Journal of Applied Sciences

ISSN 1812-5654

ANSInet
an open access publisher
http://ansinet.com

Journal of Applied Sciences 8 (7): 1249-1255, 2008
ISSN 1812-5654

Tropical Cyclone Wind Characteristics for the Bangladesh Coast Using Monte Carlo Simulation

[1]Tanveerul Islam and [2]Richard E. Peterson
[1]Center for Texas Beaches and Shores, Texas A and M University-Galveston,
5007 Avenue U, Galveston, Texas 77551, USA
[2]Atmospheric Science Group, Texas Tech University, Lubbock, Texas 79409, USA

Abstract: The aim of this study is to understand the characteristics of landfalling tropical cyclones along the coast of Bangladesh by estimating the maximum wind speed and the maximum surge height in different locations during cyclone landfall. Using the Monte Carlo simulation procedure, 1000 simulated storms are generated for each site based on the historical inputs. The modified Holland wind field model is used to obtain the horizontal winds. A simple bathystrophic storm surge model is used in the simulation that gives maximum surge height for the locations to be struck by a simulated storm. Finally, the return periods of maximum wind speeds at different locations are calculated which provide the design wind speed for structures in coastal areas. The wind, surge and return period information can be utilized in different mitigation measures against tropical cyclones in Bangladesh such as devising a standard building code for the coastal areas and to improve the basic wind speed map of Bangladesh.

Key words: Tropical cyclone, Bangladesh, Monte Carlo simulation, Holland wind model, storm surge, Bay of Bengal, bathymetry

INTRODUCTION

The estimation of maximum wind speed and surge height in cyclone-prone regions can be developed in either of two ways: (1) directly from historical measurement, or (2) indirectly using numerical simulation procedures e.g., Monte Carlo method (Kriebel *et al*.,1996).

Batts *et al*. (1980) determined that it is not possible to use statistical analysis of the highest annual wind speeds at a particular site in order to determine the extreme wind speeds in cyclone-prone regions. The first method can only be performed if sufficient data exists on extreme annual wind speed and extreme annual water level at locations of interest.

In practice, it is found that very few tropical storms or hurricanes actually strike at a particular site and historical records only exist for upwards of a hundred years. Thus, there exist a limited number of observations at each site. Therefore, it is preferable to follow the second procedure, i.e., an indirect numerical simulation method to obtain the extreme wind statistics for the cyclone prone regions. In this case, the Monte Carlo simulation method is chosen as the indirect method to obtain the extreme wind statistics for the coastal areas of Bangladesh.

Skwira (1998) used the Monte Carlo simulation technique to obtain extreme wind statistics for the 11 sites chosen along the United States Gulf and Atlantic coasts. One thousand randomly generated individual storms in the form of hurricanes, tropical storms or tropical disturbances were simulated for each site. As each storm was simulated the maximum wind and the direction of the maximum wind were identified and cataloged. Using the generated wind information at a site, the extreme wind speed for a particular return period was determined. Exactly the same procedure is used in this study to determine the extreme cyclone wind speed for the sites along the Bangladesh coast of the Bay of Bengal.

WIND FIELD MODEL

A wind field is required in the Monte Carlo simulation to represent the storms that made landfall. Skwira (1998) compared five wind field models using the parameters of Hurricane Hugo, which struck the coast of South Carolina. These include Rankine Vortex, Modified Rankine Vortex, Gradient wind model, Holland wind model and modified Holland wind model. Among the wind models, the modified Holland wind field model performed better and

---

Corresponding Author: Tanveerul Islam, Texas A and M University, 5007 Ave U, Galveston, Texas 77551, USA
Tel: 1-409-740-0722 Fax: 1-409-740-4787

was chosen in the study (Skwira, 1998). Here are some of the reasons for choosing this wind field model to carry out the Monte Carlo simulation:

Firstly, this model is flexible and can represent a wide variety of storms in both size and shape. All of the other wind models are basically locked into one particular shape and only their size can change depending on the radius of maximum winds. In reality, hurricanes are observed to occur in a wide variety of both shapes and sizes.

