Climate Variability of Tropical Cyclone Impacts in the North Indian Ocean and Exploration of Risk Reduction Strategies for Bangladesh

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Statement of Originality

I certify that the work in this dissertation entitled "Climate Variability of Tropical Cyclone Impacts in the North Indian Ocean and Exploration of Risk Reduction Strategies for Bangladesh" has not previously been submitted for a degree and nor has it been submitted as part of a requirement for a degree to any other university or institution other than Macquarie University.

I also certify that the thesis is an original piece of research and it has been written by me, except as otherwise indicated. Any help and assistance that I have received in my research work and the preparation of the thesis have been appropriately acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

All study protocols have been approved by the Macquarie University Human Research Ethics Committee, with reference number 5201600982, where necessary.

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Abstract

Tropical cyclone (TC) is a well-known natural disaster that can devastate much of a society, environment, economy and result in people's deaths. The North Indian Ocean (NIO) is one ocean basin that is very prone to TC. TCs often cause huge human casualties in densely populated communities like Bangladesh, India and Myanmar around the Bay of Bengal (BoB) region of the NIO. Unlike those in the other oceans, the TC frequency over the NIO has a unique bimodal annual distribution, and reaches it peak during the pre-monsoon (April-June) and post-monsoon (October-December) seasons, respectively. Past studies focused on climatology of TC in terms of large-scale environmental parameters as well as interannual climate variability, for example El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) for the NIO. More studies have been conducted in the BoB than the Arabian Sea (AS).

This dissertation has adopted an interdisciplinary and integrated approach to examine TC impacts, which include climate variability analysis, future impact assessment and study on TC risk perception. The specific aims of the dissertation are to: (i) analyse the teleconnection patterns of different types of El Niño events on TC formation, development and landfall over NIO; (ii) identify the climate factors accounting for the asymmetric active or inactive TC seasons over AS and BoB; (iii) estimate potential impacts of TCs from storm surges and inundation for the rim countries of NIO for past and future climates; and (iv) explore cyclone risk reduction strategies for coastal Bangladesh based on a field survey on risk perception.

For aim (i), a new type of ENSO the central Pacific (CP) El Niño, or known as El Niño Modoki, has been identified recently and its impact on TCs in the NIO is still not well known. Under this CP-type ENSO, the oceanic warming pattern is very different from that in the canonical (EP)-type ENSO. This study reveals that although there is no significant change in TC number and tracks during the major CP and EP years, there is a general reduction in the number of TCs during the post-monsoon season in the CP years. Genesis Potential Index (GPI)

analysis shows that the mid-level humidity and vertical wind shear contribute to the suppression of TC formation during CP years. These changes in humidity and vertical wind shear are due to the large-scale circulation pattern originating from the Pacific in response to the CP event.

TC activity in AS have become more active in recent years. During 1983-2015, AS was very active in a few years (but with quiet BoB season) and the opposite occurred in some other years. Aim (ii) seeks to identify the climate factors for this asymmetry. Results reveal that no single climate mode (such as ENSO and IOD) can well explain the TC development concentrating on the AS or the BoB only. Instead, it is found that variability of the northeast (post) monsoon is an important factor responsible for the difference between the two basins. Excess moisture is available over the AS due to anomalous low-level flow from the equatorial Indian Ocean in the years when there are more TCs in that basin, and the BoB is subjected to dryer conditions.

There may be climate change signal when TC activity increases over the AS. For aim (iii) of this study, storm surges and inundation at the coastal areas due to TC landfall for the past (1990-2010) and future (2075-2099) climate are analysed via a storm surge model and Resilience-Increasing Strategies for Coasts Toolkit (RISC-KIT). While almost all intense TCs had historically made landfall around the BoB region, climate model projection simulated more intense TCs over the AS. The storm surge model and RISC-KIT estimate an average of 3-5-meter inland flooding depending on TC intensity and topography, and more high-impact cases will be shifting to the AS. An impact assessment tool, InaSAFE, is also applied to estimate the social and economic impacts of TC for the Bangladesh region.

To accomplish aim (iv), an extensive survey that consisted of face-to-face questionnaire surveys and site observation was undertaken in the southern coastal areas of Bangladesh to measure perceived and actual risk for TC impact. Results indicate the average level of perceived risk is high both at the household and expert level. Female participants perceive

slightly higher risk than males in coastal Bangladesh. Moreover, income, occupation, farm size and educational attainment/qualification influence risk perception to some extent. This survey advocates some cyclone risk reduction (CRR) measures, as follows: build more cyclone shelters; build cyclone resilient private houses; build or improve embankments and polders; build or improve roads; preserve dry food; supply adequate food and pure drinking water; and improve the quality of early warning messages or alarms. This study concludes that risk perception assessment is a prerequisite for implementing any risk reduction plan or strategy, and it is critical to integrate bottom-up and top-down approaches for CRR plans and actions.

Keywords: Tropical cyclone, North Indian Ocean, Central-Pacific El Niño, Genesis potential index, Storm surge, Inundation, Climate projection, Risk perception.

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Dedication

"To my child (Ibaad) who born on 15 October 2017 as his smile  inspired and energised me a lot"

Contents

List of Figures

List of Tables

Abbreviations and Acronyms:

ACE	Accumulated cyclone energy
ADCIRC	ADvanced CIRCulation Model
AGCM	Atmospheric general circulation model
AMJ	April-May-June
AMSU-A	Advanced Microwave Sounding Unit-A
ANN	Artificial neural network
AS	Arabian Sea
BIWTA	Bangladesh Inland Water Transport Authority
BMD	Bangladesh Meteorological Department
BNPB	National Board for Disaster Management
BoB	Bay of Bengal
COU	Cone of uncertainty
CP	Central Pacific
CRR	Cyclone risk reduction
DIMI	Dynamic Indian Monsoon Index
DMI	Dipole Mode Index
DRR	Disaster risk reduction
ENSO	El Niño–Southern Oscillation
EP	Eastern Pacific
FVCOM	Finite-volume coastal ocean model
GFDRR	Global Facility for Disaster Reduction and Recovery
GPI	Genesis potential index
HWRF	Hurricane Weather Research and Forecast

IITM	Indian Institute of Tropical Meteorology
IMD	Indian Meteorological Department
IOD	Indian Ocean Dipole
JMA	Japan Meteorological Agency
JTWC	Joint Typhoon Warning Center
MJO	Madden-Julian Oscillation
MLR	Multiple linear regression
MRI	Meteorological Research Institute
MSE	Moist static energy
MSLP	Mean sea level pressure
MSWS	Maximum sustained wind speed
MT	Monsoon trough
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Predication
NCMRWF	National Centre for Medium Range Weather and Forecasting
NIO	North Indian Ocean
NWP	Numerical weather prediction
OND	October-November-December
OSM	Open Street Map
PCR	Principal component regression
RBES	Regional background error statistics
RH	Relative humidity
RISC-KIT	Resilience-Increasing Strategies for Coasts-toolkit
RMW	Radius of maximum wind
RSMC	Regional Specialised Meteorological Centre

RST	Rough set theory
SPLASH	Special Programme to List Amplitudes of Surges from Hurricanes
SST	Sea surface temperature
TC	Tropical cyclone
TCHP	Tropical cyclone heat potential
TCO	Total column ozone
UKMO	UK Met Office
UOHC	Upper ocean heat content
VarEPS	Variable Ensemble Prediction System
VWS	Vertical wind shear
WNP	Western North Pacific
WRF	Weather Research and Forecast

Chapter 1: Introduction

1.1 Tropical Cyclone (TC) Genesis over the North Indian Ocean (NIO)

1.1.1 Climatology

The NIO is one of the most important breeding grounds for tropical cyclones (TCs) in the world (Riehl 1948; Shaji et al. 2014) where generally 5-6 TCs form annually. These account for 7-8% of the total TCs worldwide (Gray 1968). Although the TC frequency is not comparable with other ocean basins, extreme TC events have caused many casualties and damage. TC activity in the NIO has a unique bimodal annual distribution of frequency that peaks during the pre-monsoon (AMJ: April-May-June) and post-monsoon (OND: October-November-December) season, respectively (Fig. 1.1) (Akter and Tsuboki 2014; Camargo et al. 2009; Evan and Camargo 2011; Hoarau et al. 2012; Kikuchi and Wang 2010; Li et al. 2013; Xing and Huang 2013; Yanase et al. 2012; Zhi et al. 2013). Within the Bangladesh region about 70% of TCs occur in the pre-monsoon (May-June) and post-monsoon (October-November) season (Islam and Peterson 2008).

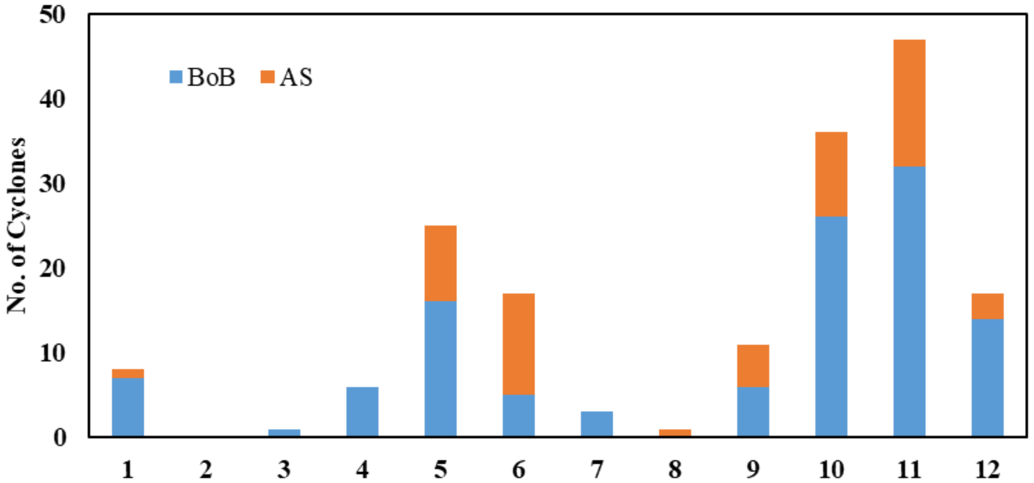


Fig. 1.1 Monthly distribution of accumulated TC number over the North Indian Ocean during 1983-2015. Blue and red colours represent the Arabian Sea and Bay of Bengal, respectively.

Previous analyses (Ali 1979; Qasim 1999; Rathore et al. 2016) have pointed out several peculiar characteristics of the warm tropical NIO ocean basin that has led to challenging tasks for TC forecasters. First, unlikely other basins the NIO is a smaller and not an open oceanic basin; it is surrounded by the South Asian land mass and thus has two branches, the BoB and AS. Secondly, compared to other basins, mean TC life span over the NIO is shorter (3-5 days) resulting in shorter lead time of TC forecasting. Last but not least, the topography, coastal geometry as well as bathymetry of the BoB are exceptional and generate more challenges. Moreover, the shallow and funnel-shaped BoB causes more TC formations and landfall along the coastal areas of Bangladesh. Therefore, it is very important to understand the characteristics of TCs over the NIO in terms of climatology and climate variability to improve forecasting quality so that damage and losses are greatly reduced or avoided.

1.1.2 Large-scale environmental parameters

The well-known large-scale TC formation parameters including both dynamics and thermodynamics variables are low-level relative vorticity, vertical wind shear (VWS), upper-level divergence, sea-surface temperature (SST) (>26 ^{o}C), mid-tropospheric relative humidity (RH), and stability measure such as the moist static energy (MSE) (Gray 1979). How the large-scale environmental parameters (Gray 1968) control such bimodal distribution of TC frequency in the NIO was the focus of several recent studies. Yanase et al. (2012) found high value in the Genesis Potential Index (GPI, to be defined in Chapter 2) during pre- and post-monsoon season but was limited by VWS in between. There is a strong relationship between the formation of intense TCs over the NIO and lower VWS (Hoarau et al. 2012). The analysis by Li et al. (2013) revealed that it was the increase in RH during boreal spring to summer that overcomes the negative effect emanating from VWS, and factors of VWS, relative vorticity and SST all contribute to the GPI minimum in boreal summer.

