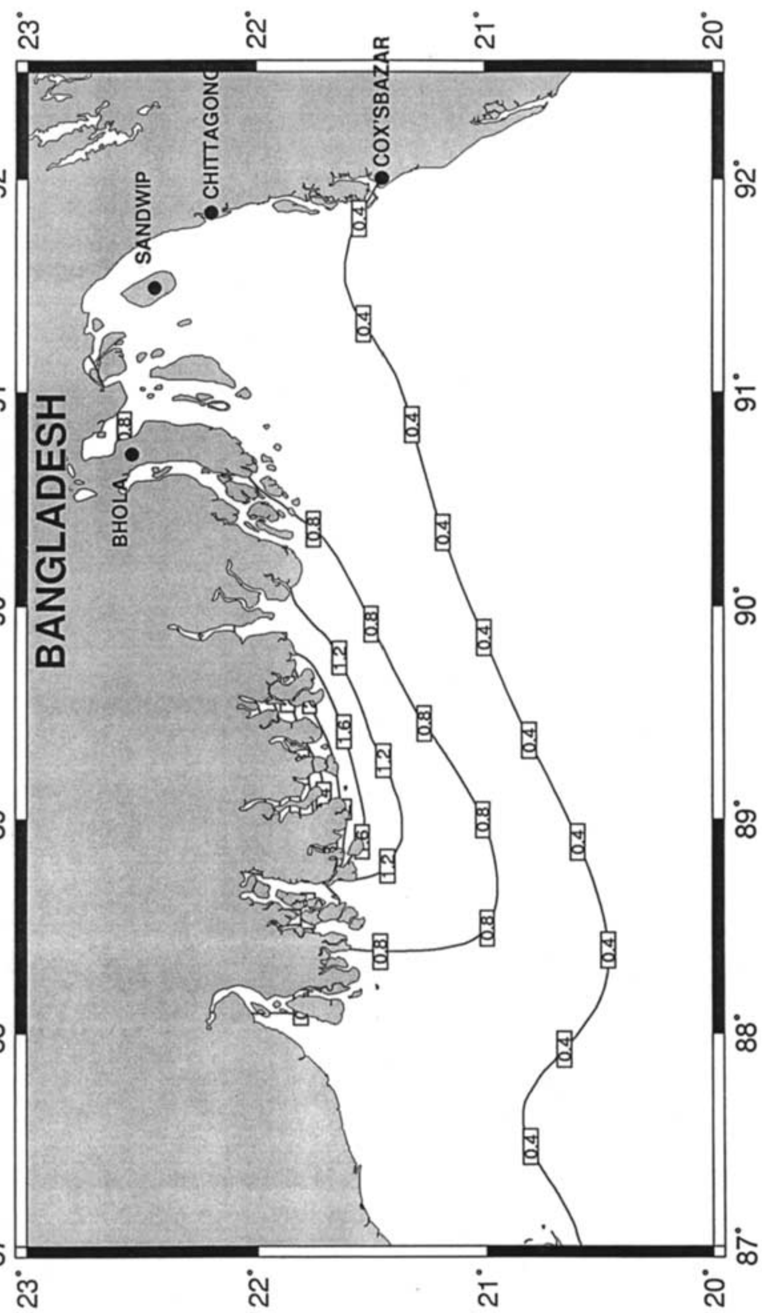

Figure 4. Peak surge contours (m) associated with 1988 Khulna cyclone.

