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Simulation of Storm Surges Along Myanmar Coast Using a Location Specific Numerical Model

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Abstract. Coastal flooding induced by storm surges associated with tropical cyclones is one of the greatest natural hazards sometimes even surpassing earthquakes. Although the frequency of tropical cyclones in the Indian seas is not high, the coastal region of India, Bangladesh and Myanmar suffer most in terms of life and property caused by the surges. Therefore, a location-specific storm surge prediction model for the coastal regions of Myanmar has been developed to carry out simulations of the 1975 Pathein, 1982 Gwa, 1992 Sandoway and 1994 Sittwe cyclones. The analysis area of the model covers from 8° N to 23° N and 90° E to 100° E. A uniform grid distance of about 9 km is taken along latitudinal and longitudinal directions. The coastal boundaries in the model are represented by orthogonal straight line segments. Using this model, numerical experiments are performed to simulate the storm surge heights associated with past severe cyclonic storms which struck the coastal regions of Myanmar. The model results are in agreement with the limited available surge estimates and observations.

Key words: storm surge, numerical model, tropical cyclone, Myanmar

1. Introduction

Countries around the Bay of Bengal are threatened by the possibility of storm surges associated with severe tropical cyclonic storms. The destruction due to the storm surge flooding is a serious concern along the coastal regions of India, Bangladesh and Myanmar (Figure 1). In particular, low lying deltaic regions of Bangladesh and Myanmar are most vulnerable to storm surges. The Bay of Bengal cyclones move in the north-westerly direction to hit the east coast of India. Very frequently these cyclones change their track and recurve towards the northerly or north-easterly direction to strike the coast of Bangladesh/Myanmar. Historical records of

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Figure 1. Map of Myanmar and its adjoining countries.

tropical cyclones in the Bay of Bengal show that lakhs of people died and property worth crores of rupees destroyed in the countries bordering this region. There can be little doubt that the number of casualties would have been considerably lower if the surge could have been predicted, say, 24 h in advance allowing effective warnings in the threatened areas.

Numerical modelling of storm surges associated with tropical cyclones in the Indian seas has been confined to the Bay of Bengal (Das, 1972; Johns and Ali, 1980; Johns *et al.*, 1981; Murty, 1984; Dube *et al.*, 1985a; Sinha *et al.*, 1986) and the Arabian Sea (Dube *et al.*, 1985b, 1997). Storm surge problem and their mitigation in the Bay of Bengal region are described by several workers (Murty *et al.*, 1986; Dube *et al.*, 1997). But, no attempt seems to have been made for modeling surges along the Myanmar coast which is also affected by tropical cyclones. Development of a numerical storm surge prediction system in this region is necessary to minimize the damage to life and property.

In view of this a location specific fine resolution (9 km×9 km) model is developed and applied to the coastal region of Myanmar. The analysis area of the model extends from 8° N to 23° N and 90° E to 100° E (Figure 2). The numerical model is a vertically integrated shallow water model which is fully non-linear. There are two open boundaries located at 8° N and at 90° E. At the open boundaries a radiation type of boundary condition is used. The bathymetry for the model is derived from the Earth-Topography-Five-Minute module (ETOPO5) from National Geophysical Data Center database (NGDC, 1988). A realistic bathymetry is generated by using a bilinear interpolation scheme. The analysis area of the model and the bottom topography are shown in Figure 2. Several numerical experiments are carried out to compute the extreme sea levels using the wind stress forcings representative of the 1975, 1982, 1992 and 1994 cyclones which affected this region. The model computed sea levels are found to be in agreement with the available estimates/observations. A sensitivity analysis was initially carried out by considering a grid resolution of 25 km × 25 km. However, with this coarse resolution the model could not adequately simulate the spatial distribution of surges along the Myanmar coast. Hence, we have chosen a grid size of 9 km × 9 km which gives results that are closer to the observed values.

2. Basic Equations

In the formulation of the model a system of rectangular Cartesian co-ordinates are used. The origin, O, is within the equilibrium level of the free surface, Ox points towards the west, Oy towards the south and Oz is directed vertically upwards. The displaced position of the free surface is given by $z=\zeta(x,y,t)$ and the position of the sea floor by $z=-h(x,y)$.

