3D-Perspective Visualization of Storm Surge:

Killer Storm of 29 April 1991

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Minimum Configuration of Computer:

a) IBM Compatible Personal Computer (PC)

1) Processor : P-IV, 1.8 GHz,
2) RAM : 128 MB
3) OS : Linux/Unix
4) Minimum 2 GB Free space on HDD
5) GMT (Generic Mapping Tool) PC Linux/Unix Version

OR b) Workstation

1) Processor : RISC-6000
2) RAM : 512 MB
3) OS : Unix
4) GMT (Generic Mapping Tool) Unix Workstation Version

1.1 Introduction

North Indian ocean is one of the regions in the world which is frequently affected by storm surges associated with tropical cyclones. Statistics show that about about 5 % of the global tropical cyclones form over the Bay of Bengal. On an average, 5 to 6 storms form in this region every year. But casualties here is 80% of the global casualties. Loss of life and property is mainly attributed to the storm surge. The Great Killer Cyclone of 12 November 1970 took away lives of 300,000 people. According to Frank and Hussain (1971) about 90% of marine fishermen suffered casualties and about 65% of total annual fishing capacity of coastal areas were destroyed. Again the 29 April 1991 Cyclone hit Chittagong coast and killed 138,882 people.

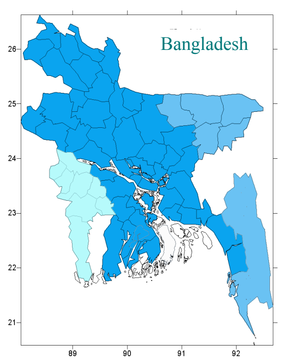
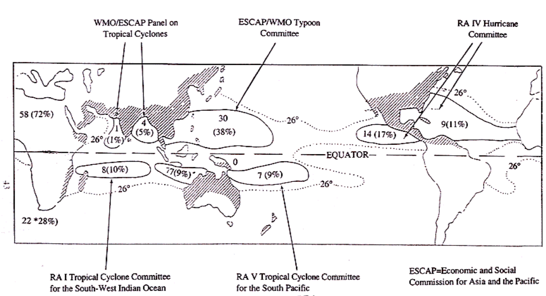


Fig. 1: Complex coastal Geometry

Long continental shelf, shallow bathymetry, complex coastal Geometry with lots of kinks and islands, and long tidal range between east and west coasts of Bangladesh are well-known features for the highest storm surge and of the longest duration.



The global occurrence (numbers and percentages) of tropical cyclones. Cyclones form only where sea temperatures exceed 26°C (dotted line); the land areas affected are shown hatched (after W. M. Gray, 1975). The names of tropical cyclone bodies and the basins covered by their programmes are also indicated.

Fig. 2: Global Distribution of Cyclones and Area of Cyclogenesis

1.2 Storm Surge

Storm surges are produced when tropical cyclones pass over the continental shelf. Winds associated with tropical cyclones are the main driving force for accumulation of the water on the shore-line which, in turn, results in a sudden and substantial rise in sea level. This abnormal rise in sea level above the astronomical tide, which reaches a maximum on the coast, normally at the time of the landfall of the cyclone, is called storm surge. Storm surges are atmospherically forced oscillations of the water level in a coastal or inland water body, in the range of a few hours to a few days, depending upon the speed of the cyclone. These come under long gravity waves which are often 100 km wide with an amplitude at times higher than 5m. The more intense the storm, the stronger the waves. If the occurrence of storm surge coincides with normal astronomical tide the total rise in the water level may be spectacular.

1.3 Damages Due to Storm Surge

Storm surges cause heavy loss of life and property. The destruction associated with storm surges rank them as one of the foremost natural disasters some times even surpassing earthquakes. About 60 % of all deaths due to storm surges have occurred in the low-lying coastal areas of the countries bordering Bay of Bengal and the adjoining Arabian Sea (Murty, 1986; Dube et al., 1997). In 1970, one of the most devastating cyclones of the century struck Meghna estuary of Bangladesh killing about 300,000 people. 1991 April Cyclone made landfall near Chittagong which tolled about 1,38,000 people. In both the cases, time of landfall coincided with the time of high astronomical tides (at night) and so loss of lives were colossal.

