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Cyclones and Causes of Cyclones over the South West Coastal Area of Bangladesh

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Abstract

This paper articulates some definition related to cyclone, gradient wind equation and gradient wind speed, explanation of cyclone and anticyclone, classification and causes of cyclones, historical cyclones in Bangladesh, the main fact of cyclonic storm surge severity in Bangladesh, the main fact that modify / amplify cyclonic storm surge along the coast of Bangladesh, storm surge inundation characteristics for cyclone. This paper reveals that to protect the coastal areas of Bangladesh from cyclonic storm surge inundation and salt water intrusion by high flood tide as well as from monsoon river flooding. The paper makes some recommendations on the existing and proposed physical planning activities and plans of the coastal areas to ensure effective cyclone management and sustainable physical development.

Keywords: *Cyclone, Storm surge, disaster, calamities.*

Introduction

Bangladesh is a country that has been intrinsically associated with natural disaster and vulnerability. Bangladesh's geographical vulnerability lies in the fact that it is an exceedingly flat, low-lying, alluvial plain covered by over 230 rivers and rivulets with approximately 580 kilometres of exposed coastline along the Bay of Bengal. In addition, there are three geological faults running underneath the capital of Dhaka. As a result of its geography, Bangladesh frequently suffers from devastating floods, cyclones and storm surges, tornadoes, riverbank erosion, and drought as well as constituting a very high-risk location for seismic activity. With the prolong natural calamities & geographical location makes it one of the poorest countries among the third world countries. Whole economy of Bangladesh ruined and level of poverty increases with the prevailing disaster scenario. Of the last 29 severe cyclones in Bangladesh that occurred in the period 1960-2012. Though after 1991 Super

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Cyclone Bangladesh government has taken some bold steps like; introduction of multi hazard warning system, National Disaster policy and action plan for sustainable disaster management .Every time a cyclone hits the coastal area of Bangladesh it causes innumerable loss for the country damaging property and killing people. Therefore, it is necessary to take appropriate measures to reduce the loss from cyclone and storm surge.

Some definition related to cyclone

- **Coriolis force:** In a rotating co-ordinate system there is an apparent force which deflects an object in internal motion from a stright line path.

  The resulting curve is a path in a direction opposite to the direction of co-ordinate rotation.This reflection force is known as coriolts force.

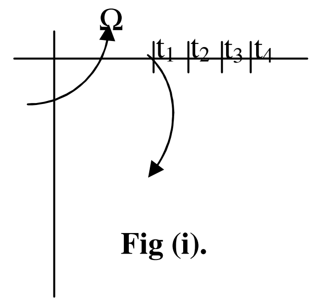


Fig (i).

- **Geostropic wind:** When the coriolis force and pressure gradient force balance, then it is called geostropic wind. In the case of geostropic wind the isobars are assumed to be straight line. In a cyclone the geostropic wind is greater than gradient wind.
- **Gradient wind:** When the centrifugal force and coriolis force are balanced with pressure gradient force, then it is called gradient wind. In the case of gradient wind the isobars are assumed to be curve. In a cyclone the gradient wind is smaller than geostropic wind.
- **Pressure gradient force:** Consider a small element of volume dxdydz. Let, p be the pressure per unit area in the direction of x-axis on the face OABC [fig. ii]. The total force is pdydz. Again the force acting on the opposite side of the parallelepiped is

$$p + \frac{\partial p}{\partial x} dx$$

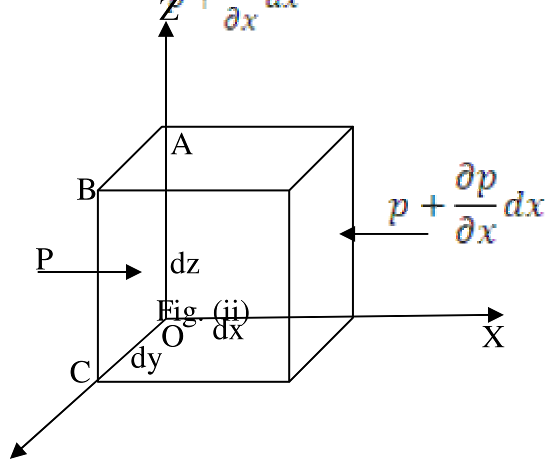


Fig. (ii)