The depth averaged equations of continuity and momentum for the dynamical processes in the sea are given in the flux form by (Dube *et al.*, 1985a, b)

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

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

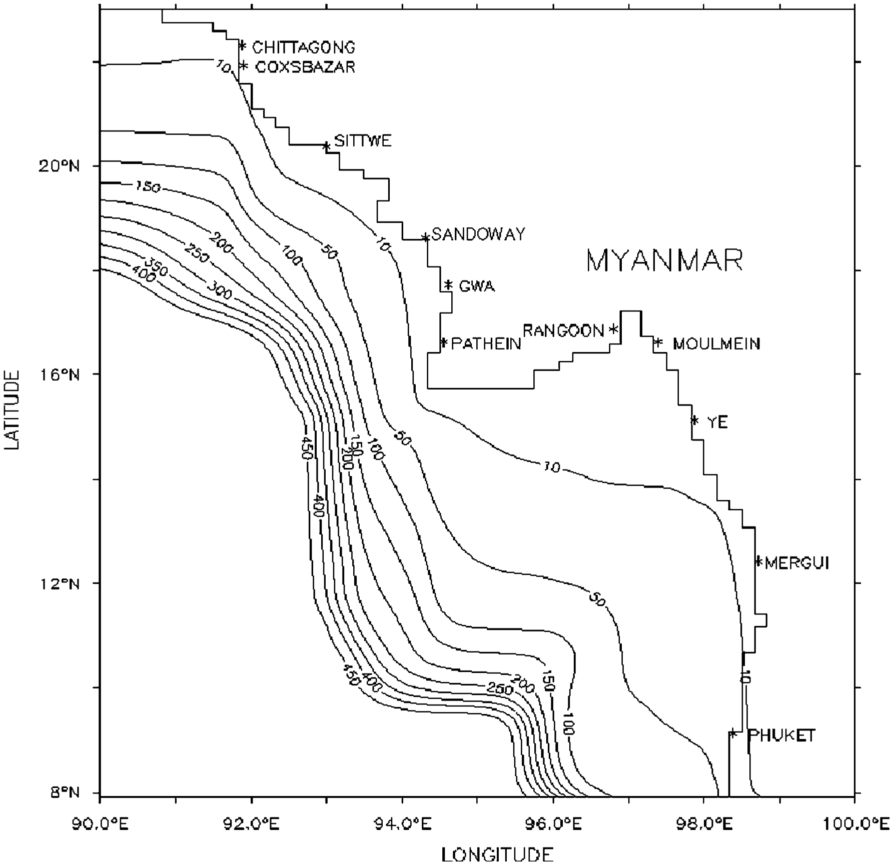

Figure 2. Analysis region and depth contours (m).

$$\frac{\partial \tilde{v}}{\partial t}+\frac{\partial}{\partial x}(u\tilde{v})+\frac{\partial}{\partial y}(v\tilde{v})+f\tilde{u}=-g(\zeta+h)\frac{\partial \zeta}{\partial y}+\frac{G_{\mathrm{s}}}{\rho}-\frac{c_{\mathrm{f}}\tilde{v}}{(\zeta+h)}(u^2+v^2)^{\frac{1}{2}} \quad (3)$$

where

$\tilde{u}=(\zeta+h)(u,v)$
u, v: averaged component of velocity in the direction of x, y, respectively,
ζ: sea surface elevation above the mean water level,
h: water depth,
t: time,
ρ: density of the sea water,
f : Coriolis parameter ($= 2\omega\sin\phi$),
g: acceleration due to gravity,
F_{S}, G_{S}: x and y components of the surface wind stress,
c_{f}: Bottom friction coefficient ($=2.6\times10^{-3}$).

The surface stresses are parameterized by a conventional quadratic law 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 the density of the air and u_a, v_a are the x and y components of the surface wind.

