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Study on Residual Flow in the Bay of Bengal considering Future Climate Change Induced Hydro- meteorological Scenarios

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ABSTRACT

The overall objective of the project was to investigate the future residual flow scenario in the northern Bay of Bengal taking into consideration of the changed hydrological as well as meteorological parameters. Observed and projected meteorological data were employed to generate present and future scenarios in the Northern Bay of Bengal. Long term tidal water level data and available short term offshore tidal water level data were analyzed to identify sea level trends. Offshore water level data suggests a trend of 0.3cm rise per year in sea level. Numerical experiments through a 3D hydrodynamic model showed that both during the monsoon as well as winter periods, residual current in the Northern Bay of Bengal showed an anti-clockwise circulation concentrating at the eastern part of the bay. The Swatch of No Ground appeared to have an important influence on the circulation patterns. Calculated future surface salinity and temperature levels, obtained through employment of projected meteorological data from RCM experiments, showed considerable increase which may hamper the ecological balance in the region in future.

CHAPTER 1
INTRODUCTION

1.1 Introduction

The Bay of Bengal (Figure 1.1) is the largest bay in the world by area, which covers 2,172,000 square kilometers and reaches a depth of up to 5,258 meters. It extends from Ganges/Brahmaputra delta around 20°N latitude to 7°S, with a maximum width of about 1000 km around 15°N latitude (Sarma et al. 2000). Many major rivers of India and Bangladesh flow into the Bay of Bengal: in the north, the Padma (distributary of Ganges), Meghna and Brahmaputra River, and in the south Mahanadi River through the Mahanadi River Delta, Godavari River, Krishna River, Irrawaddy and Kaveri River. The Ayeyarwady River of Myanmar also flows into the bay. The Sundarbans mangrove forest is formed at the delta of the Ganga, Brahmaputra and Meghna rivers on the Bay of Bengal. Although the geographical setting of The Bay of Bengal is similar to The Arabian Sea, it is widely different from the Arabian Sea in terms of physical, chemical, and biological features (Brown, 2005). At the same time, The Bay of Bengal is characteristically different from the other tropical basins of the world primarily due to the huge amount of freshwater runoff (~1.5 x 1012 m3 per year) and the associated sediment load (billions of tones) it brings in to the basin (Kumar et al., 2006).

In the Northern Bay of Bengal the bathymetry is shallow, and depth to the seabed occurs less than 2000 meters. On the other hand, the bathymetry over central Bay of Bengal is relatively flat where the average depth is around 3000 meters. The seafloor gradient decreases gradually from north to south. In the northern Bay of Bengal there exists a deep valley known as the 'Swatch of No Ground'. The deepest portion of the valley is recorded around 1340 m with an overall relief of 400-450 m from the surrounding mean seafloor depth of 1000 m. The width of the valley is about 14 km. Within this part of the deep valley, there exists another narrower valley-like feature, which runs in NE-SW direction and it changes to N-S direction in South (Sarma et al., 2000).

One important meteorological feature of The Bay of Bengal is that it is characterized by the cyclic wind systems. The current patterns associated with these reversing wind systems and enormous river runoff influence the hydrographic parameters (Varadachari et al., 1968). The seasonal variation of regional climatic condition dominated by the monsoon system influences the physical, chemical and biological properties of the water of the Bay of Bengal, particularly the upper layer at the head of the Bay. The large river discharge during monsoon and reverse during the winter greatly control the water temperature, ocean current, density and salinity of the Bay.

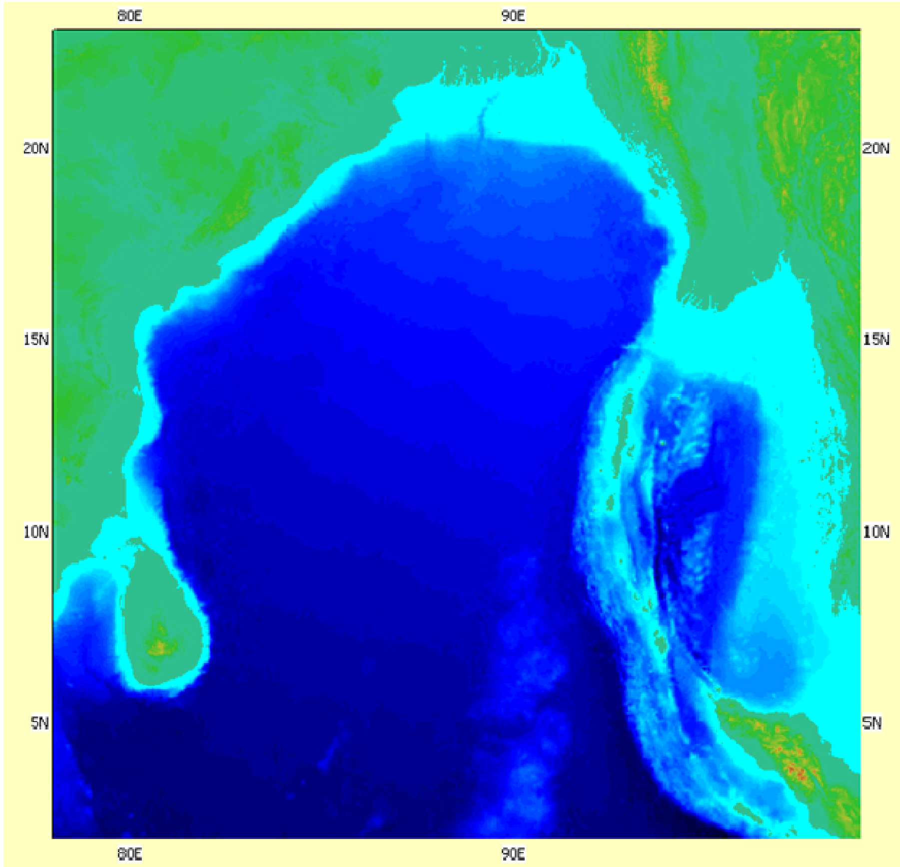

Figure 1.1. The Indian Ocean and the Bay of Bengal

According to Sarma et al. (2000), in the Bay of Bengal, ocean current, from January to October, is northward flowing, and the clockwise circulation pattern is called the 'East Indian Current'. The Bay of Bengal monsoon moves in a northwest direction striking the Nicobar Islands, and the Andaman Islands by end of May, then the North Eastern Coast of India by end of June. The remainder of the year, the counterclockwise current is southwestward flowing, and the circulation pattern is called the 'East Indian Winter Jet'. September and December see very active weather in the Bay of Bengal producing severe Cyclones which affect Eastern India.

The Bay of Bengal is one of the least scientifically explored areas of the world ocean although the oceanic features are quite diverse. Residual current (net current after the tide induced current is excluded) plays primal role for the net transport of scalars as well as suspended and bottom sediments which in turn dictate the erosion and accretion process of the estuary and coastal islands. Future climate change induced meteorological features, sea level rise and altered hydrologic conditions is expected to change the hydro-climatic conditions of the Bay of Bengal, significantly. The present research focuses on the variation of salinity distributions and residual flow during non-cyclonic conditions in the Bay of Bengal under future hydro-meteorological conditions.

1.2 Objectives

The overall objective of the research is to investigate the future residual flow scenario in the Bay of Bengal taking into consideration of the changed hydrological as well as meteorological parameters.

The specific objectives of this project would be:

a) To study the future climate change induced meteorological scenario at the Bay of Bengal using a climate change prediction model,
b) To simulate future seasonal variation of residual currents in the Bay of Bengal,
c) To identify the changes in salinity front as well as formation of thermal stratification due to increased SST in the Bay.

1.3 Scope of the Work

This report summarizes the works that have been done under a research project titled 'Institutional Strengthening of Climate Change Study Cell at BUET for Knowledge Generation and Human Resource Development' funded by Climate Change Trust Fund of Climate Change Cell under the Ministry of Environment and Forestry, Government of Bangladesh. The project duration was two years (June 2011 to May 2013). 'Residual Currents' stands for the spatial distribution of coastal/ocean currents averaged over a tidal cycle in this report. Due to unavailability of measured data in the Meghna Estuary (even though such kind of data were collected during the MES project in 1997, it was not accessible to the authors), simulation of temporal distribution of residual currents was not possible. Model calibration and validation was done for water levels. No other previous study showed 3D results for residual currents in the Bay of Bengal but results were compared with a previous 2D model study in the Meghna Estuary. For discharge data through the estuary previous estimates have been utilized rather than computations at four different seasons. Offshore salinity and SST data have been estimated from previous studies.

1.4 Limitations of the Work

Large tidal range in the low laying coastal areas may change the shoreline significantly. This has not been considered in numerical simulations. In the present study, fixed lateral boundaries has been used and it has been assumed that any changes in shore line that occurs due to tidal fluctuation takes place within the sub-grid scale which can be ignored.

1.5 Structure of the Report

This report consists of seven chapters including this introductory chapter. The second chapter summarizes several relevant literatures. In the third chapter, some of the characteristic features of the study area are discussed. Results of meteorological and hydrological data analyses are illustrated in Chapter Four. In the process of analyses, each year is divided into four seasons: pre-monsoon (March - May), monsoon (June - September), post-monsoon (October - November) and winter (December - February) following Chowdhury *et al.*, 1997. In the fifth chapter, brief overviews of the 3D numerical model and PRECIS RCM is provided, which has been followed by 3D hydrodynamic model calibration. Next, the simulation results for the numerical experiments have been provided. Finally in the sixth chapter, major conclusions from this study are listed-out and some recommendations for future studies are provided.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

This chapter summarizes some of the studies on residual current which includes observation, experimental as well as simulation efforts. Residual currents in bays and estuaries can be decomposed into three major components; density driven currents, wind driven currents and tide induced currents. Literatures which investigate these components individually as well as in a combined manner have been discussed.

2.2 Components of Residual Current

2.2.1 Density current

Effect of surface heating and cooling

Hussain (2006) performed several numerical experiments in an ideally shaped rectangular domain, with larger depth at the center of the domain, to study the effect of surface heating and cooling. It was observed that, during cooling water mass upwells along the center of the domain and sinks along the boundaries. Heating at the water surface, on the other hand, causes density stratification resulting multilayer circulations, with a thin layer of circulation above the thermocline showing diverging current at the surface and a larger circulation below the thermocline where the water mass sinks along the center of the domain. The magnitude of these density induced currents are very small compared to the currents created by other forcing factors, but these currents provide a preliminary idea of the vertical circulation patterns during winter's well-mixed conditions and summer's stratified conditions.

Effect of fresh water inflow

Kitamura and Nagata (1983) and later Nagata *et al.* (1984) have performed experimental study in rotating tank to study the behavior of fresh water injected at the surface of uniformly rotating saline water. Nagata *et al.* (1984) injected light fresh water in the side wall of a rotating tank and revealed two portions of circulations; a clockwise eddy portion with a semi-circle shape formed in front of the inlet (the center being a little left to the inlet) and a tongue-shaped portion which extends southward (anti-clockwise circulation) along the wall (coast), Figure 2.1.