2. Storm Surge Modeling

If surges could be predicted accurately well in advance then loss of lives might be minimized. Various techniques such as empirical, statistical, analytical and numerical are employed for the prediction of storm surges around the world. In general empirical and statistical methods require several years of observations on vast shelf areas which are difficult to obtain. In recent years numerical methods have been used effectively to predict storm surges. The numerical technique consists of solving the governing equations at a discrete set of points in space and time. Real time prediction is being improved with the development of high-resolution location specific models.

Storm Surge

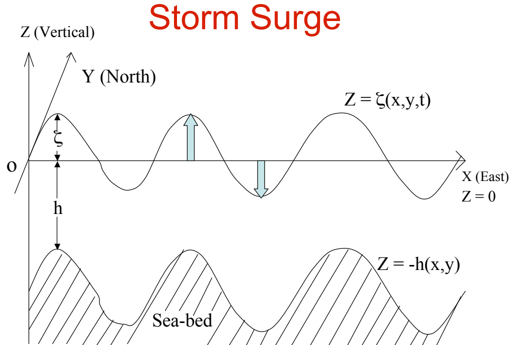


Fig. 3: Storm Surge

Storm Surge Stages

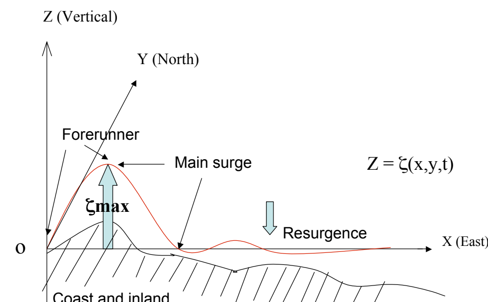


Fig. 4: Storm Surge Stages

2.1 Data Input for Storm Surge Prediction

a) Oceanographic and hydrographic data

i) bathymetry,
ii) astronomical tides, and
iii) inshore currents in closed regions.

b) Meteorological input

i) pressure drop,
ii) maximum sustained winds,
iii) radius of the maximum winds,
iv) vector motion of the storm,
v) point of landfall, and
vi) duration of the storm.

c) Hydrological input

i) river discharge in the sea, and
ii) rainfall distribution.

2.2 Numerical Modeling of Storm Surges in Indian Seas

Numerical modeling of storm surges in the Indian seas (Bay of Bengal and Arabian sea) was pioneered by Das (1972). He conducted a numerical experiment and computed the surge generated by an idealised cyclone striking the coast of Bangladesh. The importance of this work is that it demonstrated for the first time application of numerical techniques in storm surge problems in the Bay of Bengal, and it has since inspired many researchers in this field.

3 Basic equations

In the formulation of the model, the sphericity of the earth's surface is ignored. A system of rectangular Cartesian coordinates is used in which the origin, O, is in the equilibrium level of the sea surface. Ox points towards the east, Oy points towards the north and Oz is directed vertically upwards (Fig 3). 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 basic hydrodynamic equations of continuity and momentum for the dynamical process in the sea may be given by

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \qquad (1)$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}-fv=\frac{1}{\rho}\frac{\partial p}{\partial x}+\frac{1}{\rho}\frac{\partial \tau_x}{\partial z} \qquad (2)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}+fu=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\frac{1}{\rho}\frac{\partial \tau_y}{\partial z} \qquad (3)$$

$$\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}-g \qquad (4)$$

where,

u,v,w : Renolds averaged component of velocity in the direction of x ,y, and z respectively,

t : time,
p : pressure,
ρ : density of the seawater supposed homogenous and incompressible,
f : Coriolis parameter, $f = 2\omega\sin\phi$
g : acceleration due to gravity,
τ_x,τ_y : x and y components, respectively, of the frictional stress (Reynolds stress).

Molecular viscosity has been neglected in these equations. The terms τ_x and τ_y are included to model vertical turbulent diffusion. Denoting the wind stress and bottom stress components as (F_S, G_S) and (F_B, G_B) respectively and the surface pressure as p_a, the boundary conditions become,

$$u=v=w=0 \quad \text{at } z=-h$$

$$(\tau_x,\tau_y)=(F_B,G_B) \quad \text{at } z=-h \qquad (5)$$

$$(\tau_x,\tau_y)=(F_s,G_s) \quad \text{at } z=\zeta$$

$$p=p_a \quad \text{at } z=\zeta$$

$$\frac{\partial \zeta}{\partial t}+u\frac{\partial \zeta}{\partial x}+v\frac{\partial \zeta}{\partial y}=w \quad \text{at } z=\zeta \qquad (6)$$

The last condition is the kinematic surface condition and expresses the fact that the free surface is materially following the fluid.