The total force acting in the x-direction is

$$\left\{p - \left(p + \frac{\partial p}{\partial x} dx\right)\right\} dydz = -\frac{\partial p}{\partial x} dxdydz$$

The x-component of the pressure gradient force per unit mass is

$$\frac{-\frac{\partial p}{\partial x} dxdydz}{\rho dxdydz} = -\frac{1}{\rho}\frac{\partial p}{\partial x}$$

Similarly,

The y-component of the pressure gradient force per unit mass is $-\frac{1}{\rho}\frac{\partial p}{\partial y}$

The z-component of the pressure gradient force per unit mass is $-\frac{1}{\rho}\frac{\partial p}{\partial z}$

So the total pressure gradient force is $-\frac{1}{\rho}\nabla p$

- **Centrifugal force:** Centrifugal force is the outward-pushing force felt by bodies moving in a circular motion. However there is no outward force acting and centrifugal force is therefore known as a "fictitious" force. The outward pushing force is due to the combined effect of initial and inward pushing external force.
  Centrifugal force arise when rotating objects are observed from the rotating frame of reference, an accelerating and therefore non-inertial frame of reference in which Newton's Laws of motion do not hold. Centrifugal force is often confused with centripetal force.

Gradient wind equation and Gradient wind speed

In general the isobars are not straight lines but curve. In order to study the relation between pressure field and wind field it is convenient to introduce the polar coordinates $x = r\cos\theta$, $y = r\sin\theta$.

It will be assume that the motion is steady and coriolis force and pressure gradient force are present then the horizontal equation of motion are

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = fv - \frac{1}{\rho}\frac{\partial p}{\partial x} \quad \dots \quad \dots \quad \dots(1) \qquad \left[\because \frac{\partial u}{\partial t} = 0\right]$$

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -fu - \frac{1}{\rho}\frac{\partial p}{\partial y} \quad \dots \quad \dots \quad \dots(2) \qquad \left[\because \frac{\partial v}{\partial t} = 0\right]$$

Where $f = 2\Omega\sin\theta$ is coriolis parameter.

In polar coordinate,

$$x = r\cos\theta, \quad y = r\sin\theta \quad \dots \quad \dots \quad \dots(3)$$

$$\therefore r^2 = x^2 + y^2, \qquad \theta = \tan^{-1}\frac{y}{x} \quad \dots \quad \dots. \ \dots(4)$$

Differentiating (3) w.r.to *t*, we have

$$u = \frac{dx}{dt} = \cos\theta\frac{dr}{dt} - r\sin\theta\frac{d\theta}{dt}$$

$$= v_r\cos\theta - v_\theta\sin\theta \qquad \left[\because v_r = \frac{dr}{dt} \ \& \ v_\theta = r\frac{d\theta}{dt}\right]$$

Similarly

$$v = v_r \sin\theta + v_\theta \cos\theta$$

Now, $\frac{\partial}{\partial r} = \frac{\partial}{\partial x}.\frac{\partial x}{\partial r} + \frac{\partial}{\partial y}.\frac{\partial y}{\partial r}$

$$= \cos\theta \frac{\partial}{\partial x} + \sin\theta \frac{\partial}{\partial y} \quad \dots \quad \dots \quad \dots (5)$$

$$\frac{\partial}{\partial \theta} = \frac{\partial}{\partial x}.\frac{\partial x}{\partial \theta} + \frac{\partial}{\partial y}.\frac{\partial y}{\partial \theta}$$

$$= -r\sin\theta \frac{\partial}{\partial x} + r\cos\theta \frac{\partial}{\partial y}$$

$$\Rightarrow \frac{1}{r}\frac{\partial}{\partial \theta} = -\sin\theta \frac{\partial}{\partial x} + \cos\theta \frac{\partial}{\partial y} \quad \dots \quad \dots \quad \dots (6)$$