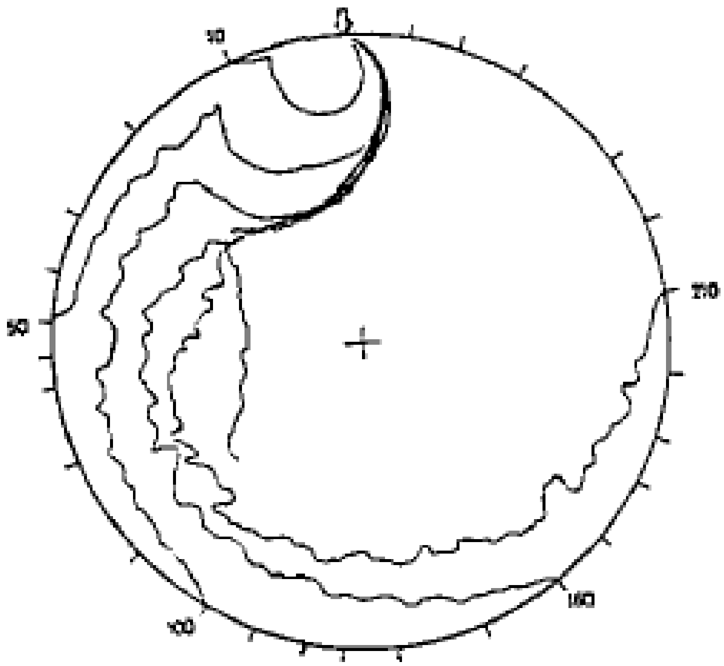

Figure 2.1. Rotating tank experiment by Nagata *et. al.* (1984), numbers show the elapsed time (in hr.) after the low density water was injected

Matsuno and Nagata (1987) have done numerical study on the behavior of heated water discharged into the ocean with a simplified rectangular calculation domain where they showed the effect of Coriolis force in creating a clockwise circulation. This circulation is generated inside the warm water mass and the low density water mass is transported towards the right hand side of the outlet (Figure 2.2). In their study they mentioned that when the Coriolis effect is neglected the shape of the isopycnal contours are symmetric with respect to the line passing through the center of the outlet, whereas when Coriolis effect is considered the contours are asymmetric and the warm water mass tends to spread towards the right of the outlet. They have also found, when rotation is considered the right ward spreading is accelerated and the left ward velocity is suppressed compared to the case without rotation. They suggested that the time needed to reach steady state is usually smaller for larger values of $\Delta\rho^*(=\Delta\rho/\Delta\rho_0)$ than for smaller values. That is, the quasi-steady state is established firstly near the inlet, and the domain of steady state expands with time.

Simpson (1997) has discussed the physical processes in the regions of fresh water influence (ROFI) and pointed out if the spatial scale is unrestricted by coastal topography and stirring is weak, the input fresh water tends to drive a coast parallel flow in which the Coriolis force constrains a wedge of low density water against the coastal boundary.

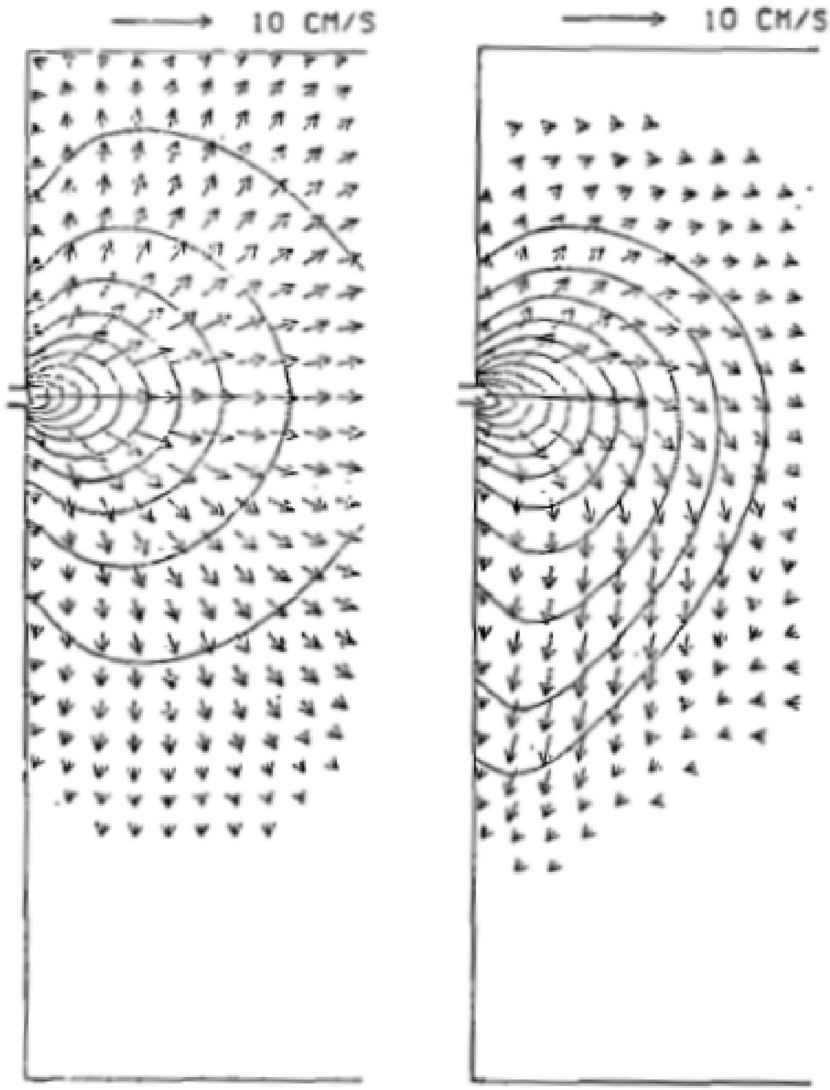

Figure 2.2. Numerical experiment by Matsuno and Nagata (1987) showing the effect of exclusion (the left panel) and inclusion (the right panel) of coriolis effect on velocity distribution and isopycnal movement due to the discharge of heated water into the ocean

2.2.2 Wind driven current

The research on wind driven oceanic circulation goes back more than a century. As R.H. Stewart (2000) compiled, the theory of wind-driven, geostrophic currents was first outlined in a series of papers by Sverdrup, Stommel and Munk between 1947 and 1951. They showed realistic currents can be calculated (in case of oceans) only if Coriolis parameter varies with latitude. Sverdrup (1947) showed that the circulation in the upper kilometer or so of the ocean is directly related to the curl of the wind stress. Stommel (1948) showed that the circulation in oceanic gyres is asymmetrical because the Coriolis force varies with latitude. Finally Munk (1950) added eddy viscosity and showed how to combine these two solutions to calculate the wind-driven geostrophic circulation in an ocean basin. In all cases the current is driven by the curl of the wind stress. Table 2.1 provides a list of contributors to the theory of wind driven current.

Table 2.1. Contributions to the theory of wind-driven current

Name	Year	Contribution
Fridtjod Nansen	1898	Qualitative theory, currents transport water at an angle to the wind
Vagn Walfrid Ekman	1902	Quantitative theory for wind-driven transport at the sea surface
Harald Sverdrup	1947	Theory for wind-driven circulation in the eastern Pacific
Henry Stommel	1948	Theory for westward intensification of wind-driven circulation (western boundary currents)
Walter Munk	1950	Quantitative theory for main features of wind-driven circulation
Kirk Brayan	1963	Numerical models of oceanic circulation
Bert Semtner and Robert Chervin	1988	Global, eddy-resolving, realistic model of the ocean's circulation

Source: Introduction to Physical Oceanography, by R.H. Stewart.

Ekman's theory for the vertical distribution of ocean currents was developed considering constant eddy viscosity throughout the depth and also the point of concern should be away from the boundary, which is not always the case for real oceans. Some of the recent research (e.g. Berger and Grisogono (1998) and Zhe-Min Tan (2000)), evaluate the variable eddy viscosity effect on Ekman's solution and Ekman transport, but still there is potential for further research in this subject in identifying the Ekman layer depth under stratified conditions.

2.2.3 Tide induced currents

For bays and estuaries which are open to the outer ocean like the Bay of Bengal and the Meghna Estuary residual currents can be strongly influenced by the tidal currents primarily due to the asymmetry created by the carioles effect as well as bathymetric configurations. At the same time, residual currents may differ under barotropic and baroclinic conditions and also the effect of asymmetry between spring and neap tide may generate residual currents at the inner bay (Yanagi *et al.* 2003).

2.3 Studies on Residual Current Around the World

The study on residual current is quite an old research topic; e.g. as early as in 1930s simple observations were made to study the residual circulations in Tokyo Bay, Japan, which can be considered as one of the preferred study sites for the study of residual current. Later during 60s, 70s and 80s full scale field observations were made in the same bay. During winter two clockwise circulations were found in the upper layers of the bay, one at the head of the bay and the other at the center. In the lower layer there was one large clockwise circulation primarily in the center of the Bay. However, observations during summer showed the diametric opposite, with a major anti-clockwise circulation in the upper and lower layers centered in mid-bay.

Field observation of the circulation in Tokyo Bay in winter has been done by several researchers (Nagashima and Okazaki, 1979, Unoki *et al.* 1980, Murakami and Morigawa, 1988; Shiozaki *et al.* 1988) and from the analysis of the cross correlation between the residual currents and wind, Unoki (1980) concluded that the clockwise circulation in Tokyo Bay during winter is mainly due to the north to north-east wind. This view has been supported by numerical simulations by Ikeda *et al.* (1981) and Nagashima (1982) by horizontal 2D model and by Odamaki *et al.* (1990) by a 3D model.

Several researches have been done, to find out the mechanism behind this seasonal change in residual current pattern in Tokyo Bay. Some of these concentrate only on specific season and consider specific forcing factors (Guo and Yanagi, 1994, 1995; Suzuki and Matsuyama 2000; Radjawane *et al.,* 2001; Yanagi *et al.,* 2003) while others considered all the forcing factors in a combined manner (Guo and Yanagi, 1996, 1998). Guo and Yanagi (1996) numerically simulated the spatial distributions of residual currents in four different seasons of Tokyo Bay where they used a diagnostic model. Later Guo and Yanagi (1998) used a predictive model to evaluate the effect of FWI to find out the effect on the change in residual current patterns at the mouth of the bay.

Holt and James (2001) studied the residual currents in northwest European continental shelf, Howarth *et. al.* (2000) investigated the eutrophication process in the Hudson River Estuary through the simulation of residual currents, Koibuchi and Isobe (2001) did the same for Ariake Bay of Japan.

2.4 Studies on Residual Current in the Meghna Estuary

Bay of Bengal is widely known for the cyclonic storm surges which has affected the lives of the coastal population of Bangladesh and at the same time severely hampered the country’s economy. This is why; most of the scientific investigations have focused on storm surges in the Bay of Bengal (e.g. Flierl & Robinson, 1972; Murty et al., 1986; Flather, 1994; As-Salek, 1996, As-Salek, 1998; Chowdhury et al., 1998, Madsen and Jakobsen 2004).

As already mentioned, the most important factor for long term material transport in bays and estuaries is ‘residual current’, which is the net current after the tide induced current is excluded. The magnitude of residual current is small compared to the tidal current but plays significant role for the net transport of suspended and bottom sediments which in turn dictate the erosion and accretion process of the estuary and coastal islands.

