TSUNAMI AND STORM SURGE MODELING IN BAY OF BENGAL

by

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LIST OF SYMBOLS

Symbols	*Descriptions*	*Units*
c	traveling speed	ms^{-1}
g	acceleration due to gravitational force	ms^{-2}
h	depth	m
L	wavelength	m
D	instantaneous water elevation	m
η	water elevation above the mean sea level (MSL)	m
t	time	s
M	discharge flux term in x- direction	m^2s^{-1}
N	discharge flux term in y- direction	m^2s^{-1}
u	velocity of x component	ms^{-1}
v	velocity of y component	ms^{-1}
n	Manning Roughness coefficient for friction	$m^{-1/3}s$
Δx	grid size of x component	m
Δy	grid size of y component	m
Δt	time step	s
h_{max}	maximum depth	m
σ	wave frequency	s^{-1}
k	wave number	m^{-1}
a	amplitude	m
σ_x	standard deviation of x component	m
σ_y	standard deviation of y component	m
f	Coriolis force	s^{-1}
K_x	horizontal eddy viscosity constant of x component	dimensionless
K_y	horizontal eddy viscosity constant of y component	dimensionless
ω	rotational angular velocity of the earth	s^{-1}
ϕ	latitude	degrees, °
u_w	wind velocity of x component	ms^{-1}
v_w	wind velocity of y component	ms^{-1}
C_D	wind drag coefficient	dimensionless
ρ_a	air density	kgm^{-3}
ρ_w	water density	kgm^{-3}

p	atmospheric pressure on MSL	hPa
F_{wx}	wind forcing in x- direction	m^2s^{-2}
F_{wy}	wind forcing in y- direction	m^2s^{-2}
F_{px}	pressure gradient in x- direction	m^2s^{-2}
F_{py}	pressure gradient in y- direction	m^2s^{-2}
V_t	tangential wind	ms^{-1}
V_r	radial wind	ms^{-1}
R_{max}	radius of the storm	m
V_{max}	maximum tangential wind	ms^{-1}

PEMODELAN TSUNAMI DAN LURUAN RIBUT DI TELUK BENGGALA

ABSTRAK

Kemusnahan yang disebabkan oleh Andaman tsunami pada 26 Disember 2004 merupakan masalah utama komuniti di seluruh dunia. Pelbagai usaha telah diambil untuk mengurangkan impak yang disebabkan oleh tsunami yang mungkin berlaku pada masa hadapan. Satu penyelidikan yang berdasarkan ciri-ciri penyebaran gelombang Andaman tsunami pada 26 Disember 2004 akan dibentangkan untuk mengkaji risiko di negara-negara sekeliling Teluk Benggala dengan bantuan model simulasi tsunami, TUNA-M2. Tesis ini juga akan membentangkan pemodelan sirkulasi lautan dan luruan ribut di Teluk Benggala. TUNA-M2 diubahsuai menjadi TUNA-SU selepas ia bergabung dengan empat sebutan iaitu daya angin, tekanan perbezaan paras lautan, daya putaran bumi dan kelikatan pusaran. Bagi penyelidikan dalam sirkulasi lautan, TUNA-SU bergabung dengan purata angin monsun barat daya dan timur laut yang berjangka panjang untuk mesimulasikan sirkulasi lautan di Teluk Benggala. Aliran sirkulasi yang dihasilkan dibandingkan dengan aliran sirkulasi dari kajian yang lain. Bagi penyelidikan dalam luruan ribut, TUNA-SU bergabung dengan satu model janaan angin iaitu Modified Rankine Vortex untuk mesimulasikan kenaikan paras air laut di sepanjang kawasan persisiran pantai di Myanmar bagi peristiwa 1992 ribut siklon Sandoway. Kenaikan paras air laut yang dihasilkan dari simulasi dibandingkan dengan kenaikan paras air laut yang dilaporkan. Diharapkan tesis ini dapat menyumbang kepada penyelidikan lanjutan bagi pemodelan tsunami, luruan ribut dan sirkulasi lautan pada masa hadapan.

TSUNAMI AND STORM SURGE MODELING IN BAY OF BENGAL

ABSTRACT

Destruction due to 26 December 2004 Andaman tsunami has become a major concern to the communities around the world. Several efforts have been undertaken to minimize the potential impacts of future tsunamis. In this thesis, a theoretical investigation of tsunami propagation properties and characteristics, with particular reference to the 26 December 2004 Andaman tsunami will be presented to highlight the potential risks and vulnerability of the countries around the Bay of Bengal, with the assistance of a tsunami simulation model TUNA-M2. This thesis will also discuss ocean circulation and storm surge modeling in the Bay of Bengal. TUNA-M2 is then modified to TUNA-SU by incorporating four additional terms: wind forcing, sea level pressure (SLP) gradient, Coriolis force and horizontal eddy viscosity. For ocean circulation study, TUNA-SU incorporates long-term averaged winds of the southwest and northeast monsoon to simulate the ocean circulations in the Bay of Bengal. The simulated current circulations by means of TUNA-SU are compared to the observed current patterns. For storm surge study, TUNA-SU incorporates a parametric wind field model, the Modified Rankine Vortex model to simulate the surge levels along the affected coastal areas in Myanmar for the event of 1992 Sandoway cyclone. The simulated surge levels are compared to the reported surge heights. It is hoped that this thesis will contribute towards further research on tsunami, storm surge and ocean circulation modeling in the future.

