

Numerical Modelling of Tides and Storm Surges in the Bay of Bengal

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by

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Dedicated to

Kaartic

Kanettan

Amma and Pappa

Statement

As required under the University Ordinance 0.19.8 (vi), I state that the present thesis entitled '**Numerical modelling of tides and storm surges in the Bay of Bengal**' is my original research work carried out at the National Institute of Oceanography, Goa and that no part thereof has been submitted for any other degree or diploma in any University or Institution.

The literature related to the problem investigated has been cited. Due acknowledgements have been made wherever facilities and suggestions have been availed of.

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Certificate

This is to certify that the thesis entitled '**Numerical modelling of tides and storm surges in the Bay of Bengal**' submitted by **Sindhu Mole** for the award of the degree of Doctor of Philosophy in the Department of Marine Sciences is based on her original studies carried out by her under my supervision. The thesis or any part thereof has not been previously submitted for any degree or diploma in any University or Institution.

A S UNNIKRIISHNAN

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Abstract

The massive destruction and loss of human life associated with a tropical cyclone can be attributed mainly to the sudden inundation and flooding of the coastal areas produced by storm surges. Storm surges are caused through the action of the high wind stress and pressure gradient. In addition, the phasing of astronomical tide relative to ocean surge is very critical. The most disastrous destruction often results when an extreme storm surge event occurs in conjunction with high tides, for example, during Bangladesh cyclone in 1970, the peak surge coincided with high tide killing more than 300000 people. Whereas a comparable surge in May 1963 occurred at low tide and hence was far less destructive. Thus real time monitoring and warning of storm surges in the Bay of Bengal are of great concern.

During the last few decades, much effort has been directed to the modelling of storm surges generated by intense cyclonic systems in the Bay of Bengal. A large number of location specific high resolution models have been developed to study the impact of cyclonic events along the coast of different countries in the Bay of Bengal and along the east coast of India. However, only a few attempts have been done to develop large scale storm surge models for the Bay of Bengal. Moreover, most of the storm surge models have been developed to simulate individual storm surge events. It is also essential to include tides in the storm surge model itself in order to obtain accurate estimates of total water level as the non-linear interactions between tides and storm surge affects the simulated water levels.

It is very well known that accurate bathymetric datasets are essential to produce reliable modelling results. A variety of bathymetric datasets with different coverage, resolutions, and accuracies are now available. Among these is the ETOPO5 [National Geophysical Data Centre (NGDC), 1988] that are now in wide use. ETOPO5 has been generated by digitizing the depth contours above 200 m from hydrographic charts. Subsequently, the ETOPO5 dataset is not reliable in regions where the depth values are less than 200 m. The shallow-water bathymetric data are usually collected and managed by regional organizations for regional interests. Hence the shallow-water bathymetric datasets are often not as

coordinated internationally and not as standardized as deep-water datasets. This leads to the use of different sources of bathymetry data by the ocean modellers.

Objectives of the present study are as follows

- Generate improved reliable bathymetric dataset for the continental shelf of the Indian Ocean.
- Simulation of tides and generation of co-range and co-tidal charts of the major semi-diurnal and diurnal constituents for the Bay of Bengal.
- Develop storm surge model to simulate total water levels and derive surges caused by low pressure systems identified during the past 27 years (1974-2000) in the Bay of Bengal.
- Estimation of return levels of extreme sea-level events at major coastal stations along the east coast of India.

Chapter 1 describes the background, area of study, motivation for the study and objectives.

Chapter 2 describes the numerical model used in the present study. The vertically integrated 2D model developed by Unnikrishnan et al. [1999] was used to simulate tides in the Bay of Bengal. The governing equations (equation of continuity and momentum equations), represented in Cartesian co-ordinates, were solved using an explicit finite difference scheme on an Arakawa C grid of resolution approximately 9.2 km. The time step chosen was 12 seconds to satisfy the Courant-Friedrichs-Lewy (CFL) criterion. The model domain extends from 1.5°N to 23°N and 79°E to 103°E with open boundaries along 79.8°E and 1.5°N.

The major input for the numerical model is bathymetry which can influence the accuracy of the simulated tides. In addition, accurate bathymetry of the bay is very essential to get accurate simulations of tides and surges as most of the coastal region bordering Bay of Bengal, especially the head bay, Gulf of Martaban and Malacca Strait, are very shallow and characterized by sudden change in depth contours. Hence, the bathymetry data for the present work was obtained from one of our recent works [Sindhu et al., 2007] in which improved shelf bathymetry for the Indian Ocean was prepared by digitizing the depth contours and sounding depths less than 200 m from the hydrographic charts published by the Naval

Hydrographic Office, India. The digitized data was then merged with the ETOPO5 dataset (masked for depths lower than 200 m) through appropriate blending techniques. The modified dataset showed significant improvements in many regions in the Bay of Bengal, such as the head bay, Gulf of Martaban, Malacca Strait and around Andaman Islands. Chapter 3 describes the methodology used in generating the modified shallow water bathymetry and the assessment of its improvements over original ETOPO5 dataset.

