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Storm surges in the Gulf of Thailand

M. C. SINHA
Meteorological Office, New Delhi

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ABSTRACT. The paper describes a linear model for computing storm surges in the Gulf of Thailand. The coastal configuration of this Gulf is similar to the Bay of Bengal, but the seabed contours are different. There is no extensive shallow region in the Gulf of Thailand as in the Bay of Bengal. In this paper we compare the response of these two basins to forcing by an idealized storm.

1. Introduction

Many tropical cyclones move westwards from the south China sea across the Gulf of Thailand. Some of these cyclones generate storm surges in the coastal regions surrounding the Gulf of Thailand.

As we have developed a model for storm surges on the northern sector of the Bay of Bengal (Das *et al.* 1974, Das 1980 a, b, c), we felt it would be interesting to use the model for the Gulf of Thailand. We noted that both the northern part of the Bay of Bengal and the Gulf of Thailand have the same kind of coastal geometry, because they represent basins that are surrounded by a narrow concave coastline with an open sea boundary to the south. But, the two basins have different bottom topography. A surge prediction model will enable us to compare the response of these two basins. The purpose of this paper is to make such a comparision.

2. Symbols

The following symbols, which are not defined in the text, have been used:

C_0, C_D : Drag coefficients for surface and sea-bed friction

d : Unit grid length

f : Coriolis parameter ($2\Omega \sin \Phi$)

F_s, F_b : Components of surface and sea-bed friction towards the east

G_s, G_b : Components of surface and sea-bed friction to the north

h : depth of basin

ζ : surge amplitude

u, v : depth averaged currents of water towards the east and north respectively

u_a, v_a : Components of the wind towards the east and north respectively

p : sea level atmospheric pressure

$\triangle p$: pressure deficit at storm centre

r : radial distance from the storm centre

r_0 : radius of maximum winds

ρ : density of water

ρ_a : density of air

t : time

OX, OY : distances to the east and north respectively in a cartesian coordinate (OXYZ) system

3. Basic equations

We used the shallow water equations :

$$\frac{\partial u}{\partial t} - fv = - \frac{\partial \zeta}{\partial x} - \frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{1}{h+\zeta}(F_s - F_b) \quad (3.1)$$

$$\frac{\partial v}{\partial t} + fu = - \frac{\partial \zeta}{\partial y} - \frac{1}{\rho}\frac{\partial p}{\partial y} + \frac{1}{h+\zeta}(G_s - G_b) \quad (3.2)$$

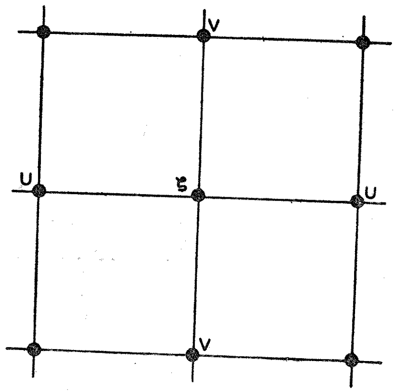

Fig. 1. Location of u, v, ζ points in staggered grid

$$\frac{\partial \zeta}{\partial t}+\left[\frac{\partial}{\partial x}\left\{(\zeta+h)\,u\right\}+\frac{\partial}{\partial y}\left\{(\zeta+h)\,v\right\}\right] = 0 \quad (3.3)$$

A quadratic law was used to represent the wind stress at the surface, and for the retarding effect of sea-bed friction. We put

$$F_s = C_0\, u_a\, (u_a^2 + v_a^2)^{\frac{1}{2}} \quad (3.4)$$

$$G_s = C_0\, v_a\, (u_a^2 + v_a^2)^{\frac{1}{2}} \quad (3.5)$$

and

$$F_b = C_D\, u\, (u^2 + v^2)^{1/2} \quad (3.6)$$

$$G_b = C_D\, v\, (u^2 + v^2)^{1/2} \quad (3.7)$$

We wish to emphasize that in (3.1), (3.2) and (3.3) we neglect non-linear terms, and the hydrostatic assumption is used for the vertical variation of pressure. As the equations use depth averaged velocity profiles, they also imply the neglect of certain small terms, such as $\overline{u^2} - \bar{u}^2$. These assumptions are justified for storm surge computation, unless we have a very shallow sea, as demonstrated by Johns (1979).

The governing equations were solved, numerically, by using finite differences to replace partial derivatives.

A horizontal staggered grid was used, and the location of the dependent variables is shown in Fig. 1.

Let us use the symbols m, n, and k for numbering the grid points in space and time We have

$$x=m.d, \quad y=n.d \quad \text{and} \quad t=k.\Delta t$$

here, $d = \Delta x = \Delta y$ is the unit grid interval.