CHAPTER 1

INTRODUCTION

1.1 Introduction

There has been a renewed interest in tsunami and storm surge modeling following recent events. Furthermore, attention has been given to the development of numerical models for simulating physical processes in the coastal areas with particular reference to tsunami and storm surges. An in-house tsunami numerical model, namely TUNA-M2 (Teh et al., 2005b; Koh et al., 2005; Cham et al., 2006) has been developed to simulate the tsunami propagations. In this thesis, we use TUNA-M2 to simulate the propagation of 26 December 2004 tsunami waves along the affected coastal regions in the Bay of Bengal. This model is then modified to TUNA-SU (Loy et al., 2006a; Loy et al., 2006b; Cham et al. 2007a; Cham et al. 2007b) to study monsoon driven sea circulations and storm surges. Four additional terms wind forcing, sea level pressure gradient, Coriolis force and horizontal eddy viscosity are incorporated into TUNA-SU model and the model is applied to study storm surge in the Bay of Bengal. The model enhancement will provide better representation of the sea motion in the Bay of Bengal. This enhanced model is validated by some observed data available in the study area.

1.2 Bay of Bengal

In this thesis, the Bay of Bengal is chosen as a study area to model the tsunami propagations, monsoon driven sea circulations and storm surge. In general, the Bay of Bengal (Figure 1.1) is a northern extended arm of the Indian Ocean, which is covered by an area of about 2.2 million km^2 between equator and 22^0 N latitude and 80^0 E and 100^0 E longitudes (Unger et al., 2003).

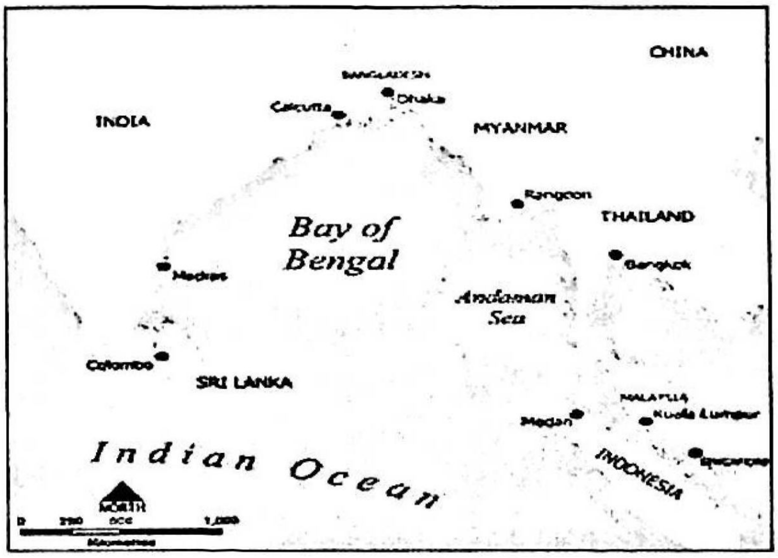

Figure 1.1: Map of Bay of Bengal

The Bay of Bengal is bounded in the west by the east coasts of Sri Lanka and India, on the north by the deltaic region of the Ganges-Brahmaputra Meghna river system, and on the east by the Myanmar peninsula. The southern boundary of the Bay is located approximately along the line drawn from Dondra Head in the south of Sri Lanka to the northern tip of Sumatra. A broad U-shaped basin characterizes the bottom topography of the Bay of Bengal, with its south opening to the Indian Ocean. An average and the maximum depths in Bay of Bengal are about 2600 m and 4694 m respectively. There are a number of large rivers that flow into the Bay of Bengal, such as the Mahanadi, Godavari, Krishna, and Kaveri (Cauvery) on the west and the Ganges and Brahmaputra on the north. Further, the Andaman and Nicobar groups, which are the only islands, separate the bay from the Andaman Sea. It should be noted that the information on Bay of Bengal are obtained from the Encyclopedia Britannica (2007). In this thesis, the details of the coastal topography, bathymetry and atmospheric forcing data are essential to study the tsunami propagations, sea circulations and storm surge in Bay of Bengal.

