

## Chapter 6

# Summary

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The destruction due to storm surge flooding is a serious concern along the coast of Bay of Bengal. Amongst other natural disasters affecting the coast of India and Bangladesh, storm surges stand out, so far, as the most damaging and as an agent of death and destruction on a scale at least as massive as earthquakes, especially in the head bay region and at some parts along the east coast of India. The high disastrous surges produced at these coastal areas can be caused due to the shallow bathymetry, geometrical configuration of the coastline, wide continental shelf, funnelling effect of the bay and favourable cyclone track. The high death toll could have occurred due to the high population residing in the low-lying coastal areas of India and Bangladesh, which are at higher risks of flooding during cyclonic events. In addition, tidal ranges in the northern Bay of Bengal are very high and the destruction caused by surges can be massive if the surges occur at the time of high tide. Thus real time monitoring and warning of storm surges in the Bay of Bengal is important, for which numerical modelling is the best approach.

As a first step toward simulating the combined effect of tides and surges and prior to the storm surge model, a tidal model was developed to simulate tidal propagation in the Bay of Bengal.

The vertically averaged equation of continuity and the equations of momentum and the numerical techniques used to solve these equations are described in Chapter 2. The model domain has a north-south extension from  $1.5^{\circ}\text{N}$  to  $23^{\circ}\text{N}$  and east-west extension from  $79.8^{\circ}\text{E}$  to  $103^{\circ}\text{E}$  covering the entire Bay of Bengal, with two southern open boundaries along  $1.5^{\circ}\text{N}$  and a western open boundary along  $79.8^{\circ}\text{E}$ . The model domain was spatially discretized into

uniform grids of 5 minute (9.2 km), depending on which the time step was chosen to be 12 seconds.

The major factor that could influence the accuracy of simulated elevations is the actual representation of the bathymetry of the region. The open source datasets such as ETOPO5 are found to have low accuracy in shallow waters (depths less than 200m). Therefore, the lack of open source accurate data for shallow regions encouraged us to develop a modified bathymetric datasets for the region by digitizing the depth contours and sounding depths less than 200 m from hydrographic charts published by Naval Hydrographic Organization. The digitized data was then gridded and combined with ETOPO5 data (masked for depths less than 200m) using appropriate blending techniques. The generation of this dataset is described in Chapter 3. The modified ETOPO5 dataset showed improvements in many regions such as head bay, Gulf of Martaban and around Andaman Island. The improvements in the modified ETOPO5 dataset has been assessed by comparing the tidal elevations simulated using the original ETOPO5 and modified dataset in a tidal propagation model, with the observed tidal levels. With modified dataset, the simulated tidal elevation showed good agreement with the observed levels, while for the original ETOPO5 dataset, the simulated elevations showed lower amplitudes and a shift in phase. Though the domain of the present study covered only Bay of Bengal, the task to generate the reliable dataset was extended to the shallow waters of the entire Indian Ocean. The generation and improvements in the modified dataset for the entire Indian Ocean has been illustrated in Sindhu et al. [2007]. The modified bathymetric data is available in [http://www.nio.org/index/option/com\\_subcategory/task/show/title/Sea-floor%20Data/tid/2/sid/18/thid/113](http://www.nio.org/index/option/com_subcategory/task/show/title/Sea-floor%20Data/tid/2/sid/18/thid/113). The data has already been used in many numerical studies [Neetu et al., 2011; Aboobacker et al., 2011; Rao et al., 2010].

The 2D non linear barotropic model, described in Chapter 2, was used to simulate composite tides and the five major tidal constituents ( $M_2$ ,  $S_2$ ,  $N_2$ ,  $K_1$  and  $O_1$ ). In order to simulate composite tides, the model was driven by tidal elevations extracted from FES2004 and for the simulation of the constituents, the amplitudes and phases of the respective constituent extracted from the FES2004 dataset was

prescribed at the open boundaries. The simulated composite tidal elevations were harmonically analyzed to obtain the amplitudes and phase of the major semi-diurnal and diurnal constituents, which are referred to as model-derived constituents. The model was validated by comparing the simulated composite tides and the model derived constituents with the hourly tide gauge observations available at few stations and the amplitude and phase of the constituents extracted from Admiralty Tide Table, respectively. The root mean square error (RMSE) for the simulated tidal elevation covering a period of 30 days was found to be less than 7.5 cm. The RMSE between the observed and simulated amplitudes (phase) of each of the constituent is;  $M_2$ : 7.0 cm ( $9.4^\circ$ );  $S_2$ : 4.4 cm ( $9^\circ$ );  $K_1$ : 3.5 cm ( $3^\circ$ ); and  $O_1$ : 2.5 cm ( $38^\circ$ ). The RMS misfit (ORM) is found to be less than 9 cm which illustrates the ability of the model to reproduce the observed tidal characteristics in the region.