The numerical algorithm first defined average values of u and v for each time step (k),

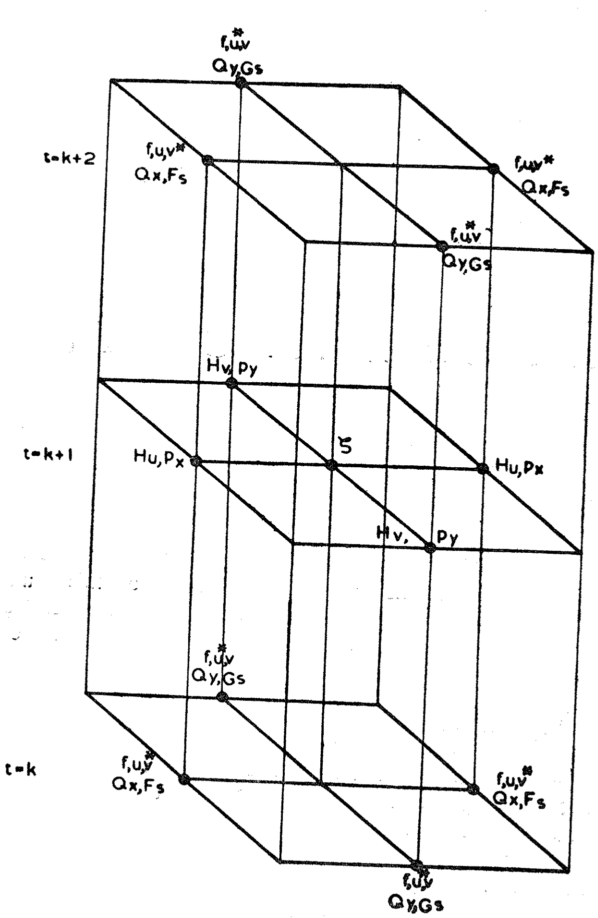

Fig. 2. Stagge red variables in space and time

$$u_*(m, n, k) = \tfrac{1}{4}\,[u\,(m+1, n+1) + u\,(m+1, n-1) + u\,(m-1, n+1) + u\,(m-1, n-1)] \quad (3.8)$$

$$v_*(m, n, k) = \tfrac{1}{4}\,[v\,(m+1, n+1) + v\,(m+1, n-1) + v\,(m-1, n+1) + v\,(m-1, n-1)] \quad (3.9)$$

The total depth of water $(h+\zeta)$ was similarly evaluated by using average values of ζ. We have for every value of k,

$$H_u\,(m, n) = h\,(m, n) + \tfrac{1}{2}\,[\zeta\,(m+1, n) + \zeta\,(m-1, n)] \quad (3.10)$$

$$H_v\,(m, n) = h\,(m, n) + \tfrac{1}{2}\,[\zeta\,(m, n+1) + \zeta(m, n-1)] \quad (3.11)$$

The components of the quadratic sea-bed friction were thereafter computed by using the values of u_*, v_* at k but H_u, H_v at $k+1$. We have :

$$Q_x\,(m, n, k) = 2C_D\,\Delta t\,[u^2\,(m, n, k) + v_*^2(m, n, k)]^{1/2} \div H_u\,(m, n, k+1) \quad (3.12)$$

$$Q_y\,(m, n, k) = 2C_D\,\Delta t\,[u_*^2\,(m, n, k) + v^2\,(m, n, k)]^{1/2} \div H_v\,(m, n, k+1) \quad (3.1$$

This averaging procedure was necessary because we had to compute Q_x, Q_y at every grid point (m, n), but u, v were not available at each m, n because of the staggered grid. A staggered grid enabled us to save computer memory and time. Details of the mode of computation are shown in Fig. 2.

New values of u, v were computed by using a mix between centred and forward time differences. Thus, we have

$$u(m, n, k+2) = [1 - Q_x(m, n, k)]\, u(m, n, k) + 2\Delta t\, f(n)\, v_*(m, n, k) - \frac{2\Delta tg}{d}\Big[\zeta(m+1, n, k+1) - \zeta(m-1, n, k+1)\Big] - \frac{2\Delta t}{d}\Big[p(m+1, n, k+1) - p(m-1, n, k+1)\Big] + 2\Delta t\, F_s(m, n, k) \div H_u(m, n, k+1) \quad (3.14)$$

$$v(m, n, k+2) = [1 - Q_y(m, n, k)]\, v(m, n, k) - 2\Delta t f(n)\, u_*(m, n, k) - \frac{2\Delta tg}{d}\Big[\zeta(m, n+1, k+1) - \zeta(m, n-1, k+1)\Big] - \frac{2\Delta t}{d}\Big[p(m, n+1, k+1) - p(m, n-1, k+1)\Big] + 2\Delta t\, G_s(m, n, k) \div H_v(m, n, k+1) \quad (3.15)$$

$$\zeta(m, n, k+1) = \zeta(m, n, k-1) - 2\Delta t[H_u(m+1, n, k-1)\, u(m+1, n, k) - H_u(m-1, n, k-1)\, u(m-1, n, k)] - 2\Delta t[H_v(m, n+1, k-1)\, v(m, n+1, k) - H_v(m, n-1, k-1)\, v(m, n-1, k)] \quad (3.16)$$