1.3 Tsunami

In this thesis, we study the 26 December 2004 Andaman tsunami which is triggered by a sudden deformation in the sea water surface due to earthquake. The Sumatra-Andaman earthquake of magnitude 9.3 on the Richter scale occurred on 26 December 2004. It was located where the India Plate dives under the Burma Plate, and was extremely large in geographical extent, beginning off the coast of Aceh and proceeding northwesterly over a period of about 100 seconds. As a consequence, it triggered off a series of tsunami waves that caused tremendous damage to the properties and lives along the affected coastal areas. The potential tsunami impact with particular reference to the affected coastal areas in Bay of Bengal, therefore, has brought further urgency to the need for simulations of coastal flooding levels and damages. In this thesis, we will present the simulations for 26 December 2004 tsunami propagations in the Bay of Bengal. Further, we discuss the wave height characteristics near the coast of Sri Lanka, Bangladesh and India to highlight tsunami hazards and coastal vulnerability.

1.4 Monsoon Wind Systems

The Bay of Bengal plays a major role in the climatic conditions of the adjacent land regions such as India, Bangladesh, Myanmar, Indonesia and Sri Lanka. The hydrographs and circulations for Bay of Bengal are mainly determined by the monsoon winds (i.e., Southwest and northeast monsoons), which reverse semi-annually. According to Potemra et al. (1991), the southwesterly winds of oceanic origin blows over the Bay of Bengal with a very high speed of about 10 m/s during the southwest monsoon months of June to September; whereas during northeast monsoon month of November to February, the northeasterly winds of dry continental origin blows over the Bay with speeds of about 6 m/s.

1.5 Storm Surge

Generally, storm surge is primarily induced by wind stress of great magnitudes probably from a hurricane, typhoon, tropical cyclone and even seasonal monsoons that are present at the open sea. They are categorized based upon their centre pressure, wind speed and their height by means of the Saffir-Simpson scale (Unisys, 2004). The inverse barometric effect and the onshore wind stress from a hurricane or cyclone can pile up the water above the normal sea level and surge up to the coastal land when they make a landfall and this event is called storm surge (Liu, 1997). The destruction due to a storm surge is a serious concern particularly for the coastal regions of India, Bangladesh and Myanmar (Jain et al., 2006). Other regions that are vulnerable to hurricanes and storm surges are the east coast of United States, Turkey along the Mediterranean Sea, some European coasts along the Adriatic Sea, Aegean Sea and North Sea, the Great Australia Bight, Hong Kong and some bays along East China Sea. The severity of the storm surge will be observed particularly during the periods of spring tide. Storm surge may cause extensive damage to lives and properties almost every year (Jakobson, 2004). In this thesis, the potential impact and implication induced by storm surge, with particular reference to 1992 Sandoway cyclone will be evaluated and analyzed. The details for the storm surge that are associated with the 1992 Sandoway cyclone will be discussed. The storm surge simulation studies for the affected coastal regions in the Bay of Bengal particularly in Myanmar are then performed.

1.6 The Objectives

The objectives for this study are as follows:

1. To enhance and implement tsunami numerical model TUNA-M2 for simulating tsunami propagations in the Bay of Bengal;
2. To study wind driven sea circulations during the occurrence of southwest and northeast monsoons by TUNA-SU model;
3. To apply TUNA-SU for modeling a storm surge case induced by the 1992 Sandoway cyclone;
4. To develop graphic packages to display simulation results.

1.7 Scope and Organization of Thesis

This thesis consists of six chapters. The overall theme of the thesis and the objective, scope and organization are briefly discussed in Chapter 1. Meanwhile, Chapter 2 will discuss the most recent studies conducted in tsunami and storm surge modeling by other researchers. Literatures related to this study will be reviewed.

Chapter 3 begins with a brief introduction of graphical software tools that are applicable to this thesis, such as GrADS (IGES, 2005), Surfer (Golden Software, 2006), and MATLAB (The MathWorks, 2006). The main focus of this chapter will be on the development of the graphic packages by means of MATLAB. In this Chapter, MATLAB is used for developing three graphic packages. The conceptual graphic components, which are in two- or three-dimensional graphics, are introduced. In two-dimensional graphics, vector and contour plots are displayed; whereas surface and mesh plots, which are in three-dimensional are presented. The conceptual graphics will be enhanced to more complicated graphic packages in this chapter.