Secondly, in the modified Holland model, the wind is shifted 20° counterclockwise in order to place the maximum wind speeds 70° to the right of the direction of the cyclone motion. The maximum winds are actually less as the radius of maximum winds passes the site for the second time than its first passage over the site. This creates an asymmetric wind pattern unlike the other wind field models, which is more realistic in nature.

Lastly, the radial wind field is constructed by rotating the flow to a constant inflow angle of 25° outside the radius of maximum winds. According to the research with this new wind and pressure model, it appears that these pressure and wind fields are as good and are often better than previous models (Hubbert *et al*., 1991).

The parameters needed to generate a cyclone wind field with the modified Holland model are: central pressure, radius of the maximum wind, storm heading or angle of attack, forward speed, pressure at the storm periphery and latitude of the site to be struck. The pressure at the storm periphery is held constant for all locations and all simulations at 1013.25 hPa (mean sea level pressure).

STORM SURGE MODEL

A storm surge is a massive rise in the sea-surface level caused by strong wind-stress forcing and (to a lesser extent) by a drop in the atmospheric pressure. In tropical regions, these forcing agencies result from the often erratic passage of a tropical cyclone, hurricane or typhoon (Johns and Lighthill, 1993). A detailed review of the problem of storm surges in the Bay of Bengal is given by Dube *et al.* (1997), Das (1994), Murty *et al.* (1986) and Murty (1984).

Numerical storm surge models provide good sources of information concerning the range of expected peak surge heights during tropical cyclones. The governing hydrodynamic equations in most of the storm surge models are the depth-integrated equations for the conservation of momentum for shallow water long wave motions in the x- and y-directions:

$$\frac{\partial U}{\partial t} + \frac{U}{D}\frac{\partial U}{\partial x} + \frac{V}{D}\frac{\partial U}{\partial y} = f V - gD\frac{\partial S}{\partial x} - \frac{D}{\rho}\frac{\partial P}{\partial x} + \frac{1}{\rho}(\tau_{wx} - \tau_{bx}) \quad (1)$$

$$\frac{\partial V}{\partial t} + \frac{U}{D}\frac{\partial V}{\partial x} + \frac{V}{D}\frac{\partial V}{\partial y} = -f U - gD\frac{\partial S}{\partial y} - \frac{D}{\rho}\frac{\partial P}{\partial y} + \frac{1}{\rho}(\tau_{wy} - \tau_{by}) \quad (2)$$

and also the equation for conservation of mass:

$$\frac{\partial S}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 \quad (3)$$

Where:

S = Storm surge or departure of water surface from mean sea level
U = Depth-integrated flow in x-direction (units: length squared per time)
V = Depth-integrated flow in y-direction (units: length squared per time)
D = Total water depth
P = Atmospheric pressure at water surface
ρ = Density of water
τ_w = Shear stress at water surface due to wind
τ_b = Shear stress at sea floor due to bottom friction
x = Defined as positive in the offshore direction, zero at shoreline
y = Defined as positive to the left when facing in the +x direction (right hand coordinate system), zero at the point of interest (Kriebel *et al*., 1996)

In this study, the modified wind model developed by Holland (Hubbert *et al*., 1991) is installed into a simplified Bathystrophic Storm Surge model. The simplified model, the Bathystrophic storm surge model as developed by Freeman *et al.* (1957), has the following key assumptions:

- Nonlinear convective acceleration terms are neglected
- The bathymetry, the wind field and the storm surge are assumed to be uniform in the alongshore direction so that spatial gradients in the y-direction are zero. As a result, computations are carried out along a single line specifying the bathymetry perpendicular to the coast at the point of interest
- Onshore flows are assumed to reach steady-state such that any onshore-directed flow due to onshore wind stress is balanced by an offshore-directed return flow near the ocean bottom. Thus, there is no net discharge, U, in the cross-shore direction. As a result of these simplifications, Eq. 1 through 3 are reduced to the following form:

$$\frac{\partial S}{\partial x} = \frac{f V}{gD} - \frac{1}{\rho g}\frac{\partial P}{\partial x} + \frac{n\,\tau_{wx}}{\rho g D} \quad (4)$$

$$\frac{\partial V}{\partial t} = \frac{1}{\rho}(\tau_{wy} - \tau_{by}) \quad (5)$$