Chapter 4 describes the simulation of tides in the Bay of Bengal. The driving force for the tidal model was applied at the open boundaries in the form of composite tidal elevations derived from the global tidal model, FES2004. The time series of the simulated tidal elevations, extracted at selected grid points along the coast of Bay of Bengal, were harmonically analyzed using the TASK2000 software to extract the amplitude and phase of major semi-diurnal (M_2 , S_2 and N_2) and diurnal constituents (K_1 and O_1), referred as model derived tidal constituents. The simulated tidal elevations covering a period of 30 days agreed fairly well with the observed hourly tide gauge data at Paradip, Visakhapatnam and Chennai, with root mean square error less than 7.5 cm. In addition, the amplitude and phase of the model derived major tidal constituents were compared with those obtained from Admiralty Tide Table (ATT) for 13 Standard Ports and 31 Secondary Ports and were found to agree favourably, with correlation coefficient of 0.99 for M_2 , S_2 and N_2 and 0.92 for O_1 .

The validated tidal model was used to simulate major tidal constituent separately in order to construct the co-range and co-tidal charts for the Bay of Bengal. The amplitudes of semi-diurnal tides increase from the southern boundary towards the northern coast of Bay of Bengal, with maxima in the head bay, Gulf of Martaban and Malacca Strait. The variation of the diurnal tides is small compared to the semi-diurnal tides.

The detailed analysis of the co-range charts reveals that semi-diurnal constituents (M_2 , S_2 , N_2) amplify in areas characterized by wide continental shelf (approximately 200 km) such as the head bay and along the southern coast of Myanmar, (the amplitudes are doubled), which is in agreement with Clarke and

Battisti [1981] theory. The diurnal constituent K_1 shows marginal amplification in these regions, but amplifies significantly in the north eastern end of the head bay. The head bay is also characterized by two degenerate amphidromic points. The geometrical configuration, in addition to the wide continental shelf, could contribute to the amplification of both semi-diurnal and diurnal tides in the north eastern end of head bay. The highest amplification of semi-diurnal is observed in the Gulf of Martaban and the diurnal tide K_1 also shows relatively significant amplification in this region, which could be due to its funnel shaped geometrical configuration and wide continental shelf. In the Malacca Strait, the amplitudes of semi-diurnal and diurnal tides increase towards the southern region. The diurnal constituents K_1 and O_1 have maximum amplitudes in the Malacca Strait. A virtual amphidromic point is also identified for M_2 tide in the Malacca Strait.

The forcing and the boundary conditions of the validated tidal model were appropriately defined to simulate the storm surges caused due to cyclones that affected the coast of Bay of Bengal, which is described in Chapter 5. The pressure field and the wind stress associated with low pressure systems (LPS) were estimated using Holland cyclone model. The parameters, such as the radius of maximum winds, core pressure and the position of the core of the cyclone required as input for Holland cyclone model, were obtained from Indian Daily Weather Report and Mausam, which are also documented in National Institute of Oceanography Report [2004].

The storm surge model was forced with tides and meteorological forcing, simultaneously, former derived from FES2004 and applied along the open boundaries and latter estimated from Holland model for each of the 136 event and applied at each grid point of the model domain at every time step of the storm surge model. The tidal forcing was included in the storm surge model itself, rather than adding the individual tidal model output and the surge model output, in order to take into account the non-linear interaction between tides and surges. Therefore, the storm surge simulation gave the total sea level and the depth mean current due to combined effect of tide and meteorological forcing as output. In order to compute the storm surge component of total sea level, the storm surge model was

simulated with tidal forcing alone and the resulting tidal elevations were subtracted from the total sea level. The model results were validated by comparing the simulated level due to few selected cyclones that crossed the coast of Paradip, Visakhapatnam and Chennai with the observed hourly tide gauge data available at these locations and fairly good agreement was obtained.

The 5, 50 and 100-year return level for the total sea level and surge component were estimated for 26 stations along the east coast of India using the r-largest annual maxima method. The spatial variation of return levels of total sea level along the east coast of India shows an increase towards the head bay, the lowest being at Nagapattinam and the highest being at Sagar Island, which is similar to the increasing tidal range. However, the spatial variation of the return levels of surge component is found to be affected by shallow bathymetry and wide continental shelves. The variations in surge return levels along the east coast of India show that shallow and wide coastal shelves result in larger surges than deep and narrow shelves. 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 (3.17 m and 3.19 m, respectively) because of the relatively lower tidal ranges, high return levels of surge component (0.96 m and 0.66 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 surge component are attributed to the effect of geometrical configuration at Surya Lanka and width (100 km) and orientation of continental shelf at Machilipatnam. Similarly, the 100-year return levels of total water level at Chandipur is not high as that at Sagar Road, but the return level of surge component is found to be the highest due to its geometrical configuration.

The results described above are summarized in Chapter 6.

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Chapter 1

Introduction

1.1 Overview

Storm surges are the fluctuations in water level generated during the passage of low pressure systems (LPS), such as tropical or extra-tropical cyclones, over a coastal or inland water body which can last up to a few days. Storm surges constitute one of the world's foremost natural disasters. A brief description of the general characteristics of tropical cyclones is given below, while the extra-tropical cyclones that usually form in the mid-latitudes is beyond the scope of the present study. The major factors that affect the height of storm surges and the methods used for the prediction of storm surges are also described in the following sections.