Chapter 4 begins with a brief introduction to the 26 December 2004 Andaman tsunami. To study tsunami propagation, we then develop a tsunami model TUNA-M2 (Teh et al., 2005b; Koh et al., 2005 and Cham et al., 2006), which is based upon the shallow water model. In this chapter, we will also enhance TUNA-M2 to a model based upon a concept of flag matrix or stair-step fashion models. The flag matrix model will use several integer numbers to indicate water, coastal and tidal boundaries, and land areas. At the open sea, we introduce radiation boundary conditions in TUNA-M2 to allow the wave disturbances to pass through the open boundary without reflection. An analytical model is used to provide a means to verify the accuracy of model TUNA-M2 as well as to facilitate a good understanding of general tsunami propagation in the deep ocean. This chapter also discusses some conceptual studies on the effects of different bathymetry to tsunami wave propagations. Finally, a real simulation for the 26 December 2004 tsunami is performed by using realistic bathymetry for the Bay of Bengal.

Chapter 5 will discuss the enhancement of TUNA-M2 to a storm surge model TUNA-SU (Loy et al., 2006a; Loy et al., 2006b; Cham et al. 2007a; Cham et al. 2007b). Four additional terms included are wind forcing, sea level pressure gradient, Coriolis force and horizontal eddy viscosity, which are crucial to model storm surge. The presence of these terms is required to represent the physics of storm surge more realistically. In this chapter, the sea circulations in the Bay of Bengal during the occurrence of northeast and southwest monsoons will be introduced. The simulated velocity fields agree well with observed results, which is available from the Potemra et al. (1991). To study storm surge in the Bay of Bengal, an event of tropical cyclone that occurred on 15th to 20th of May 1992 at Sandoway, Myanmar will be discussed in this chapter. In this study, a parametric wind field model Modified Rankine Vortex (Behera et al., 1998; Deo et al., 2004) will be used to generate the wind field for TUNA-SU model. To achieve this purpose, a program for Modified Rankine Vortex model is developed. In this program, the input data that are obtained from Unisys (2004) such as the 1992 Sandoway cyclone track and maximum wind is required. Further, the simulated surge elevations and current velocities are analyzed and discussed.

Finally, the conclusions and recommendations are discussed in Chapter 6. It is hoped that this thesis will contribute towards further research on tsunami, sea circulations and storm surge modeling in the future.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Numerical computation has become a powerful and popular tool to study ocean natural disasters, coastal processes, etc. In this chapter, we will review some relevant studies that are capable of providing recommendations, motivations and ideas for a researcher to model tsunamis, ocean circulations and storm surges.

2.2 Tsunami Studies

In this section, we will review some available tsunami models, dispersion and nonlinear effects for tsunami studies, tsunami and tide interaction effects and some other related studies.

2.2.1 Tsunami Models

The tsunami numerical simulation model based upon two-dimensional shallow water model has become routine in tsunami modeling. In this respect, the nonlinear shallow water (NLSW) approach, which ignores the effect of linear wave dispersion, is very attractive for tsunami computation simply because it has very low computational cost. Further, the NLSW results are useful for preliminary hazard assessment, where a simple and quick estimation of maximum wave height and maximum runup are required (Horrillo et al., 2006). It is noted that our in-house model, TUNA-M2 (Teh et al., 2005b; Koh et al., 2005; Cham et al., 2006) and TUNA-SU (Loy et al., 2006a; Loy et al., 2006b; Cham et al. 2007a; Cham et al. 2007b) also apply NLSW to model tsunamis, wind driven sea circulations and storm surge.

There are also several well-known numerical models that are used to simulate some or all phases of tsunamis. The method of splitting tsunami model (MOST) is developed by Titov and Gonzalez (1997) based upon the shallow water equations. MOST is associated with the activities of the Tsunami Inundation Mapping Efforts (TIME). It is used to compute all three stages of tsunami evolution: generation, propagation and runup, thus, providing a complete tsunami simulation capability. MOST is used to develop a tsunami hazard mitigation tools in the Pacific Disaster Center (PDC). This model is also used to simulate the tsunami generation by a source near Alaska, the propagation across the Pacific Ocean, and the subsequent runup onto the Hawaiian shorelines. Another numerical model, TUNAMI-N2 is developed in Tohoku University by Imamura et al. (1988), and is provided through the Tsunami Inundation Modeling Exchange (TIME) program (Goto et al., 1997). This model has been used for real case simulations of tsunami events in Mediterranean, Caribbean and Black Seas (Pelinovsky, et al., 2002; Zahibo et al., 2003, Yalciner, et al., 2004). Watts et al. (2003) apply a tsunami numerical model, GEOWAVE to simulate the tsunami runup and inundation. It should be noted that GEOWAVE is the combination of the Tsunami Open and Progressive Initial Condition System (TOPICS) and the fully non-linear Boussinesq water wave model (FUNWAVE). Under Advanced Ocean State Forecast activity at MOG/AC, a comprehensive multi-model ensemble so called TOAST is developed, comprising an ocean general circulation model, coastal surge and tide prediction model coupled with tropical cyclone prediction model. This model is designed specifically to simulate and predict ocean disasters like storm surge, etc. TOAST has a flexible grid structure and apart from calculation of the surge height, it can provide the area of intense inundation in the coastal regions. By using this model, Agarwal et al. (2005) simulate the whole life cycle of tsunami, i.e. from generation to runup stage for the 26 December 2004 Andaman tsunami.