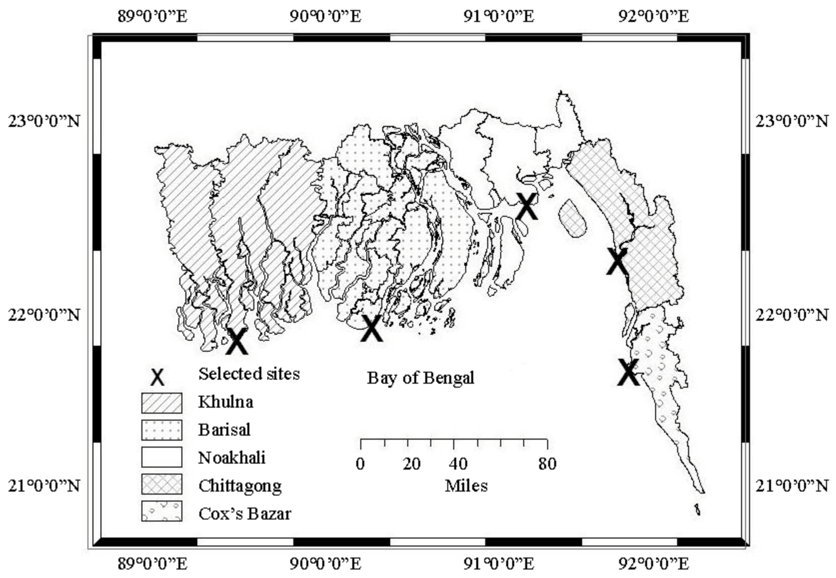

Fig. 1: Sites used in the simulations

Where:

n = Coefficient to approximate effects of bottom stress

Equation 4 and 5, though quite simplified compared to the full governing equations, represent the dominant physical mechanisms responsible for storm surge generation on the open coast (Kriebel *et al*., 1996).

DATA RESOURCES

For the wind field model, the primary data collected for central pressure are dated from 1971 to 2003 and for the radius of maximum wind are from 1981 to 2000. The corresponding data for the earlier storms are not available. The data of the radius of maximum wind are obtained from the Statistical Year Book of Bangladesh 2000 provided by The Bangladesh Meteorological Department (BMD) (Bangladesh Bureau of Statistics, 2003). Data for other parameters are obtained from the Global Tropical Cyclone Climatic Atlas (GTCCA 1.0, 2.0) database. The primary data collected for angle of attack and forward translation speed are dated back from 1877 to 2003. The bathymetry data of the Bay of Bengal are collected from the nautical chart produced by the National Imagery and Mapping Agency (NIMA).

SELECTION OF TEST SITES

In the study, five coastal sites have been selected at approximately equal interval of 40-50 miles. The actual sites where the Monte Carlo simulations are performed are depicted by X in Fig. 1.

Table 1: Sites with their latitudes and longitudes (NIMA nautical chart)

Site	Latitude (°N)	Longitude (°E)
Khulna	21.48	89.25
Barisal	21.55	90.25
Noakhali	22.35	91.12
Chittagong	22.15	91.45
Cox's Bazar	21.27	92.00

However, all of these five sites fall within the existing and old district lines of the five popularly known regions. These are Khulna, Barisal, Noakhali, Chittagong and Cox's Bazar. It is assumed that the results drawn from the Monte Carlo simulations among these five coastal sites would represent respectively the five coastal regions mentioned above. The latitudes and longitudes of the selected sites to carry out the Monte Carlo simulations are given in Table 1.

MATERIALS AND METHODS

Two computer programs written in FORTRAN are used to perform the Monte Carlo simulations for each site. The first program generates 1000 randomly selected variables for each of the four parameters for each site. These randomly generated variables of storm parameters are stored in a separate file for each site.