Evan and Camargo (2011) conducted a comprehensive study on TC climatology over the AS. Their study confirmed that the large-scale parameters provide a conducive environment for TC formation over the AS. It was also found that the timing of onset of the southwest monsoon and mean sea level pressure (MSLP) in the BoB does influence TC activities over the AS during May, June and November. In particular, it has been identified that there was usually high MSLP over the BoB when TCs formed in the AS during November, and thus storms usually do not form in both basins during that month (Evan and Camargo 2011). Detailed analysis will be presented in Chapter 4 to elucidate this issue. Moreover, mid-level moisture has been identified as playing an important role in controlling TC formation in the AS. Such variation of moisture during the withdrawal and onset of the summer monsoon is also essential to higher TC activity during late October and November versus early May over the BoB (so-called asymmetric distribution), because there is convergence of low-level moisture flux by westerlies during late summer monsoon in autumn. However, there is divergence of moisture flux by northerlies before the onset of the monsoon in late spring.

It was recognised that SST has stronger relationship with TC development during pre-monsoon season compared with post-monsoon (Sebastian and Behera 2015). This may be related to the reported absence of barrier layer and presence of high enthalpy flux in the pre-monsoon season over the BoB, and high amount of accumulated TC heat potential (TCHP) required for TC intensification (Vissa et al. 2013). Although other studies found high correlation between TCHP and Atlantic and Pacific hurricane intensities, there is no existence of such kind of strong relationship over NIO (Jangir et al. 2016). Therefore, this parameter alone cannot serve as TC predictor for the NIO region. Nevertheless, Suneeta and Sadhuram (2018) showed a significant contribution of upper ocean heat content (UOHC) to GPI for the BoB. Moreover, such large ocean heat content was also linked to intraseasonal oscillations associated with monsoon onset over the BoB in Li et al. (2013). Another study conducted by

Chaudhuri and Dutta (2014) revealed a strong relationship between the total column ozone (TCO) values and TC genesis, development and landfall over the NIO. This study found higher TCO values just before the formation of depression and the TCO values gradually decrease with the development and landfall of TC. Afterward the values return to their normal range immediately after TC landfall. Furthermore, accumulated cyclone energy (ACE) values increase as TCO values decrease. Similar results have been reported in the study by Midya et al. (2012) for the NIO region.

1.1.3 Monsoon Trough (MT)

There is a significant correlation between TC frequency during the post-monsoon season and summer monsoon rainfall for the BoB, which was reported by Sadhuram and Maneesha (2016). Their study found both a significantly positive and negative correlation for several sub-divisional rainfall data and their results are presented in Fig. 1.2. Summer monsoon modulates the TC-related environmental parameter (e.g., low-level relative vorticity, RH, etc.), which favours TC genesis during the post-monsoon season over the BoB. Furthermore, many studies elucidated the role of MT in controlling the two peaks in TC frequency, with a post-monsoon primary and a pre-monsoon secondary over the BoB (Akter 2015; Akter and Tsuboki 2014; Fosu and Wang 2014; McBride 1995; Xing and Huang 2013). McBride (1995) reported that TC genesis in the pre- and post-monsoon season over the BoB is primarily controlled by the location of MT and VWS. Recently, similar results were simulated employing the Weather Research and Forecast (WRF) model in the study by Akter (2015). Akter and Tsuboki (2014) explained the mechanisms of MT in terms of why more TCs form post-monsoon compared to pre-monsoon over the BoB. This study showed in addition to moist southwesterly wind, dry northwesterly winds enter the BoB during the pre-monsoon season which may suppress TC genesis (Fig. 1.3a). In contrast to pre-monsoon, moist converging winds enter into BoB during the post-monsoon season which may favour more TC genesis (Fig. 1.3b). This study concluded that both the location of MT and environmental convective inhibition govern higher TC frequency during post-monsoon and lower TC frequency during the pre-monsoon season.

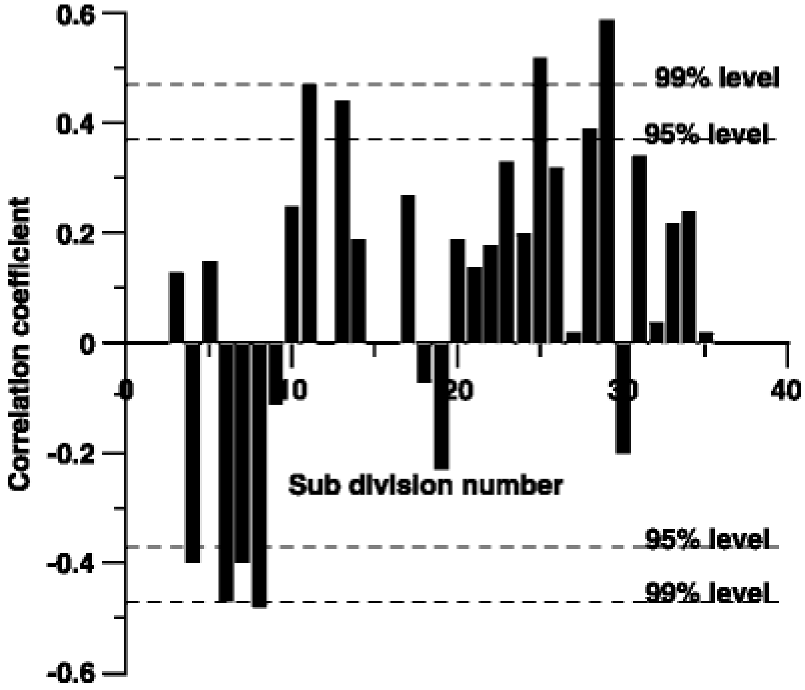


Fig. 1.2 Correlations between the total number of depressions, cyclones and severe cyclones (TNDC) over the Bay of Bengal during the post-monsoon (October–December) season, and the sub-divisional rainfall during summer monsoon (June–September) season for the period, 1984–2013. 95% and 99% significant levels are indicated as dotted lines. This figure has been adopted from Sadhuram and Maneesha (2016).

Xing and Huang (2013) analysed the contribution of MT to GPI and consistent results of MT activity with TC frequency over the BoB were discovered. The contrast between the pre- and post-monsoon can be explained by the change of wind direction that is linked to the onset and withdrawal of the summer monsoon. These two distinct seasons are characterised by opposite prevailing wind directions that contribute to TC genesis (Shankar et al. 2002).

Another study reported that no intense TC formed during the months of July-August-September, since by this time monsoon season reaches its peak and VWS values are higher during these months, which is not favourable for intensification of TC (Hoarau et al. 2012). This study also revealed that TC have tended to increase in intensity for the past three decades over the NIO. In general, how this trend is related to warming SST over the NIO and the roles of natural modes of climate variability in contributing to such trend has not been studied in depth.

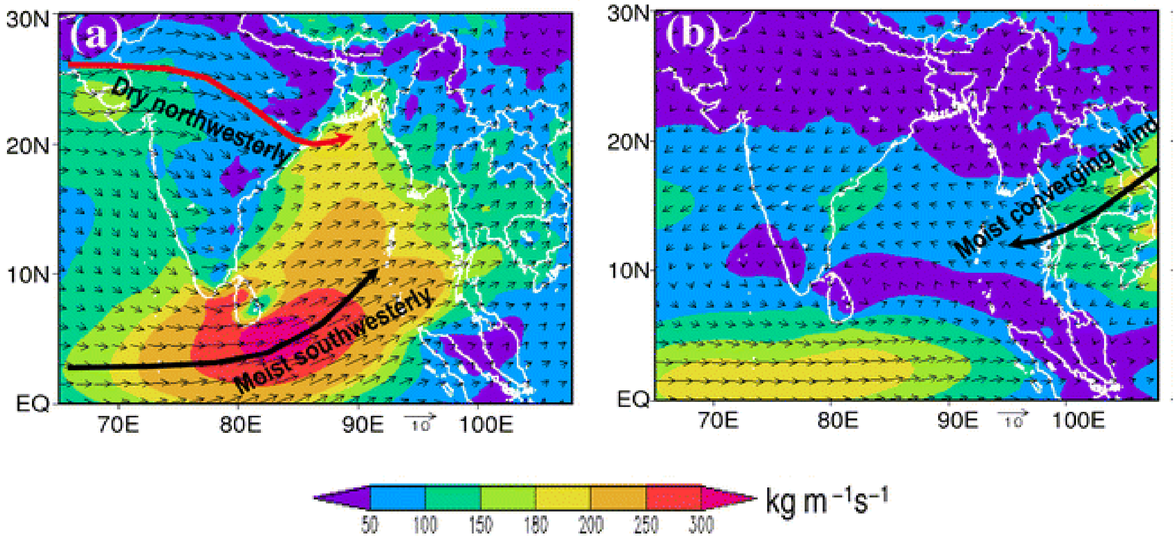


Fig. 1.3 Composite of vertically integrated 700-hPa moisture flux (colour shades; kg m^{-1} s^{-1}) and horizontal wind (vectors; m s^{-1}) at 850-hPa during (a) the pre-monsoon and (b) post-monsoon season during 1990–2009. Figures have been adopted from Akter and Tsuboki (2014).

1.2 Influences from ENSO, IOD and MJO

Interannual climate variability such as El Niño–Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) are known to greatly influence TC activity in the NIO. The ENSO plays a vital role in TC activity over NIO by altering atmospheric circulation and TC formation parameters remotely, which have been extensively discussed elsewhere in recent times (Felton et al. 2013; Girishkumar et al. 2014, 2015; Mahala et al. 2015; Mohapatra and Vijay Kumar 2017; Ng and Chan 2012; Sumesh and Ramesh Kumar 2013). Ng and Chan (2012) found that the TC-related large-scale parameters are less favourable to post-monsoon TC development in the BoB during El Niño, but almost the opposite occurs during La Niña. More specifically, Felton et al. (2013) found that the Niño-3.4 index is negatively (and significantly) correlated with the BoB TC activity with a lead time of 5 months. It was also found in Girishkumar and Ravichandran (2012) that during La Niña events the low-level relative vorticity and TCHP are larger over the BoB than during El Niño and thus more favourable for TC development. Hoarau et al. (2012) came to a similar conclusion regarding other environmental parameters. The average TC formation location is more to the east during La Niña and thus the TCs have longer westward tracks to intensify. Sumesh and Ramesh Kumar (2013) noted that ENSO is an important phenomenon like IOD and Madden-Julian Oscillation (MJO), and one that can trigger TC formation by splitting and modifying the Walker circulation over the NIO.

In recent decades, apart from canonical El Niño (or named eastern Pacific (EP) El Niño / traditional El Niño) (Harrison and Larkin 1998; Rasmusson and Carpenter 1982), researchers have identified a new type of El Niño, which was defined as central-Pacific (CP) El Niño (Hu et al. 2016; Kao and Yu 2009) or El Niño Modoki (Ashok et al. 2007; Weng et al. 2009) / dateline El Niño (Larkin and Harrison 2005) / warm-pool El Niño (Kug et al. 2009). The responses of EP- and CP-type El Niño in the large-scale atmospheric circulation and ocean dynamics relevant to TC activity may be different. It is obvious that the traditional measures such as Niño3.4 cannot properly monitor the CP events. Over a decade ago, Ashok et al. (2007) proposed a new type of index they called the El Niño Modoki index to represent the equatorial central Pacific SST warming. On the other hand, Ren and Jin (2011) proposed two unique measures: N_{CT} and N_{WP} - to explain the new type of El Niño flavours by simple linear transformation of the Niño3 and Niño4 indices. These will be discussed in more detail in the methodology section of Chapter 2.

The teleconnection of CP El Niño on TC formation, development, tracking and landfall over the NIO has not been explored intensively as it has been for the Pacific Ocean (Boucharel et al. 2016; Hong et al. 2011; Hsu et al. 2013; Kim et al. 2016; Wang et al. 2014; Xu and Huang 2015; Yang et al. 2017; Yang et al. 2016; Zhan et al. 2016; Zhang and Guan 2014; Zhang et al. 2015a) or the Atlantic Ocean (Chen et al. 2015; Kim et al. 2009; Larson et al. 2012; Lee et al. 2010). Boucharel et al. (2016) revealed contrasting oceanic and atmospheric responses of EP and CP El Niño for TC activity over the eastern Pacific Ocean. This study identified that the oceanic control via meridional redistribution of subsurface heat plays vital role in TC formation and intensification in the post-EP events compared to post-CP events, although there is no statistically significant difference between EP and CP events in terms of subsurface heat and atmospheric TC parameters. However, they concluded that the consequences of CP events bring favourable atmospheric circulation for TC formation, in particular lower VWS and higher RH. In contrast, Xu and Huang (2015) found both temporal and spatial differences of CP and EP El Niño regarding parameters that contribute to the GPI over the Pacific Ocean.