Since the main objective of the paper lies in the prediction of long waves in shallow coastal waters, it is reasonable to assume that the wavelength is large compared to the depth. With this assumption, it may be shown (Welander, 1961) that equation (4) reduces to the hydrostatic pressure aproximation

$$\frac{\partial p}{\partial z}=-\rho g \qquad (7)$$

The principal equations (1), (2), (3) and (7) could be solved, but the procedure would be laborious because of the presence of the vertical coordinate. Unlike problems of the atmosphere, a boundary layer would need to be designed both at the top and bottom of the domain of integration. There is insufficient knowledge about the flow in such boundary layers.

To get over this difficulty, a simplification is generally introduced by integrating the governing equations in the vertical. The unknown dependent variables are then (a) the water transport (or mean current) and (b) the surface height. This procedure has commonly been adopted for storm surge computations because the water level is of primary importance. Integrating (1) to (3) in the vertical from $z = -h$ to $z = \zeta$ and using conditions (5) to (7) we get

$$\frac{\partial \zeta}{\partial t}+\frac{\partial}{\partial x}[(\zeta+h)\bar{u}]+\frac{\partial}{\partial y}[(\zeta+h)\bar{v}]=0 \qquad (8)$$

$$\frac{\partial \bar{u}}{\partial t}+\bar{u}\frac{\partial \bar{u}}{\partial x}+\bar{v}\frac{\partial \bar{u}}{\partial y}-f\bar{v}+\frac{1}{(\zeta+h)}\left[\frac{\partial}{\partial x}(\zeta+h)(\overline{u^2}-\bar{u}^2)+\frac{\partial}{\partial y}(\zeta+h)(\overline{uv}-\bar{u}\bar{v})\right]$$
$$=-g\frac{\partial \zeta}{\partial x}-\frac{1}{\rho}\frac{\partial p_a}{\partial x}+\frac{1}{(\zeta+h)\rho}\left[F_s-F_B\right] \qquad (9)$$

$$\frac{\partial \bar{v}}{\partial t}+\bar{u}\frac{\partial \bar{v}}{\partial x}+\bar{v}\frac{\partial \bar{v}}{\partial y}+f\bar{u}+\frac{1}{(\zeta+h)}\left[\frac{\partial}{\partial x}(\zeta+h)(\overline{uv}-\bar{u}\bar{v})+\frac{\partial}{\partial y}(\zeta+h)(\overline{v^2}-\bar{v}^2)\right]$$
$$=-g\frac{\partial \zeta}{\partial y}-\frac{1}{\rho}\frac{\partial p_a}{\partial y}+\frac{1}{(\zeta+h)\rho}\left[G_s-G_B\right] \qquad (10)$$

where over bars denote the depth averaged values, e. g.,

$$(\bar{u},\bar{v})=\frac{1}{(\zeta+h)}\int_{-h}^{\zeta}(u,v)\,dz, \qquad (11)$$

$$(\overline{u^2},\overline{v^2})=\frac{1}{(\zeta+h)}\int_{-h}^{\zeta}(u^2,v^2)\,dz, \qquad (12)$$

$$(\overline{uv})=\frac{1}{(\zeta+h)}\int_{-h}^{\zeta}uv\,dz, \qquad (13)$$

In most of the storm surge simulation models, the non-linear advective terms have been neglected mainly on the basis of scale analysis. This is justifiable when the characteristic amplitude of the surge is smaller than the characteristic depth of the basin. But in shallow water regions, particularly at the head of the Bay of Bengal, the non-linear terms are of special importance and must be retained in the formulation. However, the retention in (9) of terms such as $(\overline{u^2},\bar{u}^2)$ leads to a fundamental difficulty as they cannot be evaluated within the framework of a vertically integrated model. In many well - documented applications of non-linear vertically integrated equations (8) to (10), it is usual to make assumptions typified by

$$(\overline{u^2}-\bar{u}^2)=0, \qquad (14)$$
$$(\overline{v^2}-\bar{v}^2)=0,$$
$$(\overline{uv}-\bar{u}\bar{v})=0 \qquad \bar{u} \quad and \quad \bar{v}$$

This is equivalent to saying that the currents do not vary significantly in the vertical and the flow is dominated by the midstream flow. The validity of the assumption (14) has been demonstrated by Nihoul (1975) and Johns (1981). In the latter work it has been found that

$$(\bar{u}^2/\overline{u^2})<1.04 \qquad (15)$$

for all instants of time.