3. Boundary Conditions

The boundary and initial conditions take the form (Dube *et al.*, 1985a, b)

$$\begin{aligned} \tilde{u} &= 0 \quad \text{at the meridional boundaries} \\ \tilde{v} &= 0 \quad \text{along the latitudinal boundaries} \end{aligned} \tag{4}$$

and

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

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

$$v - \left(\frac{g}{h}\right)^{\frac{1}{2}} \zeta = 0 \quad \text{at } y = L \text{ (southern open sea boundary)} \tag{5}$$

$$u - \left(\frac{g}{h}\right)^{\frac{1}{2}} \zeta = 0 \quad \text{at the western open sea boundary} \tag{6}$$

Application of a radiation type of condition, as mentioned above, at the open sea boundary of a model allows the propagation of energy (disturbances) only outwards from the interior in the form of a simple progressive wave. It also helps to eliminate the transient response more quickly, as a result of the frictional dissipation in the system. Concerning its effectiveness Flather (1976) notes that the application of such a radiation condition in the numerical model may remove the unrealistically large currents and grid-scale oscillations in the vicinity of the open boundary, which may possibly be produced by the application of conventional open-sea boundary conditions.

4. Finite Difference Formulation

The predictive Equations (1)–(3) are solved numerically by considering a discrete set of grid points defined by

$$x = x_i = (i - 1)\Delta x, \quad i = 1, 2, 3, \ldots\ldots\ldots, m \text{ (even), and}$$
$$y = y_i = (i - 1)\Delta y, \quad i = 1, 2, 3, \ldots\ldots\ldots, n \text{ (odd)} \tag{7}$$

A sequence of time-instants is defined by

$$t = t_p = p\Delta t, \quad t = 0, 1, 2, \ldots\ldots\ldots \tag{8}$$

where Δx and Δy are the grid increments and Δt is the time step. The computations are performed on a staggered grid in the x, y plane, similar to that described by Johns and Ali (1980). The lateral boundaries of the finite difference grid are so constructed that the northern boundary ($y = 0$) and southern open sea boundary ($y = L$) consist of ζ-points and u-points. The western open-sea boundary consists of ζ-points and v-points. Meridional side-walls consist of u-points and the latitudinal side-walls consist of v-points. As there is no transport normal to a solid boundary, the u-component of the velocity vanishes along the y-directed boundaries and the v-component of the velocity vanishes along the x-directed boundaries. Thus, the boundaries are formed by joining u and v points so that the natural coast is approximated as closely as possible by a stepwise boundary configuration (Figure 2). The finite difference formulation and complete numerical treatment of the above Equations (1)–(5) can be found in Dube *et al.* (1985a, b).

5. Numerical Experimentation

The model has been used to compute the maximum surge associated with the cyclones that struck the Myanmar coast during 1975, 1982, 1992 and 1994. A conditionally stable semi-explicit finite difference scheme with staggered grid is used for the numerical solution of the model equations. The staggered grid consists of three distinct types of computational points on which the sea surface elevations and the zonal and meridional components of depth-averaged currents are computed. The wind stress forcing for driving the model has been computed by using the storm model of Jelesnianski and Taylor (1973). In the present model, with a fine resolution grid specification of 9 km$\times$9 km, it is found that computational stability is achieved with a time step of 60 s.

6. Results and Discussion

6.1. 1975 PATHEIN CYCLONE

A depression developed over the eastern Bay of Bengal on 4th May 1975 centered near 12.5° N and 96° E at 1200 UTC. The system moved north-westward and it intensified into a cyclonic storm by the evening of 5th May, centered near 14.5° N, 94.5° E. The system intensified further into a very severe cyclonic storm by 1200 UTC on 6th May and recurved towards the northeasterly direction. It continued its strength till 1200 UTC on 7th May before weakening to a cyclonic storm 6 h later on the same day. The system struck the coast of Myanmar north of Pathein on 7th May at about 1830 UTC.