Dube *et al.* (1981) have studied the effect of defferent pressure and wind profiles on storm surges. In the present study the pressure distribution for an idealized circular symmetric cyclone was

$$p = 1010 - \Delta p / [1 + (r/r_0)^2] \quad (3.17)$$

where, Δp is the pressure anomaly at the centre of the vortex, and r_0 is the radius of the eye. The distribution of winds corresponding to this vortex is

$$U_a = 2 \times 13 \times \Delta p \times (r/r_0)^2 \div [1 + (r/r_0)^2]^2$$

where, $U_a = |u_a\mathbf{i} + v_a\mathbf{j}|$ and $\mathbf{i}$, $\mathbf{j}$ are unit vectors along OX and OY.

Dube *et al.* (1981) find this gives a little overestimate of the wind very near the storm centre ($r \leq 80$ km). We have not investigated this aspect in the present paper.

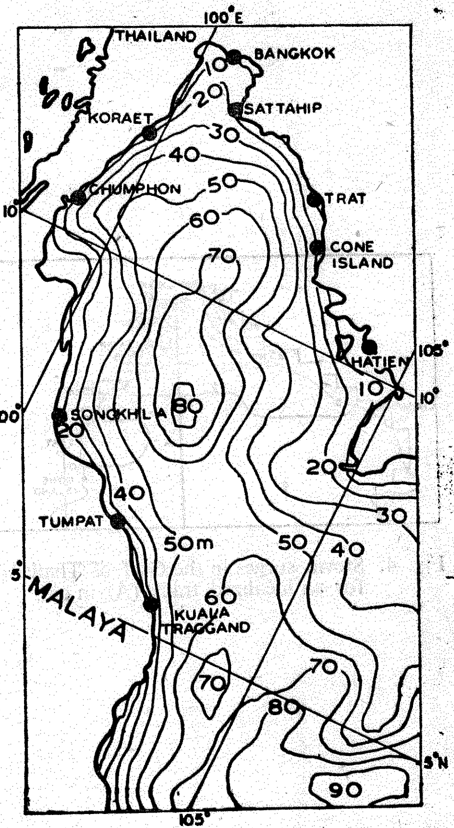

Fig. 3. Sea-bed contours (m) of the Gulf of Thailand

4. Boundary conditions

We prescribed no normal flow across the land boundaries but, on the open boundary facing the sea, we put

$$v(m, 1, k) = v(m, 2, k)$$

at the southern boundary.

On the eastern boundary, we put

$$u(M, n, k) = u(M-1, n, k)$$

It was realised that these open-sea boundary conditions were to some extent unrealistic but, in the absence of data, we adopted these boundary conditions as being the simplest possible.

5. Results

The grid adopted for this study is shown in Fig. 3 which also shows the sea-bed contours of the Gulf of Thailand. We note that, unlike the northern sector of the Bay of Bengal, there is no extensive shallow region to the north of the Gulf. Moreover, an additional difficulty with the Gulf of Thailand is the fact that we have to contend with two open-sea boundaries, while the Bay of Bengal had only one open boundary.

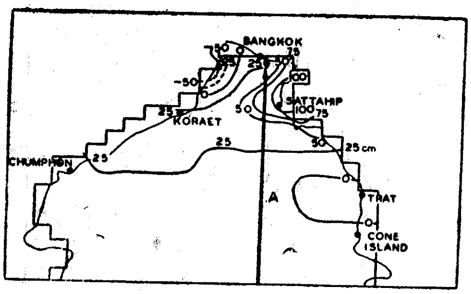

Fig. 4. Storm surges in the Gulf of Thailand for an idealized track (A) in cm.