V_r*(5) +v_θ*(6)

$$\Rightarrow v_r \frac{\partial}{\partial r} + \frac{v_\theta}{r}\frac{\partial}{\partial \theta} = v_r \cos\theta \frac{\partial}{\partial x} + v_r \sin\theta \frac{\partial}{\partial y} - v_\theta \sin\theta \frac{\partial}{\partial x} + v_\theta \cos\theta \frac{\partial}{\partial y}$$

$$= (v_r \cos\theta - v_\theta \sin\theta)\frac{\partial}{\partial x} + (v_r \sin\theta + v_\theta \cos\theta)\frac{\partial}{\partial y}$$

$$\Rightarrow v_r \frac{\partial}{\partial r} + \frac{v_\theta}{r}\frac{\partial}{\partial \theta} = u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} \quad \dots \quad \dots \quad \dots (7)$$

Using (7) in equation (1) ,we have

$$\left(v_r \frac{\partial}{\partial r} + \frac{v_\theta}{r}\frac{\partial}{\partial \theta}\right) u = fv - \frac{1}{\rho}\frac{\partial p}{\partial x}$$

$$\Rightarrow \left(v_r \frac{\partial}{\partial r} + \frac{v_\theta}{r}\frac{\partial}{\partial \theta}\right)(v_r \cos\theta - v_\theta \sin\theta)$$

$$= f(v_r \sin\theta + v_\theta \cos\theta) - \frac{1}{\rho}\left(\cos\theta \frac{\partial}{\partial r} - \frac{\sin\theta}{r}\frac{\partial}{\partial \theta}\right) p$$

Equating the coefficient of $\cos\theta$ & $\sin\theta$ we get,

$$v_r \frac{\partial v_r}{\partial r} + \frac{v_\theta}{r}\frac{\partial v_r}{\partial \theta} - \frac{v_\theta^2}{r} = f v_\theta - \frac{1}{\rho}\frac{\partial p}{\partial r} \quad \dots \quad \dots \quad \dots (8)$$

$$v_r \frac{\partial v_\theta}{\partial r} + \frac{v_\theta}{r}\frac{\partial v_\theta}{\partial \theta} + \frac{v_\theta v_r}{r} = -f v_r - \frac{1}{\rho r}\frac{\partial p}{\partial \theta} \quad \dots \quad \dots \quad \dots (9)$$

These are the equation of steady horizontal motion in polar coordinates. It may be assume that the isobars are concentric circles around the origin,

So that $\frac{\partial p}{\partial \theta} = 0.$

It also require that the velocity distribution have circular symmetry, then

$$\frac{\partial v_r}{\partial \theta} = 0, \; \frac{\partial v_\theta}{\partial \theta} = 0.$$

Under these conditions, the equation (9) will be satisfied if $v_r = 0$ and equation (8) will be

$$\frac{{v_\theta}^2}{r} + f v_\theta = \frac{1}{\rho}\frac{\partial p}{\partial r}$$

$$\Rightarrow \frac{v^2}{r} + f v = \frac{1}{\rho}\frac{\partial p}{\partial r} \qquad \text{Here } [v_\theta = v]$$

This is the gradient wind equation.

$$\Rightarrow \frac{v^2}{r} + f v - \frac{1}{\rho}\frac{\partial p}{\partial r} = 0$$

$$\Rightarrow v^2 + f v r - \frac{r}{\rho}\frac{\partial p}{\partial r} = 0$$

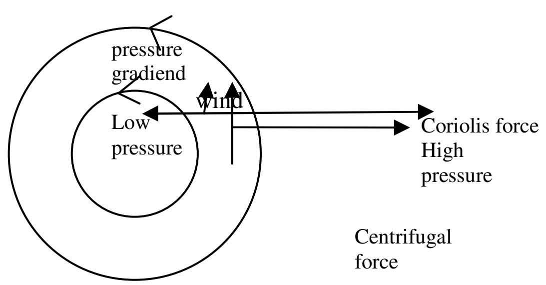
$$\therefore v = \frac{-fr \pm \sqrt{f^2 r^2 + 4\frac{r}{\rho}\frac{\partial p}{\partial r}}}{2}$$

$$\therefore v = -\frac{fr}{2} \pm \sqrt{\frac{f^2 r^2}{4} + \frac{r}{\rho}\frac{\partial p}{\partial r}} \quad \dots \quad \dots \quad \dots(10)$$

This is the gradient wind speed.

