Analysis of Wave Characteristics along the Coast of Bangladesh Using a Coupled Wave-Hydrodynamic Delft3D Model of the Bay of Bengal

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Abstract. Bangladesh has a unique geophysical location at the northern apex of the Bay of Bengal. Waves originating in the Indian Ocean, are constantly travelling up the bay area and interacting with the Bangladesh coastlands. In order to estimate the major wave properties required for coastal engineering purposes, a 2D coupled Wave-Hydrodynamic model of the greater bay area was developed in this study, using the Delft3D modeling suite. The model was simulated for a year and from the model outputs, significant wave height was primarily assessed at multiple locations along the Bangladesh coastline. Considerable spatial variation was observed in the wave parameters, along the whole coast at different locations, with the south-eastern coastal region showing high trends of wave height; whereas in the deltaic south-western, and south-central zones, wave heights were rather moderate. Strong seasonal variation was also observed for the different parameters, as both wave heights and depth-average current velocity were very high during the wet monsoon season, compared to the lean winter period. The results of this study is expected to provide a reasonably sound characterization of the wave spectrum along the coastline of Bangladesh.

1. Introduction
Geographic location, along with the general low elevation and climatic conditions, make the coastlands of Bangladesh uniquely vulnerable [1,2]. The country is situated at the northern apex of the Bay of Bengal, with its southern coastline forming a funnel-shape at the head of the bay [3]. Ocean waves are continuously shoaling and interacting with the local morphology in the energetic nearshore coastal regions. A vast array of coastal engineering projects is currently commencing in Bangladesh, as well as carried out in the past years to protect the densely populated coastal areas from natural calamities like cyclone, storm surges, funded by both nationally and internationally [4,5,6]. In order to reach and maintain an acceptable level of functioning of these structures, a thorough understanding of the wave behavior is necessary. To provide a deeper insight regarding this wave interaction, a numerical model for the Bay of Bengal area was developed in this study, and wave properties of the greater bay area and along the coast of Bangladesh were analyzed. Among the various wave parameters, significant wave height was primarily investigated, which is a basic parameter in characterization of sea waves, and in most coastal engineering projects it is used as the design wave height [7]. In physical oceanography, the significant wave height is defined...
traditionally as the average height of the highest third of the waves [8]. Nowadays it is usually defined as four times the standard deviation of the surface elevation – or equivalently as four times the square of the wave spectrum [9]; the difference in magnitude between the two definitions being only a few percent (5~10%). Buoys, wave gauges, synthetic aperture radars etc. are some of the commonly employed in-situ wave measurement techniques. However, these methods tend to be highly expensive, labor-intensive and especially difficult during energetic sea states; and thus often times measured records of wave data may not be available or may be too insufficient for design purposes. Mathematical modeling can prove to be a viable alternative to combat these limitations, and provide reasonably acceptable estimates for wave properties.

A few others [10,11] had previously used a numerical model of the Bay of Bengal in their studies, but the focus of their research was mainly on the hydrodynamic phenomena (flow structures, their speed, direction) in the coastal region of Bangladesh. Analysis of wave characteristics of the bay area was not covered in these studies. However, for an efficient approach towards coastal planning, management as well as sustenance of coastal structures, a comprehensive documentation of wave behaviour has no alternative. The present study aims to achieve that by developing a coupled hydrodynamic-wave model in Delft3D, with model domain enclosing the northern Bay of Bengal, to enhance the understanding of wave properties in the greater bay area and along the coast of Bangladesh. The model was simulated for a year and from the results, approximations were obtained for wave properties such as, significant wave height, peak wave period, wave length, wave direction, and also hydrodynamic features such as depth average velocity. Seasonal variation of these parameters, as well as their spatial variation across the coastal belt was also observed. The results from the simulated model is expected to be useful in understanding the nature and characteristics of wave spectrum along the Bangladesh coastline.

2. Study area

The numerical model developed in this study encloses the northern part of Bay of Bengal, with model boundaries extending from longitude 82.5˚E near Vishakhapatnam, India, to 94.5˚E near Gwa Bay, Myanmar; and from latitude 17˚N, to the coastal lands upwards north, as shown in figure 1(a). The domain boundaries were set in accordance with previous numerical studies conducted in this region [10,11]. In addition to observation of general wave characteristic in Bay of Bengal, the study focused on assessing the time-dependent wave characteristics at eight specific locations along the coastline of Bangladesh.