The second program generates 1000 landfalling storms for a selected site using the output file of the first program and the bathymetry information of the selected site. Two output files are produced which contain the maximum wind speed and maximum surge height at landfall location. The simulation is run for a total of 30 h for each of the storms; 20 h over the sea when the storm approaches to the site and 10 h more after landfall to allow the storm enter well inland.

During the period the storm approaches the site, central pressure, radius of the maximum wind, storm heading and forward speed all are held constant. Once the storm makes landfall, the central pressure is allowed to decrease at a rate of 3% of the original value for the first six hours the storm over land. After that, the central pressure is held constant at 82% of the original central pressure. The other parameters are not allowed to change any time during the simulation.

In the simulations, friction is also taken into account at the land/water interface. Over land, the winds are reduced to 70% of their value over the ocean due to the roughness of land. At the shoreline, the winds are reduced to 89% of their strength over the open ocean if the winds are onshore and 70% for offshore. Also, for the offshore winds, the wind speeds are reduced to 90% of their value over open ocean within less than one nautical mile from shore (Kriebel *et al.*, 1996). Considering all these factors, the wind speed is then reduced by a factor of 0.7 to adjust it to a 10 min mean wind speed at 10 m (Hubbert *et al.*, 1991).

RESULTS AND DISCUSSION

At each of the five sites 1000 simulated storms are generated through Monte Carlo simulations. The mean maximum wind speeds of these storms at each site are shown in Fig. 2. These mean wind speeds are steady for Khulna, Barisal and Noakhali, which are located to the western side of the coastline. The mean wind speeds are slightly higher for Chittagong and Cox's Bazar located along the eastern part of the coasts.

Although the mean central pressure used in the simulations is almost identical for all sites, but the mean radius of the maximum wind is higher for Chittagong (34.06 nmi) and Cox's Bazar (33.81 nmi) than the other three coastal sites. The mean forward speeds are also higher for Chittagong (13.35 knots) and Cox's Bazar (9.72 knots) than Khulna (5.28 knots), Barisal (7.48 knots) and Noakhali (8.11 knots). Thus, the variation of the mean wind speeds is certainly influenced by the radius of maximum wind and forward speed of the storms.

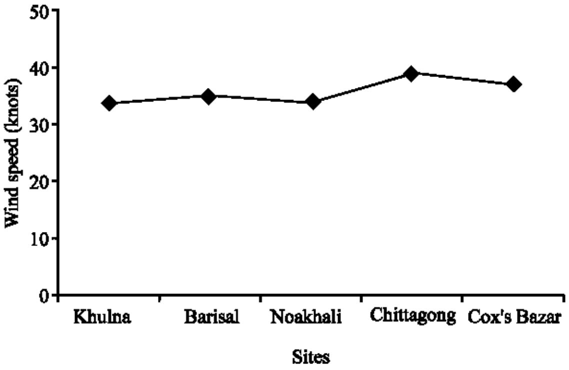

Fig. 2: Mean maximum wind speeds of five sites obtained from Monte Carlo simulations

In terms of storm heading, the mean angles of attack for Khulna (195), Barisal (197) and Noakhali (162) are closer to normal (180° being a heading from the south and normal to coastline) than for Chittagong (208) and Cox's Bazar (210.2). In reality, storms gain more strength during re-curvature than just approaching straight. The location of Chittagong and Cox's Bazar along the coastline is as such that most of the storms have to re-curve to strike unlike the sites located on the western side. Thus, the storm heading might play a role for higher mean wind speeds at Chittagong and Cox's Bazar. Among the 1000 simulated storms at each site, the highest maximum wind speeds at Khulna is 85.5 knots, at Barisal is 86.88 knots, at Noakhali is 88.91 knots, at Chittagong is 94.56 knots and at Cox's Bazar is 102.07 knots.

One useful method to interpret the results for each site individually is to determine the wind speed for a given return period. This is very important from the structural engineering standpoint as the engineers can determine the appropriate wind speed strength or the design wind speed for a given certain life of a structure. The ASCE 7 wind speed map for the United States is based upon a 50 year recurrence level, which presumes that 50 years is the useful life expectancy of a facility (ASCE Standard No. 7-98, 2000).