1.1.1 Tropical cyclones

Tropical cyclones are large revolving vortices with a ring of strong winds around a warm core and extending horizontally from 150-1000 km and vertically to about 12-14 km above sea level. The core has an average radius of about 20-30 km and is almost cloud free with light winds. It is surrounded by a wall of clouds (known as eye wall) arranged in the form of hollow cylinder rising up to an altitude of 15-18 km and a radial thickness of 10-15 km. This zone, though very narrow, constitutes the most hazardous zone as it is characterized by largest pressure gradient, strongest winds (V_{\max}), heavy rainfall, high vertical velocity and strongest convection. The evolution of cyclones is defined in different stages from genesis to dissipation with a life of two to three weeks. The atmospheric and oceanographic conditions favourable for the formation of tropical cyclones are:

- Warm ocean waters with temperatures above 26.5°C to a minimum depth of 50 m;
- High amount of moisture at mid-troposphere elevations;
- An unstable atmosphere which cools rapidly with increasing altitude such that heated air parcels near the warm surface can rise freely into the atmosphere to cool down and condense;
- The presence of pre-existing near-surface disturbance to provide a localized spin (vorticity) and low level convergence;
- Significant Coriolis forces to rotate the cyclone;
- Relatively calm winds in the upper troposphere so that rising air columns and clouds can grow continuously into a vertical column without being cut off.

Tropical cyclones rotate counter-clockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. Tropical cyclones normally decay when they move into unfavourable environment such as land or over cooler waters in higher latitudes. The three major destruction causing hazards associated with the landfall of tropical cyclones are extreme wind speeds, heavy rains and storm surges.

1.1.2 Storm surges

The passage of cyclones over ocean surface impacts the surface elevation in two distinctly different ways. Firstly, the water surface responds to the pressure gradient associated with a cyclone through the *inverted barometer effect*, wherein a 1-hPa (mb) decrease of atmospheric pressure increases the sea level by about 1 cm [Pugh, 2004]. Secondly, drag forces, proportional to the square of wind speed, are generated at and parallel to the sea surface due to strong winds. These forces set up sea level gradient which result in a flow in the direction of wind in shallow waters. The impact of low pressure on sea surface elevation is minimal in comparison to the water being pushed towards the shore by the wind. These fluctuations in the sea surface elevations caused due to pressure gradient and strong winds are known as storm surges. The maximum surge height is produced when the cyclone crosses the coast [Murty et al., 1986].

1.1.3 Factors determining storm surge heights

The nature and magnitude of storm surges at a particular location depends upon the meteorological parameters associated with the tropical cyclone and the physical characteristics of the coastal areas. The meteorological factors affecting the height of storm surge include:

- The intensity of the cyclone, which is defined by the high horizontal pressure gradient and maximum wind speed attained at the eye wall.
- The forward speed of the cyclone - longer the storm stays at a location, larger will be the amount of transport and surge height. Due to the complimentary effect of forward motion and the counter-clockwise rotation of the cyclone in the Northern Hemisphere, highest (positive) surge for a cyclone occurs at the northeast quadrant of the storm's track. A negative surge may also occur on the northwest quadrant of the cyclone track due to offshore winds in this region.
- The radius of maximum winds which is measured radially from the cyclone centre to the location of highest wind speeds. Peak storm surge may vary drastically within a relative short distance along the coastline depending on the radius of maximum winds.
- The angle of approach to the coast; surge height is maximum for a tropical cyclone that moves onshore perpendicular to the coastline as this maximizes the onshore water transport.

The physical characteristics of a coastal area that influence the surge heights are:

- Bathymetry,
- Width of continental shelf,
- Configuration of coastline.

Another factor that determines the extent and severity of storm surges on coastal areas is the phase of the tide during which cyclone crosses the coast. If the peak surge elevation occurs at the time of high tide, the total sea level will be very high and will, thereby, produce the maximum impact. Hence, in order to estimate surge heights and their impact on coastal areas, information on the phase of tide at the time tropical cyclones crosses the coast is as important as the cyclone parameters.

1.1.4 Tides

Tides are the periodic oscillations in sea level produced by the combination of gravitational force of the moon and the sun and the centrifugal force generated as the earth rotates about the common centre of mass of earth-moon-sun system. Tides propagate as long waves on the rotating earth. The combined constraint of ocean basin geometry and the influence of the Coriolis force results in the development of amphidromic systems, in each of which the tidal wave rotates around the amphidromic point in counter-clockwise direction in the Northern Hemisphere and in clockwise direction in the Southern Hemisphere. The tidal range is zero at amphidromic point and increase outward away from it. The positioning of these points in an ocean basin depends on the geometry of the basin, including the coastal configuration and bathymetry, and they can even occur inland as degenerate amphidromic points.

Tides can be represented as a sum of N number of harmonic constituents. The major tidal constituents, their periods and angular speeds are tabulated in Table 1.1. The general form of representing each of the tidal constituent is

$$H_n \cos(\omega_n t - g_n) \quad (1.1)$$

where, H_n is the amplitude, ω_n is the angular speed (related to period T_n as $\omega_n = 2\pi/T_n$), g_n is the phase lag of the observed constituent relative to the theoretical Equilibrium Tide obtained by adjusting 'G_n' to a particular time meridian. 'G_n' is the phase lag of the constituent on the Equilibrium Tide at Greenwich, in Greenwich Mean Time. The relation between the two phase lag is as follows:

$$G_n = g_n + T_z \omega_n \quad (1.2)$$

where T_z is the time zone defined as the shift in time at any place with respect to the Greenwich Mean Time.