Additionally, a parameterisation of the bottom stress must be made in terms of the depth-averaged current. This is frequently done by conventional quadratic law

$$F_B=\rho c_f\,\bar{u}\,(\bar{u}^2+\bar{v}^2)^{\frac{1}{2}}$$
$$G_B=\rho c_f\,\bar{v}\,(\bar{u}^2+\bar{v}^2)^{\frac{1}{2}} \qquad (16)$$

where $c_f = 2.6 \times 10^{-3}$ is an empirical bottom friction coefficient.

The validity of (16) is also questionable on the grounds that it attempts to relate the bottom stress to purely local conditions in the averaged flow. Some other models use a form of bottom stress, which is dependent on the surface stress. An example is

$$F_B=-5\,c_f\,F_S+c_f^{\,2}\,\rho\bar{u}(\bar{u}^2+\bar{v}^2)^{\frac{1}{2}}$$

$$G_B=-5\,c_f\,F_S+c_f^{\,2}\,\rho\bar{v}(\bar{u}^2+\bar{v}^2)^{\frac{1}{2}} \qquad (17)$$

It may appear surprising that the surface stress is also included in (17). This is because sea -bed friction is largely determined by the current profile above the sea-bed which, in turn, is dependent on the vertical gradient of the current near the surface.

However, substituting the values from (14) and (16) into the equations (9) and (10), we get (the over bars have been dropped for convenience)

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}-f\,v=-g\frac{\partial \zeta}{\partial x}-\frac{1}{\rho}\frac{\partial p_a}{\partial x}+\frac{1}{(\zeta+h)}\left[\frac{F_S}{\rho}-c_f\,u\,(u^2+v^2)^{\frac{1}{2}}\right] \qquad (18)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+f\,u=-g\frac{\partial \zeta}{\partial y}-\frac{1}{\rho}\frac{\partial p_a}{\partial y}+\frac{1}{(\zeta+h)}\left[\frac{G_S}{\rho}-c_f\,v\,(u^2+v^2)^{\frac{1}{2}}\right] \qquad (19)$$

For numerical treatment, it is convenient to express equations (18) and (19) in flux form as

$$\frac{\partial}{\partial t}[(\zeta+h)u]+\frac{\partial}{\partial x}[(\zeta+h)uu]+\frac{\partial}{\partial y}[(\zeta+h)uv]-f(\zeta+h)v=$$
$$-g(\zeta+h)\frac{\partial \zeta}{\partial x}-\frac{1}{\rho}(\zeta+h)\frac{\partial p_a}{\partial x}+\frac{F_S}{\rho}-c_f\,u\,(u^2+v^2)^{\frac{1}{2}} \qquad (20)$$

$$\frac{\partial}{\partial t}[(\zeta+h)v]+\frac{\partial}{\partial x}[(\zeta+h)uv]+\frac{\partial}{\partial y}[(\zeta+h)vv]+f(\zeta+h)u=$$
$$-g(\zeta+h)\frac{\partial \zeta}{\partial y}-\frac{1}{\rho}(\zeta+h)\frac{\partial p_a}{\partial y}+\frac{G_S}{\rho}-c_f\,v\,(u^2+v^2)^{\frac{1}{2}} \qquad (21)$$

The equation (8), (20) and (21) can be written for the sake of simplicity as

$$\frac{\partial \zeta}{\partial t}+\frac{\partial \tilde{u}}{\partial x}+\frac{\partial \tilde{v}}{\partial y}=0 \qquad (22)$$

$$\frac{\partial \tilde{u}}{\partial t}+\frac{\partial}{\partial x}(u\tilde{u})+\frac{\partial}{\partial y}(v\tilde{u})-f\tilde{v}=-g(\zeta+h)\frac{\partial \zeta}{\partial x}-\frac{1}{\rho}(\zeta+h)\frac{\partial p_a}{\partial x}+\frac{F_s}{\rho}-\frac{c_f\tilde{u}}{(\zeta+h)}(u^2+v^2)^{\frac{1}{2}} \qquad (23)$$

$$\frac{\partial \tilde{v}}{\partial t}+\frac{\partial}{\partial x}(u\tilde{v})+\frac{\partial}{\partial y}(v\tilde{v})+f\tilde{u}=-g(\zeta+h)\frac{\partial \zeta}{\partial y}-\frac{1}{\rho}(\zeta+h)\frac{\partial p_a}{\partial y}+\frac{G_s}{\rho}-\frac{c_f\tilde{v}}{(\zeta+h)}(u^2+v^2)^{\frac{1}{2}} \qquad (24)$$