Explanation of cyclone and anticyclone

Cyclone: In the case of a centre of low pressure, the wind blows counter clockwise direction so that the centrifugal force and coriolis force counter act the pressure gradient force. This type of motion is called cyclone.



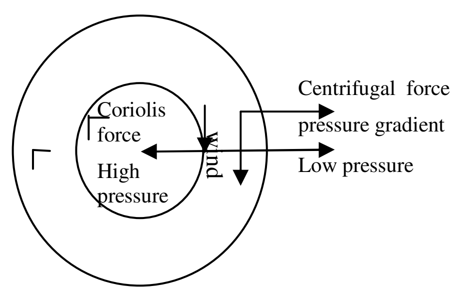


Fig-iii. Cyclonic motion **Fig-iv. Anticyclonic motion**

Anticyclone: In the case of a centre of high pressure, the wind blows clockwise direction so that the centrifugal force and pressure gradient force must balance the coriolis force. This type of motion is called anticyclone.

Explanation: We have the gradient wind speed is

$$v = -\frac{fr}{2} \pm \sqrt{\frac{f^2r^2}{4} + \frac{r}{p}\frac{\partial p}{\partial r}} \quad \text{.................................(1)}$$

Where $f = 2\Omega \sin\theta$ is coriolis force parameter.

The positive value of v means counter clock wise motion and the negative value of v means clock wise motion.

Case (1):

Consider the positive root of (1)

$$\text{i.e } v = -\frac{fr}{2} + \sqrt{\frac{f^2r^2}{4} + \frac{r}{p}\frac{\partial p}{\partial r}} \quad \text{.................................(2)}$$

For low pressure area:

(a) If $\frac{\partial p}{\partial r} \to 0$ then $v \to 0$

(b) If $\frac{\partial p}{\partial r} > 0$ then $v > 0$ [from (2)]

This represents cyclonic motion as shown in [fig. (iii)].

For high pressure area:

(c) Where $\frac{\partial p}{\partial r} < 0$, then $v < 0$ [from (2)]

This represents anticyclonic motion as shown in [fig. (iv)].

Case (2):

Consider the negative root of (1)

$$\text{i.e } v = -\frac{fr}{2} + \sqrt{\frac{f^2r^2}{4} + \frac{r}{p}\frac{\partial p}{\partial r}} \quad \text{.................................(3)}$$

(a) If $\frac{\partial p}{\partial r} \to 0$ then from (3) we get $v < 0$.

This represents anticyclonic motion with no pressure gradient in the limit. (b) If $\frac{\partial p}{\partial r} > 0$ then from (3) we get $v < 0$

This represents anticyclonic motion . (c)If $\frac{\partial p}{\partial r} < 0$, but $\frac{f^2 r^2}{4} + \frac{r}{p}\frac{\partial p}{\partial r} > 0$ then $v < 0$

This represents anticyclonic motion .

Classification and Causes of cyclones

Typhoons are tropical revolving storms. They are called Cyclones' in English, when they occur in the Indian Ocean area. The coastal regions of Bangladesh are subject to damaging cyclones almost every year. They generally occur in early summer (April-May) or late rainy season (October-November). Cyclones originate from low atmospheric pressures over the Bay of Bengal.

Figure v. shows a typical cyclone structure formed in the tropics of the northern hemisphere.