In this experiment the cyclone track (Figure 3) and the relevant data are taken from Unisys Weather Information Systems (1975). Using this data a two day simulation of the surge generated by the 1975 Pathein cyclone was carried out, taking the radius of maximum winds as 20 km and the pressure drop of 22 hPa. Model computed surge contours are shown in Figure 3. It may be seen that the maximum surge of 1.2 m occurs towards the right of the landfall point near Pathein. The surge value at Rangoon is around 0.6 m. Also, the coastal stretch from Moulmein to Ye is affected

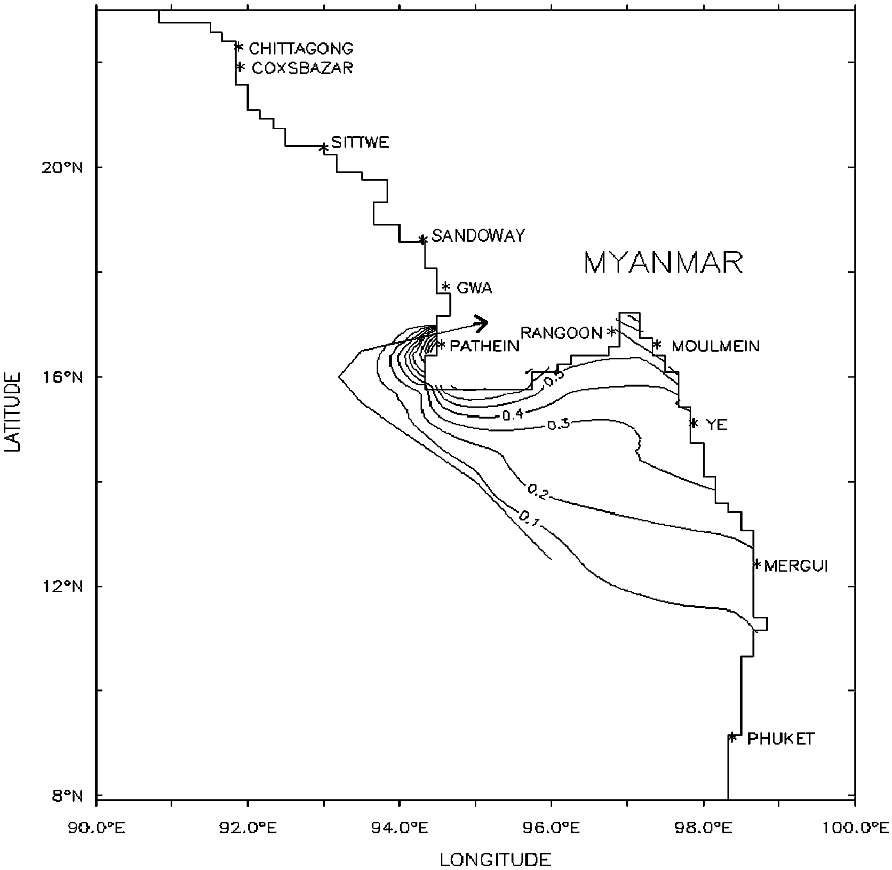

Figure 3. Surge contours (m) associated with 1975 Pathein cyclone.

by surges of 0.4–0.7 m. The computed surge height is found to be in agreement with the surge value 0f 1.0 m provided by the Unisys Weather Information Systems (1975).

6.2. 1982 GWA CYCLONE

A well marked depression formed over the southwest Bay on 30th April 1982 at 0600 UTC. Moving northwards it intensified into a deep depression on Ist May at 0000 UTC. The system developed into a cyclonic storm by 1200 UTC of Ist May and moved north-eastwards. It intensified into a severe cyclonic storm by 2nd May at 1200 UTC and moved eastwards. Thereafter, it further intensified into a very severe cyclonic storm on the same day after 6 h. The system gained further strength till 4th May at 1200 UTC with maximum wind speed of 62 ms^{-1}. Afterwards, it slightly weakened at 1800 UTC of the same day and finally crossed the coast around midnight of 4th May near Gwa. The track of the cyclone (Figure 4) and the relevant data are taken from the Unisys Weather Information Systems (1982).