2.2.2 Dispersion Effect

Dispersion effects can be significant for amplitude estimation when tsunamis are generated far from the region of interest (Titov, 1997; Horrillo et al., 2006). The propagation of tsunamis will undergo several changes over a long stretch in the ocean. This may also bring to the question of accuracy of the model used for numerical simulations of tsunamis. Several studies have highlighted the importance of dispersion in tsunami propagation. Sato (1996), in the numerical calculation of the 1993 Okushiri Island tsunami, found that local tsunami enhancement could be explained by a series of dispersive waves which ride on the main tsunami front. Ortiz et al. (2001) suggested that the frequency dispersion mechanism, as prescribed by dispersive theory plays a main role in the propagation of large and medium-size tsunamis. Other authors (Imamura et al., 1988; 1990; Liu et al., 1995) also considered the dispersion effect and concluded that they are important for their studies. To take into consideration the dispersion effects, the propagation of tsunamis may be better modeled by using the Boussinesq equations (Dunbar et al., 1991; Heinrich et al., 1998; Madsen et al., 1999; Yoon, 2002). Their numerical solutions require small grid resolution and often implicit schemes are used due to stringent numerical stability requirement (Shigihara, 2004). Imamura and Shuto (1989) constructed a numerical scheme that uses numerical dispersion to simulate physical dispersion. This scheme is improved and applied to the propagation of tsunamis over slowly varying topography by Yoon (2002), thus opening the possibility to consider for the dispersion of distant tsunamis. In the runup region, at the steep wave front where the tsunami wave starts to break, the dispersive effects due to physical processes tend to interact with the short wave numerical instability generating turbulent motion. To suppress such oscillations, Goto and Shuto (1983) and Sato (1996) suggested introduction of the eddy diffusivity term.

Sometimes, it is difficult to model tsunami simply because they are intermediate, quasi-infra-gravity waves, having the combined characteristics of long and short ocean waves. The tsunami wave propagation is a combination between a dispersive and non-dispersive model (Koutitas and Laskaratos, 1988; Pedersen et al., 2005). Further, the non-dispersive model, for example, nonlinear shallow water model is commonly used in the deep ocean where the ocean depth is small compared to the tsunami wavelength. However, the dispersive model, for example, nonlinear Boussinesq model is applied in shallower regions because the wavelength is not much larger than the water depth. Incidentally, the nonlinear dispersive momentum equations were originally applied in the study of long waves in oceans and beaches (Peregrine, 1967; Wu, 1981). There are various combinations of momentum terms, such as those proposed by Madsen and Sorensen (1992). Eventually, the momentum equations are simplified due to negligible effect of some higher-order terms.

The nonlinear shallow water (NLSW, nondispersive), the nonlinear Boussinesq (NLB) and the full Navier-Stokes equations aided by the volume of fluid method to track the water surface (FNS-VOF) are important tools for the tsunami investigations. Using these tools and hydraulic experiments, Fujima (2001) examined the wave transformation on large bottom obstacles. He points out that NLB approach reproduces the wave dispersion effects well when compared with experiments and FNS-VOF approach. Another study using these models has been conducted by Horrillo et al. (2006) in the Indian Ocean to examine the effect of dispersion and to reproduce the 26 December 2004 Andaman tsunami propagation. The results are compared against each other. It is observed that the general features of the wave propagation agree well for all numerical studies. However some important differences are observed in the wave patterns, that is the development in time of the wave front is shown to be strongly connected to the dispersion effects.

2.2.3 Nonlinear Effect in Tsunami Study

In tsunami modeling, nonlinear effects due to friction terms are sometimes ignored because this term is small in the deep ocean (Titov and Synolakis, 1998) and because its inclusion will increase computation time. Here, an example of study for nonlinear effect due to friction terms is presented in the shallowest Java Sea by using tsunami model, TUNAMI (Zahibo et al., 2005). The bathymetry of the Java Sea is taken from GEBCO (British Oceanographic Data Center) with grid resolution of 1 km. In their simulation, full reflection boundary conditions (vertical wall approximation) are imposed on the land areas; whereas they apply the radiation condition for the open boundaries to allow the waves to propagate out of the boundaries. The results show that the nonlinear effects are not manifested for the depth more than 10–20 m. The reproducing of the nonlinear effects in the tsunami wave requires high quality of bathymetric maps and long computations, and it is why the nonlinear theory of water waves is applied mainly to describe the runup stage, but not the tsunami propagation (Zahibo et al., 2005).