As a matter of fact, more CP El Niño events have occurred in the past three decades and the frequency of this type of El Niño is likely to increase based on climate projection (Kim and Yu 2012; Yeh et al. 2015; Yeh et al. 2009). Furthermore, Liu et al. (2017) argued that the increased CP El Niño events may be triggered by increased anthropogenic greenhouse gas concentrations. Climate model simulations also projected more extreme El Niño events in the future (Cai et al. 2014). The impact of CP El Niño events on TC activity in the NIO has not been well studied in the literature. Virtually the only study is by Sumesh and Ramesh Kumar (2013), which indicated a possible suppression of TC activity in the BoB by the CP El Niño events based on historical TC records. However, no explanation of the physical mechanisms was provided. Chapter 3 focuses on investigating the mechanisms of how this type of El Niño may modulate TC activity in the NIO.

Although a number of studies (Girishkumar and Ravichandran 2012; Saji and Yamagata 2003; Saji et al. 1999; Webster et al. 1999) claimed that Indian Ocean Dipole (IOD) is an independent event, other studies (Allan et al. 2001; Baquero-Bernal et al. 2002; Wang and Wang 2014; Yu and Lau 2005) believe that IOD is not an independent phenomenon but is in fact associated with other climate modes like ENSO, and this debate is still ongoing. Nevertheless, Ng and Chan (2012) identified a significant (insignificant) correlation between the Dipole Mode Index (DMI) and NIO TC number during post-monsoon (pre-monsoon). The significant correlation is largely attributed to TCs in the BoB, but correlation for AS TCs is weak. This finding is consistent with that reported by Yuan and Cao (2013), who examined the NIO atmospheric responses during positive and negative phases of IOD. Mainly the influences to BoB TCs were identified by Yuan and Cao (2013), as being increased TC occurrence frequency and more westward movement. Recently, Li et al. (2016) analysed the controlling factors for the interannual variability of post-monsoon TCs over the BoB. It was revealed the most important parameters are the interaction between the mid-tropospheric RH and the long-term mean states of absolute vorticity, VWS and potential intensity. Mahala et al. (2015) found the highest TCs frequency over the BoB during La Niña, negative IOD events and co-occurrence of La Niña and negative IOD for the period from 1891-2007. This study also concluded that TCs occurring during positive IOD years lasted longer compared to that in negative IOD years.

In addition, intraseasonal variability such as MJO (Madden and Julian 1972) plays an important role in TC genesis over the NIO, which has been reported in other studies (Girishkumar and Ravichandran 2012; Girishkumar et al. 2014; Oouchi et al. 2014; Tsuboi et al. 2016). It was reported that during the active convection phase of MJO, environmental conditions bring favourable conditions for TC genesis over the BoB (Girishkumar and

Ravichandran 2012). In another study, Girishkumar et al. (2014) found that the co-occurrence of active MJO and La Niña events resulted in higher frequency and more intense TCs over the BoB. The main underlying mechanisms are the increasing mid-tropospheric RH and decreasing VWS during their co-occurrence. The contribution of MJO to more TC genesis may surpass that offered by La Niña events (Tsuboi and Takemi 2014). It is interesting to note that Oouchi et al. (2014) projected diminishing future TC genesis potential for the NIO whereas they projected an increasing genesis potential for the central North Pacific region associated with MJO activity.

1.3 TC Modelling and Forecasting over the NIO

1.3.1 Seasonal, frequency and track forecast

Since TCs form and make landfall frequently over the NIO and result in widespread human deaths and property damage along the coastal areas of the rim countries of Bangladesh, India, Myanmar and Sri Lanka, attempts have been taken in recent decades to improve TC forecasting. First, seasonal TC forecasting was developed in many regions. For example, Nicholls (1979) developed a seasonal TC model for the Australian region, and recent developments include the Poisson regression model (McDonnell and Holbrook 2004a, 2004b) and the Bayesian model of Werner and Holbrook (2011). Gray (1984) developed a seasonal forecast model for the north Atlantic region and Chan et al. (1998) for WNP and the South China Sea (SCS). Since then, many attempts have been taken to forecast TCs for all other ocean basins including the NIO. Pattanaik and Mohapatra (2016) developed a principal component regression (PCR) model for TC genesis forecasting for the NIO during the primary (post-monsoon) TC season and reported significant correlation coefficients of 0.77 and 0.76, between predicted and observed TC frequency during 1971-2010 over the BoB and NIO, respectively. This model was developed on the basis of six parameters including SST over equatorial central and northwest Pacific, SLP, 850-hPa meridional wind, speed of upper-level easterly and monsoon westerly. This study concluded that PCR model performs very well especially for the above- and below-normal TC years during the model validation period of 2011-2014.

Chaudhuri et al. (2015) developed an artificial neural network (ANN) model by taking into account five input parameters: minimum central pressure (MCP), maximum wind speed (MWS), pressure drop (PD), SST, and vertical wind (VW) for predicting TC landfall location and a neuro-fuzzy coupled (NFC) model for forecasting storm surge height for NIO. They revealed that the ANN model can predict TC landfall location very well and the NFC model can also predict surge height well with 2.448% error with 6-h lead time. By using inputs of five large-scale TC formation parameters, namely, 500-hPa geopotential height, 500-hPa RH, SLP, 700-hPa and 200-hPa zonal wind, Nath et al. (2015) also developed a seasonal TC forecast model based on ANN. They showed that the ANN model can predict TC frequency very well, and the ANN model performs better than multiple linear regression (MLR) model, which demonstrates its substantial value for TC operations and forecasting systems.

Recently, Wahiduzzaman et al. (2017) developed a climatological model for the NIO for seasonal TC genesis, track and landfall forecast and revealed a very good hindcasting expertise. Mohapatra et al. (2017) depicted the newly developed TC track forecasting at the India Meteorological Department (IMD) known as the cone of uncertainty (COU) forecast. They reported that the new forecast system can predict TC track with up to 70-80% accuracy, which is comparable with those of other international TC forecast centres.

Remarkable progress has been achieved in terms of TC prediction by using high resolution dynamical models and meso-scale modelling systems like Advanced Research WRF (ARW) and Hurricane WRF (Mohanty et al. 2013; Osuri et al. 2012; Osuri et al. 2013; Osuri et al. 2017; Yukimoto et al. 2012). However, due to the peculiar and dynamic characteristics of the NIO, it is still a challenging task. An example is that although operational models such as the UK Met Office's (UKMO) Hadley Centre GloSea5 model shows very good predicting skill for most of the world's ocean basins, it does not show any seasonal prediction skill for the NIO (Camp et al. 2015). Thus, the statistical seasonal models developed for the NIO remain the major references for TC outlook on a monthly timescale. Fu and Hsu (2011) argued the importance of integrating MJO and northward-propagating intraseasonal variability (ISV) influences into the existing weather and climate forecasts models to enhance their prediction skills. Furthermore ISV is known to modulate TC activity in the NIO significantly (Kikuchi and Wang 2010; Yanase et al. 2012). Therefore, much more research has to be done to improve forecasting skills ranging from extensive to long-term TC prediction in the NIO. From an observational perspective, the Indian Space Research Organisation launched India's polar orbiting satellite Oceansat-2 on 23 September 2009 and by using this satellite a new technique of data mining was applied for TC detection over the NIO during 2009-2011 with an accurate detection rate (Jaiswal et al. 2013). Such technological advances may further improve TC structure monitoring in the basin, and in turn help us to understand better how changes in the large-scale environment control the long-term variability of TC activity in the region.

1.3.2 Storm surge and inundation forecast

Every year the low-lying coastal areas of Bangladesh are frequently inundated during the monsoon season by the upstream rivers, basically because of the existing geographical conditions. Most of the population resides in these low-lying coastal areas and most settlement areas are formed by riverine sedimentation. These areas will suddenly and excessively inundate due to TC landfall along the Bangladeshi coast of the BoB, which causes massive flooding and immense damage and losses in material goods and people's lives. Therefore, it is vitally important to analyse the impacts due to inundation by TC activity and what measures and support systems will be required to reduce the carnage.

It is known that several factors are responsible for coastal inundation that could make the coast more vulnerable (Gayathri et al. 2017). For example, sea-level rise (SLR), coastal erosion, changes of geomorphology and man-made disturbances will cause permanent flooding, while TC, tsunami and tide strikes will trigger short-term flooding. When a TC approaches the coast, it brings an enormous amount of water with it and subsequently increases the sea level. In addition, landfall of TC brings excessive rainfall together with windy to wild weather conditions. Numerical models play a vital role in predicting storm surges and their associated flooding outcomes. Storm surge modelling research began in the 1970s for the BoB basin since most TCs formed there. Das (1972) took the first attempt to develop a numerical storm surge model for the BoB region, especially the east coast of India and Bangladesh. In general, this model simulated surge height as being too high compared with observed values by the tide gauges. Since then, several initiatives have been taken by other modellers.

The study by Gayathri et al. (2017) argued that although remarkable achievements have been reported in terms of storm surge and inundation forecasting, it is still critical to investigate the coastal risk associated with TC landfall because SLR is expected to increase in the future. Furthermore, these authors argued it is necessary to collect field data regarding actual flood level, bathymetry and topography of coastal areas in order to predict inundation depth more accurately. This statement was support by Krien et al. (2017) , who identified some points in order to improve inundation modelling. The foremost point is improving topographic and bathymetric data especially at nearshore areas and embankment features. The authors also mentioned that governments are the key organisations that must take urgent actions on this issue.

Currently, there is no single model or tool that can forecast TC risk originating from a storm surge combined with potential impacts from inland flooding. Only a few studies have discussed the coupling of storm surge and river flooding. The issue is complicated by the fact that TC impacts are not only concentrated within inundated areas but can extend beyond those areas that vary with wind speed. The extent of water level over the flooded areas depends on mainly five factors: i) pressure; ii) direct wind; iii) earth's rotation; iv) waves; and v) rainfall effects (Harris 1963). Therefore, various approaches and models are necessary to achieve a realistic impact assessment.

Many researchers developed models for estimating and predicting coastal inundation globally including the NIO region (Chen et al. 2006; Dietrich 2011; Dube et al. 2000; Kennedy et al. 2012; Lewis et al. 2013; Madsen and Jakobsen 2004; Peng et al. 2004; Sheng et al. 2010; Yoon and Shim 2013). These studies attempted to couple a surge model (ADCIRC: ADvanced CIRCulation Model) with other models such as the coastal wave model (SWAN). However, most studies concentrated on the Atlantic and Pacific Oceans, while the NIO has received less attention (Bode and Hardy (1997). Past studies mainly focused on predicting peak surge height. For instance, the SPLASH (Special Programme to List Amplitudes of Surges from Hurricanes) model (Jelesnianski 1972), the FVCOM (Finite-volume coastal ocean) model (Chen et al. 2006), the SLOSH (NOAA) and ADCIRC (Luettich et al. 1992) were developed for storm surge forecasting. Recently, several attempts have been made to address coastal area inundation caused by TC and a few other studies developed tools and models for the assessment of coastal inundation and their associated impacts worldwide (Cheung et al. 2003; Graeme and Kathleen 1999; Lian et al. 2004).

Nicholls (2004) predicted that around 10 million people globally have experienced coastal flooding impacts due to TC landfall in 1990 and the number of people affected by flood events is expected to increase even without SLR. The study projected this number could be 50 million as population density is increasing globally by 2080. The impact of coastal inundation is very much location-specific, which is associated with many factors, for instance, coastal geometry, topography, characteristics of the TC, population density, agricultural and other commercial activities near the coast. Woodruff et al. (2013) reported that for the densely populated coastal areas, global impacts from flooding due to TC activity may even be larger than that from SLR. Jisan et al. (2018) applied the hydrodynamic model Delft3D in their study and reported that if TC activity over the Bangladeshi coast remains the same as what is currently happening, there will still be an increase in surge height and inundation areas due to SLR. Both vulnerability and model performance vary from one region to another. Thus, location-specific validation of the storm surge inundation model is very important. In line with this view, Dube et al. (2000) argued for location-specific storm surge inundation model development and they devised models for the Andhra and Orissa coasts of India. This study found a reasonable agreement between model simulated inland flooding and what was observed. Another separate comprehensive study has been recently conducted for the east coast of India by Sahoo and Bhaskaran (2018), which examined the possible coastal inundation impacts by using the ADCIRC model. In this study, the authors generated synthetic TC tracks and assessed their associated impacts in terms of inland inundation by taking into account the characteristics of storms and coastal geomorphology.