The model is integrated with a pressure drop of 55 hPa and radius of maximum winds of 30 km. The model computed surge contours along the Myanmar coast are shown in Figure 4. A maximum surge of 4 m is predicted to the right of the landfall point near Gwa. During this cyclone the surge of the order of 4 m was reported along the Deltaic coast of Myanmar near Gwa (IOC-UNESCO, 1999). This is in good agreement with our simulated sea level elevations.

6.3. 1992 SANDOWAY CYCLONE

A depression developed over the central bay on 15th May 1992 centered at 0000 UTC near 9.6° N and 90.3° E. The depression continued to move in a northwesterly direction with a speed of 13 ms^{-1} till 16th May at 0600 UTC. The system intensified into a deep depression followed by a cyclonic storm by 17th May at 0000 UTC. It further intensified into a severe cyclonic storm by 18th May at 0000 UTC and moved north-eastwards. The system crossed the Myanmar coast north of Sandoway on 19th May at 0400 UTC.

The track of the cyclone (Figure 5) and the relevant data are taken from the Unisys Weather Information Systems (1992). Numerical experiments are carried out with a pressure drop of 25 hPa and radius of maximum winds of 20 km. The surge contours computed by the model are depicted in Figure 5. It may be seen that the maximum surge of 1.4 m occurred to the right of the landfall point near Sandoway. The surge values at Gwa and Pathein are 0.7 and 0.3 m, respectively. The observed maximum surge at Sandoway was reported to be 1.5 m (Unisys Weather Information Systems, 1992). This is in good in agreement with model computed surge height (Figure 5).

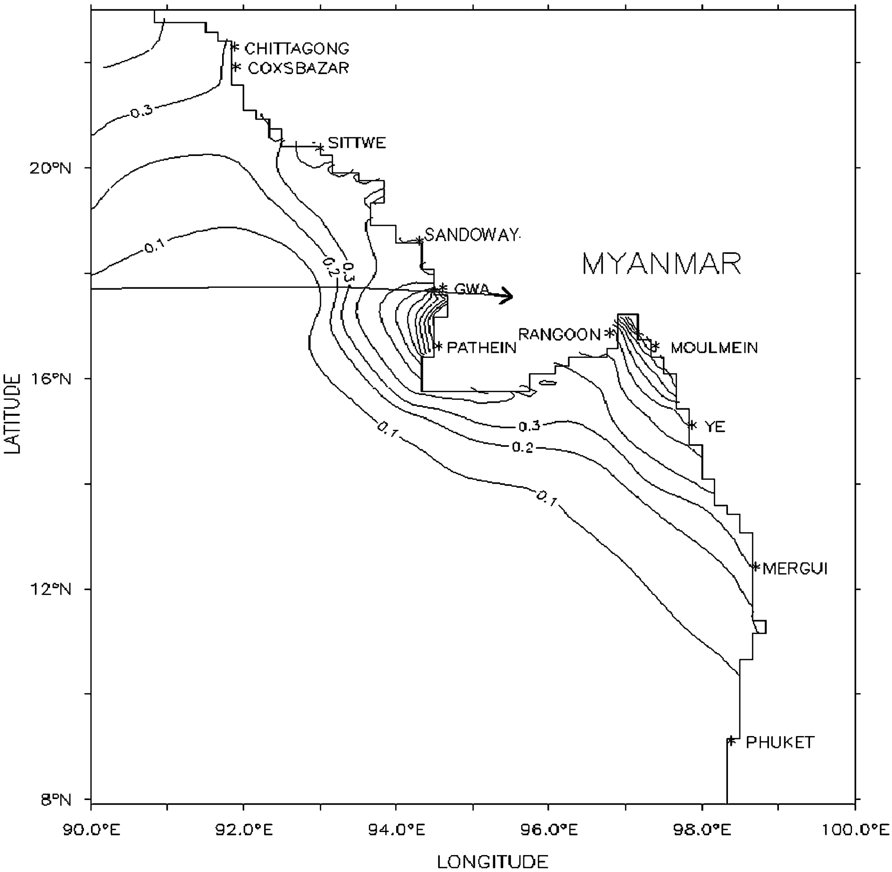

Figure 4. Surge contours (m) associated with 1982 Gwa cyclone.