Three basic equations of the numerical model where $\tilde{u} = (\zeta + h)u$ *and* $\tilde{v} = (\zeta + h)v$ are new prognostic variables and $(\zeta+h)$ gives the total depth of the basin.

The equation of continuity (22) along with the two momemtum equations (23) and (24) form the three basic equations of the numerical model. It consists of a set of three coupled equations for the unknowns u, v and ζ. The forcing terms in these three equations arise out of (i) Coriolis terms, (ii) the inverted barometric effect i.e. $\frac{\partial p_a}{\partial x}$ *and* $\frac{\partial p_a}{\partial y}$ due to fall in atmospheric pressure, (iii) the component of wind stress (F_S, G_S) and (iv) the bottom stress component. (F_B, G_B).

If these forcing terms could be specified by meteorological data and the geometry of the continental shelf then the problem would be solved by numerical integration. The response in the sea at any instant $t > 0$ then determines the surge heights.

Before proceeding to the numerical integration, it is necessary to have certain boundary and initial conditions.

3.1 Boundary and initial conditions

In addition to the fulfillment of the surface and bottom conditions (5) and (6), appropriate conditions have to be satisfied along the lateral boundaries of the sea area under consideration for all time. Theoretically the only boundary condition needed in the vertically integrated system is that the normal transport vanish at the coast, i.e.,

$$u\cos\alpha + v\sin\alpha = 0 \quad \text{for all} \quad t \geq 0 \qquad (25)$$

where α denotes the inclination of the outward directed normal to the x-axis. It then follows that $u = 0$ along the y-directed boundaries and $v = 0$ along the x-directed boundaries.

At the open-sea boundary, the normal currents across the boundary may be prescribed, yielding a condition such as (25) modified by a non = zero term on the right hand side of the equation. Alternatively, a radiation type of condition may be applied, which leads to (Heaps, 1973)

$$u\cos\alpha + v\sin\alpha + \left(\frac{g}{h}\right)^{\frac{1}{2}}\zeta = 0 \qquad (26)$$

Application of a radiation type of condition (26) at the open sea boundary of a model allows the propagation of energy (disturbances) only outwards from the interior in the form of simple progressive waves. 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 application of 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 condition (i.e., $\zeta = 0$ at $y=0$).

As usual it is assumed that the motion in the sea is generated from an initial state of rest, so that

$$\zeta = u = v = 0 \text{ everywhere for } t = 0. \qquad (27)$$

3.2 Determination of forcing functions

As already mentioned, the forcing terms in the prediction equations (22)-(24) are the Coriolis force, the surface pressure, wind stress components and the seabed friction. The surge is generated by an idealised cyclone, of constant strength, tracking across the analysis area with constant speed. In view of the strong ssociated winds and consequently high values of the wind stress forcing, the forcing due to barometric changes $\frac{\partial p_a}{\partial x}$ *and* $\frac{\partial p_a}{\partial y}$ may be neglected in the surge prediction models. Further, the Coriolis force can be determined by knowing the latitudinal position of the area and the bottom stress may be parameterised in terms of depth averaged currents by a quadratic law. The problem thus remains to compute the surface winds and the wind stresses.

So far no good theory exists on which a computation of the surface winds can be based. A number of numerical models use the model storms in which the wind speed is related to the pressure gradient. The pressure field is specified by

$$p(r) = p(\infty) - \frac{\Delta p}{[1+(r/R)^2]^{1/2}} \qquad \text{(Isozaki, 1970)} \qquad (28)$$

$$p(r) = 1010 - \frac{\Delta p}{[1+(r/R)^2]} \qquad \text{(Das et al., 1974)} \qquad (29)$$

$$p(r) = p(\infty) - \Delta p \exp(-r/R) \qquad \text{(John and Ali, 1980)} \qquad (30)$$

where p (r) and p (∞) represent sea level pressure at r and at the cyclone periphery, R is the radius of maximum winds and Δp is the pressure drop.