Jacobsen *et al.* (2002) performed numerical simulations through the two-dimensional MIKE 21 model during the 'Meghna Estuary Study' (MWR, 1997) and obtained a counter-clockwise circulation with a northward flow in the Sandwip Channel and a southward flow in the Tetulia River and in the area from Hatia to Sandwip. During the study it was also observed that the residual circulation, to some extent, traps the river water inside the Meghna Estuary and thus increases the residence time, which is one of the reasons for the relatively low salinity in the estuary even during the dry season. During the study wind stress was considered not to influence the residual currents of the Meghna Estuary significantly but earlier another numerical investigation in the Northern Bay of Bengal by Ali (1995) established that south-westerly monsoon wind may increase water level in the estuary and create back water effects in the rivers. Potemra (1991) also studied the seasonal circulation in the upper Bay of Bengal.

According to Azam et al., (2000), the incoming tides from the southern part of the Bay of Bengal are important for the flow features in the Meghna Estuary and they contribute to the residual circulation significantly. Also, MWR (1997) reported that the salinity in the Meghna Estuary varies significantly throughout the year. Wind field and river discharge are two of the important factors which are expected to have significant influence on the residual currents of the Meghna Estuary, and as they encompass considerable seasonal variation there is need for further clarification and in-depth research regarding this issue for the Meghna Estuary.

Hussain et al., (2012, 2009a and 2009b) applied a 3D model to investigate the seasonal variation of residual circulations in the Meghna Estuary considering four different seasons following Chowdhury et al., (1997). It was observed that throughout the year a counterclockwise circulation exists in the Meghna Estuary almost at all the depths. Average values of wind stress at different seasons of the year did not alter this circulation pattern significantly. Numerical experiments suggested that tidal current along with Coriolis effect is the primary forcing factor behind the counterclockwise residual current in the Meghna Estuary. The results showed that residual circulations at different seasons were only influenced by wind stress when averages of maximum wind stress were applied as boundary conditions.

CHAPTER 3
FEATURES OF THE NORTHERN BAY OF BENGAL

3.1 General Features of the Bay of Bengal

The Bay of Bengal (Figure 3.1) is the largest bay in the world by area, which covers 2.2 million square kilometers (2,172,000 km^2) (Hudson Bay, in Canada, is the world's largest bay measured by shoreline, which covers 12,268 kilometers but total area stands at 1.23 million km^2) and reaches a depth of up to 5,258 meters. It extends from Ganges/Brahmaputra delta around 20° N latitude to south of 7° S, with a maximum width of about 1000 km around 15" N latitude. Many major rivers of India and Bangladesh flow into the Bay of Bengal: in the north, the Padma (distributary of Ganges), Meghna and Brahmaputra River, and in the south Mahanadi River through the Mahanadi River Delta, Godavari River, Krishna River, Irrawaddy and Kaveri River. The Ayeyarwady River of Myanmar also flows into the bay. The Sundarbans mangrove forest is formed at the delta of the Ganga, Brahmaputra and Meghna rivers on the Bay of Bengal.

In the northern end of the Bay of Bengal the bathymetry is shallow, and depth to the seabed occurs less than 2000 meters. The bathymetry over central Bay of Bengal is relatively flat. The average depth is around 3000 meters. The seafloor gradient decreases gradually from north to south. In the northern Bay of Bengal there exist some deep valleys. One such deep valley is known as the "Swatch of No Ground". The deepest portion of the valley is recorded around 1340 m with an overall relief of 400-450 m from the surrounding mean seafloor depth of 1000 m. The width of the Swatch of no ground valley is about 14 km. Within this part of the deep valley channel, there exists another narrower valley like feature, which runs in NE-SW direction and it changes to N-S direction in South. For the morphological development of the fan mass movement, turbidity currents, sea level fluctuations, tectonics and the effect of Himalayan uplift might have played a vital role (Sarma et al., 2000).

Large volume of continental sediments are being discharged by Ganges and Brahmaputra Rivers into the Bay of Bengal and the finer sediment particles reach even 7° S latitude. The Bay of Bengal is a region where thick pile of sediments covers the entire basement and renders the ocean floor bathymetry virtually featureless. The sediment cover is exceptionally thick (about 21 km) at the apex of the Bengal fan in the Bangladesh offshore region and decreases gradually to about 8 to ‹ 2 km in the central and southern parts (Curray 1991). In the distal reaches of the fan at 7° S, the sediments are a few hundred meters thick.

Ocean current, from January to October, is northward flowing, and the clockwise circulation pattern is called the 'East Indian Current'. The Bay of Bengal monsoon moves in a northwest direction striking the Nicobar Islands, and the Andaman Islands by end of May, then the North Eastern Coast of India by end of June. The remainder of the year, the counterclockwise current is southwestward flowing, and the circulation pattern is called the 'East Indian Winter

Jet'. September and December see very active weather in the Bay of Bengal producing severe Cyclones which affect Eastern India.

3.2 Hydro-Morphological Features

The hydrological and morphological features of the study area of the present study are described below in two sub-sections.

3.2.1 Hydrological Features

Tides and Sea Level Changes

The area around Sandwip island is macro-tidal with variation in tidal range of about 3 to 6 m (Hayes, 1979). The area between Bhola and Hatia (Shahbazpur Channel) is meso-tidal, with tidal range of 2 to 4 m. Tetulia River and the upper rich of Lower Meghna upstream of Char Gazaria are micro-tidal, with tidal range less than 0.2 m (Sokolewics and Louters, 2007). This is shown in Figure 3.2

The flow distribution in the Northern Bay of Bengal is determined by the combined action of tides and fresh water flow. The flow in the western part (upper and mid-estuary, Tetulia and the Shabhazpur Channel) is dominated by the fresh water flow from the Lower Meghna. The eastern part of the estuary is mainly influenced by the tide and much less by the fresh water flow from the river system. Most of the fresh water discharge is conveyed to the Bay of Bengal through the Shabhazpur Channel, while the Hatia Channel is mainly a tidal channel. A prominent counter-clockwise residual circulation is present around Sandwip. The water flow is generally very strong and turbulent. Current velocities up to 4 m/s have been observed in the Sandwip Channel during spring tide and in the upper reach of the Lower Meghna during high monsoon (Sokolewics and Louters, 2007).

Fresh Water Inflow

Although several large and tiny rivers discharge into the Bay of Bengal, discharge from the lower Meghna River dominates all other rivers by its enormous volume as well as its large influence on the hydrological and morphological processes of the northern Bay of Bengal. Lower Meghna conveys the rainwater from the enormous catchments of the Ganges and Brahmaputra, combined in the Padma River, and from the Upper Meghna catchment. The river flow in the Lower Meghna has a distinct seasonal characteristic, and varies between approximately 10,000 m^3/s during the dry period and 100,000 m3/s during the monsoon months (June – September) (Sokolewics and Louters, 2007). Figure 3.2 (Islam *et. al.*, 2002) shows the water and sediment discharge through the Lower Meghna into the Bay of Bengal.

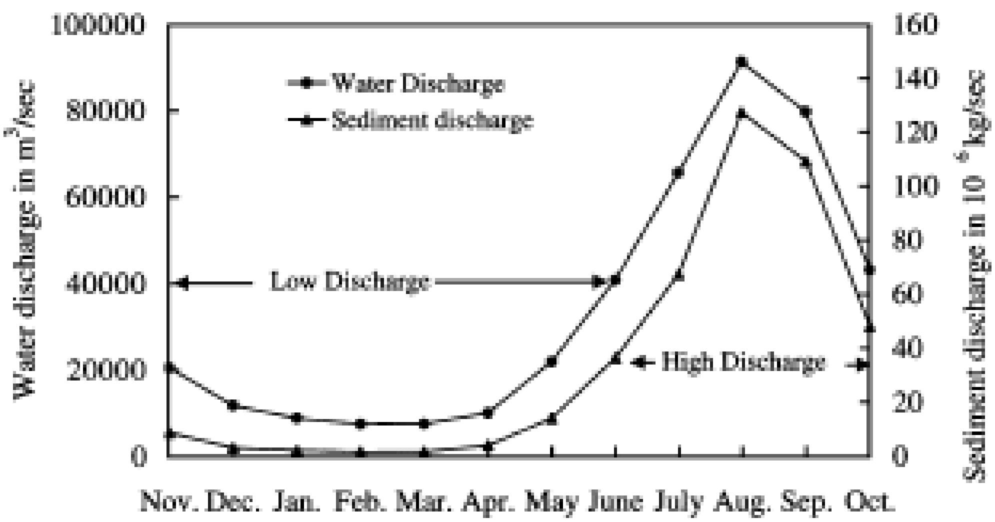

Figure 3.2 Water and sediment discharge into Bay of Bengal from the Lower Meghna River

Salinity and Temperature

Salinity distribution in the northern part of the bay of Bengal is strongly influenced by the seasonal changes in the fresh water discharge from the Lower Meghna River. During monsoon, the salinity drops considerably and the water becomes almost completely fresh. Saline water is generally well mixed, with stratification found only in the deep Sandwip Channel. After the monsoon, the salinity rises again and the seawater intrudes into the estuary. However, even during the period with low river discharges the salinity in the area never approaches normal seawater salinity (34 g/l) but always remains distinctly lower. Penetration of saline water during dry period stops north of Char Gazaria, where salinities less than 1 g/l are found (Sokolewics and Louters, 2007).

The salinity in the Northern Bay of Bengal varies significantly during the year (MWR, 1997). The highest salinities are observed in March and April (approximately 20 at Sandwip), whereas the lowest salinities are observed in August and September (below 5 at Sandwip). The variation in salinity is highly correlated to the river runoff, i.e. the lowest salinities are found during the wet season.

3.2.2 Morphological Features

Meghna Estuary region of the Northern Bay of Bengal experiences the most dynamic morphological changes like formation of new islands and erosion of coastal areas under significant sediment supply from the rivers. Nearly a billion tons of sediment enters into the northern Bay of Bengal through the Brahmaputra/Jamuna, Ganges and Upper Meghna rivers. Compared to other two rivers sediment input in the estuary through the Upper Meghna River is relatively small. A part of the sediment forms new land in the estuary, another sets off lateral and vertical accretion of the shelf area, and the rest is lost forever through the canyons in the ocean floor (Goodbred and Kuehl, 1999). Approximately overall sediment budget in the study area over the period 1997-2000 (based upon data from extensive bathymetric surveys) indicates that the deposition processes exceeded the erosion processes. Net accretion during this 3-year period amounted to approximately 300 million m^3. However, the net change in the sediment volume is only about 6% compared to the total accretion and erosion. Erosion dominates in the northern part of the river system. Erosion in the Lower Meghna from the northern end down to northern head of Hatia is approximately 0.1 - 0.2 m/yr (Sokolewics and Louters, 2007). High rate of accretion (approximately 0.2 m/yr) was found in the northeast of the estuary, between Noakhali mainland, Urir Char and Sandwip. Also the area between Bhola and Hatia, and the south-west end of the estuary were accreting, with an accretion rate up to 0.1 m/yr. In other areas in the estuary, erosive and depositing processes were more or less in balance (Sokolewics and Louters, 2007).