An integrated forecast system has been developed by Madsen and Jakobsen (2004) for Bangladeshi coast by using the MIKE 21 together with other models' components. This model served to analyse the storm surge height and inland flooding caused by Super Cyclone in April 1991. In addition, two more TC scenarios were analysed, and the authors found a reasonable agreement of model results with the observed surge height. The most important inundation model for the Bangladesh coastal areas is the LISFLOOD_FP (the flood forecast model) that was developed by Lewis et al. (2013). This model considered actual topographic data obtained from the Shuttle Radar Topography Mission (SRTM) and river run-off. The authors concluded that this model can be used for flood risk management since the model is not expensive to operate and data can be freely available. Incorporation and validation of developed inundation models into a single form is essential for effective inundation forecasting and for proper disaster risk reduction (DRR) actions and management. In view of this issue, the World Meteorological Organization (WMO) together with other partner organisations (the Joint

WMO-IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM) and the WMO Commission for Hydrology (CHy)) developed an integrated flood forecasting system known as the Coastal Inundation Forecasting Demonstration Project (CIFDP) (http://www.jcomm.info/index.). Under this project, four sub-projects are ongoing in four countries aiming to improve both institutional and technical aspects of inundation forecasting and warning in line with disaster risk management.

The pilot projects were launched in Bangladesh (CIFDP-B), Fiji (CIFDP-F), the Caribbean (CIFDP-C) and Indonesia (CIFDP-I), and there is also a plan to implement this project in China (Shanghai) (CIFDP-S) and South Africa (CIFDP-SA). For forecasting coastal flood risk, RISC-KIT (Resilience-Increasing Strategies for Coasts - toolKIT) (http://www.risckit.eu) was embraced in this project where flood forecasting system (Delft-FEWS) (https://www.deltares.nl/en/software/flood-forecasting-system-delft-fews-2/) was incorporated (explained in the methodology section in Chapter 2) Furthermore, a very useful tool, the InaSAFE, has recently been developed jointly by Indonesia (BNPB), Australia and the World Bank (GFDRR), which is freely available (http://inasafe.org/). Based on the flood plain estimate, this tool provides a realistic natural hazard impacts together with what logistic supports will be required for effective disaster preparedness and responses. The present study considers both storm surge inundation modelling and the application of InaSAFE.

1.4 Impact Risk Perception and Analysis

Risk assessment as well as risk perceptions play a vital role in disaster risk reduction (DRR) through formulating and implementing DRR policies and interventions (Mills et al. 2016; Peacock et al. 2005; Pidgeon 1998; Zhou et al. 2015). Similar to the importance of community participation in DRR activities, understanding people's risk perceptions have been well recognised for successfully formulating and implementing DRR management strategies in recent disaster risk management-related literature (Birkholz et al. 2014; Li 2008; Pidgeon

1998). Nevertheless, some studies reported there is wide gap between public risk perceptions and experts' risk assessments, which ultimately proves the success or failure of a DRR intervention or related policies (Garvin 2001; Li 2008; Peacock et al. 2005; Sjoberg 1999). Therefore, this study attempts to assess people's risk perceptions and explores the prescriptions to reduce risk, both from households' and experts' perspectives. In addition, actual risk is assessed based on households' experiences with the extreme cyclone phenomenon during the last decade.

Cyclones are one of the most important and continuing devastating natural disasters in Bangladesh and the world, creating much damage and destruction to a society, its economy and the environment. Rising global temperatures may trigger an expanding pattern of tropical cyclone winds with more serious consequences in the twenty-first century (Emanuel 2005). While Sugi et al. (2017) demonstrated that the worldwide recurrence of tropical cyclones will diminish, extremely intense tropical cyclones may actually increase in the world's future warmer climate. The coastal zone of Bangladesh consists of 19 districts that cover 47,150 km^2 areas where 38.52 million people live (BBS 2014). Moreover, Neumann et al. (2015) estimated the highest number of individuals living in the low-height coastal zone and people exposed to flooding from 1-in-100 year storm surge occasions is in Asia including Bangladesh for the past (2000) and future (2030 and 2060).

The coastal areas and off-shore islands of Bangladesh are low lying and very flat, and the height above mean sea level of the coastal zone is less than 3 metres. Bangladesh is a cyclone prone country due to its geographical location that makes even weak cyclones fatal, and 55% of aggregate coastal zone that populate inside the 100 km of drift territory of this country are generally vulnerable (Ali 1996; Khan et al. 2015; Mallick and Vogt 2014; Nazir Hossain 2015). Shaw et al. (2013) reported that tropical cyclones in the BoB during April to June and September to November produce the most emotional outcomes in Bangladesh. Furthermore, Paul (2012) revealed that shorelines and islands are more defenceless than inland areas regarding deaths, wounds, injuries, spreading of transferable sicknesses and property damage. As well, Haque and Jahan (2016) reported that coastal regions of Bangladesh, especially Barisal, Chittagong, and Khulna, are more vulnerable to cyclone disaster than other parts of the country.

Cyclones bring both direct and indirect serious consequences for people's lives and a nation's socio-economic fabric (Ahamed 2012). According to MoEF (2009), on average every three years a severe cyclone makes landfall along the coastal areas of Bangladesh. Bangladesh experiences some of the world's worst natural disasters including TCs. In recent decades, Bangladesh had extreme cyclones with traumatic human casualties and immeasurable economic losses, for example: 1970 (300,000.0 deaths), 1988 (5704.0 deaths), 1991 (138,868.0 deaths), 1997 (550 deaths), 2007 (3406.0 deaths), 2009 (191.0 deaths), 2013 (45.0 deaths) and 2016 (23.0 deaths) (GOB 2008). Although human deaths have been decreasing dramatically due to a better cyclone preparedness program and an early warning system, the damage and losses still remain enormous (Haque et al. 2012). Alam and Dominey-Howes (2015) elucidated the relationship between number of deaths and damage due to the three most destructive cyclones that hit Bangladesh in 1970, 1991 and 2007. They showed that the number of deaths diminished between events; however, economic damage and the number of people made homeless expanded. Similarly, Cyclone Mahasen made landfall in southern Bangladesh on 16 May in 2013, affecting nearly 1.5 million individuals and killing 23, and more than 26,500 houses were destroyed and almost 124,500 damaged. Moreover, substantial tracts of standing crops were flattened and various fish lakes and fish culture washed away (IFRC 2013). For these reasons it is urgent to reduce all kinds of damage and loss.

Several studies have been conducted on coastal Bangladesh and they assessed cyclone risk perceptions, vulnerability, impacts and adaptations (Ahsan 2017; Alam and Collins 2010; Hossain and Paul 2017; Kulatunga et al. 2014; Nazir Hossain 2015; Parvin et al. 2008; Paul and Routray 2011; Saha 2014). For instance, Ahsan (2017) analysed household perceptions and responses to cyclone in the Koyra Upazila area of southwestern coastal Bangladesh and revealed that most participants believed that cyclones constitute the number one natural hazard. A disaster preparedness training program makes coping mechanisms more acceptable and achievable. Residents have their own way of coping with any kind of disaster including cyclones (Paul and Routray 2011) and their vulnerability largely depends on socio-economic and physical factors (Nazir Hossain 2015). However, people have only a moderate ability to reduce the risk as well as curtail any damage and losses (Saha 2014). Studies found differences in terms of people's access to cyclone shelters, food and other services; socio-economic and political factors result in some people being more vulnerable than others (Kulatunga et al. 2014; Mahmud and Prowse 2012; Mallick 2014). Furthermore, the lack of adequate shelter capacity, maintenance funding, and community participation has exacerbated the vulnerability of Bangladesh's coastal people (Dhakal and Mahmood 2014). Up to now, almost no study has assessed the actual versus perceived cyclone risk at the household level in Bangladesh. Recently, Rana and Routray (2016) analysed actual versus perceived flood risk in three urban communities in Pakistan and found a positive correlation between actual and perceived risk, and significant spatial differences in terms of risk perception. This thesis is similarly motivated to quantify actual and perceived risk of cyclones at the household level from three study sites in coastal Bangladesh. Cyclone risk reduction (CRR) strategies are explored from both experts' and households' perspectives. The present study also examines experts' opinions about what community people think concerning future cyclone risk.

1.5 Problem statement

The NIO is one of the less researched ocean basins in the world despite having the highest human life toll due to TC landfall over the rim countries especially in Bangladesh and India. Due to the socio-economic contexts of the surrounding countries and peculiar characteristics of the NIO such as the salient features of the BoB, these regions are much vulnerable to TC disasters (Alam and Collins 2010). Nevertheless, due to TC preparedness and early warning systems, human deaths have been decreasing gradually worldwide. For improving TC forecasting models on the climate timescale, the factors that influence the trends of TC genesis, development and landfall should be analysed. Many studies have researched impacts from ENSO, IOD and MJO, however, variability of TC activity in the NIO especially where climate change is exerting its effects, is still not well understood. Recent studies reported the evolution of CP El Niño events and their associated impacts on TC genesis over the ocean basins worldwide, yet little is known about the impacts on TC genesis in the NIO regions.

On the other hand, it has been identified that TC activities in the two sub-basins of the NIO, namely the AS and BoB, have interesting variability. For example, in 2015 while the AS became very active with two intense TCs formed one after another, BoB remained almost inactive, a situation very unusual for the NIO. Such a situation never occurred for several years in the past when reliable TC best tracks were available. It is essential to understand this kind of contrast between the two sub-basins because totally different preparedness plans are necessary when the geographic distribution of storms has changed. Although the extremely active TC season in the AS or BoB may be rare events, future projection of TCs in the NIO under climate-change scenarios actually predicts that more TCs will be expected in the AS while less will occur in the BoB (Murakami et al. 2017). Therefore, understanding the asymmetry between the two sub-basins would help to diagnose to what extent natural variability in the past decades has contributed to the anomalous geographic TC pattern.

Although several studies on storm surge simulation have been carried out for the NIO, most of them were very much location-specific and focused on past events. Again, very few studies have been conducted that considered both storm surge modelling and their associated inundation impacts for the past and future especially for Bangladesh. Recently, several initiatives have been developed to protect coastal areas. Therefore, it is worth investigating both past and future storm surge climatology for the entire NIO and their associated potential impacts over the coastal areas. In this study, both storm surge modelling and inundation of the coastal areas are considered. Furthermore, the potential damage and losses due to landfall of TC are considered.

TC risk assessment and forecasting play a vital role in disaster preparedness, which ultimately reduces physical/material damage and human losses. It is revealed that accurate forecasting alone cannot reduce human casualties without improving people's perceptions of risk and how to combat it. Recently, Peter Otto (2018) showed that although a very consistent and accurate forecasting was issued well in advance of Typhoon Yolanda/Haiyan that hit the Philippines in 2013, it still caused over 6,300 casualties. Therefore, improvement of risk communication becomes a critical issue for DRR. Many previous studies reported that people's perceptions of disaster risk play a vital role in the implementation and execution of any DRR interventions. Also, the different risk perceptions that experts and household people have, and variations of risk perceptions deter successful implementation of DRR policies and innovative strategies. This is the first study to consider both experts' and households' risk perceptions and what they think building disaster resilient communities in the coastal areas of Bangladesh should entail. For this reason the results of a field survey become important.

1.6 Research Objectives and Structure of the Thesis

After critically reviewing a substantial number of existing studies on the topics covered in this project, the following general research objectives are formulated:

1) To analyse the teleconnection patterns of both CP- and EP-type El Niño events on TC genesis, development and landfall over the NIO especially during the post-monsoon season.
2) To identify the meteorological and climate factors that account for the exclusively active or inactive TC seasons over the AS and BoB.

3) To estimate potential impacts of TCs for the rim countries of the NIO for the past and future by simulating both the storm surge and inundation patterns in the region.
4) To explore cyclone risk reduction strategies for coastal Bangladesh both from households and experts perspectives.

This thesis is organised as follows. There are four core chapters and each chapter fulfils one general research objective excluding the literature review, methodology and concluding chapters. Research approaches and explanation of different data sources are depicted in Chapter 2. In Chapter 3, research objective 1 is addressed in which a detailed analysis about CP- and EP- El Niño in terms of TC activity over NIO is conducted to achieve the objective. Chapter 4 describes research objective 2 and in this chapter climatological, meteorological and environmental parameters are considered to differentiate the AS and BoB in terms of TC climatology. Chapter 5 is concerned with research objective 3 and incorporates a brief background on storm surge and inundation modelling including their potential impacts. Chapter 6 elucidates research objective 4 and experts' and households' perceptions, opinions and preferences for TC risk and risk reduction strategies for the coastal areas of Bangladesh. Finally, the significant contributions of this study to the subject are summarised in Chapter 7.