The wind distribution in the cyclone is then calculated from the cyclostrophic wind or gradient wind formula. The cyclostrophic wind corresponding to the pressure field given by (29) is

$$V^2 = 4V_m^2[\mu^2 \div (1+\mu^2)^2] \qquad (31)$$

where $\mu = r/R$ and V_m is the maximum wind at R. The maximum wind (in knots) and the pressure drop (mb) may be related by

$$V_m = C(\Delta p)^{\frac{1}{2}} \qquad \text{(nothing but Fletcher's Formula)} \qquad (32)$$

where C is a numerical constant.

Johns and Ali (1980) use the following gradient wind formula for computing the wind distribution corresponding to the pressure field (30)

$$V = -\frac{fr}{2} + \left[\frac{f^2r^2}{4} + \frac{r}{\rho_a}\frac{\partial p}{\partial r}\right]^{\frac{1}{2}} \qquad (33)$$

where ρ_a is the density of the air, taken as 1.293 kg m^{-3}.

A number of other cyclone models compute the wind field by one of the following expressions

$$V = V_m\left(\frac{r}{R}\right)^{3/2}, 0 \leq r \leq R \qquad \text{, (Jelseninanski, 1965)} \qquad (34)$$

$$V = V_m\left(\frac{R}{r}\right)^{1/2}, r > R \qquad , \qquad (35)$$

$$V = V_m\left(\frac{2Rr}{R^2+r^2}\right) \qquad \text{(Jelesnianski, 1972)} \qquad (36)$$

With the surface winds estimated one can proceed to the computation of the stress at the sea surface. The surface stress is expressed by conventional quadratic law as

$$F_S = \rho_a c_D u_a (u_a^2 + v_a^2)^{\frac{1}{2}}$$
$$G_S = \rho_a c_D v_a (u_a^2 + v_a^2)^{\frac{1}{2}} \qquad (37)$$

where u_a and v_a are the x and y components of surface wind, c_D is the drag coefficient. Observational studies suggest that the drag coefficient may be related to the wind speed by

$$c_D = (1.00 + 0.07\,v_{10}) \times 10^{-3} \qquad (38)$$

in which v_{10} is the wind speed at 10m from the mean sea level. This expression is generally valid for wind speed less than 14 m sec^{-1}. At wind speeds between 10 and 30 m sec^{-1}, c_D varies from 2 x 10^{-3} to 3 x10^{-3} with no significant dependence on wind speed. Most of the workers use an uniform value of drag coefficient (=2.8 x 10^{-3}).

4 Formulation of the model

4.1 Introduction

This model is a coastal zone model which covers an analysis area from 6° N to 22° N and 80 ° E to 90°E. The model has the fixed eastern boundary at about 250 km from the east coast of India at $x=b_2(y)$. The treatment of the coastal boundaries involve a procedure leading to a realistic curvilinear representation of both the western and the eastern sides of the Bay of Bengal. The model also incorporates the increased resolution adjacent to the coastline.

For the formulation of the model a system of rectangular Cartesian co-ordinates described in the earlier section is used. A western coastal boundary (the east coast of India) is situated at $x = b_1(y)$ and an eastern open sea boundary is situated at $x = b_2(y)$. Southern and northern open sea boundaries are at y =o and y = L respectively.

After neglecting barometric forcing terms the governing equations (22) to (24) reduce to

$$\frac{\partial \zeta}{\partial t} + \frac{\partial \tilde{u}}{\partial x} + \frac{\partial \tilde{v}}{\partial y} = 0 \qquad (39)$$

$$\frac{\partial \tilde{u}}{\partial t} + \frac{\partial}{\partial x}(u\tilde{u}) + \frac{\partial}{\partial y}(v\tilde{u}) - f\tilde{v} = -g(\zeta+h)\frac{\partial \zeta}{\partial x} + \frac{F_s}{\rho} - \frac{c_f\tilde{u}}{(\zeta+h)}(u^2+v^2)^{\frac{1}{2}} \qquad (40)$$

$$\frac{\partial \tilde{v}}{\partial t} + \frac{\partial}{\partial x}(u\tilde{v}) + \frac{\partial}{\partial y}(v\tilde{v}) + f\tilde{u} = -g(\zeta+h)\frac{\partial \zeta}{\partial y} + \frac{G_s}{\rho} - \frac{c_f\tilde{v}}{(\zeta+h)}(u^2+v^2)^{\frac{1}{2}} \qquad (41)$$