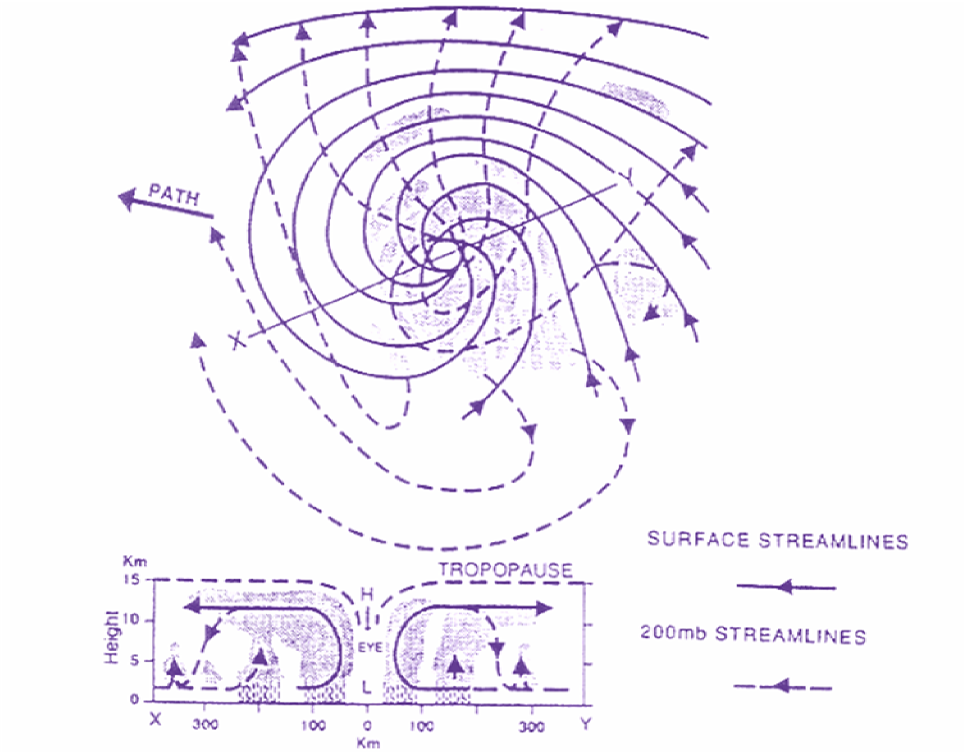


Figure v. A model of the aerial and vertical structure of a tropical cyclone. The areas of rainfall are indicated in the vertical section X-Y across the system.

Cyclones in the South Asian Sub-Continent are presently classified according to their intensity and the following nomenclature is in use:

Depression	Winds up to 62 km/hr
Cyclonic Storm	Winds from 63-87 km/hr
Severe Cyclonic Storm	Winds from 88-118 km/hr
Severe Cyclonic Storm of Hurricane Intensity	Winds above 118 km/hr

Most of the coastal areas of the world are at risk from natural hazards created by geological or meteorological disturbances. The hazards are classified as:

i. Short term (minutes, hours, or days) events associated with storms or earthquakes (tsunamis), and

ii. Long-term events (decades, millennia) related to changes in rise of sea level caused by secular eustatic (atmospheric, cryospheric, geoidal) or isostatic (tectonic) processes.

Tropical cyclones or hurricanes are common within latitude 30^{o} north and south. These intense storms move across shallow shelf seas; the water is being piled-up along the coast as a surge. In most cases the mixture of these effects creates most dreadful effects in the coastal regions - a gradual rise in the regional sea level produces enhanced landward penetration of surges and storm waves.

Historical Cyclones in Bangladesh

During the years 1960 to 2012, Bangladesh has been hit by 29 severe cyclones, most of which were accompanied by storm surges. Table1. gives a brief account of these disasters with particular reference to the date of occurrence , nature of phenomenon , landfall area ,maximum wind speed, tidal surge height, central pressure, etc. A tropical cyclone forming in the Bay of Bengal has a lifetime of one week or longer. The height of the surges is limited to a maximum of 10 meters in the bay.

When propagating into the shallower inland coastal areas, the heights of these waves are further reduced. The frequency of a wave (surge plus tide) with a height of about 10 m is approximately once per 20 years. A storm surge of approximately once in 5 years has a height of about 7 m (surge plus tide). Besides these exceptional surges, wind waves occur, the dimensions of which depend on wind speed and direction, fetch, water depth, and duration. Waves of 3 m height may occur under unfavorable conditions in the coastal regions.

Table1. Chronology of major cyclones and storm surges in Bangladesh (compiled from Bangladesh Meteorological Department, Meteorological Complex, Agargaon, Dhaka – 1207.)