![Figure 1](image)

Figure 1. (a) Domain of the numerical model in Bay of Bengal (b) Locations of interest along the coastline of Bangladesh
Bangladesh, as shown in figure 1(b). The locations were namely: Hiron point, Kuakata, Hatiya, Sandwip, Patenga, Kutubdia, Cox’s Bazar and Teknaf. On the basis of geo-morphological characteristics, coastslands of Bangladesh are divided into three distinct regions: the south-west Ganges Tidal Plain, the south-central Meghna Deltaic Plain and the south-east Chittagong Coastal Belt, more commonly referred to as western, central and eastern zones respectively [12]. The monitoring locations were so chosen, that regional variations of wave characteristics could be observed spatially across the whole coastal belt of Bangladesh.

3. Methodology

3.1. Model description

To estimate the major wave properties and some hydrodynamic features, a 2D mathematical model was developed using the Delft3D modelling system. The WAVE module of Delft3D was used with an online coupling with the FLOW module. In this coupled simulation, the two modules have a dynamic linkage through a two-way wave-current interaction. Both the effect of waves on current and the effect of flow on waves are accounted for in this coupling of modules. For a two dimensional model, the FLOW module solves the depth-averaged unsteady shallow water equations; namely continuity equation (Eq. 1) and momentum equations (Eq. 2-3).

\[
\frac{\partial \xi}{\partial t} + \frac{1}{\sqrt{\xi \xi / \eta \eta}} \frac{\partial [(d + \xi) U \sqrt{\eta \eta}]}{\partial \xi} + \frac{1}{\sqrt{\xi \xi / \eta \eta}} \frac{\partial [(d + \xi) V \sqrt{\eta \eta}]}{\partial \eta} = Q \tag{1}
\]

\[
\frac{\partial u}{\partial t} + \frac{u}{\sqrt{\xi \xi / \eta \eta}} \frac{\partial u}{\partial \xi} + \frac{v}{\sqrt{\eta \eta / \xi \xi}} \frac{\partial u}{\partial \eta} + \frac{\omega}{\partial \xi \partial \sigma} + \frac{\omega}{\partial \xi \partial \sigma} - \frac{u}{\sqrt{\xi \xi / \eta \eta}} \frac{\partial \sqrt{\eta \eta}}{\partial \xi} + \frac{u}{\sqrt{\xi \xi / \eta \eta}} \frac{\partial \sqrt{\eta \eta}}{\partial \eta} - f v = - \frac{1}{\rho_0 \sqrt{\xi \xi / \eta \eta}} P_\xi + F_\xi + \frac{1}{(d + \xi) \partial \sigma} (v \nu_c \frac{\partial u}{\partial \sigma}) + M_\xi \tag{2}
\]

\[
\frac{\partial v}{\partial t} + \frac{u}{\sqrt{\xi \xi / \eta \eta}} \frac{\partial v}{\partial \xi} + \frac{v}{\sqrt{\eta \eta / \xi \xi}} \frac{\partial v}{\partial \eta} + \frac{\omega}{\partial \xi \partial \sigma} + \frac{\omega}{\partial \xi \partial \sigma} - \frac{u}{\sqrt{\xi \xi / \eta \eta}} \frac{\partial \sqrt{\eta \eta}}{\partial \xi} + \frac{u}{\sqrt{\xi \xi / \eta \eta}} \frac{\partial \sqrt{\eta \eta}}{\partial \eta} + f u = - \frac{1}{\rho_0 \sqrt{\xi \xi / \eta \eta}} P_\eta + F_\eta + \frac{1}{(d + \xi) \partial \sigma} (v \nu_c \frac{\partial v}{\partial \sigma}) + M_\eta \tag{3}
\]

In the continuity equation, integrated over the vertical (Eq. 1), $\xi$ denotes water level above some horizontal plane of reference, $U$ and $V$ are the depth averaged flow velocities in the horizontal ($\xi$) and curvilinear ($\eta$) directions respectively. $Q$ represents the contributions per unit area due to the discharge or withdrawal of water. An extensive description of all the parameters, equations and methods of numerical solution used, can be found in the Delft3D-FLOW manual [13].