The tides, however, behave differently as they enter small water bodies such as marginal seas and estuaries. The propagation of tides in these areas is affected by the shape of the marginal sea, bathymetry and configuration of sea bed (width and slope of continental shelf). As tides propagate into shallow waters, the non-linear mechanism causes transfer of tidal energy to other frequencies, which are

represented as shallow water tidal constituents known as overtides and compound tides (Table 1.2). The frequency of an overtide (such as M_4 , M_6) is always an exact multiple of the frequency of the constituent that undergoes transformation in shallow waters. A compound tide results from the shallow-water interaction of two major tidal constituents (such as MS_4 is generated by the interaction of M_2 and S_2).

The propagation of tides in ocean and marginal seas can be represented by co-range and co-tidal charts of tidal constituents; the former helps to visualize the amplitudes of the tide while the latter provides a convenient way to illustrate the progression of tides. Co-range lines indicate locations where amplitudes of the tides are same. A co-tidal line connects locations where the phase of tide is same.

Table 1.1 Major tidal constituents [Pugh, 1987]

	Tidal species	Name	Speed (°/hour)	Period (hour)
Semi-diurnal	Principal lunar	M_2	28.9841	12.4206
	Principal solar	S_2	30.0000	12.0000
	Larger elliptical lunar	N_2	28.4397	12.6584
	Smaller elliptical lunar	L_2	29.5285	12.1916
	Declinational lunar	K_2	30.0821	11.9673
Diurnal	Luni-solar	K_1	15.0411	23.9344
	Principal lunar	O_1	13.9430	25.8194
	Principal solar	P_1	14.9589	24.0659
	Larger elliptical lunar	Q_1	13.3987	26.8684
	Elliptical lunar	J_1	15.5854	23.0984
	Smaller elliptical lunar	M_1	14.4920	24.8412
Long Period	Lunar semi-monthly	M_f	1.0980	327.85
	Lunar Monthly	M_m	0.5444	661.31
	Solar Annual	S_a	0.0411	8765.76
	Solar semi-annual	S_{sa}	0.0821	4383.05

Table 1.2 Important shallow water tidal constituents [Pugh, 1987].

Tidal species	Name	Speed (°/hour)
Long-period	Msf	1.016
Semi diurnal	$2SM_2$	31.016
	$2MS_2$	27.968
Fourth diurnal	M_4	57.968
	MS_4	58.984
	S_4	60.000
Sixth diurnal	M_6	86.952
	$2MS_6$	87.968

1.1.5 Storm surge prediction methods

The casualties and damages caused by storm surges can be limited if surges are predicted reasonably well in advance in order to implement effective warnings and evacuations of threatened areas. Earlier approaches for the prediction of surge heights included the use of empirical formulae that correlate the sea surface elevations with atmospheric pressure exerted on sea surface and strength and direction of prevailing winds [Rao and Mazumdar, 1966; Flierl and Robinson, 1972; Choudhury and Ali, 1974; Das et al., 1978; Qayyum, 1983; Chowdhury, 1994]. However, these methods require long term observation data to establish appropriate correlations.

The best approach is to apply numerical techniques to solve the vertically integrated form of the hydrodynamic equations [Murty et al., 1986; Dube et al., 1997]. It involves spatial discretization of the study area and the governing equations (equation of continuity and momentum equations) using either finite difference or finite element method and integration of the resulting equations over time using a suitable time stepping procedure. The numerical models based on these equations, which include non-linear interactions, is a most powerful method for practical prediction of surges especially for regions with complex bathymetry and coastline configuration. The accuracy in the simulation of storm surges using

numerical models depends on various input parameters such as storm characteristics, bathymetry, tides and representation of the coastal geometry. The implicit inclusion of tides in the storm surge model is essential to provide accurate estimates of total water level as the non-linear interactions between tides and storm surge affects the simulated water levels [Johns et al., 1985; McInnes et al., 2003].

1.1.6 Extreme value analysis

It is essential to quantify the risk of storm surges in order to formulate proper and effective risk management to mitigate the large scale damages caused due to storm surges. Once the heights of surges due to different cyclonic events in a coastal area are determined, it is possible to derive estimates of extreme sea levels; such as return periods, using statistical techniques. A return period is a statistical measurement, expressed as the reciprocal of the exceedance probability of an event, which denotes the average recurrence interval over an extended period of time. For instance, at a given location, the 50-year return period storm surge height being 2.46 m denotes that the probability of maximum surge height to exceed 2.46 m next year is only 0.02 (i.e., 1/50). Return period estimates are typically required for risk analysis and to design coastal protection structures which will be capable of withstanding an event of a certain return period.

The methods used for the estimation of exceedance probability are the annual maximum method [Jenkinson, 1955; Gumbel, 1958], r-largest annual maxima method [Smith, 1986; Tawn, 1988], joint probability method (JPM) [Pugh and Vassie, 1979], revised joint probability method (RJPM) [Tawn and Vassie, 1989] and exceedance probability method [Middleton and Thompson, 1986; Hamon et al., 1989]. Annual maximum method uses the annual maximum value in several years to fit a Generalized Extreme Value (GEV) distribution [Bury, 1999]. However, the disadvantage of the classical annual maximum method is the use of only the highest value of sea level in a year. Additionally, a successful application of the annual maximum method requires several years of data. In order to overcome the drawbacks, the r-largest annual maximum method

was developed by Smith [1986] and Tawn [1988], which allows to incorporate more than one maximum in a year and therefore more reliable estimates of return periods can be obtained using less number of years. The JPM involves the combination of individually estimated Probability Density Functions (*pdf*) of tide and surge. However, the nature of combination of the *pdf* depends on whether there is interaction between tide and surge. This method is not applicable at locations with short length of data and when the site is surge dominant. Later, the JPM was improved by Tawn and Vassie [1989] to obtain the revised joint probability method (RJPM). An alternative method of obtaining extreme sea level estimates from short data sets is the exceedance probability method (EPM).