SL. No.	Date	Nature of Phenomenon	Landfall Area	Max.Wind speed in km/hr	Tidal Surge Height in ft.	Central Pressure (mbs)
1	11.10.60	Severe cyclonic storm	Chittagong	160	15	-
2	31.10.60	Severe cyclonic storm	Chittagong	193	20	-
3	09.05.61	Severe cyclonic storm	Chittagong	160	8-10	-
4	30.05.61	Severe cyclonic storm	Chittagong (Near Feni)	160	6-15	-
5	28.05.63	Severe cyclonic storm	Chittagong– Cox's Bazar	209	8-12	-
6	11.05.65	Severe cyclonic storm	Chittagong	160	12	-
7	05.11.65	Severe cyclonic storm	Chittagong	160	8-12	-
8	15.12.65	Severe cyclonic storm	Cox's Bazar	210	8-10	-
9	01.11.66	Severe cyclonic storm	Chittagong	120	20-22	-
10	23.10.70	Severe cyclonic storm of Hurricane intensity	Khulna-Barisal	163	Moderate	-
11	12.11.70	Severe cyclonic storm with a core of hurricane wind	Chittagong	224	10-33	-
12	28.11.74	Severe cyclonic storm	Cox's Bazar	163	9-17	-
13	10.12.81	Cyclonic storm	Khulna	120	7-15	989
14	15.10.83	Cyclonic storm	Chittagong	93	-	995
15	09.11.83	Severe cyclonic storm	Cox's Bazar	136	5	986
16	24.05.85	Severe cyclonic storm	Chittagong	154	15	982

SL. No.	Date	Nature of Phenomenon	Landfall Area	Max.Wind speed in km/hr	Tidal Surge Height in ft.	Central Pressure (mbs)
17	29.11.88	Severe cyclonic storm with a core of hurricane wind	Khulna	160	2-14.5	983
18	18.12.90		Cox's Bazar coast	115	5-7	995
19	29.04.91	Severe cyclonic storm with a core of hurricane wind	Chittagong	225	12-22	940
20	02.05.94	Severe cyclonic storm with a core of hurricane wind	Cox's Bazar – Teknaf coast	278	5-6	948
21	25.11.95	Severe cyclonic storm	Cox's Bazar	140	10	998
22	19.05.97	Severe cyclonic storm with a core of hurricane wind	Sitakundu	232	15	965
23	27.09.97	Severe cyclonic storm with a core of hurricane wind	Sitakundu	150	10-15	-
24	20.05.98	Severe cyclonic storm with a core of hurricane wind	Chittagong coast near sitakundu	173	3	-
25	28.10.00	Cyclonic storm	Sundarban coast near mongla	83	-	-
26	12.11.02	Cyclonic storm	Sundarban coast near Raimangal river	65-85	5-7	998
27	19.05.05	Cyclonic storm	Cox's Bazar coast between Teknaf and Akyab	65-90	2-4	990
28	15.11.07	Severe cyclonic storm with a core of hurricane wind (SIDAR)	Khulna – Barisal coast near baleshwar river	223	15-20	942
29	25.05.09	Cyclonic storm (AILA)	West Bengal – Khulna coast near sagar Island	70-90	4-6	987

The main fact of cyclonic Storm Surge Severity in Bangladesh

Table 2. Shows the approximate percentage of storm-surge impact in various regions on the globe. Storm surges generated by tropical cyclones are most common in the Bay of Bengal and the Gulf of Mexico.

Table 2. Approximate percentage of storm surge impact.

Reigion	Percentage
Bangladesh	40
Asia(excluding Bangladesh)	20
North America	20
Europe	10
Africa and South America	5
Australia and New Zealand	5

The reasons for this disproportional large impact of storm surges on the coast of Bangladesh are the following.

i. The phenomenon of recurvature of tropical cyclones in the Bay of Bengal,
ii. Shallow continental shelf, especially in the eastern part of Bangladesh,
iii. High tidal range,
iv. Triangular shape at the head of the Bay of Bengal,
v. Almost sea-level orography of the Bangladesh coastal land,
vi. High density of population and coastal defence system.

The phenomenon of recurvature of tropical cyclones in the Bay of Bengal is the single most cause of the disproportional large impact of storm surges on the Bangladesh coast. Extra-tropical cyclones, such as those that occur in Canada and Europe, generally travel from west to east. On the other hand, tropical cyclones such as those that occur in the Bay of Bengal, are expected to travel from east to west, as would be expected from considerations of the general circulation of the atmosphere. However, in the Bay of Bengal, tropical cyclones most often do not travel towards the west or Northwest, but they turn towards the north or even Northeast. This turning back, referred to as recurvature, is still not fully understood. If the phenomenon of recurvature does not happen, then Bangladesh would rarely be affected by tropical cyclones and the storm surges that result from them.