Chapter 2: Data and methodology

2.1 Data sources

2.1.1 TC best tracks

For TC formation location and time, the U.S. Navy Joint Typhoon Warning Center (JTWC) TC best tract dataset, which starts from the mid-1940s for the NIO and has been archived in the International Best Track Archive for Climate Stewardship (Knapp et al. 2010), is used. For most of this study, the climatological analysis period is 1983-2015 since TC best track data in the NIO is considered reliable only from 1983 (Ng and Chan 2012). However, in order to include as many large sample sizes of the CP-El Niño and EP El Niño years as possible, especially given that most of the major EP events occurred before the 1980s, Chapter 3 examines the period 1951-2016. Certainly, reliability of the TC best tracks before the satellite era, in the case of the NIO from the late 1990s, is questionable. In that chapter the GPI will be analysed to justify the application of the early TC data. In this study, TC formation is defined as the time when the intensity is equal to or over 25 kt (~12.9 m s^{-1}).

TC information for running the storm surge model was obtained from the best track data of the IMD because the IMD best tracks include the mean-sea-level pressure, which is necessary for inclusion in the storm surge model. Radius of maximum wind and that for 30-kt wind are not available for all storms. Recently, the JTWC reported this data for some TC cases over the NIO. When the radius of wind is not available from both operational centres, estimate of TC size is done based on TC reports and satellite images. This information is part of the TC track input to the storm surge model.

In Chapter 5, future projection of TC genesis and track in the NIO are considered. These projection data were provided by Murakami et al. (2017), in which the authors simulated both the past (1970-2010) and future (2075-2099) period. In an earlier study, Murakami et al. (2013) generated TC formation scenarios under the International Panel on Climate Change (IPCC) A1B scenario and fifteen ensembles were performed using the Japan Meteorological

Agency - Meteorological Research Institute (JMA-MRI) GCM. It was reported that the ensemble mean simulated reasonable TC frequency for the NIO basin in comparison to the observed TC frequency. Furthermore, this study projected a significant increase of TC frequency (46%) for AS, but a substantial decrease of TC frequency (31%) for the BoB basin. Murakami et al. (2017) came to a similar conclusion based on the US Geophysical Fluid Dynamics Laboratory model.

2.1.2 Reanalysis datasets

Data were obtained from various sources for analysing different parameters and indices aiming to fulfil the research objectives in this study. Monthly mean atmospheric data of air temperature, geopotential height, relative humidity (RH), specific humidity, zonal wind and meridional wind were obtained from the National Center for Environmental Prediction (NCEP)- National Center for Atmospheric Research (NCAR) global Reanalysis 1 datasets having 2.5° latitude/longitude spatial resolution (Kalnay et al. 1996). For analysing the climatology within shorter periods, such as that for comparing the AS and BoB in Chapter 4, monthly and daily data from the NCEP–DOE Reanalysis 2 (Kanamitsu et al. 2002) with the same 2.5° latitude/longitude resolution is also used.

Monthly SST and Outgoing Longwave Radiation (OLR) data are derived from the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed SST V4 (Huang et al. 2015) and NOAA Interpolated Outgoing Longwave Radiation (OLR) dataset (Liebmann and Smith 1996), respectively. The spatial resolution of monthly SST data is 2.0° latitude/longitude while that for OLR data is 2.5° latitude/longitude.

To analyse GPI, monthly mean data of relative RH, air temperature, zonal wind and meridional wind were obtained from 20th Century Reanalysis datasets of the Earth System Research Laboratory of NOAA (Compo et al. 2011). This is because the spatial resolution

(2.0° latitude/longitude) of this dataset is equal to that of the SST data, and no data interpolation is necessary.

2.1.3 Observations

To analyse the South Asia monsoon phenomenon, observed rainfall data were acquired from the Indian Institute of Tropical Meteorology (IITM) (https://tropmet.res.in/static_pages.php?page_id=53). These data comprise monthly rainfall from the 306 ground-based stations, which have been grouped into 35 subdivisions across India. The availability of these data was up to 2013 during this study. Missing data have been identified in some subdivisions, and only those subdivisions with complete time series during 1983-2013 are utilised.

2.1.4 Hazard data

For estimating TC impacts, hazard data in terms of coastal areas inundation level due to TC landfall were obtained by simulating the RISC-KIT tool coupling with JMA-MRI storm surge model. A brief description of the RISC-KIT tool and JMA-MRI storm surge model will be presented in section 2.5. Exposure data such as spatial distribution of people, buildings, roads and land uses were obtained from the Open Street Map (OSM) database. After acquiring hazard and exposure data, InaSAFE tool served to estimate potential impacts of a specific cyclone landfall for both present and future scenarios. A brief description of this emerging tool will be given in section 2.5 as well.

2.2 Environmental parameters and climate indices

2.2.1 Environmental parameters associated with TC development

Large-scale environmental parameters associated with TC formation such as MSLP, SST anomaly (SSTA), RH, vertical stability, low-level relative vorticity, 200-hPa divergence and VWS (Cheung 2004) are analysed. Vertical stability is measured by moist static energy (MSE), which is defined by

$$MSE = C_p T + gz + L_v r, \tag{2.1}$$

where T is the air temperature, z the height, r the water vapour mixing ratio, C_p the specific heat at constant pressure for air, g the gravitational acceleration and L_v the latent heat of vaporisation. Composite analysis of these environmental parameters for the months April-May-June (AMJ or pre-monsoon) and October-November-December (OND or post-monsoon) is performed to represent the two distinct peaks in TC frequency.

The annual activity of TCs is measured by the accumulated cyclone energy (ACE) that is the sum of the squared intensity for each TC. That is,

$$ACE = 10^{-4} \sum v_{max}^2 \tag{2.2}$$

where v_{max} is the intensity (i.e., one-minute sustained wind speed in the JTWC data). The ACE is calculated based on the six-hourly best track from JTWC and when intensity is equal to or over 25 knot (12.86 m s^{-1}).

The GPI is a well-known index that indicates how favourable the environmental conditions are for TC formation (Emanuel and Nolan 2004; Camargo et al. 2007), which is represented in the following equation:

$$GPI = |10^5 \eta|^{\frac{3}{2}} (\frac{H}{50})^3 (\frac{V_{pot}}{70})^3 (1 + 0.1 V_{shear})^{-2}, \tag{2.3}$$

where η is the 850-hPa absolute vorticity, *H* the 600-hPa relative humidity, V_{pot} the potential intensity and V_{shear} the magnitude of the VWS between 200 and 850 hPa. The potential intensity is the same as that defined in Emanuel and Nolan (2004), which is computed from the SST, outflow temperature, sea-surface and outflow saturation equivalent potential temperature. For examining how GPI differs between the CP and EP years, a technique similar to that employed by Li et al. (2013, 1016) is applied. In this technique, the total differential of the natural logarithm of equation (1) is taken. According to this, any change in the GPI (i.e., δGPI) can be expressed as a linear combination of the individual changes of the four factors contributing to index. Moreover, the relative change (δGPI/GPI) can be expressed as the sum of the relative changes from individual terms. In the following, the relative change of GPI in the composite CP years with respect to the EP years will be examined, and thus the base reference is the composite index in the EP years.

As will be seen, the relative humidity term in the GPI plays an important role in modulating TC formation potential in the NIO. Thus, diagnostic analysis is conducted on the processes responsible for modulating the moisture content in the basin. The following moisture budget equation (Howland and Sikdar 1983) is considered:

$$E - P = \frac{1}{g}\int_{Pt}^{Pb} q(\nabla . V)dp + \frac{1}{g}\int_{pt}^{pb} (V . \nabla q)dp, \tag{2.4}$$

where P is the precipitation, E the evaporation, g the gravitational acceleration, q the specific humidity, P_b and P_t represent the bottom and top pressure of the troposphere, respectively. The divergence term is computed from the zonal (U) and meridional (V) wind component. In the equation, the storage term (temporal change of q integrated from surface to upper troposphere) has been neglected because it is usually small in large-scale analysis (Vishnu et al. 2016). Then approximately the sum of the moisture divergence and advection terms is the net moisture change (i.e., $E – P$).

2.2.2 Climate indices

The impacts from climate variability such as ENSO and IOD to NIO TCs are considered in this study. Following the definition developed by the U.S. Climate Prediction Center, ENSO is measured by the Oceanic Niño Index (ONI), which is the 3-month running mean of ERSST.v4 SSTA in the Niño 3.4 region (5°N-5°S, 120°-170°W). It will be explained in the following that the focus is on the months OND for comparing TC activities over the AS and BoB. Therefore a threshold of 0.5°C in the OND average of ONI is used to identify El Niño and La Niña years, which are listed in Table 2.1.

Table 2.1: Identified years of PIOD, NIOD, El Niño and La Niña within the study period 1983-2015.

Climate Modes	Years
PIOD	1987, 1991, 1994, 1997, 2002, 2006, 2007, 2008, 2011, 2012 and 2015
NIOD	1992, 1996 and 1998
El Niño	1986, 1987, 1991, 1994, 1997, 2002, 2004, 2006, 2009, 2014 and 2015
La Niña	1983, 1984, 1988, 1995, 1998, 1999, 2000, 2005, 2007, 2008, 2010 and 2011

For IOD, the Dipole Mode Index (DMI) is used to represent the state of the SSTA pattern in the Indian Ocean. The DMI is defined as the SST difference between the western region (60°-80°E, 10°S-10°N) and the eastern region (90°-110°E, 10°S-Equator). Positive Indian Ocean Dipole (PIOD) years occur when the average DMI during September-November is larger than 0.27 and negative Indian Ocean Dipole (NIOD) years when this value is less than -0.27 (Table 2.1). Most of the selected IOD years agree with what has been documented in previous studies (Cherchi and Navarra 2013; Girishkumar and Ravichandran 2012; Ng and Chan 2012; Saji and Yamagata 2003).

2.3 Canonical and central-Pacific El Niño events

In this study two indices, N_{CT} and N_{WP}, are used to measure the strength of the EP and CP events, respectively, following Ren and Jin (2011) and Zhang et al. (2011, 2015b). These indices are defined as

$$\begin{cases} N_{CT} = N_3 - \alpha N_4 \\ N_{WP} = N_4 - \alpha N_3 \end{cases} \qquad \alpha = \begin{cases} 0.4, & N_3 N_4 > 0 \\ 0, & N_3 N_4 \leq 0 \end{cases}, \qquad (2.5)$$

where N_3 and N_4 represent the standard Niño3 and Niño4 indices, respectively. The monthly Niño3 (5°N-5°S, 150°W-120°W) and Niño4 (5°N-5°S, 160°E-150°W) indices are downloaded from the Earth System Research Laboratory of NOAA. α is a conversion factor whose value is 0.4 or 0 when $N_3N_4 > 0$ or $N_3N_4 \leq 0$, respectively. The indices N_3 and N_4 are computed by using monthly mean SST anomalies (with respect to 1951-2000 climatology) for the period 1951-2016. It will be shown that the impact of CP events to TC activity concentrates in the post-monsoon season, therefore the definition in Zhang et al. (2015b) is followed by examining the average of these indices during September-November (Fig. 3.1 in Chapter 3) to identify the warming events. This is chosen instead of examining the developing phase as many previous studies have done. The CP (EP) years are identified when the average value of N_{CT} (N_{WP}) exceeds 0.6 standard deviation. The years with close values of the N_{CT} and N_{WP} indices have been discarded and only the years with clear CP or EP development are analysed. After this procedure, 9 EP years are found: 1951, 1957, 1965, 1972, 1976, 1982, 1997 and 2015; and there are also 9 CP years: 1977, 1986, 1990, 1991, 1994, 2002, 2004, 2009, 2012 and 2014. It can be seen that only a very few major EP events occurred in the early 21st century, while the number of major CP events has increased and this will be discussed further in Chapter 3.

2.4 Climatology of the NIO

In the NIO, the BoB is more active than the AS in terms of TC activity. In total 172 TCs formed in the NIO during 1983-2015 and among these, only 56 formed in the AS while the remainder (116) formed in the BoB (Fig. 1.1). As has been discussed in Chapter 1, a bimodal distribution of TCs exists over the NIO in which November and May are the primary and secondary peaks, respectively. Among the 172 TCs which formed during 1983-2015, 47 and 25 TCs were in November and May, respectively. Notwithstanding this, June is more favourable for AS TC development climatologically, with 12 TCs over the AS but only 5 for the BoB in the study period.