The winds for specified return periods (Fig. 3-7) are calculated by the following procedure developed by Batts *et al.* (1980).

First, the wind speeds are ranked by their magnitude as W_i, where i = 1 is the smallest through i = 1000, the largest. Then, the cumulative probability of occurrence of wind is obtained based on the assumption that the storm occurrences follow a Poisson distribution with a mean annual rate of occurrence as given in Table 2.

The annual probability of occurrence is then determined as:

$$P(X < x_i) = \exp\left(-n\left(1 - \frac{i}{I+1}\right)\right) \tag{6}$$

and the associated mean return period (mean recurrence interval) in years is given by:

$$T_R(x_i) = \frac{1}{1 - P(X < x_i)} \tag{7}$$

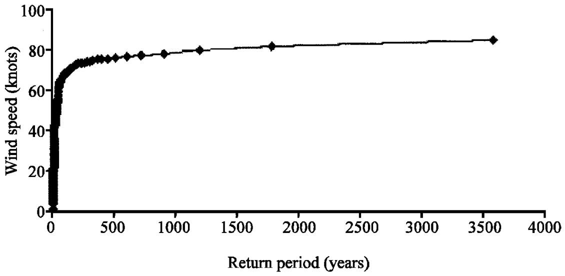

Fig. 3: Wind speed return period for Khulna

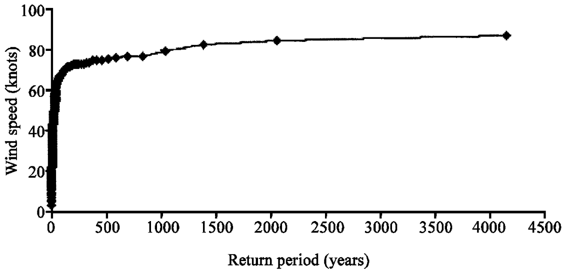

Fig. 4: Wind speed return period for Barisal

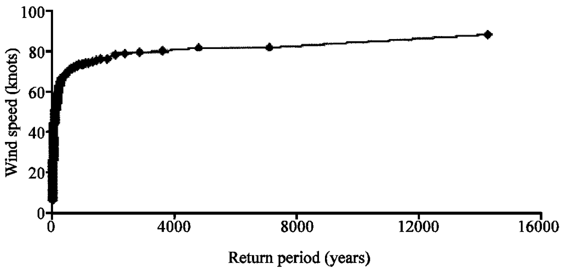

Fig. 5: Wind speed return period for Noakhali

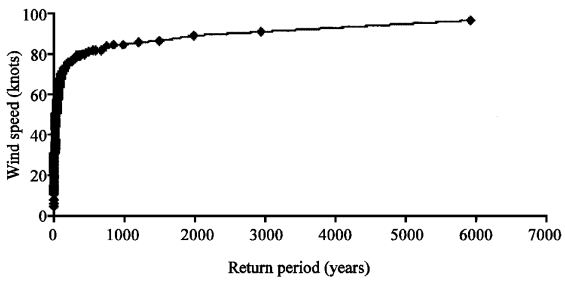

Fig. 6: Wind speed return period for Chittagong

Table 2: Frequency of occurrence of landfalling cyclones (Islam, 2006)

Location	Frequency (No. year^{-1})
Khulna	0.28
Barisal	0.24
Noakhali	0.07
Chittagong	0.17
Cox's Bazar	0.16