The coast line of Bangladesh is characterised by a wide continental shelf, especially off the eastern part of Bangladesh. This wide shelf amplifies the storm surges as the tangential sea-level wind stress field associated with the tropical cyclone pushes the sea water from the deep water side onto the shelf. Being pushed from the south by wind stress, the water has no place to go but upwards; which is the storm surge.

The triangular shape at the head of the Bay of Bengal helps to funnel the sea water pushed by the wind towards the coast and causes further amplification of the surge. This is basically what happens in the amplification of surges on the Bangladesh coast.

The storm-surge waves belong to the class of long gravity waves. Their speed of propagation is given by the square root of the product of the acceleration due to the earth's gravity and the local water depth. In deep water, the long gravity wave propagates much faster than the speed with which the weather system travels. Thus, the weather system cannot keep up with the water wave and, hence, cannot impart any momentum. But on the continental shelf, where the water depth is smaller, the gravity wave travels much slower than in deep water and a significant transfer of energy from the weather system to the water wave occurs by resonance. Hence, the storm surge which has zero amplitude in the deep water, quickly builds up to several meters amplitude on the shallow continental shelf. As this amplified water level approaches the coast, the coastal areas become flooded with surge water.

The many fact that modify/ amplify cyclonic storm surge along the coast of Bangladesh

Once storm surges are generated, a number of local factors contribute to their modification/amplification. Contributions from some of such factors are discussed below in the context of Bangladesh.

- **Impact of shallow water:** Storm surges are mostly shallow water phenomena. The amplitude/height of surges depends inversely on the depth of water. The impact of shallow water on the modification/amplification has been discussed in the previous section.
- **Impact of coriolis force:** The coriolis force due to the rotation of the earth has a minor contribution to surge modification/amplification. This force acts to the right of the direction of water motion in the Northern Hemisphere and to the left in the Southern Hemisphere. Thus, for example, if surge water is moving northward in the northern Bay of Bengal, it will be deflected towards the east, thereby increasing surge height along the east coast.
- **Convergence impact:** Surge height is directly proportional to convergence. Convergence leads to amplification .Because of the northward converging nature of the Bay, surge water is funnelled towards Bangladesh in the north (depending on the track of a cyclone) leading to amplification of surge height. Amplification by convergence takes place somewhat like amplification due to shallow water.
- **Impact of tidal range:** Tidal range in Bangladesh shows a gradual increase from west to east to reach a maximum at the Meghna estuary and then it decreases south eastward. Tidal amplitude varies in different seasons along the coast of Bangladesh. During the monsoon time a large volume of water discharges through the Meghna estuary and other distributary channels. This non-saline water when mixed with the saline water of the bay, because an increase of the volume of the water; and consequently the tidal amplitudes are increased. Pattalo et al. estimated an increase of tidal height above the normal height between 60 cm to 100 cm during the monsoon period. When this high tide level (during the months of October and November) coincide with the storm surge, the impact becomes severe, especially around the estuary. Tide and surges are not linearly additive but interactive. This means that if, for example, a 5m surge is superimposed on a 5m tide, and the total height will not be 10m. Tides modify the surge amplification.
- **Impact of river system:** A river system can have a number of effects on surges and tides. Firstly, the presence of rivers has a negative effect on surge amplification. If there were no rivers, then the surges in the coast would be higher .Secondly, fresh water discharge through rivers will modify the sea surface elevation. Thirdly, the presence of a number of waterways allows a deep inland penetration of surges originating in the Bay. A consequence of this is an inland flood hazard and saline water intrusion, which may extend over several hundred of kilometres. Lastly, the surge and tidal water has a back water effect on river discharges. This is particularly important during flood periods. The back water effect slows down the discharge rates, thus making the flood situation more disastrous.