1.2 Cyclones and storm surges in the Northern Indian Ocean

The cyclonic disturbances formed in the Northern Indian Ocean are categorized according to their maximum sustained wind speeds and each category has been assigned with different nomenclatures as defined by WMO [2010] and shown in Table 1.3. The expected damage potential of cyclones based on their intensities, as suggested by Attri and Tyagi [2010] is also summarized in Table 1.3. On an average, about 5 to 6 tropical cyclones generate every year in northern Indian Ocean, of which 2 or 3 could develop into severe cyclones, with more number of cyclones (4:1 ratio) developing in the Bay of Bengal than in the Arabian Sea [Dube et al., 1997]. Table 1.4, reproduced from Figure 1 of Niyas et al. [2009], shows the frequency of cyclones and severe cyclones in the Bay of Bengal and Arabian Sea during the last 118 years from 1891 to 2008. Though Arabian Sea and Bay of Bengal are northward extension of Indian Ocean separated by Indian subcontinent with many physiographic similarities, some of the meteorological and oceanographic parameters are strikingly different which are responsible for higher frequencies of cyclogenesis over Bay of Bengal than Arabian Sea [Mooley and Shukla, 1989]. During the pre-monsoon season (April-May), the highest temperature is observed in the Northern Indian Ocean which remains to be above

28°C in the Bay of Bengal even after the onset of monsoon due to strong near-surface stratification and weaker winds in the Bay [Shenoi et al., 2004]. The high SST enhances the convective activities in the atmosphere. This, in turn, strengthens the near-surface stratification giving rise to a cyclic process with positive feedback. Shenoi et al. [2004] demonstrated that these favourable characteristics of the Bay are responsible for more cyclogenesis in the Bay of Bengal than in the Arabian Sea.

The months of October, November and December (post-monsoon season) are found to be principal season for cyclone formation over the Bay of Bengal, followed by the pre-monsoon months of March, April, and May [Attri and Tyagi, 2010]. Niyas et al. [2009] examined long term data from 1891 to 2008 and observed a decrease in the frequency of cyclone formation over the Bay of Bengal, with the maximum rate of decrease during monsoon season. However, in the months of May and November, they observed an increase in the frequency of cyclone formation. The tropical cyclones formed in the Bay of Bengal usually move toward west, north-west or north and finally curve towards east and move into north-east corner of the bay, and thereby, affecting the east coast of Sri Lanka and India, coast of Bangladesh, and north western coast of Myanmar.

Though the cyclones generated in the Northern Indian Ocean are weaker and smaller than those generated in Pacific and Atlantic Ocean, the death toll is highest. According to Frank and Hussain [1971], there were a total of 9-recorded cases of heavy human loss over past 300 years, in which 7 (77%) cases occurred in the Indian subcontinent. Among the destruction causing parameters associated with tropical cyclones, storm surges produce the major devastations. The destruction due to storm surge flooding is a serious concern along the coast of Bay of Bengal (Bangladesh, east coast of India, Myanmar, and Sri Lanka) and Arabian Sea (west coast of India, Pakistan and Oman). However, since the formation of cyclones in the Arabian Sea is less compared to that in the Bay of Bengal (Table 1.4), the frequency of storm surges affecting the coastline of Arabian Sea is lower than that affecting the coastline of Bay of Bengal. Still, a few major destructive surges have occurred along the eastern coast of Arabian Sea as well, particularly

along the coast of Pakistan and that of Gujarat (India) [Joseph et al., 2010]. Dube et al. [1997] had listed out the storm surges that caused major destruction and loss of life at different places along the coast of Arabian Sea during 1782-1996, which are shown in Table 1.5. A list of major storm surges that produced high death tolls along the east coast of India and the coast of Bangladesh, selected from Murty et al. [1986], is shown in Table 1.6.

Table 1.3 Nomenclature for Low Pressure System (LPS) defined by WMO [2010] and their damage potential as defined in Attri and Tyagi [2010].

Weather systems	Maximum wind speeds		Damage Expected
	V_{\max} (knots)	V_{\max} (km/hr)	
Low Pressure (LP)	< 17	< 31	
Depression (D)	17 – 27	31 – 51	
Deep Depression (DD)	28 – 33	52 – 61	Minor damage to loose and unsecured structures
Cyclonic Storm (CS)	34 – 47	62 – 88	Damage to thatched huts. Breaking of tree branches causing minor damage to power and communication lines
Severe Cyclonic Storm (SCS)	48 – 63	89 – 118	Extensive damage to thatched roofs and huts. Minor damage to power and communication lines due to uprooting of large avenue trees. Flooding of escape routes.
Very Severe Cyclonic Storm (VSCS)	64 – 119	119 – 221	Extensive damage to kachcha houses. Some damage to old buildings. Large-scale disruption of power and communication lines. Disruption of rail and road traffic due to extensive flooding. Potential threat from flying debris.
Super Cyclones	> 120	> 222	Extensive structural damage to residential and industrial buildings. Total disruption of communication and power supply. Extensive damage to bridges causing large scale disruption of rail and road traffic. Large-scale flooding and inundation of seawater. Air full of flying debris.