In order to analyze the spatial variations in tidal heights and the propagation of tides in the shallow regions of Bay of Bengal, the individually simulated tidal constituents were used to construct co-range and co-tidal charts for each of the five major constituents. The distribution of the semi-diurnal constituents shows a degenerate amphidromic point at the south eastern tip of Sri Lankan coast, but for the diurnal tides it is found to be located along the south-western boundary of the model domain. The semi-diurnal and diurnal tides propagate northward in the central bay, north eastward in the Andaman Sea and southward in the Malacca Strait, with increasing amplitudes. The variation in the amplitudes of diurnal tides across the Bay is very low as compared to the semi-diurnal tides. The detailed analysis of the distribution of semi-diurnal tides in shallow regions such as the head bay, Gulf of Martaban, and Malacca Strait reveals the presence of some characteristic features. The semi-diurnal tides ( $M_2$ ,  $S_2$ , and  $N_2$ ) are found to amplify nearly twice in the head bay, along the southern coast of Myanmar and in the Gulf of Martaban. The diurnal constituent  $K_1$  amplifies significantly mainly in the north eastern end of the head bay and in the Gulf of Martaban region. The continental shelf in the head bay is wide enough to cause significant amplification of semi-diurnal tides which is in agreement with the Clarke and Battisti [1981]

theory. In the north eastern end of the head bay, the geometrical configuration of the coastline could also contribute to the amplification of semi-diurnal and diurnal constituents. The funnel shaped geometrical configuration of the Gulf of Martaban and wide continental shelf in this region could be the factors responsible for the highest amplification of semi-diurnal tides and relatively significant amplification of diurnal tides in the Gulf. The continental shelf along the southern coast of Myanmar is about 200 km wide and the amplitudes of semi-diurnal tides are doubled in this region while the diurnal tides amplify only marginally, which is consistent with Clarke and Battisti [1981] theory. In the Malacca Strait, the amplitudes of both semi-diurnal and diurnal tides are found to increase from the northern end to the southern region. Diurnal tides  $K_1$  and  $O_1$  are found to have maximum amplitudes in the Malacca Strait.

Another salient feature observed in the co-tidal and co-range charts of semi-diurnal tide is the presence of degenerate amphidromic point in the head bay and Malacca Strait. However, it is evident from the charts that the magnitude of displacement of amphidromic points away from the central axis to transform into degenerate amphidromic points depends on the bottom friction as well as latitude, as shown by Rizal [2002]. The Malacca Strait (located at  $3^\circ\text{N}$ ) has a purely virtual amphidromic point for  $M_2$  while the head bay (located at  $21^\circ\text{N}$ ) is characterized by an easily identifiable degenerate amphidromic point, which agrees with the results of Rizal [2002] who evaluated that the probability of occurrence of virtual amphidromic point decreases with increase in the latitude.

We have, therefore, illustrated in detail the significant characteristics of propagation of tides and the major semi-diurnal and diurnal constituents in the Bay of Bengal, especially in the shallow regions such as head bay, Gulf of Martaban and Malacca Strait, where these studies had been scarce.

Now that the tidal model has been applied to the Bay of Bengal, we modified the 2D vertically integrated tidal model to develop the storm surge model, which has been described in Chapter 5. Storm surges produced due to each of the 136 low pressure systems (LPS) that had occurred in the Bay of Bengal during the past 27 years from 1974-2000, were simulated using the storm surge

model. Out of the 136 LPS that formed in the Bay during the specified period, 100 (73%) systems crossed the coast of India, 13 (9%) crossed Bangladesh, 10 (7%) crossed Myanmar and 2 (1%) crossed Sri Lanka and 11 (8%) weekend or dissipated over sea. It is evident that among the 100 cyclones which crossed the Indian coast during the considered 27 years, Orissa had the largest fraction of 43% followed by Andhra Pradesh 29%, West Bengal 16% and Tamil Nadu 12%. For each of the event, the model was driven simultaneously by tides and wind forcing and MSLP fields. The tidal elevations were extracted from FES2004 and applied at the open boundaries and meteorological forcing, derived from the Holland Cyclone model using the position and core pressure at each day of cyclone development, was applied at each grid point in the form of wind and pressure field. We also simulated the tides alone using the tidal model for the period during which each of the event occurred, so as to compute the surge component as the difference between the elevations obtained from the two simulations. A good agreement was obtained between the simulated total water levels (surge and tide) and observed water levels (RMS error less than 15 cm) caused due to some selected LPS that crossed the coast of Chennai, Visakhapatnam and Paradip.