3.3 Meteorological Features

3.3.1 Wind Field

The wind field in the Bay of Bengal area is characterized by a south-westerly monsoon of 4–5 m/s, which predominates from June through September and a north-easterly monsoon of 1·5–3 m/s predominating from December to February. Wind is often of relatively little importance to the flow in the estuary. Still, the south-westerly monsoon can occasionally increase the water level in the estuary and create back water in the rivers (Ali, 1995). The wind pattern is forced by the differential heating between land and water. Cyclones typically occur in the pre and post-monsoon periods.

CHAPTER 4
METEOROLOGICAL AND HYDROLOGICAL DATA ANALYSIS

4.1 Introduction

In this chapter, results for meteorological and hydrological data analysis have been presented. Fifteen years of observed meteorological data from thirteen BMD stations (shown in Figure 4.1) in the coastal zone of the country was collected to analyze the seasonal as well as spatial variation of nine meteorological parameters (wind speed, wind direction, air pressure, air temperature, precipitation, evaporation, relative humidity, cloud cover and solar radiation) which are used as input to the numerical model. In general, the spatial variation of different parameters was found to be insignificant among these stations. There is considerable seasonal variation of these meteorological parameters but the year to year variations are also not significant except for the cyclonic years. Projections of meteorological parameters have been obtained from PRECIS from 1961 to 2100 which have been subdivided into four time slices: base (1961- 1990), 2020 (2010-2040), 2050 (2041-2070) and 2080 (2071-2100).

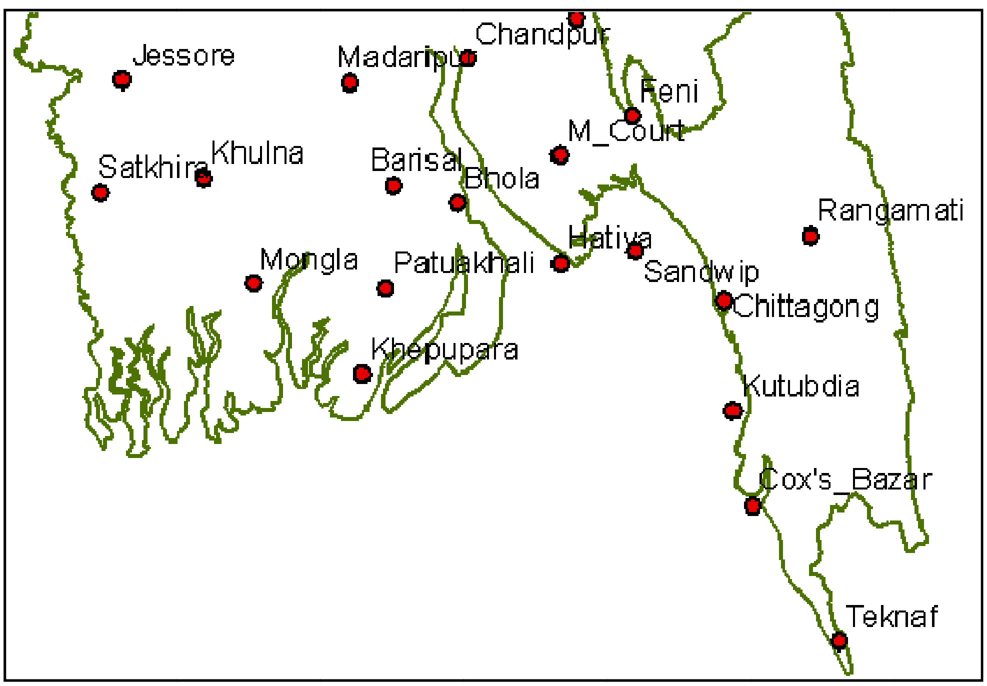

Figure 4.1 BMD stations for meteorological data analysis

Four seasons were identified based on previous studies (e.g. Chowdhury *et al.*, 1997) on climatic conditions of Bangladesh, namely pre-monsoon (March - May), monsoon (June - September), post-monsoon (October - November) and winter (December - February). Hydrological data (mostly water level data) of several coastal rivers were obtained from BWDB and also Survey of Bangladesh. Meteorological and hydrological data have been analyzed for these periods to set-up a three dimensional numerical model which has been applied in the present study to compute residual currents in the Meghna Estuary.

4.2 Seasonal Variation of Observed and Projected Meteorological Parameters

Wind data shows that its direction is mainly from South and South-East during pre-monsoon and monsoon periods and from North and North-West during post-monsoon and winter periods. Average wind speed at different stations is quite small in the coastal region of Bangladesh, which is due to the fact that 30 ~ 40% of the time in a year wind remains calm (<1.0m/s). The wind speed is the strongest during monsoon period and the weakest during winter. The spatial variation of maximum wind speed during pre-monsoon is 5.6 ~ 17.0 m/s, during monsoon 6.3 ~ 25.1 m/s, during post-monsoon 5.9 ~ 22.0 m/s and during winter 3.6 ~ 9.8 m/s. Projected wind speed and direction by PRECIS does not show significant change (Table 4.1 and Table 4.2) during its projection period over the calculation domain.

Table 4.1. Seasonal variation of observed and projected wind speed at the Bay of Bengal

		Pre-monsoon	**Monsoon**	**Post-monsoon**	**Winter**
Observed (1994~2008)		3.1	4.2	1.2	1.4
Projections	Base (1961~1990)	5.9	5.8	2.8	2.5
	2020 (2010~2040)	6.0 (+1.2%)	5.7 (-3.3%)	2.8 (+0.0%)	2.5 (-0.6%)
	2050 (2041~2070)	6.3 (+7.1%)	5.8 (-0.1%)	2.7 (-0.3%)	2.5 (+0.2%)
	2080 (2071~2100)	6.5 (+9.7%)	5.9 (+0.5%)	2.9 (+3.6%)	2.4 (-5.9%)

In Table 4.1, percentage values in parentheses indicate the % of change in projected period compared to projections of base period; positive values indicate there has been an increase and vice-versa. In Table 4.2, percentage values in parentheses indicate the percent of days experiencing dominant wind direction.

Table 4.2. Seasonal variation of observed and projected major wind direction at the Bay of Bengal

		Pre-monsoon	Monsoon	Post-monsoon	Winter
Observed (1994~2008)		S (37%)	S (39%)	N (16%)	N (20%)
Projections	Base (1961~1990)	S (32%)	S (41%)	N (21%)	N (17%)
	2020 (2010~2040)	SW (29%)	S (33%)	NE (19%)	N (21%)
	2050 (2041~2070)	SW (23%)	S (33%)	N (14%)	N (16%)
	2080 (2071~2100)	S (31%)	S (31%)	NE (12%)	N (18%)

Similar analyses are made for air temperature (^{0}C), relative humidity (%) and average daily precipitation (mm) at the same BMD stations which are summarized in Table 4.3. Here also, percentage values in parentheses indicate the % of change in projected period compared to projections of base period; positive values indicate there has been an increase and vice-versa. The trend of average temperature going down after the end of monsoon season is evident both at present and in future. More significantly, temperature rises from 3.3^{0}C to 5.5^{0}C after 100 years in projected values. Relative humidity is reduced for most part of the year and the reduction is more during post-monsoon and winter periods. Distribution of precipitation throughout the year will remain skewed but total precipitation shows more than 27% increase in projected values and the increase in precipitation appears to be drastic during the monsoon and post-monsoon periods.

Table 4.3. Seasonal variation of observed and projected seasonal variation of air temperature, relative humidity and precipitation

		Pre-Monsoon	Monsoon	Post-Monsoon	Winter
Air Temperature (^{0}C)	Observed (1994~2008)	28.0	28.3	25.8	20.6
	Base (1961~1990)	28.2	27.5	22.7	17.2
	2020 (2010~2040)	29.4 (+4.4%)	28.6 (+4.1%)	24.3 (+7.1%)	18.9 (+10.4%)
	2050 (2041~2070)	30.5 (+8.3%)	29.3 (+6.6%)	26.0 (+14.3%)	20.4 (+19.1%)
	2080 (2071~2100)	32.3 (+14.7%)	30.8 (+12.0%)	27.9 (+23.0%)	22.7 (+32.2%)
Relative Humidity (%)	Observed (1994~2008)	78.3	88.0	83.5	77.7
	Base (1961~1990)	80.7	88.4	82.2	77.5
	2020 (2010~2040)	80.4 (-0.4%)	87.8 (-0.6%)	81.4 (-1.1%)	78.0 (+0.6%)
	2050 (2041~2070)	79.9 (-1.0%)	87.8 (-0.6%)	74.2 (-9.7%)	75.7 (-2.4%)
	2080 (2071~2100)	78.0 (-3.3%)	85.4 (-3.0%)	74.9 (-8.9%)	72.3 (-6.7%)
Precipitation (mm/day)	Observed (1994~2008)	3.60	15.50	4.90	0.30
	Base (1961~1990)	3.63	7.73	1.16	0.44
	2020 (2010~2040)	2.73 (-24.8%)	8.43 (+9.1%)	1.79 (+53.7%)	0.38 (-15.0%)
	2050 (2041~2070)	4.40 (+21.2%)	7.93 (+2.6%)	1.66 (+42.7%)	0.68 (+52.4%)
	2080 (2071~2100)	3.81 (+4.8%)	10.34 (+33.8%)	1.82 (+57.0%)	0.55 (+23.4%)

Other than these parameters observed data for solar radiation (Cal/cm2/min), evaporation (mm/day) and cloud cover are presented in Table 4.4. Solar radiation and evaporation are at a maximum during the pre-monsoon periods compared to the rest of the year. Cloud cover is significantly higher during the monsoon period.

Table 4.4. Observed seasonal variation of solar radiation, evaporation and cloud-cover

	Pre-Monsoon	Monsoon	Post-Monsoon	Winter
Solar radiation (Cal/cm^2/min)	227	152	160	168
Evaporation (mm/day)	46.3	35.0	34.9	29.9
Cloud cover (fraction)	0.37	0.71	0.30	0.13

4.3 Seasonal Variation of Observed and Projected Hydrological Parameters

There is significant variation of fresh water discharge through the Meghna Estuary. Table 4.5 shows the discharge (m^3/s) through the Meghna Estuary following Islam et al., (2002), which has been implemented as boundary condition for the numerical investigation for the present study. Nohara et.al. (2006) suggests that the discharge from the rivers in the Asian monsoon region (Changjiang, Ganges, and Mekong) is sensitive to the seasonal cycle in precipitation. The amounts of the discharge from these rivers are estimated to increase by 7.8%, 18.0%, and 9.9% in the future through the application of number of global models. So, to make a reasonable estimate, future river discharge into the Bay of Bengal has been obtained by increasing the present discharge by 18%. Long term discharge data for many of the rivers are not available. Discharge data for these rivers are obtained either estimated or obtained from CEGIS (2006).