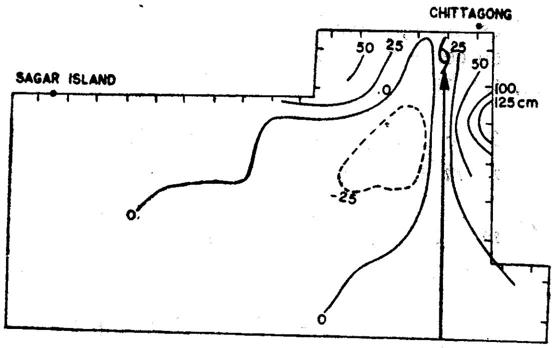

Fig. 5. Surges for a similar track as in Fig. 4 but for the Bay of Bengal (cm)

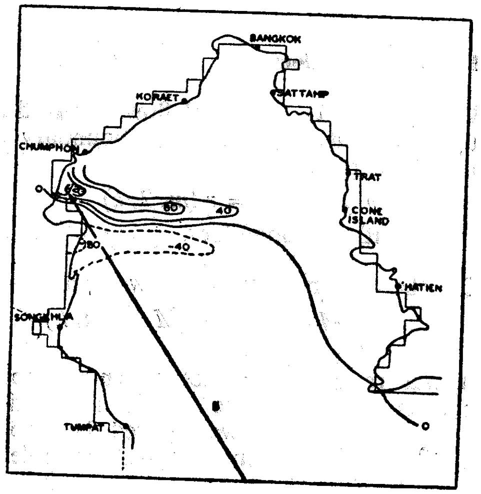

Fig. 6. Storm surges for track (B) in cm

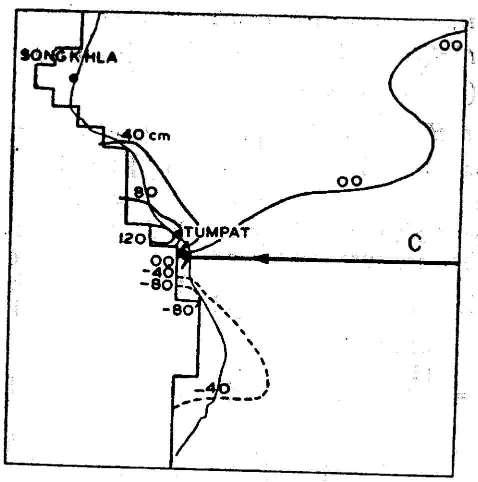

Fig. 7. Growth of the total kinetic energy in the Gulf of Thailand with the movement of storm along track (C)

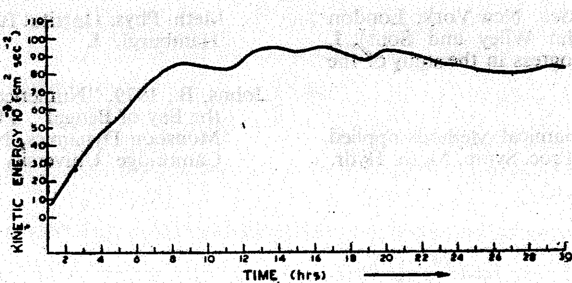

Fig. 8. Growth of total kinetic energy in the Gulf of Thailand with the movement of storm along track (A)

We computed surge amplitudes for the Gulf of Thailand by considering three idealized storm tracks for a storm with central pressure deficit of 50 mb and moving with a constant speed of 20 km per hour.

The distribution of storm surges in the Gulf of Thailand for a storm moving along a track (A) towards Bangkok is shown in Fig. 4. For a similar situation in the head Bay of Bengal, surges were computed for a northerly track towards the Sunderbans. Fig. 5 provides a picture of the areal distribution of surges for storm. On comparing the two basins, we see that the Gulf of Thailand has a negative surge of about 50 cm to the left of the storm, and a positive surge of more than a metre to the right of the track. But, for the Bay of Bengal over most of the shallow region a positive surge of more than 50 cm on both sides of the track develops. Negative surges generated by the model for the Bay of Bengal are very small.

Similarly, the storm surge for another idealized track (B) in the Gulf of Thailand is shown in Fig. 6. Surges for another idealized track (C) is shown in Fig. 7.

6. General remarks about the programme

Fortyeight hour simulation of the surge took about 80 minutes of computer time on an IBM 360/44 computer for a grid of 26 by 50 points. The programme could be made to simulate the surge for any track, and for any speed or intensity of the storm. It could be also used for estimating the surge on real time. The storm intensity, speed and track are read as input data and they could be used for any location in the Gulf of Thailand.

7. Energy considerations

The finite difference schemes and approximations are consistent and conserve energy. Modified versions of this scheme have been used by Hansen (1962 a, b) and Grijalva (1962, 71). The scheme was found to be very stable. The kinetic energy

$$K = \frac{1}{2}(u^2+v^2)$$

was computed for the duration of the surge growth. Its variation with time is shown in Fig. 8. The figure shows that when the storm was moving close to the Cambodia-Vietnam coast, the kinetic energy increased and remained steady up to the time of landfall.

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