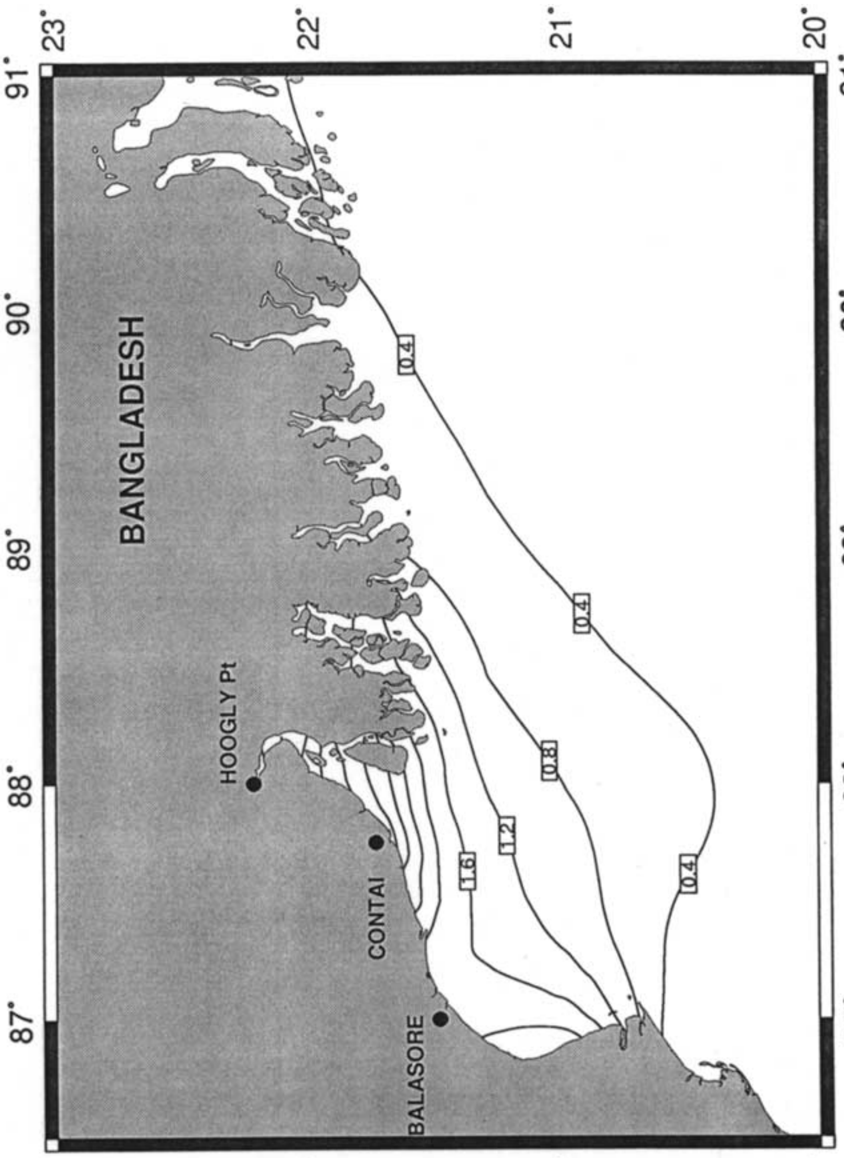

Figure 5. Peak surge contours (m) associated with 1989 Balasore cyclone.

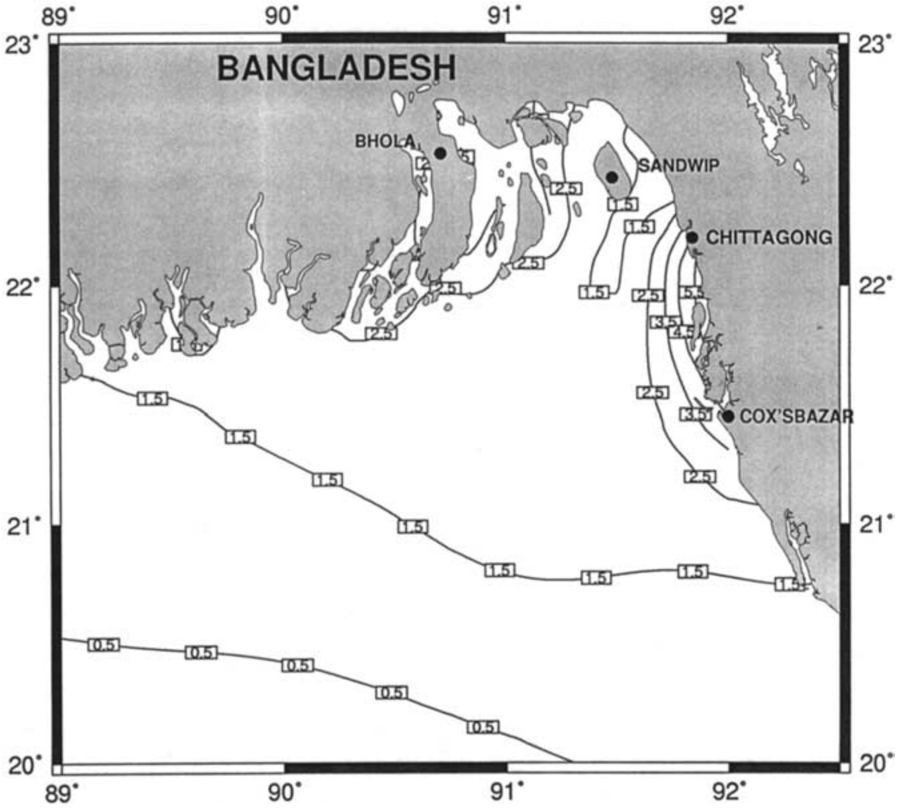

Figure 6. Peak surge contours (m) associated with 1991 Chittagong cyclone.

history. The estimated maximum wind speed is 235 km/h. A surge height of 6–7.6 m is reported. As per media reports tidal waves of 6 m in height swept a coastal stretch of nearly 240 km in Bangladesh.