2.2.4 Tsunami-Tide Interactions

It is also essential to investigate the dynamics of tsunami enhancement in the coastal regions related to interaction with tides. Observations and computations of the Indian Ocean Tsunami usually show amplifications of the tsunami in the near-shore regions due to water shoaling. Additionally, numerous observations indicate quite long ringing of tsunami oscillations in the coastal regions, suggesting either local resonance or the local trapping of the tsunami energy. In the real ocean, the short-period tsunami wave rides on the longer-period tides. The question is whether these two waves can be superposed linearly for the purpose of determining the resulting sea surface height or rather in the shallow water they interact nonlinearly, enhancing or reducing the total sea level and currents. Since the near shore bathymetry is important for the run-up computation, Weisz and Winter (2005) demonstrated that the changes of depth caused by tides should not be neglected in tsunami run-up considerations. On the other hand, Kowalik et al. (2006) hypothesize that much more significant effect of the tsunami-tide interaction should be observed through the tidal and tsunami currents. In order to test this hypothesis they apply a simple set of one-dimensional equations of motion and continuity to demonstrate the dynamics of tsunami and tide interaction in the vicinity of the shelf break for two coastal domains: shallow waters of an elongated inlet and narrow shelf typical for deep waters of the Gulf of Alaska. In a channel with narrow shelf the time for the tide and tsunami interactions is very short and mainly limited to the large currents in the runup region. In the channel with extended shallow water region, the nonlinear bottom dissipation of the tide and tsunami leads to strong reduction in tsunami amplitude and tsunami currents. The tidal currents and amplitude remain unchanged through interaction with tsunami. The major difference between tide and tsunami occurs in the runup region. Tide does not undergo changes in the velocity or sea level in the near shore or runup region while for tsunami this is the region of major amplification of the sea level and currents. They summarize that the energy of an incident tsunami can be redistributed in time and space with the characteristics, which differ from the original wave. These changes are induced by the nonlinear shallow water dynamics and by the trapped and partially leaky oscillations controlled by the continental slope or shelf topography. The amplification of tsunami amplitude is mainly associated with strong amplification of tsunami currents. The nonlinear interaction of the tide with tsunami is important, as it generates stronger sea level change and even stronger changes in tsunami currents, thus the resulting runup ought to be calculated for the tsunami and tide propagating together.

2.2.5 Other Related Studies

The 1883 Krakatau volcanic eruption generated a destructive tsunami higher than 40 m on the Indonesian coast where more than 36,000 lives were lost. Sea level oscillations related with this event have been reported at significant distances from the source in the Indian, Atlantic and Pacific Oceans. There are several studies related to this tsunami event. The ray method has been performed by Yokoyama (1981) to simulate the tsunami propagation in the Sunda Strait around the Krakatau Island. The wave heights were calculated using the Green's law based on the energy flux conservation. Then, Nakamura (1984) repeated these calculations using the finite-difference scheme. He simulated also the tsunami wave propagation in the adjacent part of the Indian Ocean and the comparison with the observed data leads to the estimated depth in the equivalent tsunami source of 700 m. The Krakatau tsunami was also numerically simulated by Kawamata et al. (1992) for the region outside the Sunda Strait by assuming the caldera formation, which makes the surrounding water rush into the cavity. Nomanbhoy and Satake (1995) investigated the mechanism of the tsunami generation of the Krakatau volcanic eruption.

There is a study by Pelinovsky et al. (2001b) to investigate tsunami wave generated by variable atmospheric conditions. In this study, the simplified linear and nonlinear shallow water models are derived, and the analytical solutions for a domain of constant depth are discussed. The shallow water model describes well the properties of the generated tsunami waves for all regimes, except the resonance case. To describe the resonant mechanism of the tsunami wave generation by the atmospheric disturbances moving with near-critical speed, they use the nonlinear-dispersive model based upon the forced Korteweg-de Vries equation. Further, the analytical solutions of the nonlinear dispersive model are obtained.

2.3 Ocean Circulation Studies

Monsoon regions are considered to be those that experience seasonal reversal in winds during the year. Only a few studies have been carried out in the Indian Ocean, in particular for the Bay of Bengal to understand the influence of seasonally reversing monsoon winds on the variability of water characteristics and circulation. In earlier studies, it should be noted that the wind patterns associated with the monsoon climate are compiled in the form of wind stress into a data set by Hellerman and Rosenstein (1983). The model is forced by this climatological wind data set. This set is obtained by processing surface observations for approximately 100 years (1870-1976) and calculating monthly norms and standard deviations of the eastward and northward components of wind stress at standard anemometer height of 10 m. A study by Yu et al. (1991) suggested that for a large-scale low frequency forcing associated with monsoon wind, only long Rossby and Kelvin waves are generated. These waves act as a remote forcing, determining the upper layer circulation in the Bay of Bengal. McCreary et al. (1993) also suggested that the monsoon winds force the ocean locally and excite propagating signals, i.e. Kelvin and Rossby waves that travel a long distance to affect the ocean remotely. Theoretical studies revealed the presence of these waves in the current and temperature fields in the central and western sides of the Bay (Kindle and Thompson, 1989; Potemra et al., 1991). These studies suggest that the Rossby waves excited by the remotely-forced Kelvin waves play a significant role in the variability of circulation in the Bay of Bengal.