Table 1.4 Distribution of Cyclones and Severe Cyclones in the Bay of Bengal and Arabian Sea (from Niyas et al., [2009])

Month	Bay of Bengal		Arabian Sea	
	Cyclones	Severe Cyclones	Cyclones	Severe Cyclones
January	7	2	1	0
February	2	1	0	0
March	25	2	0	0
April	22	13	6	4
May	58	38	23	16
June	40	5	24	14
July	41	7	3	0
August	30	3	2	0
September	41	15	11	4
October	84	36	29	13
November	108	57	27	24
December	47	23	7	3
Total	505	202	133	78

Table 1.5 List of major storm surges that caused massive destruction and loss of life at different places along the coast of Arabian Sea during 1782-1996 [Dube et al., 1997].

Year	Month	Area of landfall	Area of major storms surges
1782	April	South Saurashtra coast	Gulf of Cambay
1851	May	32 km west of Karachi	Karachi
1920	June	Veraval	Gulf of Cambay
1964	June	Naliya	Gulf of Kutch
1975	October	Porbandar	Saurashtra
1977	November	Karwar	Karwar
1982	November	Veraval	Gulf of Cambay
1996	June	South Saurashtra coast	Gulf of Cambay

Table 1.6 List of storm surges that caused high death toll at different places along the coast of Bay of Bengal during 1737-1985 (selected from Murty et al. [1986]).

Year	Area of landfall	Area of major storms surges	Casualties
1737	Hooghly river	Sunderbans	300,000
1822	Bangladesh		40,000
1833	India		50,000
1864	West Bengal		50,000
1876	Bangladesh		200,000
1897	Bangladesh		175,000
1962	Bangladesh	Chittagong	50,000
1963	Bangladesh	Chittagong	50,000
1965	Chittagong	Comapaniganj	19,279
1970	Hatia, Bangladesh	Comapaniganj	300,000
1971	Paradip	Paradip	10,000
1977	Nizampatnam	Divi	10,000
1984	Karaikal, India	Karaikal	35,000
1985	Orissa	Balasore	11,069

1.3 Area of study – Bay of Bengal

Material destruction and loss of life is found to be very high due to storm surges at the coastal areas bordering the Bay of Bengal (Table 1.6), therefore, the present thesis deals with the analysis of characteristics of storm surges in the Bay of Bengal. The Bay of Bengal, including the Andaman Sea and Malacca Strait, lies roughly between latitudes 5°N and 23°N and longitudes 79.8°E and 102°E. It is bordered by eastern coast of Sri Lanka and India on the west, Bangladesh coast to the north, western coast of Myanmar (formerly known as Burma) and north western part of Malay Peninsula to the east. According to the limits defined by International Hydrographic Bureau (IHB), the Andaman and Nicobar Island separates the water eastward of it from the Bay of Bengal to form the Andaman Sea. The boundary of the Andaman Sea is considered to be a line running from Cape Negrais (16°03'N) through Andaman Islands to a point (10°48'N, 92°24'E)

in Little Andaman Island. In addition, the southern boundary of the Bay of Bengal is defined to extend from Dondra Head at the southern end of Sri Lanka in the west to a point ($5^{\circ}44'N$, $95^{\circ}04'E$) at the northern tip of the Indonesian Island while the Adam's bridge between India and Sri Lanka represent the south eastern boundary. The bay is triangular in shape with the width decreasing from approximately 1600 km at the southern boundary to as narrow as 500 km at the northern end, which is commonly known as head bay. On the eastern side, along the coast of Myanmar, the bay narrows to Gulf of Martaban and on the south eastern end, the width of the bay is constrained by the coast of Malaysia and Indonesia to form the Malacca Strait. The Malacca Strait is connected to the South China Sea on its southern end. The Bay of Bengal and the major stations along the coastline of Bay of Bengal are shown in Figure 1.1.

The width of continental shelf varies considerably along the coastline bordering the Bay of Bengal. The continental shelf is very narrow off the east coast of India and north-western coast of Myanmar. However, the shelf becomes extensively wide at the head bay and along the south-western coast of Myanmar. The Gulf of Martaban and Malacca Strait represent shallow regions with average depths of 40 and 80 m, respectively.

In order to get an idea of the tidal amplitudes in the Bay of Bengal, we used the hourly tide gauge data at Chennai, Visakhapatnam and Paradip provided by the Survey of India and the GLOSS sea level data at stations along the coast of Myanmar (Akyab) and Indonesia (Sabang and Sibolga). The GLOSS/CLIVAR data is an online database (<http://ilikai.soest.hawaii.edu/uhslc/woce.html>) distributed by UHSLC (University of Hawaii Sea Level Centre). We derived the tidal constituents at these stations using TASK2000, tidal analysis software. Among different semi-diurnal constituents that we had estimated for stations along the coastline of Bay of Bengal (Figure 1.2), the amplitudes of M_2 , S_2 and N_2 are found to be relatively significant while among the diurnal constituents, K_1 and O_1 are significant. The variation in the tidal amplitudes along the coast of Bay of Bengal can be inferred from Figure 1.2. The M_2 amplitude is relatively higher at Akyab, located along the coast of Myanmar. The comparison of tidal amplitudes

at stations along the east coast of India (Figure 1.2a, b, and c), whose locations are shown in Figure 1.1, suggests that amplitudes of semi-diurnal and diurnal tides increase towards north. These large tidal heights, when combine with storm surges, can produce very high water level that have a potential of causing widespread destruction to life and property.