Table 4.5. Seasonal variation of discharge through Ganges-Brahmaputra-Meghna river system

	Pre-Monsoon	Monsoon	Post-Monsoon	Winter
Discharge (m^3/s)	12,300	69,250	31,000	9,300

Water level data analysis of different tidal rivers does not reveal any clear indication of sea-level rise mainly because most of the gage stations are located inside the rivers and water level data are affected by several factors including river bed siltation as well as natural subsidence of the active delta in the southern part of Bangladesh. Figure 4.2(a) shows the annual mean water level variation at Patharghata Station on Bishkhali River and 4.2(b) shows the mean water level variation at the offshore station located at Rangadia, Chittagong. Even though Patharghata station has several missing data of annual mean water level, it shows a steep gradient (rise of 2cm per year) for a 52 year length of data. This station is located at a river mouth and most probably water level data is affected by river bed rise due to siltation. The offshore data at Rangadia appears to be more reliable but the length of data is comparatively short (1994~2009). It shows a rising trend in annual mean water level with 0.3cm rise per year. The trend in the change of maximum tidal range during this period has also been analyzed, which shows an increasing trend at a rate of 1.4 cm per year.

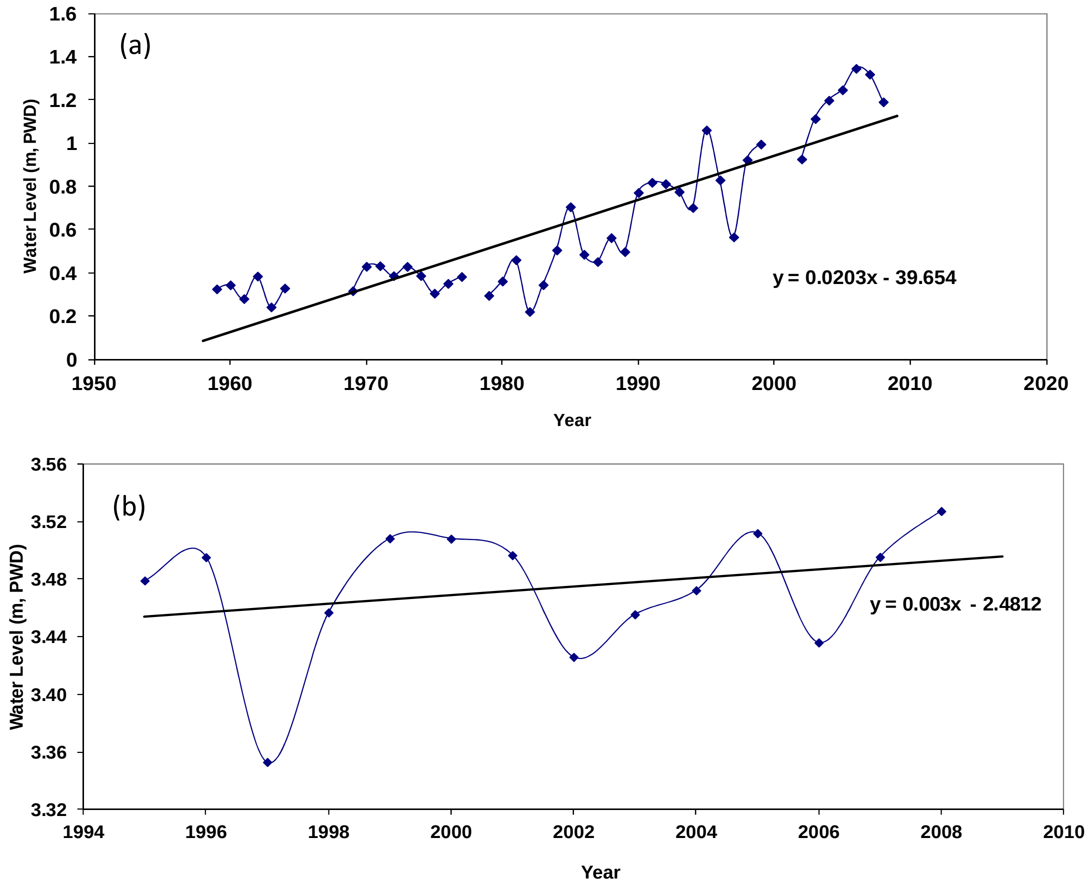

Figure 4.2. Annual mean water level variation at (a) Patharghata and (b) Rangadia.

CHAPTER 5
NUMERICAL SIMULATION OF RESIDUAL CURRENTS AND SALINITY AND TEMPERATURE FRONTS

5.1 Numerical Model

The open source Delft3D model including salinity and temperature constituents along with wind and tidal forcing have been applied for the simulation of residual currents in the Northern Bay of Bengal. In the present model, sigma coordinate system with k- ε turbulence model has been employed. In this model, boundary conditions are considered for the wind stress at surface, friction at bottom (with friction coefficient 0.0023) and frictionless along the lateral boundaries. Heat balance and moisture balance at sea surface have been considered for temperature and salinity boundary conditions, respectively. Constant values for horizontal eddy viscosity (1m2/sec) and horizontal eddy diffusivity (10m2/sec) are used.

The hydrodynamic model has been applied using a five-layer sigma coordinate system and the calculated instantaneous currents have been averaged over 25 hours to obtain the residual currents. To simulate the residual currents during the four above mentioned seasons, steady wind stress with average wind speed of the season and a constant river discharge of that season have been applied. Other meteorological parameters have been used taking the spatial and temporal average values. A uniform grid size of 1850 m by 1850 m has been employed in a calculation domain with a total domain size of 740 km in east-west direction and 259 km in north-south direction. The bathymetry data used for the present study is the one which is freely available at NOAA website; ETOPO1 is a 1 arc-minute global relief model of Earth's surface that integrates land topography and ocean bathymetry. Bathymetry of the computational domain is shown in Figure 5.1.

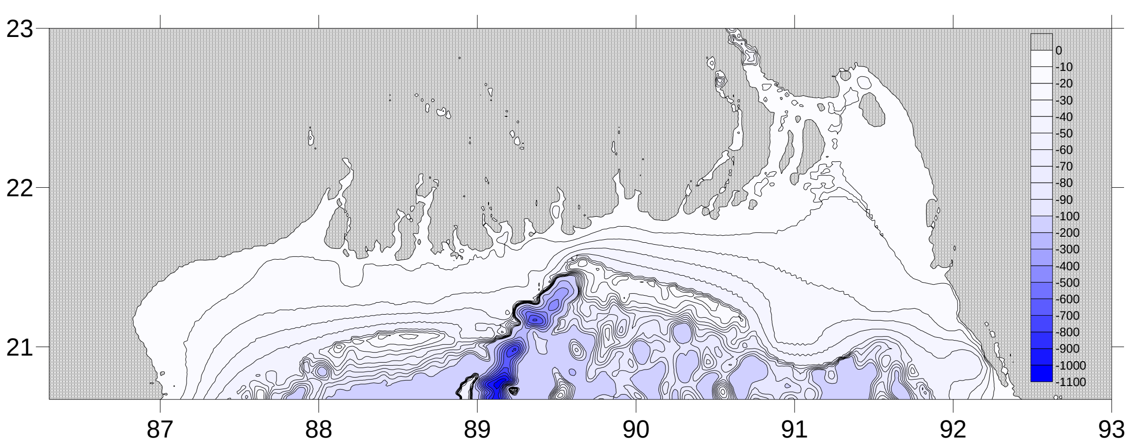

Figure 5.1. Bathymetry in the Northern Bay of Bengal (within the calculation domain)

5.2 Regional Climate Model

In this study, PRECIS (Providing Regional Climates for Impact Studies) regional climate model has been applied to simulate regional climate over a large domain which covers Bangladesh and south Asia. PRECIS is based on the Hadley Centre's regional climate modeling system which has been developed in order to help generate high-resolution climate change information. PRECIS simulation has been done using the lateral boundary data of the prognostic variables generated by the HadCM3Q model to produce diagnostic variables (e.g. spatial precipitation, orographic height etc.) over the simulation domain during 1961-2100. Simulation grids are of 50km resolution over the Indian sub-continent which includes Bangladesh (Islam et al. 2011). Projected meteorological data obtained from this simulation has been employed to generate future scenarios.

5.3 Numerical Model Calibration

The calibration period was selected so that it covers one spring tidal peak and one neap tidal peak. Observed data used for calibration process has been obtained from the MES project during 1996-97. The selected calibration period was 1st April of 1996 to 15 April 1996. Figure 5.2 shows the comparison between observed and simulated water levels. Even though there appears some discrepancy between tidal phases there is a reasonably good agreement between observed and simulated water levels. Bottom friction coefficient was found to be the most important calibration factor for adjusting the tidal amplitude effectively.

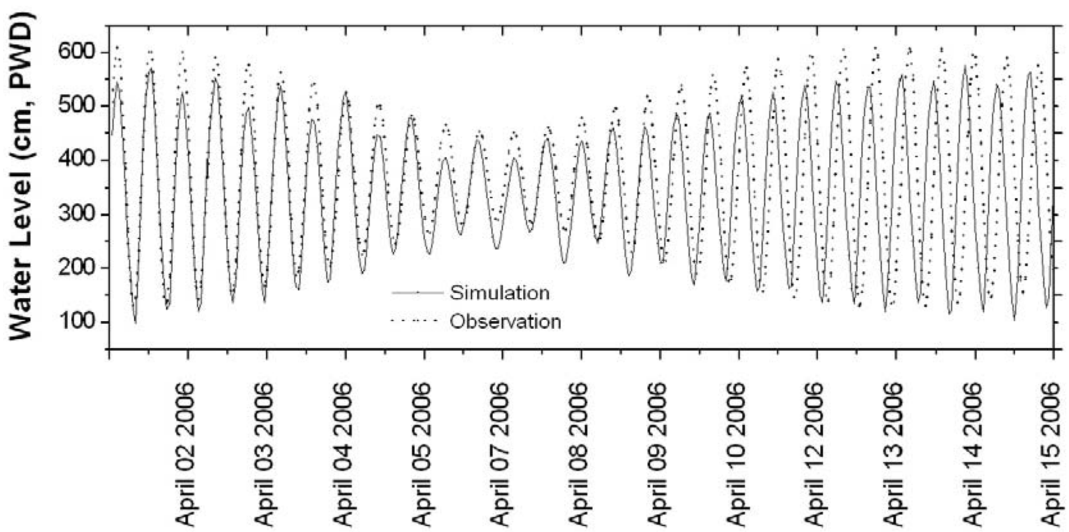

Figure 5.2. Comparison between measured and simulated water levels at Rangadia Chittagong

For depths greater than 20m bottom friction coefficient was considered as 0.0026 and for shallow areas the value of the coefficient was increased proportionately.

5.4 Seasonal Variation of Residual Currents

The calculated residual currents in the Northern Bay of Bengal at the surface, middle and bottom layers during the monsoon season is shown in Figures 5.3(a), 5.3(b) and 5.3(c), respectively. Here, average hydrological and meteorological parameters along with average wind speed from south have been employed. The results show, at all the layers the circulations are significantly influenced by the Swatch of No Ground located at the central part of the southern boundary in the calculation domain. In all the layers along the Chittagong coast there is an anti-clockwise circulation and along the West Bengal and Odisha coast there is a clockwise circulation. The south wind also appears to generate upwelling along the Odisha coast. The circulation pattern is similar to that observed in the Meghna Estuary (Hussain et al. 2009a, 2009b and Jakobsen et al. 2002) which shows an anti-clockwise circulation during monsoon in the estuary, where north-westward flow along the Sandwip Channel. During the monsoon season magnitude of residual current is the maximum (around 1m/s) through the Shahbazpur Channel (south of Meghna River) and through the Sandwip Channel (at the east of Sandwip). At other places of the northern Bay of Bengal magnitude of residual current is less than 0.5m/s.