2.4 Storm Surge Studies

The flooding that occurs in the coastal region due to the surges has been a major cause of loss of lives and properties. Although the oscillations in the sea-surface that cause flooding in coastal regions during a storm period are mainly governed by the cyclonic winds, some other factors like presence of tide, river runoff, torrential rainfall, etc. also affect the rise in the sea-level (Agnihotri et al., 2006). Thus, a proper understanding of the factors affecting surge development and its accurate prediction in a coastal region is highly desirable. In the last decade, several numerical models (Das, 1972; Das et al., 1974; Jarrell et al., 1982; Johns et al., 1983; Sinha et al., 1985; Dube et al., 1994; Rao et al., 1997; Henry et al., 1997; Murty and Flather, 1994) have been developed for the prediction of storm surges occurring in the Bay of Bengal.

One of the major problems for numerical modeling of storm surge generated by tropical cyclones is the small-scale structure of the cyclones, which requires high model resolutions in space and time (Tolman and Alves, 2005). In atmospheric modeling of tropical cyclones, this has lead to well established nesting techniques, where high-resolution grids move with the tropical system within larger domains with lower resolution (Kurihara et al., 1979; Kurihara and Bender, 1980; Bender et al., 1993; Kurihara et al., 1995). High and low resolution grids fully exchange information, and the high-resolution grids are regularly relocated, giving the impression of moving nests. However, the nests themselves are simply relocated to match the position of the cyclone, without considering actual motion of the grids.

Earlier studies showed that the efforts of modeling tropical cyclone have been mainly concerned with difficult problems of convective parameterisation, vortex movement and vortex flow interactions (DeMaria, 1985; Greatbatch, 1983; 1984; Thu and Krishnamurti, 1992). One of the potentially significant constraints on dynamical predictions of tropical cyclones is the lack of knowledge about the ocean response to the storm forcing. Various observational and numerical studies have shown that tropical cyclone produces significant changes in the underlying ocean thermodynamic structures, which also involve sea surface temperature changes (Nilsson, 1996). In earlier studies, the ocean response for moving cyclones in the Indian Ocean has been studied by considering idealized symmetric vortex and tracks similar to observed ones (Behera et al., 1998; Deo et al., 2001). The effect of moving symmetric and asymmetric tropical cyclone in the northern and southern Indian Ocean on the upper layer is studied by Deo et al. (2004).

In the event of a hurricane, the Central Pacific Hurricane Center of the National Weather Service forecasts the track and intensity primarily based on operation experience with guidance from statistical and meteorological models. Once the track and intensity are predicted, simple parametric models can accurately describe the surface wind fields of tropical cyclones (e.g. Houston et al., 1999; and Phadke et al., 2003). Common models include the Modified Rankine model described by Hughes (1952), and the Holland (1980) model. These physics-based and parametric models provide time-histories of surface wind and pressure fields to simulate the responses of the ocean.

The SLOSH model (Sea, Lake, and Overland Surge from Hurricane) was developed by Jelesnianski and Shaffer (1992) for surge prediction. SLOSH provides the possibility of identifying flooding locations from storm surge. A comparison of five different two-dimensional storm surge models applied to three European Seas, the North Sea, the Aegean and the Adriatic, is given by De Vries et al. (1995). However, such attempts were already made in the past, but it is still a complex ocean engineering problem in which many factors, including the central pressure of typhoon, the speed of the typhoon, the heavy rainfall, coastal topography and local features influence the variation of storm surge. Gica et al. (2001), simulate a storm surge case generated by Hurricane Iniki by using the finite element model, ADCIRC (ADvanced CIRCulation), which was developed by Luettich et al. (1992) based upon the shallow water equations.

Johns and Ali (1980) developed a river–bay coupled model for simulation of storm surges along the Bangladesh coast. Dube et al. (2004) coupled a one-dimensional river model with two-dimensional bay model having curvilinear representation of the natural shoreline for the Orissa coast. On the other hand, Agnihotri et al. (2006) have developed a two-dimensional river–bay coupled numerical model for the Andhra coast to study the effect of Krishna and Godavari rivers on the sea-surface elevation. They use the actual bathymetry from Naval Hydrographic Chart. Firstly, the surge was computed from a surge model for the bay where the coastal boundary is taken as a vertical sidewall through which there is no flux of water. This results in the unrealistic piling of seawater near the coast. Next, a two-dimensional river model with rectangular cross-section and uniform width was developed and coupled with the two-dimensional surge model to study the effect of Krishna and Godavari rivers on the surge development in the region. The simulations showed that the discharge of fresh water carried by the river might modify the surge height in the bay significantly. Using the model, numerical experiments were carried out to simulate the surge generated by November 1977 Divi cyclone, May 1990 Divi cyclone and November 1996 Kakinada cyclone.