1.4 Storm surges in the Bay of Bengal

Rao [1968] classified the coastline bordering Bay of Bengal (mainly Indian coast) into three categories - A, B and C based on the amplitudes of maximum water levels attained at different coasts due to a hypothetical storm with wind speed of 40 m/s. The least dangerous zone with water level less than 2 m is classified as Zone A. The major portion of Tamil Nadu coast from 10°N to 14°N and that of Andhra Pradesh from 16°N to 20°N are assigned as Zone A. The east coast of India from 14°N to 16.5°N and the regions near the southern tip of Tamil Nadu (Coromandel Coast) are Zone B. The most dangerous zone is represented by Zone C (water level higher than 5 m) which extends to three locations along the east coast of India – north of 16°N covering the entire head bay, south Coromandel coast around Palk Bay, and a small area near Nizampatnam Bay. The high disastrous surges produced at these coastal areas can be attributed 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 can also be attributed to the high population, approximately 63 and 62 million, residing in the low-lying coastal areas of India and Bangladesh, respectively which are at high risks of flooding during cyclonic events [McGranahan et al., 2007]. The extent of damage at different places along the coast of Bay of Bengal was documented in earlier studies [Murty et al., 1986; Dube et al., 2000 a, b]. The most disastrous destruction often results when an extreme storm surge event occurs in conjunction with high tide, for example, during Bangladesh cyclone in November 1970, the peak surge of 5.6 m at Chittagong coincided with a high tide (2.1 m) killing more than 300,000 people. Whereas a comparable surge (5.0 m) in

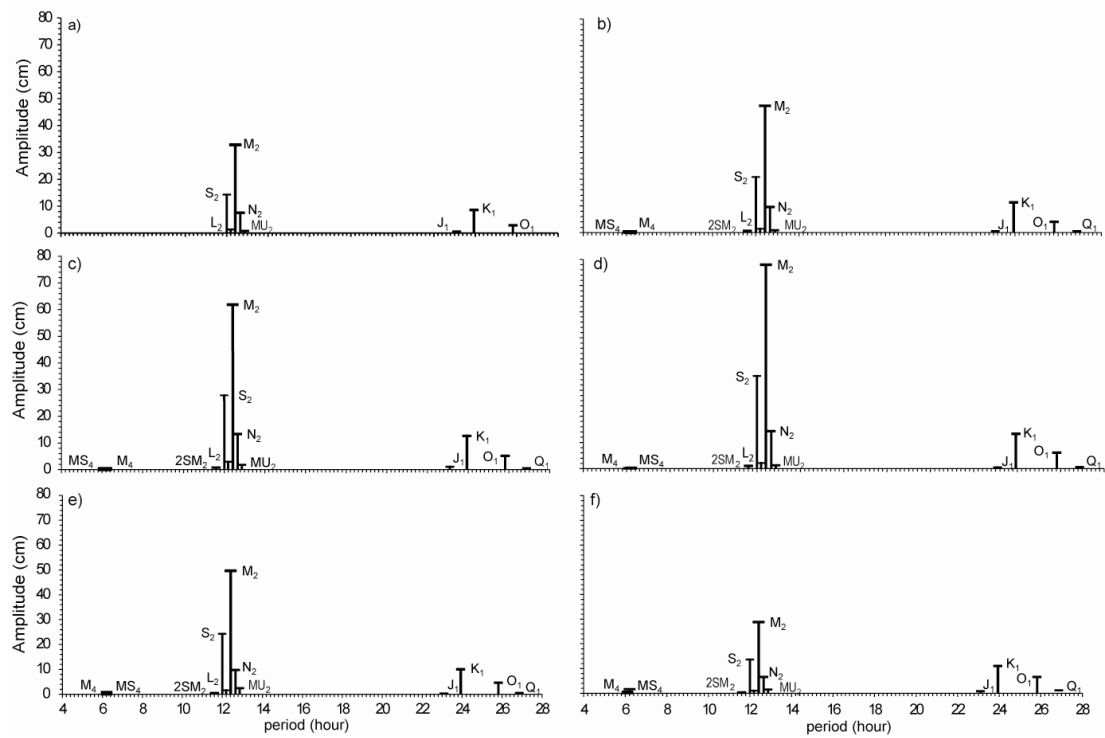
May 1963 occurred at a low tide (0.3 m) and hence was far less destructive (50,000 deaths) [Murty et al., 1986].

1.5 Motivation for the present study

The meteorological parameters and the physical characteristics, referred in Section 1.1 are assessed to be favourable in the Bay of Bengal to amplify the storm surges which causes innumerable loss of life and damages to property. Therefore, an ability to predict surges, its development in time and derive the estimates of extreme sea level using the information on cyclone track and the parameters associated with a cyclone is clearly of great practical importance.