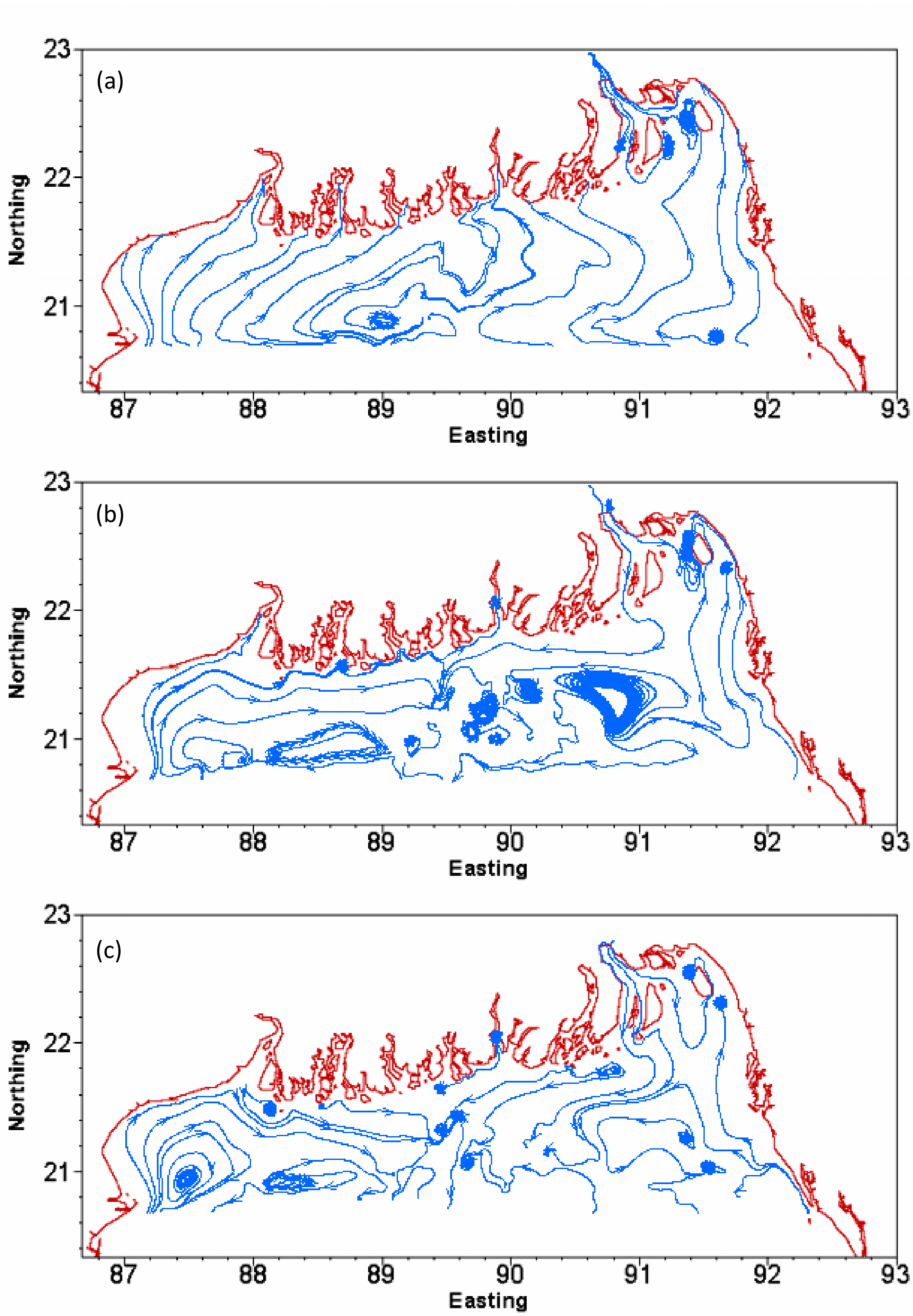

Figure 5.3. Calculated streamlines of residual currents during monsoon at the Northern Bay of Bengal at (a) surface, (b) middle and (c) bottom layer.

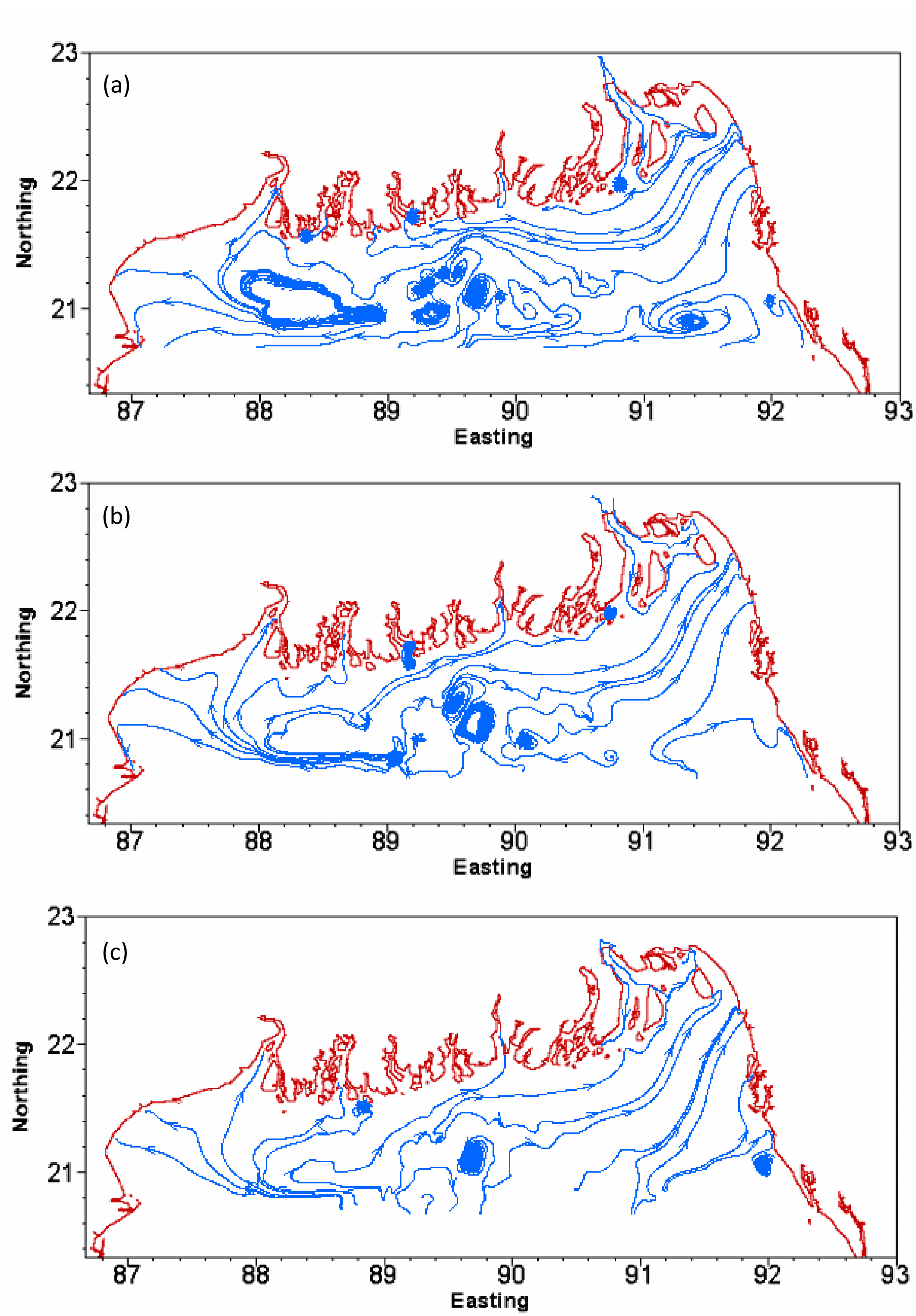

Figure 5.4. Calculated streamlines of residual currents during winter at the Northern Bay of Bengal at (a) surface, (b) middle and (c) bottom layer.

Figures 5.4(a), 5.4 (b) and 5.4 (c) show the calculated residual currents at the surface, middle and bottom layers respectively, during the winter season with average wind speed from the north. The north wind along with tidal current appears to create an eastward flow along the Bangladesh coast towards Chittagong and again creates anti-clockwise circulation in the Meghna Estuary region which seems to be stronger than the monsoon season. This was also observed by Hussain et al. (2009a and 2009b) for the Meghna Estuary. The Swatch of No Ground again seems to have a major impact on the circulation pattern in all the layers and westward flow appears in all layers, in the western part of Swatch of No Ground flowing towards Odisha coast. During the winter, magnitude is the maximum only along the Sandwip channel (around 1m/s) and it is less than 0.5m/s in the rest of the northern Bay of Bengal. As already mentioned, projected values of wind speed and direction did not show significant change (Table 4.1 and Table 4.2). Which means the major driving forces for residual flow in the Northern Bay of Bengal: tidal current, wind speed and direction, and Coriolis force will remain unchanged in future. So, circulation patterns are expected to remain the same as presently observed in monsoon and winter. In this context, the next section focuses on salinity distribution alteration due to the changed meteorological conditions.

5.5 Projections of Salinity Fronts

Figure 5.5(a) and 5.5 (b) shows the calculated surface salinity during monsoon for the year 2000 and year 2100, respectively. From the figure it clearly appears that the area of fresh water plume along the southern coast of Bangladesh will be reduced considerably in future. Especially the south-western part of Bangladesh where the Sundarbans Mangrove forest is located, is going to experience salinity level increase from 27~27.5 ppt to 29.5~30 ppt which may affect the ecosystem in the region drastically. Also, along the Sitakunda coast along the Sandwip coast, salinity level is going to increase from 27 ppt to about 30 ppt in future. The reduction of fresh water plume along the southern coast of Bangladesh suggests that even though there will be increase in precipitation and fresh water discharge in future, the rise of sea level (88 cm in 2100) will push the fresh water plume towards the north. Also the fresh water discharge through the rivers at the south-western part of Bangladesh is very small compared to that of Meghna River. This is why the plume is shifted towards the west in the Northern Bay of Bengal.