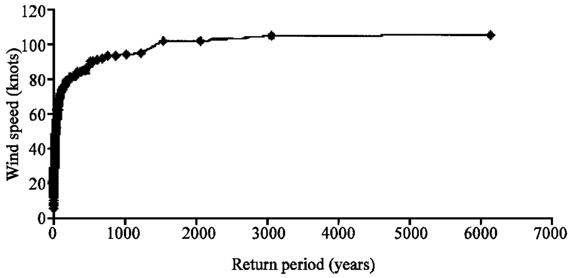

Fig. 7: Wind speed return period for Cox's Bazar

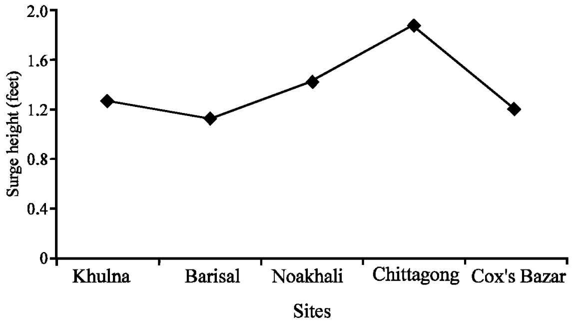

Fig. 8: Mean surge height (in feet) at coastal sites obtained from the Monte Carlo simulations

Where:

X = Variable of interest, which is the wind speed W
x_i = Ranked value of the wind speed W
I = Rank of event with i = 1 smallest and i = I largest
I = Total number of events in simulation = 1000
n = Mean number of storms per year
$P(X<x_i)$ = Annual probability that variable X is less than ranked value x_i
$T_R(x_i)$ = Mean recurrence interval in years for events equaling or exceeding value xi

The procedure described above effectively converts the 1000 storms simulated for each coastal location into an annual series with a different record length based on the mean rate of storm occurrence (Kriebel *et al*., 1996). For example, the lowest mean rate of occurrence is at Noakhali, where n = 0.07. Therefore, the largest of the 1000 storms simulated at this location corresponds to a 14,300 year return period. At the other extreme, the highest rate of occurrence is at Khulna, where n = 0.28. The most severe storm simulated at this location is assigned a return period of 3575 years.

The mean surge heights from the simulated storms at each of the five sites are shown in Fig. 8. At Khulna, Barisal and Cox's Bazar the mean surge heights are relatively low, whereas at Chittagong the mean surge height is the maximum.

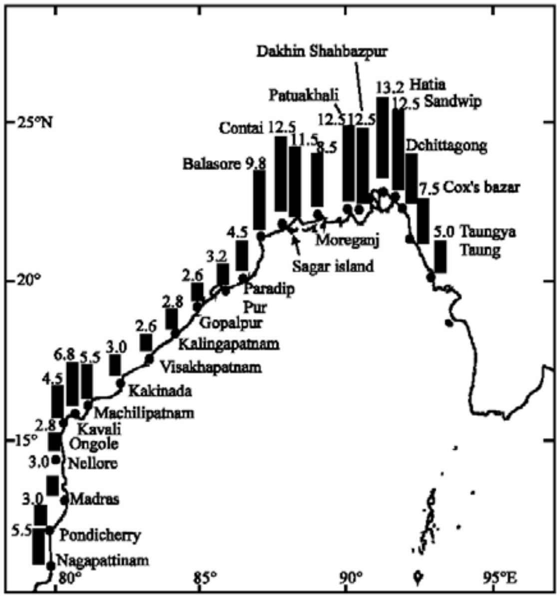

Fig. 9: Max. storm surge (m) along India and Bangladesh coastlines (Mandal, 1991)