During the last few decades, much effort has been directed to the modelling of storm surges in the Bay of Bengal. Das [1972] pioneered the study of numerical storm surge modelling in India. Subsequently several successful attempts were made to simulate storm surges in the Bay of Bengal [Ghosh, 1977; Johns and Ali, 1980; Johns et al., 1981; Dube et al., 1985; Johns et al., 1985; Dube et al. 1994; Dube and Gaur, 1995], which have been extensively reviewed by Murty et al. [1986]. Flather [1994] applied a model with 1D equations for narrow channels and 2D equations for the open sea, i.e. the northern Bay of Bengal including the coast of Bangladesh to simulate the surge due to April 1991 cyclone. A few region-specific real time numerical surge models have been developed to study the impact of cyclonic events along the coast of different countries in the Bay of Bengal such as Sri Lanka [Chittibabu et al., 2002], Bangladesh [Jakobsen et al., 2006], and Myanmar [Jain et al., 2006]. A large number of location specific high resolution models have been developed and successfully applied to the regions covering maritime states along the east coast of India - Chittibabu et al. [2002] (Tamil Nadu) and Dube et al. [2000b] (Andhra Pradesh), Dube et al. [2000a, b] and Sinha et al. [2008] (Orissa), Dube et al. [2004] (head bay). Dube et al. [2009, 2013] carried out simulation of storm surges caused due to some recent severe cyclonic events such as Male (2006), Gonu (2007), Sudr (2007), Nargis (2008), and Aila (2009), Laila (2010), Giri (2010) and Thane (2011) that hit different coast bordering the Bay of Bengal.

Figure 1.2 The amplitudes of semi-diurnal and diurnal constituents as obtained from harmonic analysis of observed sea level data available at a) Chennai, b) Visakhapatnam, c) Paradip, located along the east coast of India, d) Akyab, located along the northern coast of Myanmar, e) Sabang, and f) Sibolga located along the western coast of Indonesia. The location of these stations is shown in Figure 1.1.



The domains of the above mentioned localized models are confined to the vicinity of the coastal areas. Therefore, it is noted that major effort, in the last decade, had been to develop location specific models except for a few attempts that have been done [for instance, Dube et al., 2006; Jain et al., 2007] to develop large scale storm surge models for the Bay of Bengal. Blain et al. [1994] showed that localized domain with boundaries at or near continental shelf appear to underestimate the surges at the adjacent coast. Moreover, most of the storm surge models have been developed to simulate individual storm surge events.

In addition, there have been a few attempts to make quantitative estimates of the return periods of storm surges along the east coast of India by analysing large number of cyclone events. Rao et al. [2010, 2012] simulated storm surges using synthesized cyclones with intensity equivalent to 50 yr RP and estimated the induced water level and extent of inundation in the Kalpakkam region and along the coast of Tamil. Jain et al. [2010] estimated the probable maximum total water level along the coast of Nellore district in Andhra Pradesh by simulating the surges associated with 1972, 1977, 1979, 1982, 1984, 1985, 1987, 1989 and 1990 cyclones affecting the Nellore coast.

Chittibabu et al. [2004] estimated return periods of storm surges along the coast of Orissa based on model results. Unnikrishnan et al. [2004] analyzed the hourly tide gauge data at three stations, Paradip, Visakhapatnam, and Chennai, for a period of 15 years (1974-1988) and estimated return levels for these stations.

The availability of tide gauge data only at 4-5 locations along the east coast of India and the rare occurrence of cyclone at a given tide gauge location, however, make the direct analysis of observational data very difficult. Moreover, during some of the intense cyclonic events, tide-gauges became non-functional. Consequently, there arises the necessity to use the numerically simulated storm surges for the analysis of the extreme events in the regions where tide gauge data are not available.

Since the surge height attained at a location is significantly affected by the state of tide, accurate information on tidal elevations at that location at the time when cyclones crosses the coast is very essential. Moreover, the detailed analysis

and understanding of the behaviour and characteristic features of tides in the Bay of Bengal is essential and beneficial to interpret the variations in the return periods of extreme events at different coastal stations bordering the Bay of Bengal. It has been found that a very few studies have been made regarding tides in the region. Murty and Henry [1983] developed co-tidal charts of tidal constituents M_2 , S_2 , K_1 , and O_1 in the Bay of Bengal with the aid of numerical model. At that time, however, accurate information on open ocean tides was not available.

One of the major inputs for a numerical model is bathymetry which can influence the accuracy of the simulated tides. In addition, realistic representation of the bathymetry of the bay is very essential to simulate surge elevations accurately as most of the coastal region bordering the Bay of Bengal, especially the northern bay, are very shallow and characterized by sudden change in depth contours which can affect the surge heights considerably. The widely used bathymetric dataset ETOPO5 is assessed to be unreliable in regions where the depth values are less than 200 m.

1.6 Objectives

Objectives of the present study are as follows:

- Generate improved reliable bathymetric dataset for the continental shelf of the Indian Ocean.
- Simulation of tides and generation of co-range and co-tidal charts of the major semi-diurnal and diurnal constituents for the Bay of Bengal.
- Develop a storm surge model to simulate total water levels and surges caused by low pressure systems identified during the past 27 years (1974-2000) in the Bay of Bengal.
- Estimation of return levels of extreme events at major coastal stations along the east coast of India.

The thesis is organized as follows: The equation of continuity and the momentum equation and the numerical techniques used to solve these equations are described in Chapter 2. Chapter 3 is devoted to describe the generation of improved bathymetric datasets, which forms one of the major inputs for the tidal

model and the storm surge model. Chapter 4 documents the simulation of tides in the Bay of Bengal. The generation and detailed analysis of co-range and co-tidal charts for semi-diurnal and diurnal tidal constituents are also described in Chapter 4. The simulation of storm surges due to different LPS that crossed the coast of the Bay of Bengal and the estimation of return periods at different coastal stations along the east coast of India are described in Chapter 5. Finally, Chapter 6 summarizes and concludes the thesis.