6.4. 1994 SITTWE CYCLONE

A depression developed over the eastern bay on 27th April 1994 at 1200 UTC near 8° N, 94° E and continued till 1200 UTC of 28th April. It intensified into a deep depression after 6 h and further intensified into a cyclonic storm by 29th April at 0600 UTC. The system gained further strength to become severe cyclonic storm by 30th April at 0600 UTC and became very severe cyclonic storm on the same day at 1800 UTC. The system continued to gain strength and attained maximum wind speed of 64 ms^{-1} on 2nd May at 0600 UTC near 19.7° N, 91.7° E. Thereafter, it slightly weakened and crossed the coast north of Sittwe at about 1400 UTC on 2nd May.

The track of the cyclone (Figure 6) and the relevant data is taken from the Unisys Weather Information Systems (1994). Numerical experiments are carried out with a pressure drop of 50 hPa and radius of maximum

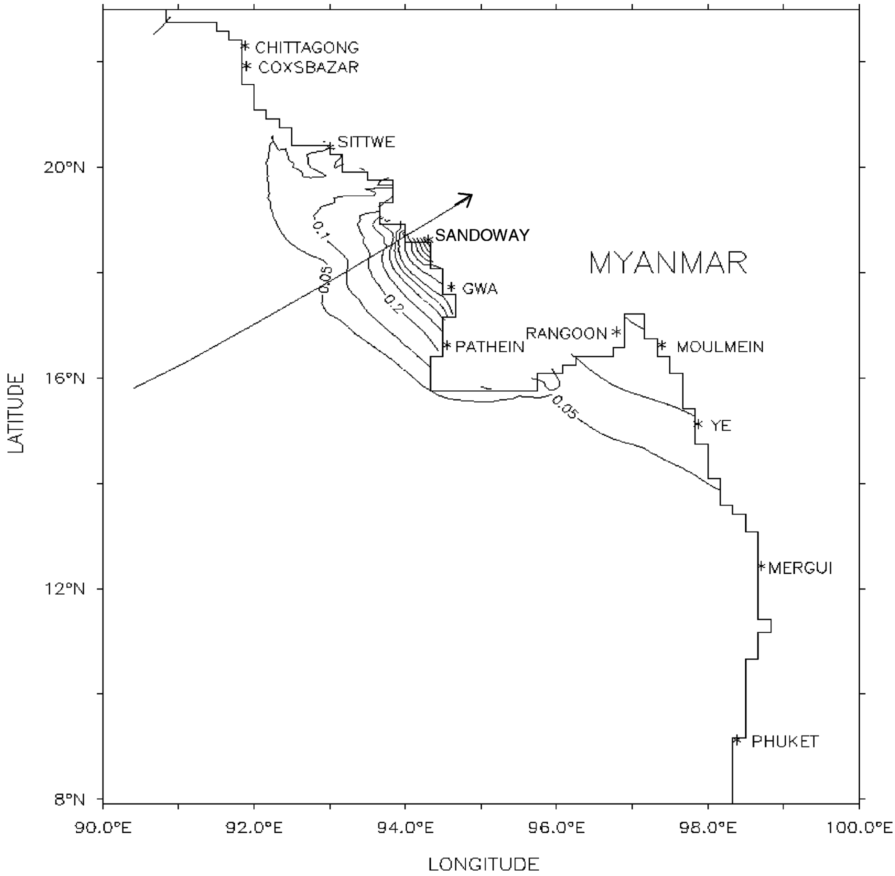

Figure 5. Surge contours (m) associated with 1992 Sandoway cyclone.

wind as 30 km. The surge contours computed by the model are shown in Figure 6. A maximum surge of 4 m is predicted to the right of the landfall point. Also, a surge of 3.7 and 0.8 m are predicted at Sittwe and Sandoway, respectively. Thus, it is found that more than 3.5 m surge is computed in the coastal stretch between the point of landfall and Sittwe. The computed results are found to be in agreement with the surge height of 3.7 m provided by Unisys Weather Information Systems (1994).