From the pre-monsoon season, SST in both the AS and BoB is warm and with a large region over 30°C (Fig. 2.1a), which is well over that necessary for TC formation (~26°C; Gray 1968). These warm SSTs last throughout the summer monsoon and post-monsoon season (Fig. 2.1b). During November, the climatological SST in most of the NIO is up to 29°C. Low-to-mid-level RH in the NIO is also usually moderate, with an average value over 70% from the pre- to post-monsoon season. At the same time, MSE is quite zonally uniform in the NIO (not shown). Thus, these thermodynamic conditions are conducive for TC development but do not determine the asymmetric distribution (between the pre- and post-monsoon) much.

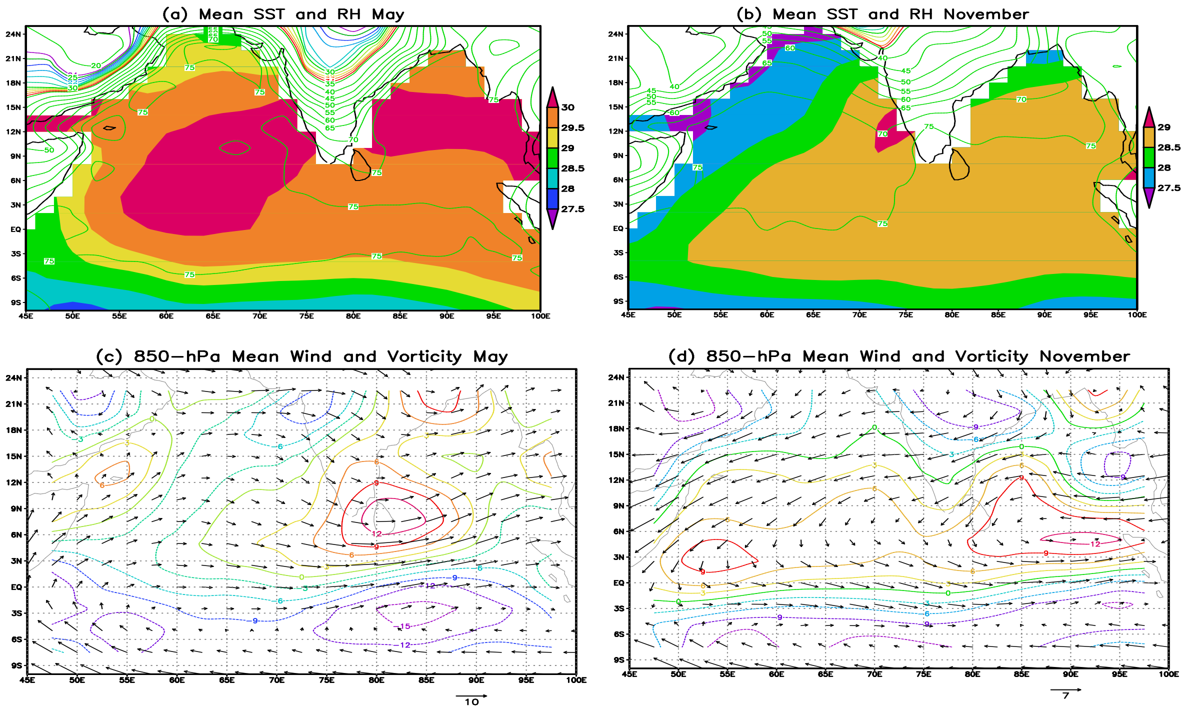
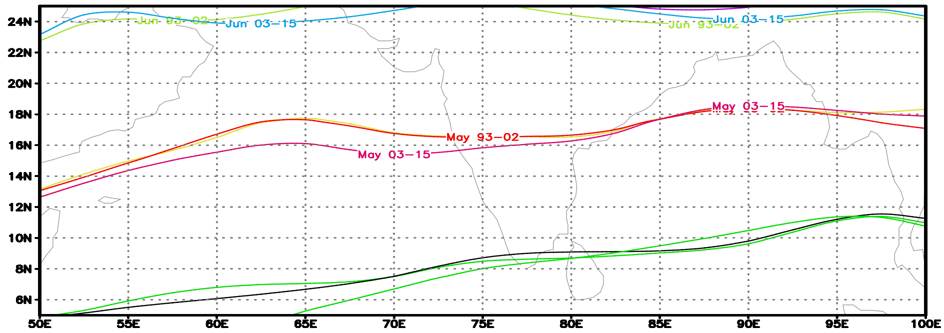


Fig. 2.1 Monthly mean SST (shaded; °C) and 500-700-hPa RH (contour; %) during (a) May and (b) November based on the period 1983-2015. Monthly mean 850-hPa wind (vector; m s^{-1}) and relative vorticity (contour; 10^{-6} s^{-1}) during (c) May and (d) November.

On the other hand, the dynamic conditions show a clear transition from the pre- to post-monsoon season. During May, prevailing low-level winds are westerlies to southwesterlies in the NIO and this is associated with the developing summer monsoon (Fig. 2.1c). There is a relative vorticity maximum in the southwest BoB that is favourable for TC development, however, given the location of the vorticity maximum there is a potential negative effect originating from land. Akter and Tsuboki (2014) suggested that the westerlies over India would bring dry air from the continent into the BoB that lowers the potential for convection development (Fig. 1.3 in Chapter 1), which seems true given the RH distribution in Fig. 2.1a. During November, northerlies and northeasterlies dominate the Indian region (Fig. 2.1d). Together with the equatorial westerlies the relative vorticity maximum over the BoB enhances the potential for TC development over there, which explains the climatological peak activity in that month.

Regions with low VWS also determine the spatial distribution of TCs over the NIO. As in Cheung (2004) that analysed TCs in the Western North Pacific (WNP), the zero 200-850-hPa zonal shear line is interpreted as the monsoon (trough) shear line. It emerged that as in the WNP, the low-shear region in the NIO also has clear seasonal meridional migration. The monsoon shear line usually starts with low latitude in April during the pre-monsoon period (Fig. 2.2a). It shifts northward in May such that the low VWS and larger planetary vorticity over both the AS and BoB make TC development possible. However, large interannual variability of this monsoon shear line position in May is found during 1983-2015, especially in the AS. In June when the summer monsoon develops, the low shear line mostly moves over land to the north and thus very few TCs form in that month. It is until late and post-monsoon season that the low shear line migrates southward where the other large-scale conditions favour TC development (Fig. 2.2b). In October, the monsoon shear line is climatologically between 15-20°N, while in November the climatological latitude is more to the south where large low-level relative vorticity is located, and thus the peak TC activity in that month. Nevertheless, the monsoon shear line is mostly a zonal feature, which does not lead to a clear east-west difference in TC activity between the AS and BoB.

(a)



(b)

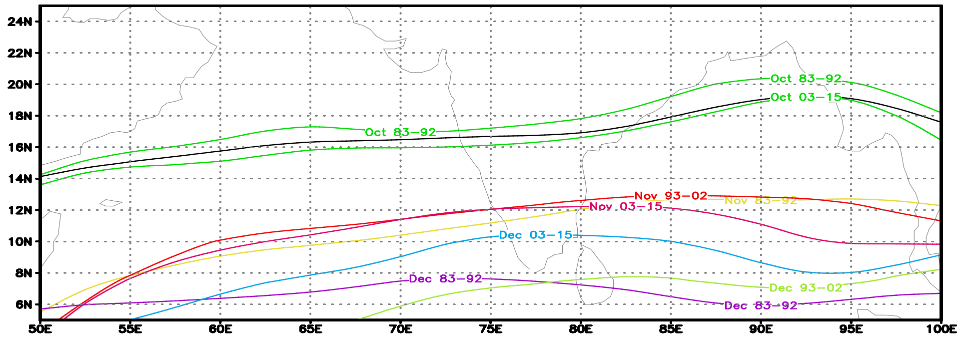


Fig. 2.2 Monthly mean zero contour of the 200-850-hPa VWS (monsoon trough or shear line), (a) for April-May-June, and (b) for October-November-December average in the following decades: 1983-1992, 1993-2002 and 2003-2015.

2.5 Tools and Models used

2.5.1 Non-parametric statistical test

In the following analyses of environmental parameters associated with periods of CP and EP events, statistical tests are performed to find the level of significance concerning the differences between the two types of events. However, it will be seen that the sample size of each type of event is only around ten, which is much lower than that required for standard parametric statistical tests such as Student's *t* test. Since Gaussian distribution cannot be assumed for the sample mean of the small sample, such parametric tests are not appropriate. Instead, non-parametric Wilcoxon-Mann-Whitney rank-sum test (Wilks 2006) is performed.

In this test, the entries in each sample are first sorted. The sum of the ranks in sample 1 (2) is R_1 (R_2) and sample size is n_1 (n_2). The null hypothesis is that if both samples are drawn from the same distribution, then *R1* and *R2* should not be very different from each other. A simple test statistic is the Mann-Whitney U-statistic:

$$U_1 = R_1 - \frac{n_1}{2}(n_1 + 1),$$

$$U_2 = R_2 - \frac{n_2}{2}(n_2 + 1). \quad (2.6)$$

for sample 1 and 2, respectively. It can be clearly seen that the product of U1 and U2 is equal to ($n_1 \cdot n_2$). The null distribution of the U-statistic follows approximately the Gaussian distribution, with the following mean and standard deviation:

$$\mu_U = \frac{n_1 n_2}{2},$$

$$\sigma_U = \left[\frac{n_1 n_2 (n_1 + n_2 + 1)}{12}\right]^{1/2}. \quad (2.7)$$

Thus, critical values (similar to the p values in Student's *t* test) of statistical significance can be identified.

2.5.2 The JMA-MRI storm surge model

The JMA-MRI storm surge model has been applied for generating inputs for the RISC-KIT estimate of inland inundation map against each TC landfall. This storm surge model is a two-dimensional ocean model and vertically integrated, which can be run by using either observed TC data or numerical weather prediction (NWP) model data. Two main equations governing the model are the momentum flux equation and water continuity equation, which have been illustrated in equation 2.8 and 2.9, respectively. The required model inputs are position of cyclone, intensity, central pressure, and radius of maximum wind.

$$\begin{cases} \frac{\partial Du}{\partial t} + \frac{\partial Du^2}{\partial x} + \frac{\partial Duv}{\partial y} = -\frac{1}{\rho_w g} D \frac{\delta(\varsigma - \varsigma_0)}{\delta x} - \frac{1}{\rho_w}(\tau_{ax} - \tau_{bx}) + fDv \\ \frac{\partial Dv}{\partial t} + \frac{\partial Duv}{\partial x} + \frac{\partial Dv^2}{\partial y} = -\frac{1}{\rho_w g} D \frac{\partial(\varsigma - \varsigma_0)}{\partial y} - \frac{1}{\rho_w}(\tau_{ay} - \tau_{by}) - fDu \end{cases} \quad (2.8)$$

$$\frac{\partial \varsigma}{\partial t} + \frac{\partial Du}{\partial x} + \frac{\partial Dv}{\partial y} = 0 \quad (2.9)$$

where,

(x, y) = horizontal direction

U = (u, v) current components

ς = height deviation

ς_0 = balance level with surface pressure

ρ_w = sea water density

f = Coriolis parameter

g = gravitational acceleration

D = the local water depth

$\tau_a = (\tau_{ax} - \tau_{ay})$ = the surface stress by winds and

$\tau_b = (\tau_{bx} - \tau_{by})$ = the bottom stress by winds

After successfully installing the JMA-MRI storm surge model with the Linux operating system, past and future TCs are simulated. The model requires seven inputs data which are (a) date: time (month, day, hour; mmddhh); (b) Pcenter: central pressure (hPa); (c) lon, lat: point of TC center (in degree); (d) Rref: radius of referenced pressure contour (in degree); (e) R0: radius of maximum wind (in km); (f) C_f: coefficients c1 (=0.70 in usual case); and (g) $P\infty$: environmental pressure (hPa). The Rref usually set as 1000hPa or it can set from R0.

Recently, this model has been upgraded and integrated into RISC-KIT for analysing coastal flooding due to storm surge for the Bangladeshi coast. Currently, BMD has adopted this model into the operational forecasting systems and reported reasonable results for the demonstration areas (Kohno et al. 2018). More importantly, RISC-KIT is used in this study and consequently, the JMA-MRI storm surge model is essential for this purpose. The performance of JMA model's is reported in several studies (Choudhury 2014; Kazuhisa et al. 2015; Mio and Tetsuo 2015). One of the salient features of the model is that it considers astronomical tide during surge simulation. Previously, adopting this model in RISC-KIT has been validated for Bangladesh as well.