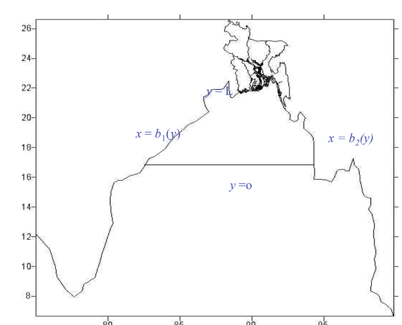


Fig. 5: Boundary Conditions

4.2 Boundary conditions

The boundary condition at the western coastal boundary which is a vertical sidewall, is given by

$$u - v\frac{\partial b_1}{\partial y} = 0 \quad \text{at} \quad x = b_1(y) \tag{42}$$

At the eastern open sea boundary, a radiation condition is applied that is identical to that used by Johns et al. (1981). This leads to

$$u = v\frac{\partial b_2}{\partial y} - \left(\frac{g}{h}\right)^{\frac{1}{2}}\zeta = 0 \quad \text{at} \quad x = b_2(y) \tag{43}$$

Conceptually similar radiation conditions are applied at the southern and northern open sea boundaries to yield

$$v + \left(\frac{g}{h}\right)^{\frac{1}{2}}\zeta = 0 \text{ at } y = 0 \tag{44}$$

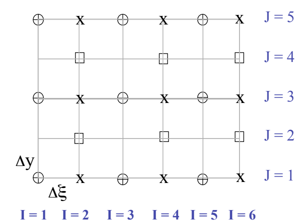
$$v - \left(\frac{g}{h}\right)^{\frac{1}{2}}\zeta = 0 \text{ at } y = L \tag{45}$$

4.3 Coordinate transformation

In storm surge work, conformal mapping had been previously considered by Reid etal. (1977) for curvilinear representation of coastal boundaries. But this treatment is of a different nature and is more similar to that reported by Jelesnianski(1976). This is achieved by applying a co-ordinate transformation in which

$$\xi = \frac{x - b_1(y)}{b(y)} \tag{46}$$

where, $b(y) = b_2(y) - b_1(y)$.



Staggerred Grid-point Arrangement in ξ–y Plane

I = Odd, J= Odd — u- Component (U) ⊕

I = Even, J = Even — v- Component □

I = Even, J = Odd — ζ – Component x

Grid-length = 9.1 km

5 Stability of the scheme

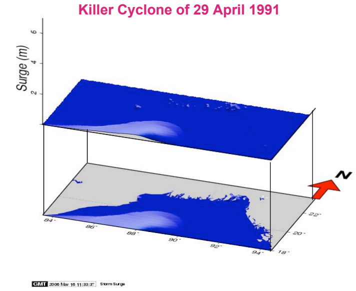
Computational stability is subjected only to the time step being limited by the space increment and gravity wave speed. This is governed by the CFL (Courant-Friedrich-Levy) criterion, i.e,

$$\sqrt{2gh_{\max}}\,\frac{\Delta t}{\Delta x} \le 1 \tag{59}$$

The Coriolis term is evaluated explicitly at the old time level where. It is evaluated at the advanced time level using the previously updated value of u. Finally, the friction term is evaluated partly implicitly. The resulting difference equations being solved algebraically before their incorporation into the updating scheme. This ensures unconditional computational stability with reference to the treatment of the dissipative terms.