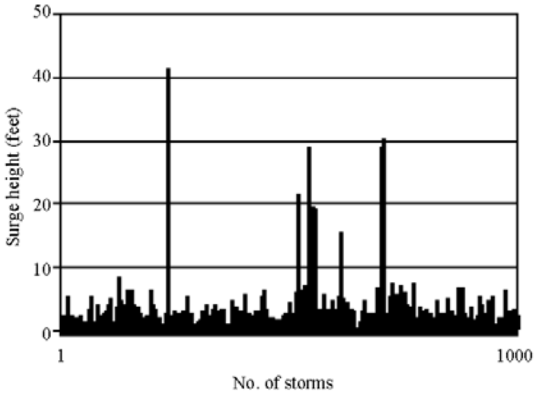

Fig. 10: Surge height at Khulna

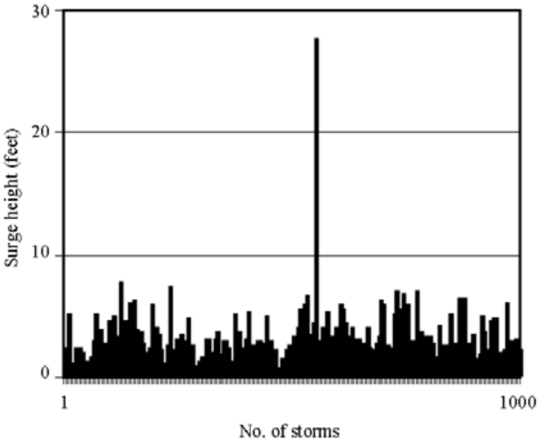

Fig. 11: Surge height at Barisal

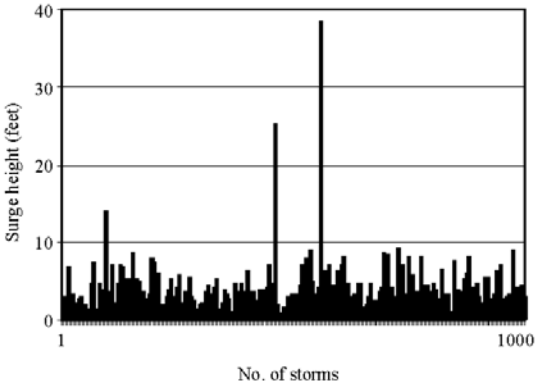

Fig. 12: Surge height at Noakhali

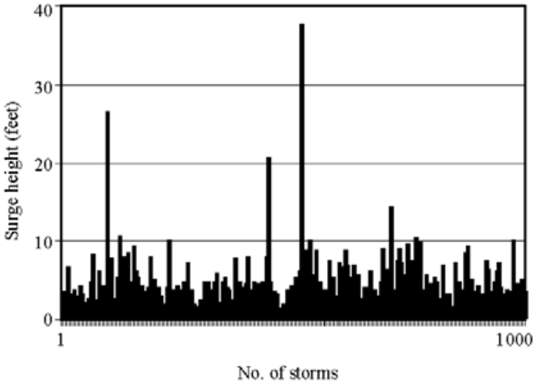

Fig. 13: Surge height at Chittagong

Mandal (1991) prepared the probable maximum storm surge for the Indian and Bangladesh coastlines using the pre-computed nomograms (Fig. 9).

According to the nomograms, the highest storm surge along the Bangladesh coastline as well as in the North Bay of Bengal may be expected at the Hatia of Noakhali region, i.e., 13.2 m. The maximum surge height obtained at Noakhali from the Monte Carlo simulations is 38.39 feet or 11.7 m. Among all of the coastal sites, the highest maximum surge height is obtained at Khulna, i.e., 41.14 feet or 12.5 meters. In the pre-computed nomograms, the maximum surge height calculated at Khulna is also 12.5 m.

Figure 10-14 show the histograms of storm surges from the 1000 simulated storms at each of the five sites. At Khulna, most of the surges are within 5 feet height and the highest storm surge is 41.14 feet. At Barisal, most of the surge heights are within 6 feet height and the highest is 27.69 feet.

At Noakhali, most of the surges are within 10 feet height with the highest surge is 38.39 feet. At Chittagong,

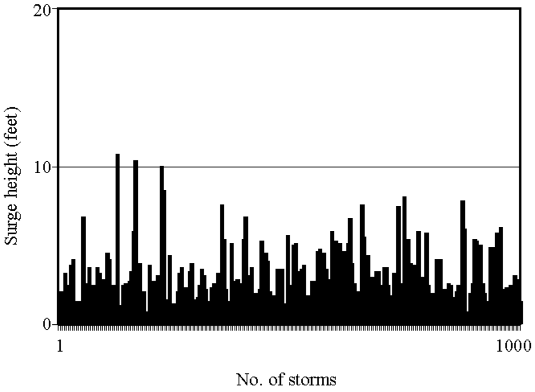

Fig. 14: Surge height at Cox's Bazar

most of the surges are also within 10 feet height and the highest surge is obtained as 37.63 feet. In the April 1991 Super cyclone, the storm surge reached around 30 feet height in Chittagong region. The maximum surge height is the lowest at Cox's Bazar, only 10.72 feet.