After validating the model and simulating the total water levels caused by 136 LPS event, we selected, for each event, the peak water levels depending on the time of occurrence of maximum surge component. Thereafter, we sorted out the  $r$ -largest total sea level and surge maxima for each year, where ' $r$ ' corresponded to 3. The annual maxima for 27 years were fitted to Gumbel distribution and return periods were estimated as reciprocal of the Gumbel cumulative function. The extreme total water levels and surge component levels corresponding to return periods of 5, 50 and 100 year were computed at 26 stations along the east coast of India. The 5-year and 50-year return levels of total sea level along the east coast of India show a considerable increase from south to north, with the 50-year return total sea levels being as high as 8.7 m and 7.0 m at stations along the north eastern coast such as Sagar Island and Chandipur, respectively. The 100-year total water return levels, being 9 m and 7.4 m, respectively are higher by 7% and 6% as compared to the 50-year return levels at

these two stations, respectively. The high return levels are expected at these stations as the cyclones developed in the Bay of Bengal generally move north or north-west, producing extreme events in the northern part. Moreover, these stations are characterized by high tidal ranges. At some regions in the southern part such as Surya Lanka and Machilipatnam, though 100-year return levels of total sea-level are not very high (3.2 m and 3.2 m, respectively) because of the relatively lower tidal ranges, high return levels of surges (1.0 m and 0.7 m, respectively) are found. In addition to the role of shallow depths (5.0 and 6.1 m, respectively) at the two stations, the high return levels of surges are attributed to the effect of geometrical configuration at Surya Lanka and width (100 km) and orientation of continental shelf at Machilipatnam. Along the coast of Orissa, high return levels are observed at Paradip (0.8 m) and Puri (0.7 m) due to their shallow depths. The highest return level corresponding to 100 year RP for surge component is evaluated to be at Chandipur (3.0 m).

## 6.1 Concluding remarks

We have illustrated that the storm surge model developed in the present work, is capable of reproducing the observed peak total water levels and surge levels produced due to the passage of a cyclone across a coast. The salient features of the model are:

- Fine grid resolution of 9 km is used.
- Use of newly constructed improved ETOPO5 bathymetry dataset which was thoroughly assessed and validated. It has been illustrated that the use of this improved bathymetry in tidal circulation model produced more accurate results.
- Simultaneous inclusion of tidal elevations and meteorological forcing to drive the storm surge model. This ensures tide-surge interaction which implies accurate simulation of total water levels.
- Large model domain which allows proper representation of the entire track of the cyclone and enables accurate generation and propagation of storm surges

throughout the domain and onto the continental shelf and minimizes the influences of the open boundary condition specification.

- The storm surge model has been developed from tidal model, which itself has been validated and shown to produce accurate results.

The extreme water levels that we have estimated in the present study forms a major input to the design of marine structures built to protect the coast and onshore facilities from huge storms and flooding. However, the total water level is the combined effect of storm surge, high tide and wave set-up. It is evident from the present study that the height of the total sea level at a location during the passage of cyclone depends on the phase of tide at the time of the occurrence of peak surge at that location. Therefore, accurate prediction of wind waves; together with its non-linear interaction with the storm surge is also essential. In order to simulate surges inside the rivers and estuaries, river systems need to be included, which is not considered in the present study.

## 6.2 Future perspectives

- Simulation methods for including wave set-up in the storm surge models of the Bay of Bengal are not well established yet. Therefore, further studies of inclusion of wave setup are needed.
- Develop coastal inundation models to estimate flooding of low-lying coastal regions in the event of storm surge, which can be applied for real-time cyclone events in order to minimize the damage and allow for pre-planned affective evacuation.
- The present approach of estimating the return levels of extremes events based on the simulation of storm surges caused by LPS systems in the past years can be used to evaluate the return levels in the future climate.

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