It can be seen from Figure 6 that there is a maximum surge of about 7 m to the south of Chittagong. The computed surge values at Chittagong and Cox's Bazar are 5.8 m and 3.8 m, respectively. According to Roy *et al.* (1999) the astronomical tide at Chittagong at the time of landfall is about 1.5 m. Thus the total water level at Chittagong is about 7.3 m, which compares well with the available reports.

4.6. 1994 TEKNAF CYCLONE

A system of low-pressure area was detected over the south east bay at 03:00 UTC on April 27, concentrated into depression near 9°N and 90°E at 03:00 UTC on April 29. It became a deep depression near 9°N and 90°E at 12:00 UTC on the same day. It intensified into a cyclonic storm near 10°N and 90°E at 17:00 UTC on April 29, concentrated into severe cyclonic storm near 13°N and 90°E at 18:00 UTC on April 30 and intensified further into a severe cyclonic storm with a core

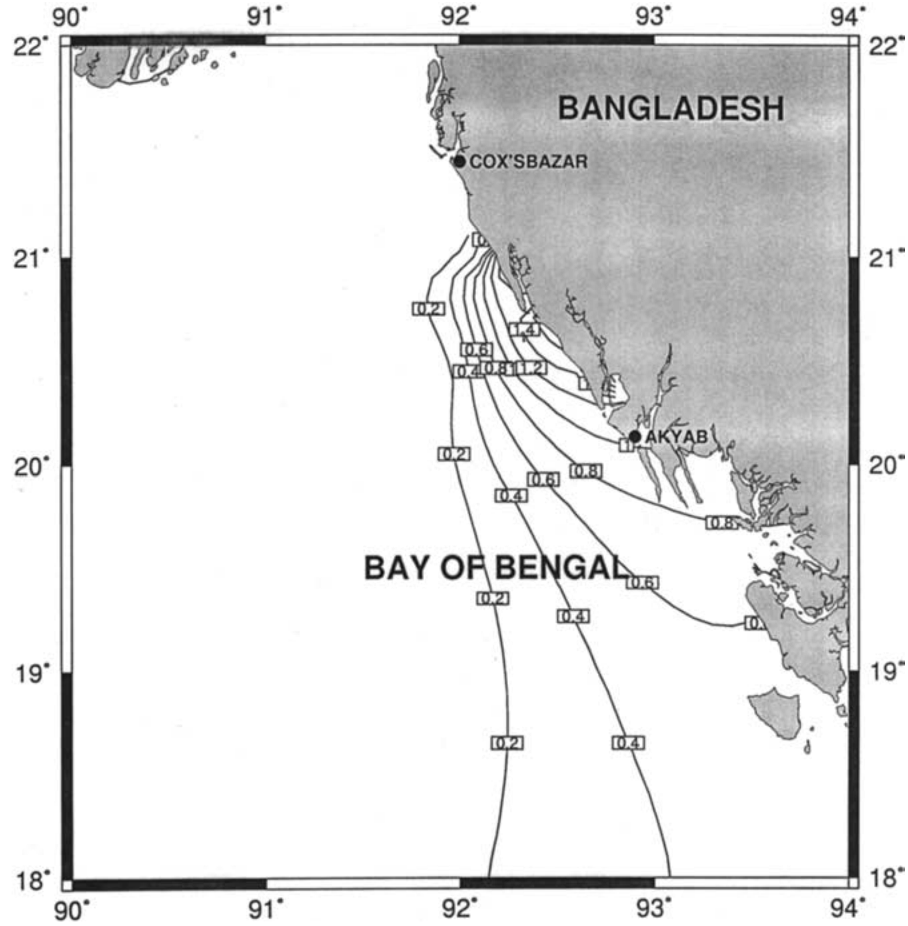

Figure 7. Peak surge contours (m) associated with 1994 Teknaf cyclone.

of hurricane winds near 15.6°N and 90°E at 12:00 UTC on May 1. The cyclone crossed Teknaf coast and lay centered south of Cox's Bazar at 15:00 UTC on May 2.