2.5.3 RISC-KIT Tools

Since risk of coastal zones due to natural hazards is likely to increase in the future, it is urgent to evaluate the existing coastal DRR measures and adoption of any new preventive, mitigation and preparedness measures. To address these issues, the RISC-KIT project (www.RISCKIT.eu), a EU-funded project having 18 partners throughout Europe which was coordinated by Deltares, which is based in The Netherlands, has been developed. It consists of a set of open access methods, tools and management strategies which are referred to as the RISC-KIT tool (Van Dongeren et al. 2014; van Dongeren et al. 2018). In order to increase coastal resiliency against low frequency and high impacts of hydro-meteorological disasters by diminishing their risk, five tools are employed: i) The Storm Impact Database; ii) The Coastal Risk Assessment Framework (CRAF); iii) The Web-based Management Guide; iv) Quantitative, high-resolution Hotspot Tool; and v) Multi-Criteria Analysis Tool (MCA). They also function to manage coastal hazards effectively (van Dongeren et al. 2018). How these five tools will deliver their services in terms of disaster management cycle have been elucidated in Fig. 2.3. Several new studies (Barquet et al. 2018; Ciavola et al. 2018; Ferreira et al. 2018; Stelljes et al. 2018; Van Dongeren et al. 2014; van Dongeren et al. 2018) described this tool kit and applied for a few other cases. The project is undergoing improvements and the application of this tool kit is not only for EU countries but also other coastal countries. For example, this tool has been adopted in the CIFDP project as well. Kohno et al. (2018) reported in their study that five CIFDP sub-projects have already been successfully implemented and completed in Bangladesh, Dominican Republic, Fiji, Indonesia and Shanghai/China in 2017. The good performance of this forecasting system was confirmed and indicated and as a result BMD has been started to use this system in their operational forecasting system. In this thesis, the RISC-KIT tools were applied to generate both past and future inundation maps due to TC landfalls.

To run this RISC-KIT tools, outputs from JMA-MRI storm surge model are used as inputs in this study. The inputs data for this tool are (a) z: storm surges (m); (b) uc: currents x (m/s); (c) vc: currents y (m/s); (d) psea: surface pressure (hPa); (e) u: wind speed (m/s); (f) v: wind speed (m/s); and (g) z0: inverse barometer effect (cm) which are generated from the storm surge model.

Fig. 2.3 Positioning the RISC-KIT tools within the disaster management cycle. This figure has been adopted from the study by van Dongeren et al. (2018).

2.5.3 InaSAFE

InaSAFE is an innovative tool which meets the needs of disaster managers for better preparedness and response to a disaster by producing user defined maps, reports and action lists by combining hazard data (e.g., flood, earthquake, volcano or tsunami) with exposure information (e.g., buildings, population, crops, etc.). It is important to note that InaSAFE is not a hazard modelling tool; rather it is a free tool that can use information from modellers, the scientific community, governments, other stakeholders, the general public, etc. It is able to generate realistic hazard impact scenarios for better contingency plans aiming to save lives. The schematic diagram of this tool is depicted in Fig. 2.4. It was firstly developed in 2012 for Indonesia through a partnership between the Indonesian National Board for Disaster Management (BNPB), Australian Government and World Bank Global Facility for Disaster Reduction and Recovery (GFDRR). Indonesia is particularly prone to natural disasters like floods, tsunamis, earthquakes, etc. This tool is not only available for Indonesia but also other nations. Moreover, the developer teams made an attempt to develop and apply a real-time InaSAFE project for providing situational awareness for disaster response and recovery. This tool has several inbuilt tools and/or programs that are easy to use and these tools are: open street map (OSM) downloader for downloading data directly from OSM (www.LearnOSM.org) where spatial data is not available; keyword wizard for setting keywords of data for analysis; ability to define the area of analysis; impact function wizard for selecting appropriate impact function; and users can choose their own requirements and run the tool according to their needs. This software has another tool which can estimate the requirements of a shelter in terms of amount of food, water, toilets, etc. Furthermore, QGIS plugin (https://qgis.org/en/site/) is an inbuilt function of this tool. For more information, refer to the following website http://docs.inasafe.org/en/training.

Recently, InaSAFE has been used in several studies for analysing different aspects of DRR by implementing better preparedness and response strategies (Cadiz 2018; McCallum et al. 2016; Mollah et al. 2017; Pranantyo et al. 2014; Vecere et al. 2017). In this dissertation, this software has been applied to estimate potential impacts of flooding due to storm surge or TC landfall. This software's impact function program can compute an impact analysis by using inputs; both a spatial component (e.g., GIS layer) and a non-spatial component (e.g., action list) for a specific hazard. For instance, if anyone wants to estimate the impacts of floods on buildings and the necessary actions required to respond, then spatial data for the flood level and building locations will be calculated. Then the users can define more precisely what they require.

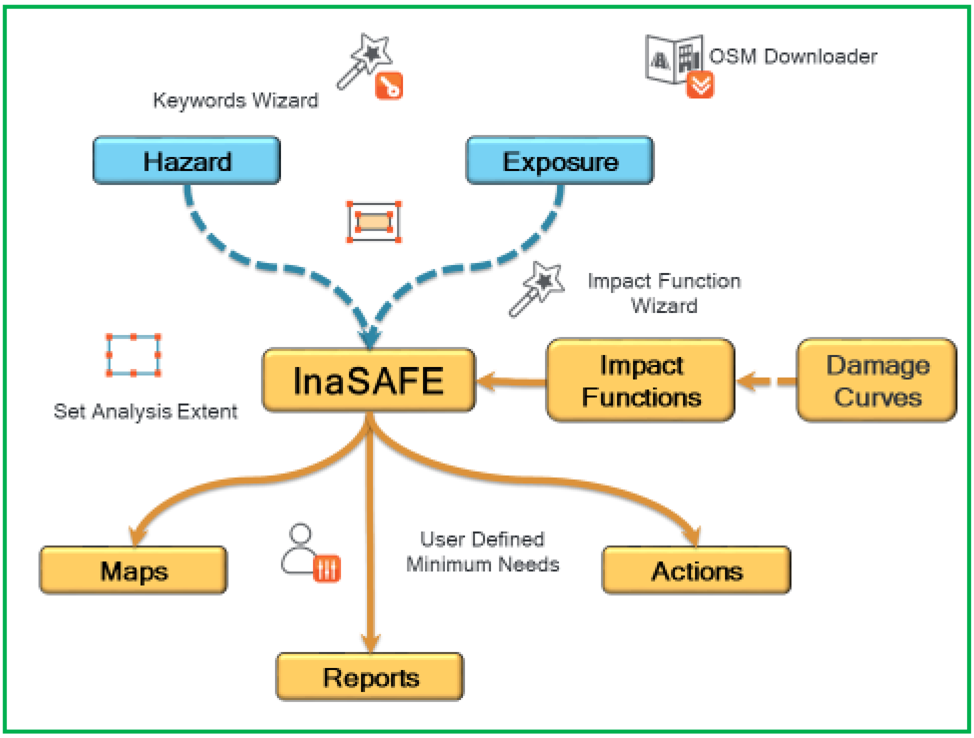


Fig. 2.4 Schematic presentation of the InaSAFE tool concept (source: http://inasafe.org/)

To run the InaSAFE tool, hazard data are obtained from the output of RISC-KIT tool and exposure data (population, buildings, roads and landuse) are downloaded from OSM website (www.LearnOSM.org).

Chapter 3: Impacts of CP- and EP- El Niño on TC activity over the NIO

3.1 Introduction

The remotely teleconnection of newly evolving CP El Niño events on TC formation, development, movement and landfall over NIO is investigated extensively in this chapter. Research objective 1: "*to analyse the teleconnection patterns of both CP- and EP-type El Niño events on TC genesis, development and landfall over NIO especially during the post-monsoon season*" is done in this chapter. This is done by analysing TC formation parameters including regional genesis potential indices and large-scale responses to ENSO events which are discussed in the following sections. Climatology in terms of TC frequency during the identified 9 CP and 9 EP years (Table 3.1) are discussed in the following section in detail. Furthermore, the impacts of IOD on CP and EP events are also explored in this chapter.

3.2 TC activities in the El Niño years

The indices of N_{CT} and N_{WP}, defined in section 2.3, are used to measure the strength of the EP and CP events, respectively. It will be shown that the impact of CP events on TC activity concentrates in the post-monsoon season, therefore the definition in Zhang et al. (2015b) is followed by examining the average of these indices within the September-November period (Fig. 3.1). This refers specifically to identifying the warming events, instead of examining the developing phase as many previous studies have already done. The CP (EP) years are identified when the average value of N_{CT} (N_{WP}) exceeds 0.5 standard deviation. The years with close values of the N_{CT} and N_{WP} indices have been discarded and only the years with clear CP or EP development are analysed. After this procedure, 9 EP years are found: 1951, 1957, 1965, 1972, 1976, 1982, 1997 and 2015; and there are also 9 CP years: 1977, 1986, 1990, 1991, 1994, 2002, 2004, 2009, 2012 and 2014. It can be seen there were very few major EP events in the 21st century, while the number of major CP events has increased.

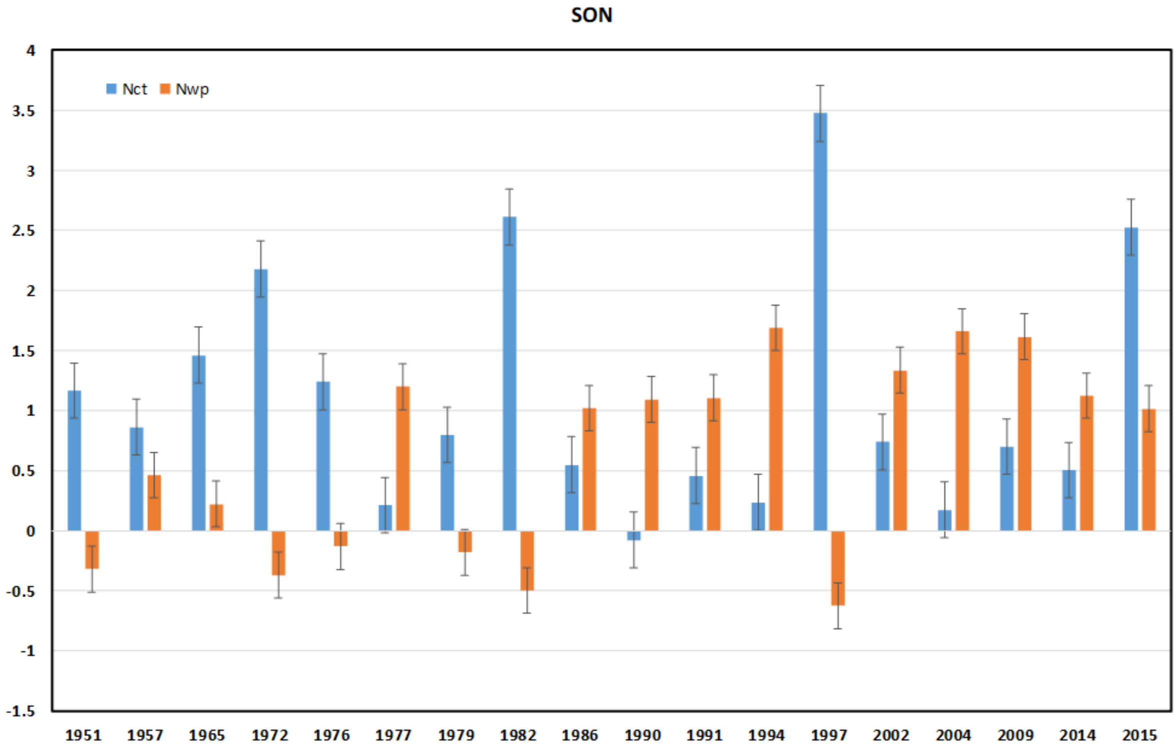


Fig. 3.1 Normalised N_{CT} and N_{WP} indices during the post-monsoon season (SON) for the selected CP and EP years in this study. Error bars represent 0.5 standard deviation estimates for the indices.