3.2. Grid generation and bathymetry

Delft3D utility RGFGRID was used to generate the computational grid, with spatially varying grid resolution as shown in figure 2(a). The objective was to attain a high grid resolution in the area of interest, by tapering the grid towards the land, and maintain a low resolution seawards, thus saving computational effort. The flow grid was further locally refined along selected strips near the coast. This allowed for the grid cells near the coast to be about as small as 1.5 km by 1.5 km. To ensure stability of the model, certain parameters of the generated grid were kept within the recommended limits (aspect ratio < 2, orthogonality ≈ 0 and courtant number < 11). Bathymetry data of study area was extracted from GEBCO_2014’s gridded bathymetric data sets, which is a continuous terrain model with spatial resolution of 30 arc-seconds. Delft3D QUICKIN module was used to process and generate the bathymetry for the model, as can be seen in figure 2(b).

3.3. Boundary conditions

The model consists of two open boundaries. Hourly water levels of Lower Meghna River at Chandpur, collected from Bangladesh Water Development Board (BWDB) was used as upstream boundary cond-
-ition; whereas the downstream boundary in the Bay of Bengal was divided into five segments, as shown in figure 2(b) and water level was extracted using Tide Model Driver (TMD), at each end of the segments. TMD is a Matlab package, that uses the eight major harmonic tidal constituents (M2, S2, N2, K2, K1, O1, P1, Q1) and can predict tidal water level from that with substantial accuracy [14].

3.4. Model setup, calibration and validation

For the initial simulation, Manning’s roughness factor for whole grid was taken as uniform value of 0.02. Three additional boundary conditions- time-varying significant wave height, wave direction and wave period were provided at the southern boundary in Bay of Bengal, from European Centre for Medium-Range Weather Forecasts (ECMWF). Wind speed data were collected from ECMWF as well, at one-degree interval across the whole computational grid. Water level obtained from the initial simulation was found to be in-phase with observed water level, but the magnitude did not correspond. So instead of the initial uniform roughness, a space-varying roughness file was incorporated in the model to calibrate it by repeated trial and error process, so that observed and simulated water levels finally coincided. Calibrated model was further validated by running a simulation for the wet period of 2017. The semi-diurnal tidal characteristics of Bangladesh was also represented by model results, as well as the spring and neap tidal patterns. The significant wave height output from the validated model also closely approximated the extracted data from ECMWF, as can be seen in comparison curves in figure 3.

Figure 3. Comparison curves for (a) Spring tide and Neap tide (b) Significant wave height from model and ECMWF

Figure 2. (a) Computational grid (b) Bathymetry and open boundaries
4. Results and discussion
The Hydrodynamic-Wave coupled model of the northern Bay of Bengal, developed in this study was used for assessing the hydrodynamic and wave properties in the Bay area, and at selected locations along the Bangladesh shoreline. The model was simulated for one year in order to establish the general wave characteristics along the whole coast of Bangladesh, which was observed to vary significantly, both spatially and temporally.

4.1. Significant wave height
The highest waves in the bay was observed in the pre-monsoon season, particularly in the month of May, as can be seen in in figure 4. During this period, significant wave height was, on average 2.5 m in the south-west to central parts of the bay. Whereas along the south-east coasts, waves were relatively much higher and in the range of 3 to 4 m on the average. After the monsoon, the waves gradually diminished again in the dry season, becoming 0.15 to 0.35 m on average in December. However, in all seasons throughout the year, prominent shoaling effect was observed as the wave approached the continental shelf from the deep waters of the bay. The wave heights observed in the different coastal zones are summarized in the following sub-sections.

4.1.1. South-west coast
In the south-western part of the coast, two locations of interest were observed, namely: Hiron Point and Kuakata. At Hiron Point, it was observed that significant wave height is greatest in the wet season (May, June, July), followed by a gradual decline in the dry winter season, except for few sudden, short-lived peaks, as shown in figure 5(a). Maximum wave height observed was 1.55 m in early July. Similar trends in wave heights were also observed at Kuakata, as shown in figure 5(b). Wave height was overall highest during the wet period, and in the dry period of January to March it was very low. The maximum significant wave height obtained was 1.82 m in May. The pattern of wave heights observed in the south-western region coincides with findings of previous studies, that strong winds from south-west and the associated strong waves flow onto the Bay from June to September (south-west monsoon), whereas weaker north-east winds and waves prevail during December–February [15].