The maximum wind speed associated with the cyclone is taken as 50 m s^{-1} and a radius of maximum wind as 30 km. The computed maximum peak surge is about 3.8 m. The peak surge value at Akyab is around 1 m. Also, it is seen that a coastal stretch of about 50 km to the north of the landfall point is flooded with a surges of more than 1 m.

4.7. 1999 PARADIP CYCLONE

A depression was formed in the Bay of Bengal near 12°N and 98.5°E at 06:00 UTC of 25 October 1999. It became a cyclonic storm in the early hours of 26th and was located at 13.5°N and 96.5°E. The cyclone moved further in a northwesterly

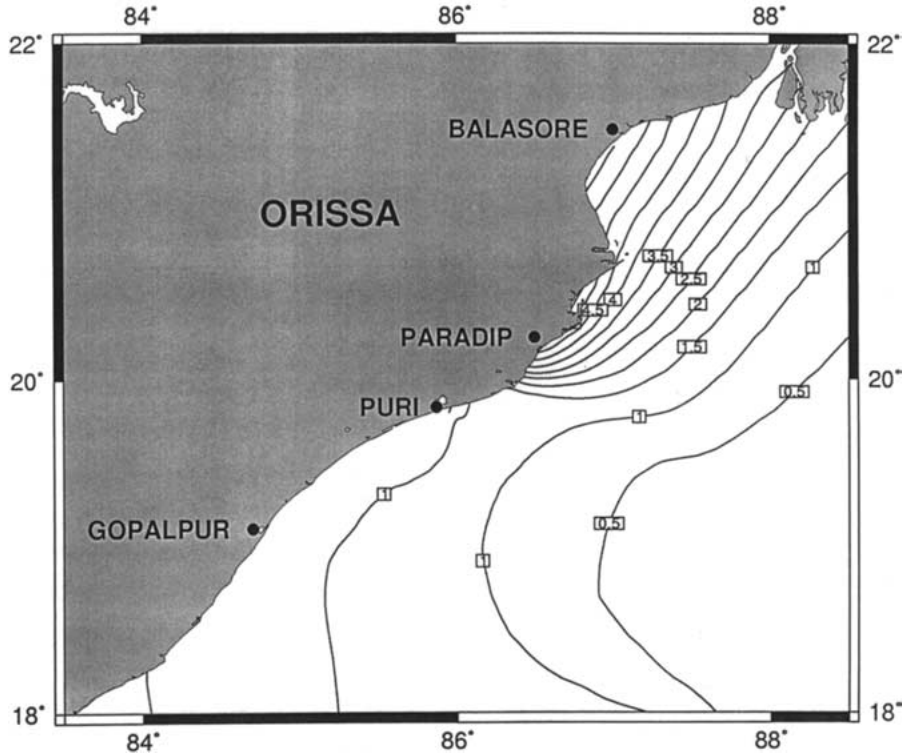

Figure 8. Peak surge contours (m) associated with 1999 Paradip cyclone.

direction and lay centered at 16°N and 92°E. It became a severe cyclonic storm with a core of hurricane winds on 27th at 03:00 UTC. The cyclone further intensified into a very severe cyclonic storm and lay centered at 17.5°N and 89.5°E on 28th. It became very severe cyclonic storm with a core of hurricane winds on 28th evening. It crossed south of Paradip coast on 29th morning. The maximum winds associated with the storm are 250 km/h.

Numerical experiment is carried out with a maximum wind of 75 m s^{-1} and with a radius of maximum winds of 40 km. Figure 8 shows the model computed peak surge contours. It can be seen that a maximum surge of about 6 m occurred close to Paradip. The coastal region between Konark and Chandbali is affected by a surge of more than 5 m. Post-storm survey reports also show that the surge is more than 6 m, near Paradip (IMD report, 1999).

5. Conclusions

A fine resolution storm surge model has been described for the head Bay of Bengal region. The model results reported in this study are in good agreement with the available peak surge observations/estimates. The results emphasize the suitability of a fine resolution location specific model for a reasonable prediction of surges along the Orissa coast, west Bengal and Bangladesh coasts. The limitation of the model is the non-inclusion of tides and river discharge and their interaction with surges, which may affect the surge prediction. The model may be used for operational prediction of storm surges in this region.

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