7. Conclusions

A fine resolution storm surge model has been described for the coast of Myanmar. Numerical experiments were carried out with a location specific high-resolution model using the data of 1975 Pathein, 1982 Gwa, 1992 Sandoway and 1994 Sittwe cyclones which crossed the Myanmar coast.

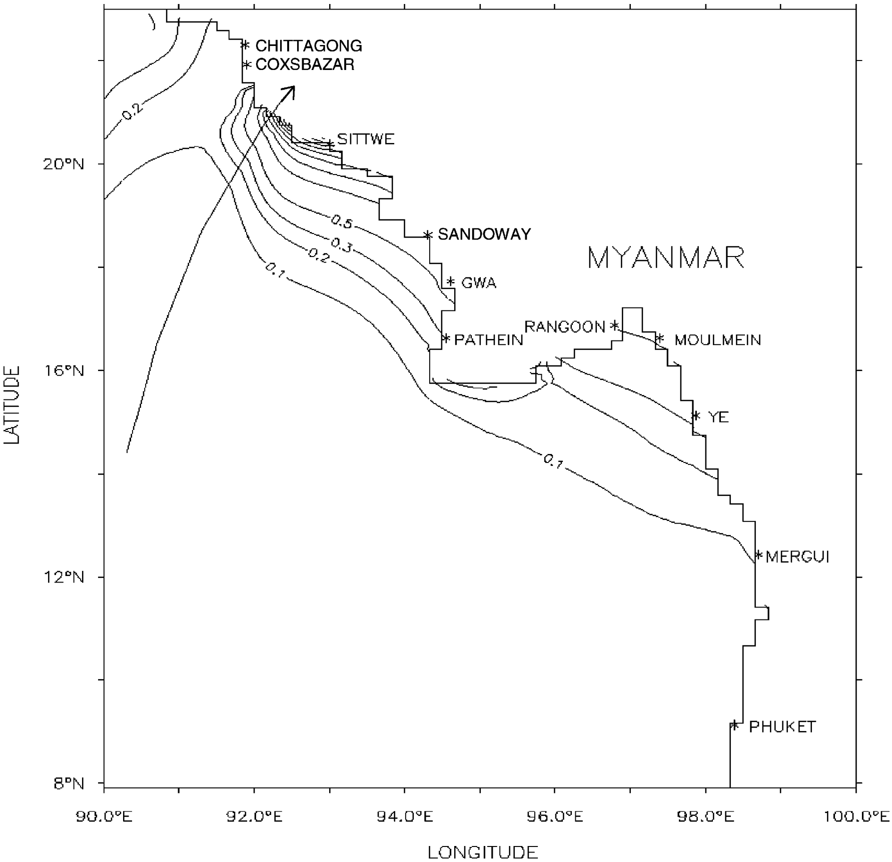

Figure 6. Surge contours (m) associated with 1994 Sittwe cyclone.

The model is able to simulate surges which are in broad agreement with the reported values. The results emphasize the suitability of a fine resolution location specific model for a reasonable prediction of surges along the Myanmar coast. The model may be used on a real time basis for predicting surges generated by a severe cyclonic storm which may strike the coast in this region.

A sensitivity analysis of the proposed model with varying grid resolution showed that the model with coarse resolution could not adequately simulate the spatial distribution of surges associated with the cyclone.

In the present study, the cyclonic storm is the sole driving force for the dynamical processes in the sea. Tidal solution has not been used to provide the initial conditions for the tide and surge interaction in the bay. Therefore, the non-linear interaction of surge and the tide has not been considered in this study. Such an interaction may be significant if the occurrence of the surge coincides with that of the high tide.

In general, if there is a break in the coast, such as a river, it provides an additional path to the water to escape into the river, instead of getting piled up. The numerical model used in the present study does not take into account the effect of Irrawady river which communicates with the eastern Bay of Bengal. However, the discharge of the fresh water carried by the river may modify the surge height along the Myanmar coast.

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