Figure 5. Simulated significant wave height at (a) Hiron Point (b) Kuakata
4.1.2. South-central coast
Near the Meghna estuary and off-shore islands, two observation points were selected. One of them was near Hatiya island, and the other in Sandwip channel. It was observed from the model results in figure 6(a) that, waves at Hatiya were not very high at any time of the year. The maximum significant wave height obtained was 1.42 m in May. Again model results indicate in figure 6(b), that waves were not very high as well near Sandwip. From January to March wave height was below 0.5 m, and peak significant height (1.22 m) was observed in May. The particularly low wave heights in Sandwip and Hatiya channel could be attributed to opposing contribution of large riverine discharge from lower Meghna [1,16] and dominance of tidal current circulations in the estuary.

4.1.3. South-east coast
The locations of interest selected in this zone were at Patenga, Kutubdia, Cox’s Bazar and Teknaf. At Patenga, a relatively high trend in significant wave height was found during the months of May to August as shown in figure 7(a), with an average around 1 m, and a lower trend in February and March. Wave heights near Kutubdia increased greatly compared to previous locations. Waves were in general high from June to first half of September, averaging around 1.5 m. During dry season however the mean wave height was averaging below 1 m, as shown in figure 7(b). At Cox’s Bazar, model results in figure 7(c) show very high trend in wave height. The peak wave height was found 3.60 m in May, and very large wave heights persisted throughout the months of May, June, July. August and mid-September. Finally, at the southern-most location Teknaf, from figure 7(d) it is evident from model outputs that waves were highest, compared to other locations. Peak wave height was found 4.29 m in May. From June to August, waves were particularly high, with average height being around 3 m. From October to December it reached as high as 2 m, and even in dry period from January to March wave height were considerably large, exceeding 1.5 m at some instances. The south-east coast of Bangladesh has a rather narrower strip of continental shelf compared to other coastal zones [17]. More shoaling is generally expected under these conditions. Again from a geomorphological aspect, the
south-east Chittagong region is separated from the tide-dominant Ganges Delta, by the Feni River [18]. Tide plays the key role in sediment dispersal and shaping of the western and central coastal zones, whereas the wave energy is rather low [16]. Again previous studies by Wright and Coleman [19,20] have also found that high wave energy flux is responsible for developing straight shorelines; and in Bangladesh the eastern zone of Chittagong forms a nearly straight coastline when compared to the rest of the Ganges Delta front. Pattern of wave heights observed from model corresponds to findings of these previous studies.

4.2. Peak wave period, wave length and wave direction
In addition to significant wave heights, the coupled model generated outputs of peak wave period, wave length and wave directions. As example, the peak wave period and wave length at the observation point near Cox’s Bazar only, is illustrated in figure 8(a) and 8(b) respectively. The mean direction of waves originating in the Bay of Bengal and approaching the coastline could also be extracted as model output. Maximum and minimum wave height in the bay area was observed in May and December respectively for the year 2016, and the typical wave vectors near the Bangladesh coast, in those corresponding month are shown in figure 9.

4.3. Depth average current velocity
The two dimensional model developed in this study could not capture velocity variation over depth, rather a depth integrated average velocity was obtained from model results. The typical velocity profiles near the Bangladesh coastline, during both wet season and dry season are shown in figure 10. It can be seen that during the wet season, velocity is very high, (reaching 3.5 m/s in north Hatiya Channel), while in the dry season, as shown in figure 10(b), velocity is on average 0.5 m/s at most places near the coast. However, even in the dry season, the flow velocity in the dynamic Meghna estuary was observed to be considerably high.