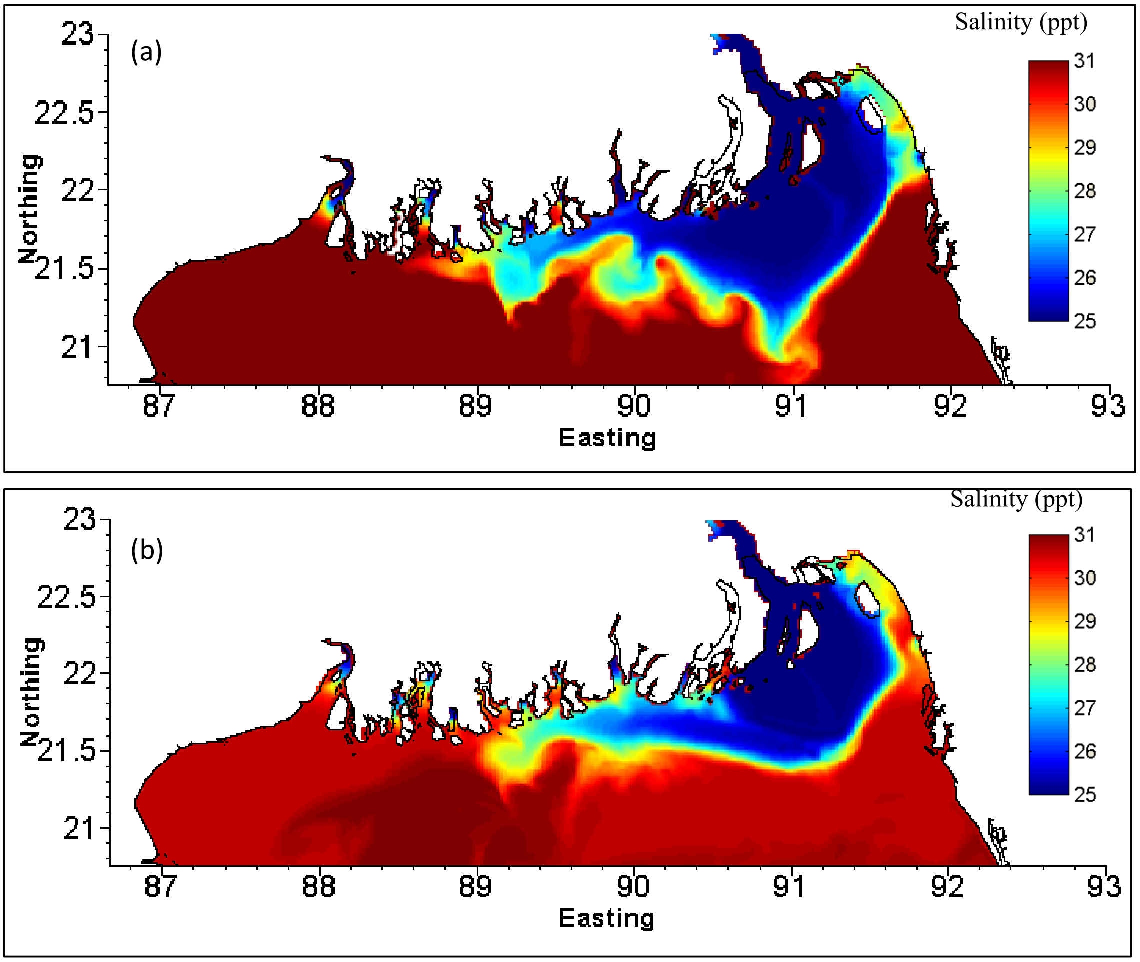

Figure 5.5. Calculated surface salinity during monsoon in the Northern Bay of Bengal (a) during year 2000 and (b) during year 2100.

Figure 5.6(a) and 5.6 (b) shows the calculated surface salinity during winter for the year 2000 and year 2100, respectively. From the figure it appears there is very little change in salinity distribution along the coast.

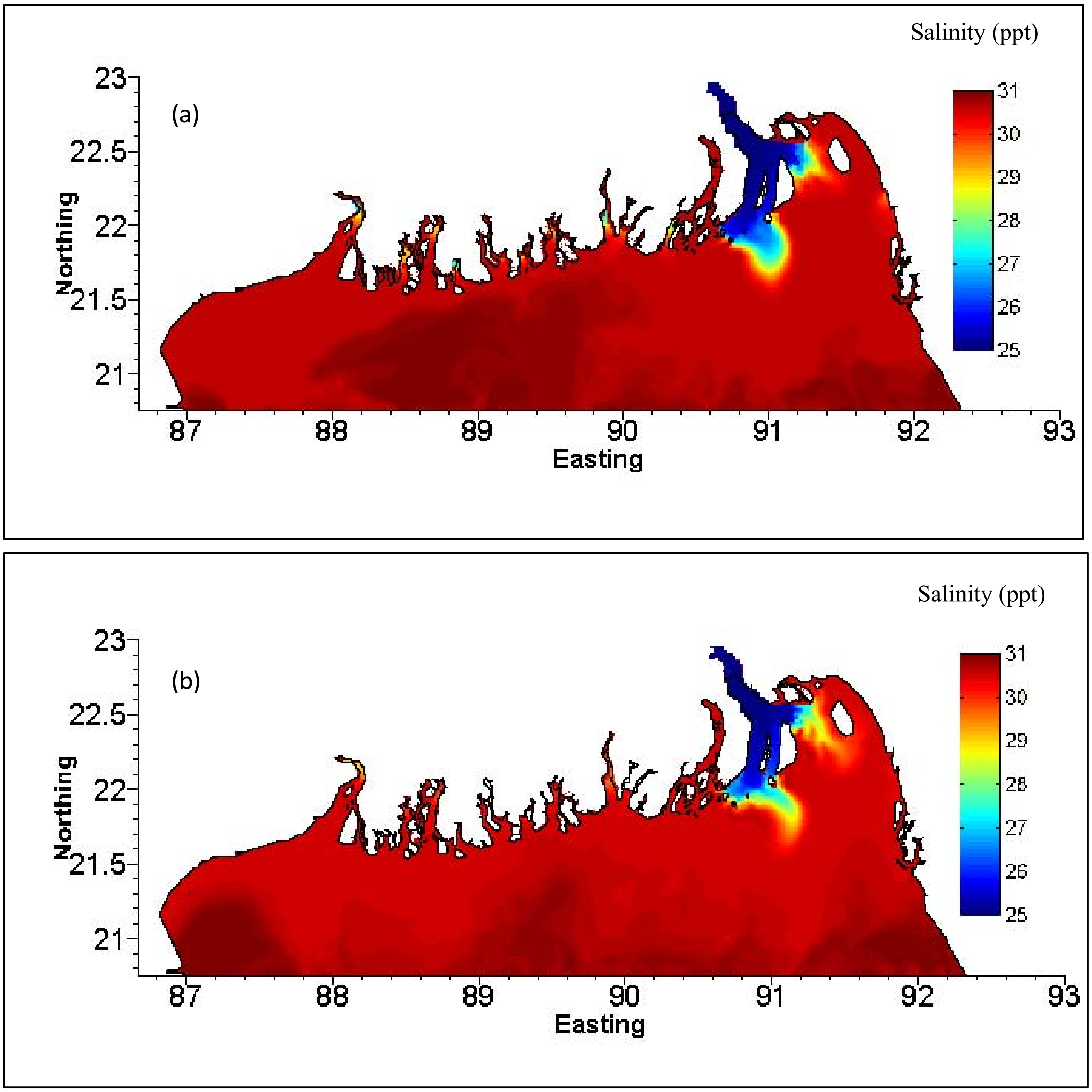

Figure 5.6. Calculated surface salinity during winter in the Northern Bay of Bengal (a) during year 2000 and (b) during year 2100.

5.6 Projections of Thermal Fronts

Figure 5.7(a) and 5.7(b) shows the calculated surface temperature during monsoon for the year 2000 and year 2100, respectively. From the figure it appears that all along the coast the surface water temperature is going to increase by 2 to 3^0C in future. Due to the increase in air temperature as well as increase in net solar radiation sea-surface temperature is going to increase along the coastline which again may have considerable impact on the coastal and wetland ecosystem in the region.

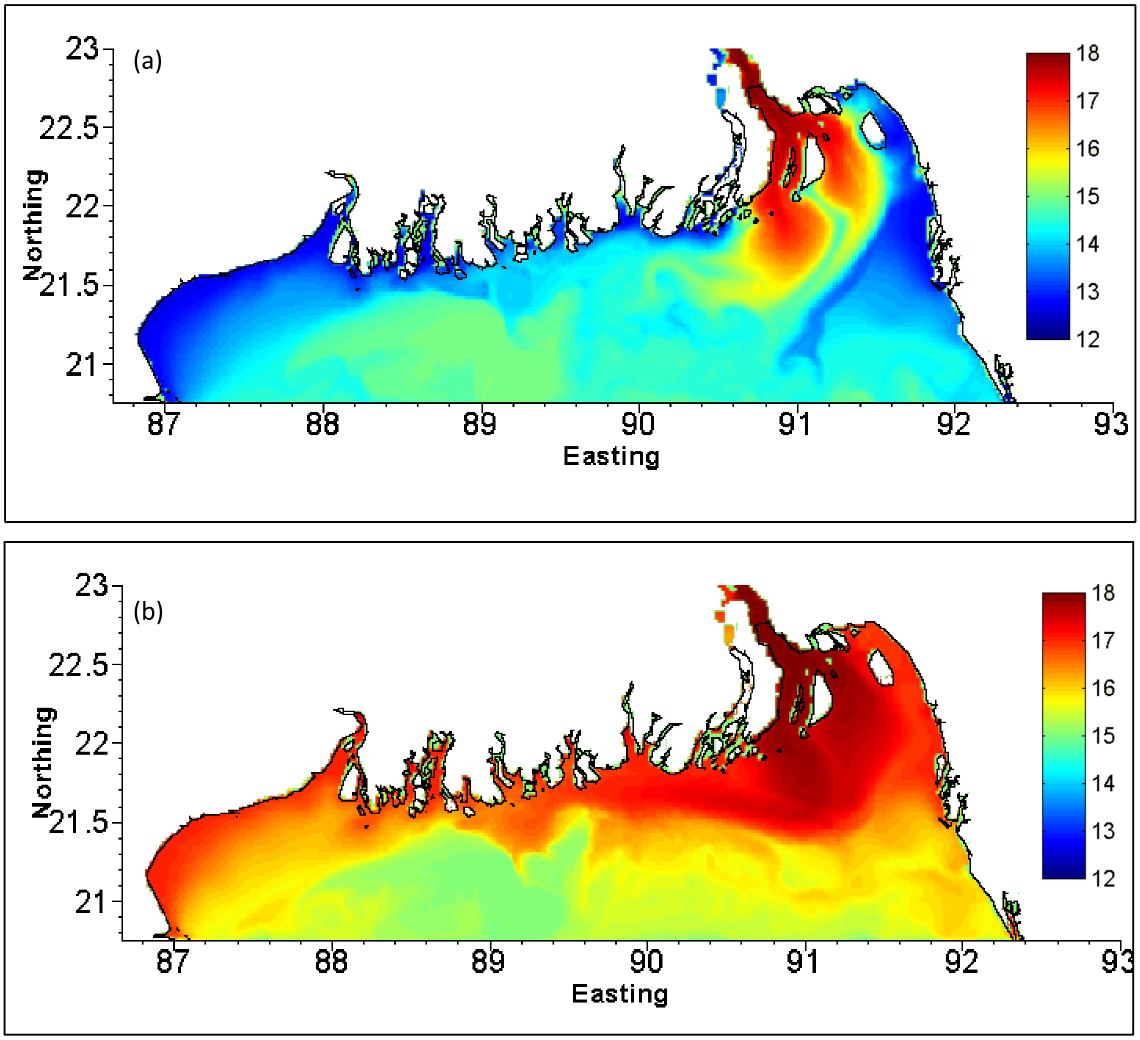

Figure 5.7. Calculated surface temperature during monsoon in the Northern Bay of Bengal (a) during year 2000 and (b) during year 2100.

CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDIES

6.1 Conclusions

Observed meteorological data from thirteen BMD stations as well as projected meteorological data by PRECIS RCM was employed to generate present and future hydro-climatic scenarios in the Northen Bay of Bengal. Analysis of long term tidal water level data from fourteen BWDB gage stations in different tidal rivers does not show any definite trend of sea-level rise as the data seem to be affected by river bed siltation. The data obtained from an offshore tidal gage seems to provide a more reliable trend indicating 0.3cm per year rise in sea level. Numerical investigations showed that throughout the year a counterclockwise circulation exists in the eastern part of the Northern Bay of Bengal i.e. in the Meghna Estuary region. Swatch of No Ground, located at the central part of the experimental domain, has a significant influence on the residual circulation in the Northern Bay of Bengal. Projected values of meteorological parameters, obtained from a RCM experiment, were employed to generate future salinity and temperature levels at the Northern Bay of Bengal. The results show considerable increase of surface salinity and temperature along the Bangladesh coast in future which may hamper the ecological balance in the region. To incorporate the influence of salinity, especially in the vicinity of the river mouth, and temperature on the residual flow measured data is necessary to provide as input to the numerical model.

6.2 Recommendations for Future Studies

Future studies on residual current at Northern Bay of Bengal may consider the currents at the southern boundary (open boundary for the present case) more accurately, possibly through the simulation of residual currents in a larger calculation domain. Finer grids possibly with curvilinear grids should be used to calculate the residual currents near the chars and mudflats with a model which includes a moving shoreline boundary condition. Spatially and temporally distributed observed data on salinity and temperature is necessary for further investigation in the region.

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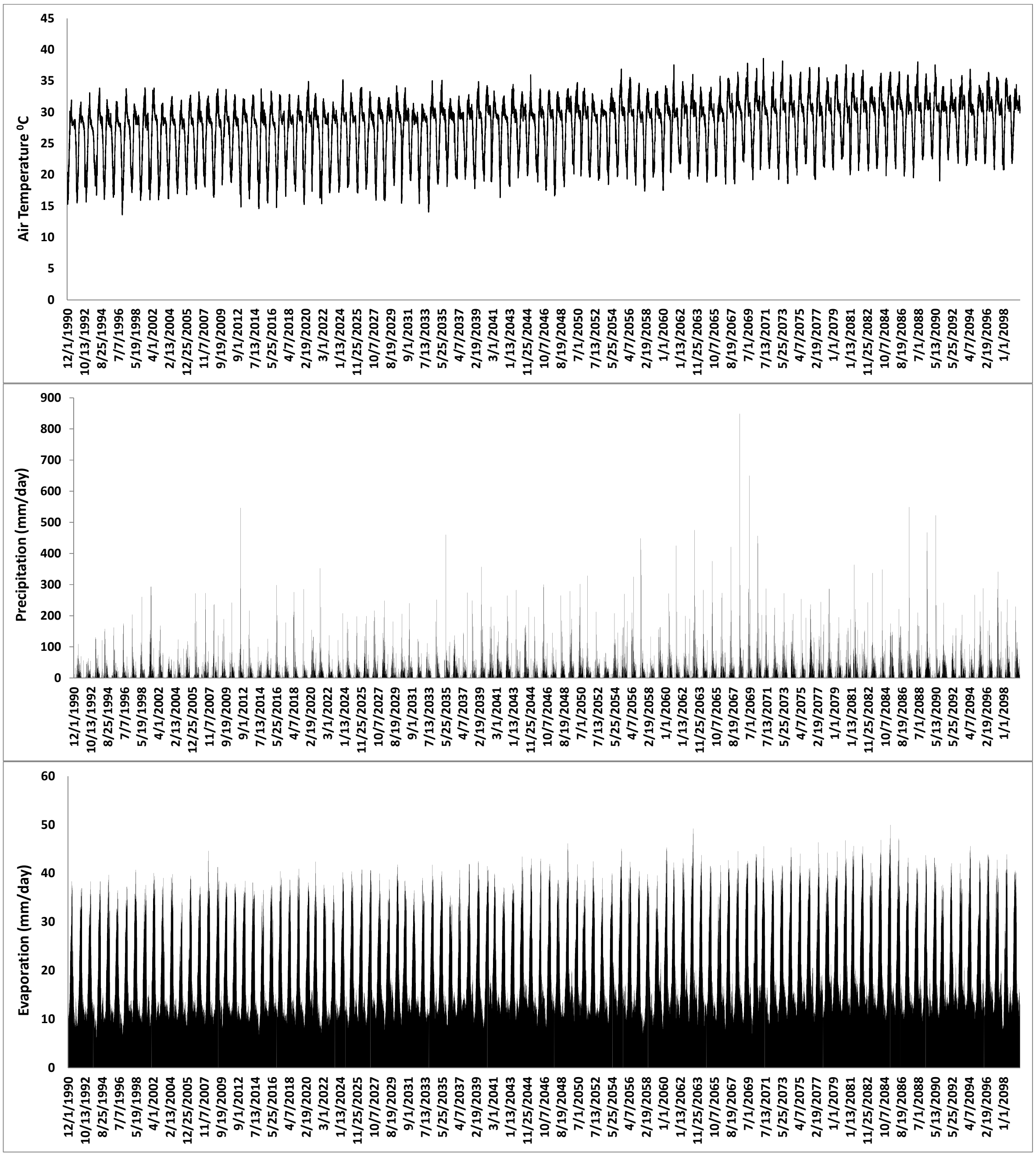
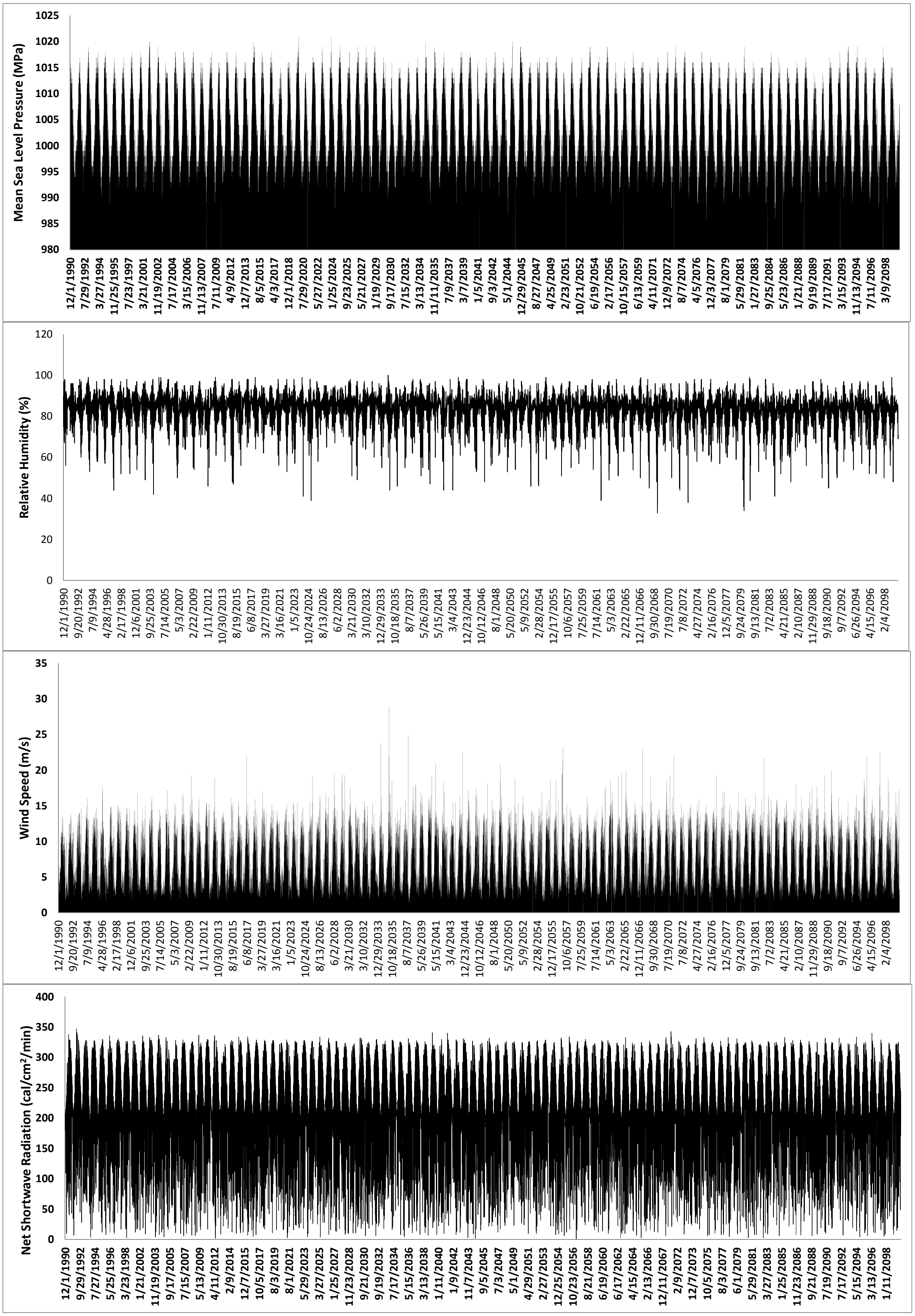
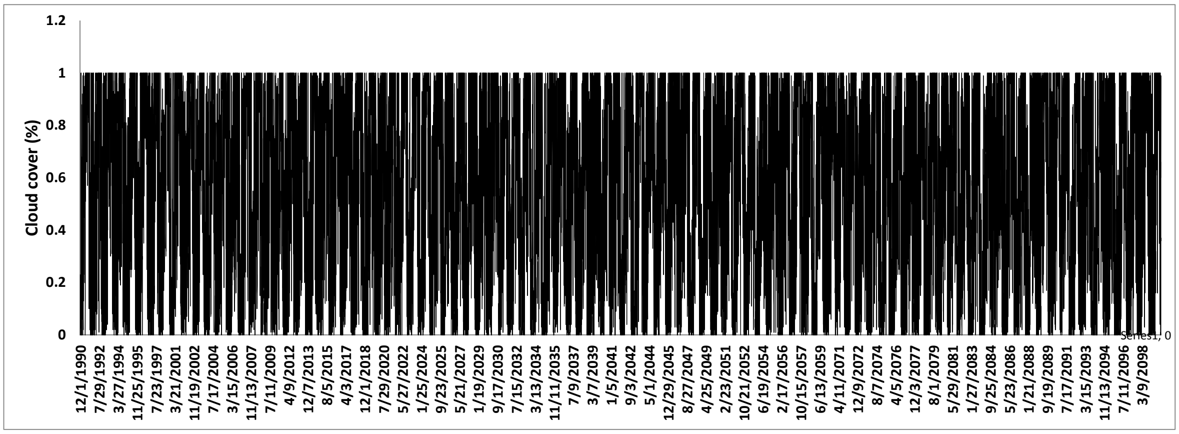
APPENDICES

Time series results from PRECIS for air temperature, precipitation, evaporation, air pressure, relative humidity, wind speed, net short wave radiation and cloud cover




Mean Sea Level Pressure (MPa)
Relative Humidity (%)
Wind Speed (m/s)
Net Shortwave Radiation (cal/cm²/min)


Cloud cover (%)
1.2
1
0.8
0.6
0.4
0.2
0