CONCLUSION

Monte Carlo simulations have been carried out to estimate the maximum wind speeds and maximum surge height at five locations along the Bangladesh coast. The modified Holland wind field model represents the structure of the landfalling storms and a simple bathystrophic storm surge model is assumed to calculate the storm surge at the landfall locations. The results can be used for devising different mitigation measures in the coastal areas of Bangladesh. The return periods of maximum wind speeds for all the coastal sites are also calculated which is important in the analysis of the vulnerability of structures in this region from tropical storms. Measures can also be taken to improve the existing building code and the basic wind speed map of Bangladesh based on this study, which in turn would contribute minimizing the impact of tropical cyclones and other windstorms in the coastal areas.

ACKNOWLEDGMENTS

The authors would like to acknowledge the Wind Science and Engineering Research Center at Texas Tech University and the State of Texas to provide financial support to carry out the study.

REFERENCES

ASCE Standard No. 7-98, 2000. Minimum design loads for buildings and other structures. American Society of Civil Engineers.

Bangladesh Bureau of Statistics, 2003. Statistical Year Book of Bangladesh 2000, Dhaka.

Batts, M.E. *et al.*, 1980. Hurricane wind speeds in the United States. National Bureau of Standards Building Science Series 124, US Department of Commerce, Washington, DC.

Das, P.K., 1994. Prediction of storm surge in the Bay of Bengal, Kalpathi Ramakrishna Ramanathan Medal Lecture 1993. Proc. Indian Natl. Sci. Acad., Part A, 60: 513-533.

Dube, S.K. *et al.*, 1997. Storm surge in the Bay of Bengal and Arabian Sea: The problem and its prediction. Mausam, 48 (2): 283-304.

Freeman, J. *et al.*, 1957. The bathystrophic storm tide. J. Mar. Res., 16 (1): 12-22.

Global Tropical Cyclone Climatic Atlas, Version 1.0, Fleet Numerical Meteorology and Oceanography Detachment, Asheville, North Carolina. Formerly be http://navy.ncdc.noaa.gov/products/gtcca/gtccamain.html (now closed).

Global Tropical and Extra-tropical Cyclone Climatic Atlas, Version 2.0 (CD-ROM), Fleet Numerical Meteorology and Oceanography Detachment, Asheville, North Carolina, September 1996.

Hubbert, G.D. *et al.*, 1991. A real-time system for forecasting tropical cyclone storm surges. Weather Forecasting, 6 (1): 86-97.

Islam, T., 2006. Integrated approach to cyclone wind analysis and disaster planning for the Bangladesh coast. Ph.D Thesis Texas Tech University.

Johns, B. and J. Lighthill, 1993. Modelling of Storm Surges in the Bay of Bengal. Tropical Cyclone Disasters, Lighthill, J. *et al.*, (Eds.). Peking University Press, Beijing, pp: 410-422.

Kriebel, D.L. *et al.*, 1996. An investigation of the load factors for flood and combined wind and flood. Phase 1 Project Report. American Society of Civil Engineers.

Mandal, G.S., 1991. Tropical cyclones and their forecasting and warning systems in the North Indian Ocean. Tropical Cyclone Programme Report No. TCP-28, World Meteorological Organization, Geneva, pp: 119.

Murty, T.S., 1984. Storm surges. Meteorological ocean tide. Department of Fisheries and Oceans, Ottawa, Canada.

Murty, T.S. *et al.*, 1986. The storm surge problem in the Bay of Bengal. Prog. Oceanogr., 16 (4): 195-233.

Skwira, G.D., 1998. Monte Carlo simulation for the United States Gulf and Atlantic Coast. M.Sc. Thesis, Texas Tech University.