5. Conclusions
This study attempted to produce an approximate scenario of the wave characteristics along the Bangladesh coast, by developing a 2D Hydrodynamic-Wave coupled model using Delft3D, and simulating it for one year. Strong seasonal variations were noted in all monitored locations throughout the Bangladesh coast.
the year, as wave height increased almost 2 to 3 times in the wet monsoon period, compared to the dry winter period. Again wave properties varied considerably along the coast spatially as well. In the eastern coastal region, the wave heights were much larger, than the western and central zones. Particularly near Kutubdia, Cox’s Bazar and Teknaf, waves were observed to be drastically higher. Whereas in the tide-dominated Meghna estuary in the central zone, wave heights were more moderate near Hatiya and Sandwip. To obtain a more refined overview around a particular area of interest, localized grid surrounding that area can be nested or incorporated in the larger grid for Bay of Bengal used in the present study. Overall the results of this study present an estimate of the spatial and temporal trends of wave properties in the Bay of Bengal, and specially along the coast of Bangladesh. Considerations of this regional wave behavior along the coastline can pave the implementation of a more effective and adaptable coastal management policy, for the vulnerable coastlands of Bangladesh.

6. References
[1] Allison M A 1998 Historical changes in the Ganges-Brahmaputra delta front. Journal of Coastal Research, 14(4) 1269-75
[2] McGranahan G, Balk D and Anderson B 2007 The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones Environment and Urbanization 19(1) 17-37
[3] IHO 1953 Limits of oceans and seas (No. 23) International Hydrographic Organization
[4] Choudhury G A, Van Scheltinga C T, van den Bergh L M, Chowdhury F, de Heer J and Hossain M 2012 Preparations for the Bangladesh delta plan (No. 2300) Alterra, Wageningen-UR
[5] Ahmad M and Rahman A 2011 The stimulating role of NGOs in Bangladesh Climate of Coastal Cooperation. Coastal & Marine Union the Netherlands pp 62-63
[6] Dewan C, Mukherji A and Buisson M C 2015 Evolution of water management in coastal Bangladesh: from temporary earthen embankments to depoliticized community-managed polders Water International 40(3) 401-16
[7] Lee D Y and Jun K C 2006 Estimation of design wave height for the waters around the Korean Peninsula Ocean Science Journal 41(4) 245-54
[8] Munk W H 1944 Proposed uniform procedure for observing waves and interpreting instrument records La Jolla, California: Wave Project at the Scripps Institute of Oceanography Rep 26
[9] Holthuijsen L H 2010 Waves in oceanic and coastal waters. Cambridge university press.
[10] Uddin M, Alam J B, Khan Z H, Hasan G J and Rahman T 2014 Two dimensional hydrodynamic modelling of Northern Bay of Bengal coastal waters Computational Water, Energy, and Environmental Engineering 3(04) 140-51
[11] Al Azad A S, Mita K S, Zaman M, Akter M, Asik T Z, Haque A, Hussain M A and Rahman M 2018 Impact of tidal phase on inundation and thrust force due to storm surge Journal of Marine Science and Engineering 6(4) 110
[12] Karim M F and Mimura N 2008 Impacts of climate change and sea-level rise on cyclonic storm surge floods in Bangladesh Global Environmental Change 18(3) 490-500
[13] Deltares 2017 Delft3D User Manuals Version: 3.15, SVN Revision: 52614 the Netherlands
[14] Padman L and Erofeeva S 2005 Tide Model Driver (TMD) Manual Earth and Space Research
[15] Unger D, Ittekkot V, Schäfer P, Tiemann J and Reschke S 2003 Seasonality and interannual variability of particle fluxes to the deep Bay of Bengal: influence of riverine input and oceanographic processes Deep Sea Research Part II: Topical Studies in Oceanography 50(5) 897-923
[16] Milliman J D and Syvitski J P 1992 Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers The journal of Geology 100(5) 525-44
[17] Finkl C W and Makowski C (Eds.) 2017 Coastal Wetlands: Alteration and Remediation (Vol. 21) Springer
[18] Akter J, Sarker M H, Popescu I and Roelvink D 2015 Evolution of the Bengal Delta and its prevailing processes Journal of Coastal Research 32(5) 1212-26
[19] Wright L D and Coleman J M 1972 River delta morphology: wave climate and the role of the subaqueous profile Science 176(4032) 282-84
[20] Wright L D and Coleman J M 1973 Variations in morphology of major river deltas as functions of ocean wave and river discharge regimes AAPG Bulletin 57(2) 370-98