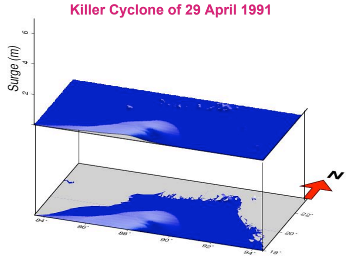
STORM SURGE

Killer Cyclone of 29 April 1991



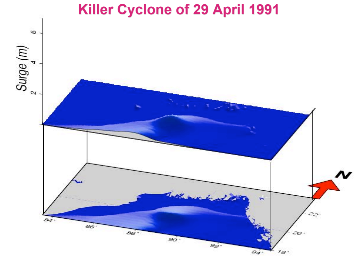
STORM SURGE

Killer Cyclone of 29 April 1991



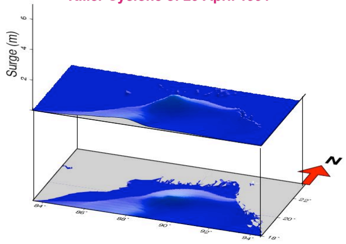
STORM SURGE

Killer Cyclone of 29 April 1991



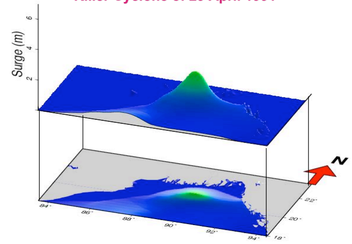
STORM SURGE

Killer Cyclone of 29 April 1991



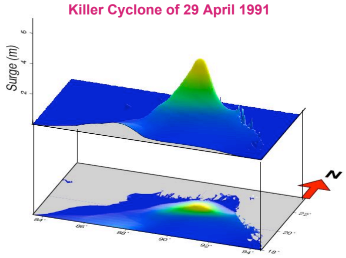
STORM SURGE

Killer Cyclone of 29 April 1991



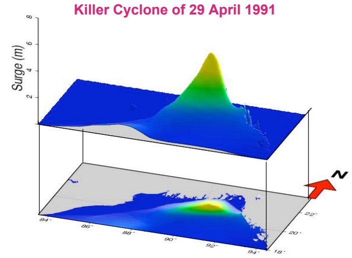
STORM SURGE

Killer Cyclone of 29 April 1991



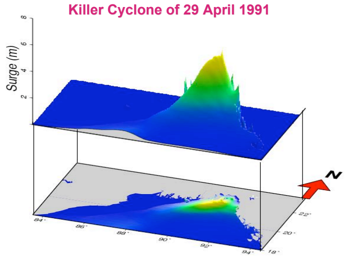
STORM SURGE

Killer Cyclone of 29 April 1991



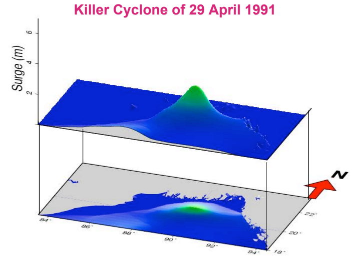
STORM SURGE

Killer Cyclone of 29 April 1991



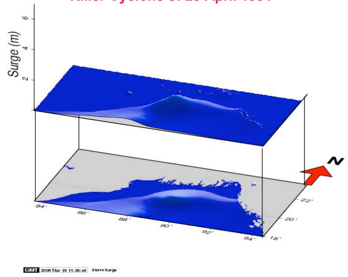
STORM SURGE

Killer Cyclone of 29 April 1991



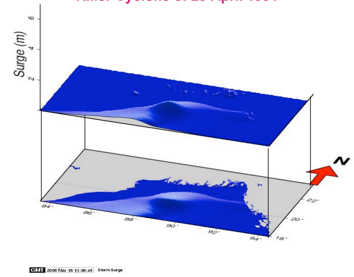
STORM SURGE

Killer Cyclone of 29 April 1991



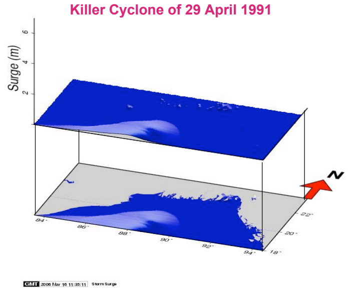
STORM SURGE

Killer Cyclone of 29 April 1991



STORM SURGE

Killer Cyclone of 29 April 1991



6 Conclusions

The Storm Surge Model can be run in a few minutes on a computer workstation or on a Personal Computer (PC). The forecasting system is based on the vertically integrated numerical storm surge model. A dynamic storm model is used for computation of surface winds associated with cyclonic storms. The meteorological inputs required for the model are the positions of the cyclone centre , pressure drop and radius of maximum wind at fixed intervals of time. Number of iterations, depending upon time of integration is also an important input. Time step is 60 sec and grid length is 9.1 kms in the high resolution model.