- **Island impact:** The presence of offshore islands plays an important role in surge modification. Some of these may be identified as follows: i) The channels in between the islands confine the water within them and compel it to pass through them (until the island becomes inundated), thereby causing surge amplification; ii) islands act as barriers to impending surge water which may lead to surge amplification; and iii) islands may also retard the outflow of surge water back to the Bay after the cyclone dissipation.
- **Impact of cyclone track:** Surge height, particularly in Bangladesh, is strongly dependent on the cyclone track. Storm surges are usually highest to the right of the track. This is principally because of the occurrence of the maximum wind speed to the right of the cyclone where the forward motion of the cyclone is superimposed on the wind speed. As a cyclone approaches the land to the north, this wind tends to pile up water against the coast. This tendency is reinforced by the shallow water and convergence effects. The consequence of all these factors is to produce even a higher positive surge to the right of the cyclone path or point of landfall. Wind on the left (being predominantly in the off-shore direction) drives water away from the coast and produces a negative surge.

Storm surge inundation characteristics for cyclone

The Multi-purpose Cyclone Shelter project (MCSP) in Bangladesh modelled storm surge along the Bangladesh coast with the help of GIS and also delineated Risk Zones.. The MCSP risk zone map extends from the coast to the inland limit of surge water where property may be damaged by flow velocity. The most important parameters of this flooding are its depth and duration. Within the risk zone is a "high risk area" where lives may be lost as a result of flooding greater than one meter deep.

MCSP also prepared a table which shows surge inundation characteristics for cyclones of varying strength in Bangladesh (Table 3).

Table 3. Typical Storm Surge Inundation Characteristics for cyclones of Varying Strength in Bangladesh.

Wind velocity (km/hr)	Storm surge height (m)	Limit to inundation (km) from the coast line
85	1.5	1.0
115	2.5	1.0
135	3.0	1.5
165	3.5	2.0
195	4.8	4.0
225	6.0	4.5
235	6.5	5.0
260	7.8	5.5

The inundation estimates in table 3 are only applicable as a guideline where the coastal plain is very flat and there is minimal friction from trees or Appendix Background Information on the Storm Surge Modelling other obstructions. For areas with large river outlets in the Bay of Bengal, these limits must be modified since those rivers allow deep inland penetration by the surge. Tidal phases, too, are not considered in the estimates.

Recommendations

By analyzing existing facilities and weaknesses in cyclone management, it is clear that there is need to improve the existing cyclone management measures of the study area. Both the structural and non-structural measures need to be improved. For this purpose, following planning guidelines for the improvement of cyclone management facilities at coastal areas should be adopted:

- To protect the house from cyclone, the row of trees should be preferred to provide natural shielding.
- Protect vulnerable areas by renovating the existing embankments and creating new ones.
- Roads, culverts and bridges should be constructed in such way that people can go to the villages in all types of weather including cyclonic period.
- Shelter belts are barriers of trees or shrubs that are planted to reduce wind velocities and as a result, reduce transpiration and prevent wind erosion. In coastal areas, shelterbelt plantation of Casuarinas as a main specie is the most suitable and effective alternative to minimize the impacts of wind velocity and saline ingress.
- Sufficient number of training and public awareness building programs should be arranged regularly both for local people and members of disaster management committees and volunteer committees. As a result, the local people can become more aware and develop their skill to cope with cyclone.
- A good coordination among the government and non-government organizations in the study area should be developed for effective cyclone management.

Conclusion

The coastal areas and off-shore islands of Bangladesh are low lying and very flat. The height above mean sea level of the coastal zone is less than 3m.The range of astronomical tide along the coast of Bangladesh is so large that the cyclonic storm induced sea level is apt to become very high. The tidal range in the southeastern part is about 3.5 to 4m. If cyclonic storm surges are superimposed on high tides, the situation becomes disastrous. A funneling coast line reduces the width of cyclonic storm induced waves and increases the height. Also the fact that the coasts are situated at right angles in the northern corner of the Bay of Bengal causes higher cyclonic storm induced waves compared to a straight coast line .If we want to protect the coastal areas of Bangladesh from cyclonic storm surge inundation and salt water intrusion by high flood tide as well as from monsoon river flooding ; we have to enrich the knowledge about the main causes of cyclonic storm, the main fact of cyclonic of surge severity and the many fact that modify/amplify cyclonic storm surge etc.

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