CHAPTER 3

GRAPHIC PACKAGES DEVELOPMENT

3.1 Introduction

Graphic visualization plays a significant role in sciences and engineering particularly in mathematical modeling. Researchers around the world use graphics visualization to interpret and analyze the model data and results. In computational methods, the approximate solutions are expressed in terms of enormous amount of discrete values in a mesh or computational cells. Even simple computations today have in excess of one million mesh points, as in tsunami simulation. Hence, advanced computer graphics and computer data visualization techniques are an integral part of computational methods (Toro, 2001). Lately, several graphic software tools are developed for visualization purposes. The graphical software tools that are applicable to this thesis are GrADS (IGES, 2005), Surfer (Golden Software, 2006), and MATLAB (The MathWorks, 2006). These software tools can be used for model illustration, in particular for the study of tide and tsunami propagations, sea circulations and storm surge. It should be noted that tsunami, sea circulations and storm surge have their particular graphics requirements. In this chapter, we will focus on the development of appropriate graphic packages. The graphic packages developed in this chapter will then be used in Chapters 4 and 5. Further, the developed graphic packages in this chapter will help to facilitate the fast take-off of the research study with particular reference to tsunami and storm surge modeling.

3.2 Software Tools

In this section, the software tools that are commonly used to visualize simulation model results are introduced, with particular reference to tsunami propagations, sea circulations and storm surge modeling.

3.2.1 MATLAB

MATLAB is the abbreviation of *MATrix LABoratory* and lately, it is considered as a professional software to be used in various areas such as scientific, mathematical and engineering. MATLAB provides advanced graphical tools for data analysis. Furthermore, MATLAB can help to reduce long computational time for heavy tasks and to perform faster than the other traditional programming languages such as C, C++, and FORTRAN (The MathWorks, 2006). It should be noted that the sequences of commands in MATLAB could be written in a text editor, i.e. *m-file*. This text editor is used to write a program or define a function, which is similar to the structure of default MATLAB functions. Further, this user-defined function or program as written in *m-file* can be linked through the MATLAB command window. In this thesis, MATLAB is used for visualizing the simulation results, with particular reference to tsunami propagations, sea circulations and storm surge modeling.

3.2.2 GrADS and Surfer

Other Software tools such as The Grid Analysis and Display System (GrADS) (IGES, 2005) and Surfer (Golden Software, 2006) may be used for graphic visualization in mathematical modeling, particularly in tsunami and storm surge modeling. GrADS is a software that may be used for visualizing contours, vector plots and streamlines which is associated with earth grid. GrADS is freely distributed via internet (IGES, 2005). Conversely, Surfer is a licensing software tool and it may also be used to produce similar types of graphics as in GrADS. Further details of GrADS and Surfer are available from IGES (2005) and Golden Software (2006) respectively. It should be noted that GrADS is operated under DOS platform; whereas Surfer is a windows-based application. Both software tools have been embedded with earth science data that enable us to display contour or velocity plots simultaneously with land-sea boundaries, which are viable to illustrate tsunami and storm surge simulation results.

3.3 MATLAB Graphic Tools

In this Chapter, MATLAB is used for developing the graphic packages. The conceptual graphic components, which are in two- or three-dimensional graphics, are introduced. We will then proceed to more complicated graphic packages in this chapter.

3.3.1 Two-Dimensional Graphics

MATLAB consists of many types of two-dimensional plots, which can be referred in the MATLAB user guide, The MathWorks (2006). In this section, we will focus on vector and contour plots.

Vector Plot

Vector plot plays a vital role to visualize the physical motions such as wind velocity and the flow of a liquid or the propagation of waves, which are measured at evenly spaced points in our model domain. In MATLAB, *quiver* is a type of function of the vector plot that illustrates the barbs at each data points of (x, y) denoting as the direction, and (U, V) denoting as speeds, with the length having been relatively scaled corresponding to the real values. A program written in MATLAB is shown in Figure 3.1 that is used to plot vector field (Figure 3.2).

```
[x, y] = meshgrid (0:10:100, 0:10:100);
u = 0.5*sin (2.5 - 0.5*x - 0.5*y);
v = -0.5*sin (2.5 - 0.5*x - 0.5*y);
quiver (x, y, u, v, 'color', 'black');
axis([0 100 0 100]);
```

Figure 3.1: Vector plot program