As mentioned in the methodology section (Chapter 2, Section 2.1.1), TC best tracks data are less reliable before the satellite era (Evan and Camargo 2011; Kossin et al. 2013; Landsea et al. 2006; Vecchi and Knutson 2011; Webster et al. 2005; Weinkle et al. 2012). The JTWC best tracks show heightened TC activity in the NIO during the 1950s and 1960s (not shown). Mohapatra et al. (2012) reviewed and analysed the quality and reliability of best track data for TC over the NIO for the period pre-1877-2010 and they concluded that the climatology of TC in terms of genesis, location, intensity, track and landfall are well represented since 1961. The GPI value can be considered a proxy of TC frequency for the

NIO. Camargo et al. (2007) found consistency between the climatological TC number and GPI during 1970-2005. In addition, Emanuel (2013) downscaled TC frequency during 1950–2005 by using six Coupled Model Intercomparison Project 5 (CMIP5) global climate models and discovered good agreement between the global TC frequency including the NIO and GPI. Moreover, Vishnu et al. (2016) identified epochal difference in the frequency of tropical depression over the NIO for the periods 1981-2010 and 1951-1980. When they examined the GPI distributions in these two epochs, higher GPI value was found in the early epoch which is consistent with the higher TC frequency during the 1950s and 1960s revealed by the best tracks. When GPI is computed using the NCEP reanalysis in this study, a similar conclusion is reached. Therefore, it should be reasonably acceptable to apply the TC best tracks during the pre-satellite decades, for depicting the impacts of early El Niño events.

Table 3.1: Tropical cyclone (TC) number during EP and CP El Niño years over the NIO.

Month	**EP (9 years)**		**CP (9 years)**	
	Total	Annual Frequency	Total	Annual Frequency
April	4	0.44	4	0.44
May	6	0.67	8	0.89
June	7	0.78	3	0.33
AMJ	**17**	**1.89**	**15**	**1.67**
October	13	1.44	6	0.67
November	14	1.56	11	1.22
December	9	1.0	3	0.33
OND	**36**	**4.0**	**20**	**2.22**

The impact from CP events on TC activity in the NIO has not been studied in detail in the literature. Sumesh and Kumar (2013) briefly examined this issue by analysing the TC records from the 1980s. They concluded that during El Niño Modoki there is a tendency of less cyclones especially in the BoB (but may be more over the AS). This is especially true when positive IOD events co-occurred. According to the JTWC best tracks, total number of TC over the NIO does not change much during the CP and EP years. The total numbers are 17 and 36, respectively, during pre-monsoon and post-monsoon in the 9 EP years, while they are 15 and 20 in the 9 CP years (Table 3.1). These results also reveal higher TC frequency in the EP years compared to the CP years for both AMJ and OND. In particular, TC frequency in the CP years has fallen more than double in June compared with the EP years (0.33 versus 0.78). In the CP years, monthly TC frequencies have all been reduced from October to December. The OND frequency in the CP years is thus only about half of that in the EP years (2.22 versus 4.0). Therefore, it can be concluded that CP events have supressed the overall TC activity in the NIO. How much this effect is due to co-occurrence of IOD events will be examined near the end of this chapter.

When the TC tracks are examined, it can be seen that overall there is no remarkable difference in terms of formation location and track type between the CP and EP years. In AMJ, almost all TCs move westward in the AS and northeastward in the BoB (Fig. 3.2). In OND, the tracks in the BoB are still mostly northwestward in all years. Consistent with the statistics presented above, there was no TC in June over the BoB when CP events occurred. The suppression of TC activity by CP events can be seen mostly in the BoB during OND. There were significantly less TC formations in the central BoB and the frequency of landfall in eastern India was much reduced in the CP years. Thus, in the following the TC-related parameters and large-scale processes are analysed for diagnosing such impacts.

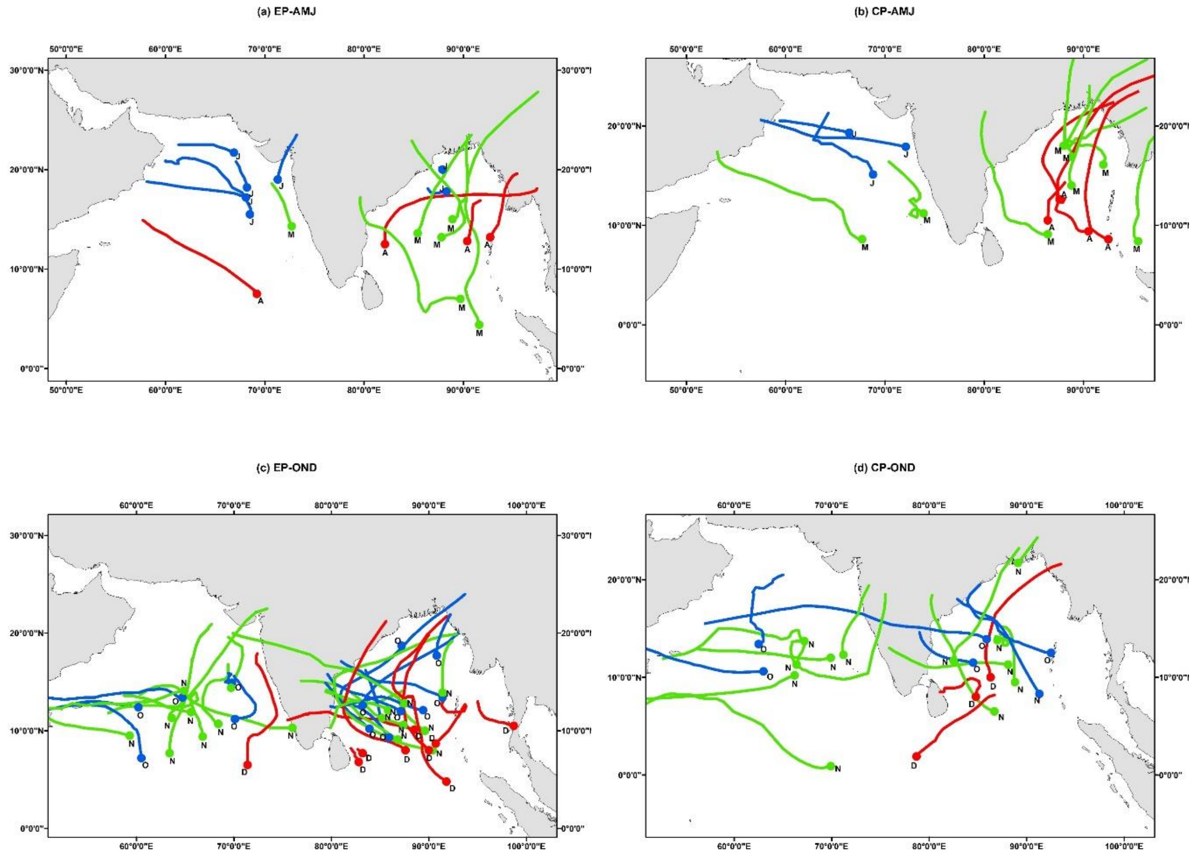


Fig. 3.2 Best tracks of TCs during pre-monsoon (AMJ in red, green, blue respectively) in the (a) EP and (b) CP years. The corresponding tracks during post-monsoon (OND in red, green, and blue, respectively) are in (c) and (d).

3.3 Regional genesis potential index analysis

The large-scale environmental parameters are first examined. The composite difference of the mid-level RH between the CP and EP years (CP relative to EP, similarly hereafter) shows a dryer environment during OND almost throughout the NIO. In December, humidity has significantly fallen over the north BoB and south AS (Fig. 3.3a). In the same month, low-level relative vorticity is significantly lower over the south BoB where many TCs form during the CP years (Fig. 3.3b). On the other hand, VWS has been significantly increased over the southeast BoB, which is linked to the enhanced low-level easterlies in that part of the ocean (Figs. 3.3c, d). Thus, overall the major thermodynamic and dynamic factors are less favourable for TC development during the post-monsoon period of CP events. This is consistent with the decline in TC frequency in December as shown in the best tracks.

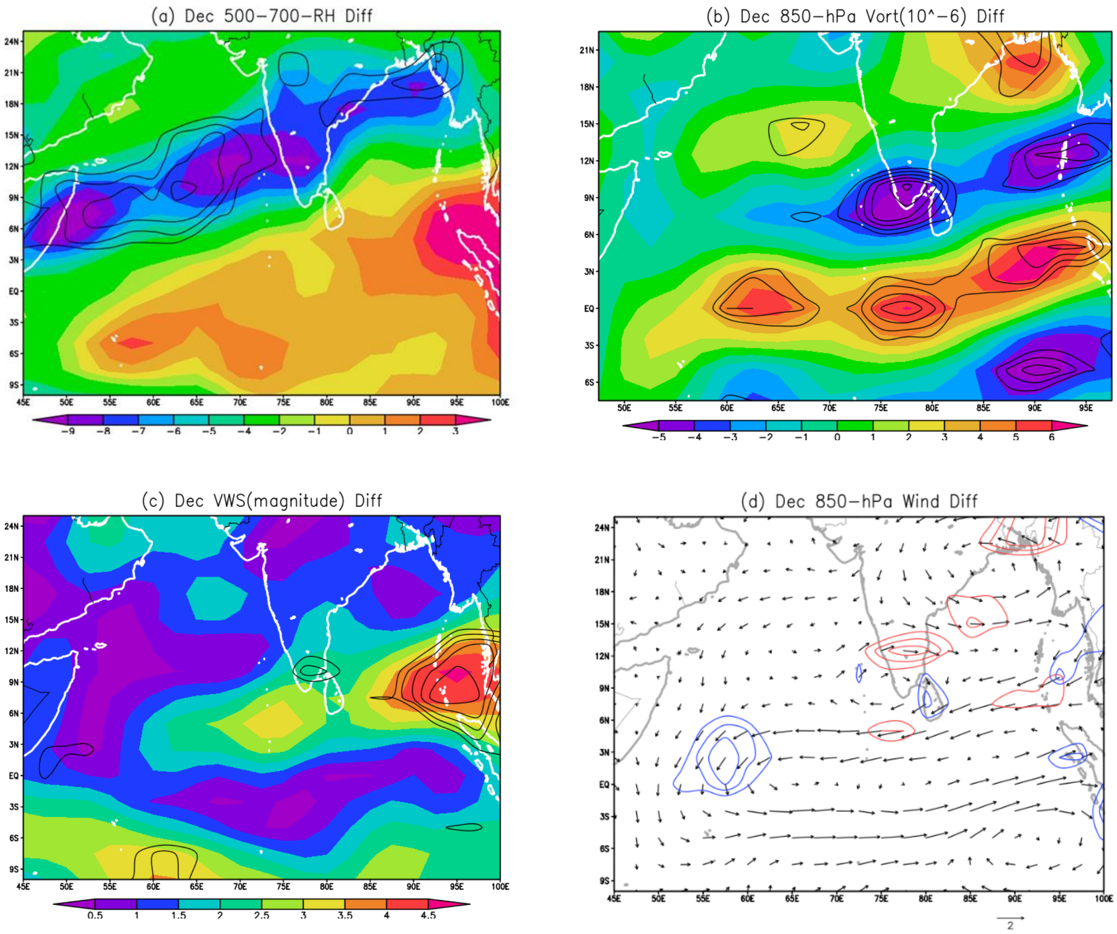


Fig. 3.3 Composite difference between the CP and EP years for (a) 500-700-hPa RH, (b) 850-hPa relative vorticity, (c) 200-850-hPa VWS magnitude and (d) 850-hPa winds. Black contours indicate the regions that pass the Wilcoxon-Mann-Whitney rank-sum significance test at 95% confidence level. For (d), red (blue) contours indicate significant difference for the zonal (meridional) winds.

The composite differences between CP and EP of the GPI and individual terms contributing to GPI have also been examined. The total GPI has been reduced by CP events throughout the BoB and AS during OND, and this is particularly true during December (Fig. 3.4). In the centres of the BoB and AS, the reduction in GPI value is up to half the value during the EP years. From the description of the large-scale environmental parameters in the last paragraph, the mid-level RH term in GPI makes a large contribution to the reduction in value, similarly for the VWS term for the BoB's southeast (Fig. 3.5). Comparatively, the contribution from the low-level relative vorticity term is less, and the change in MPI during the two types of El Niño is not very large over the NIO.

It can then be seen that changes in mid-level moisture during the CP years is an important factor for modulating TC activity. To analyse this change in more detail, the moisture budget (equation 2.4 in Chapter 2) and difference between CP and EP years are considered. It is found that the moisture advection term at mid-level (e.g., at 600 hPa that is applied in GPI) changes more during CP compared the moisture divergence term (Fig. 3.6). The pattern of change in moisture advection is similar to that in the total change in mid-level RH. Therefore, the regional change in low- to mid-level circulation is likely to be a major factor that has modified the moisture content in the NIO, and the circulation change contributes to the moisture advection more.

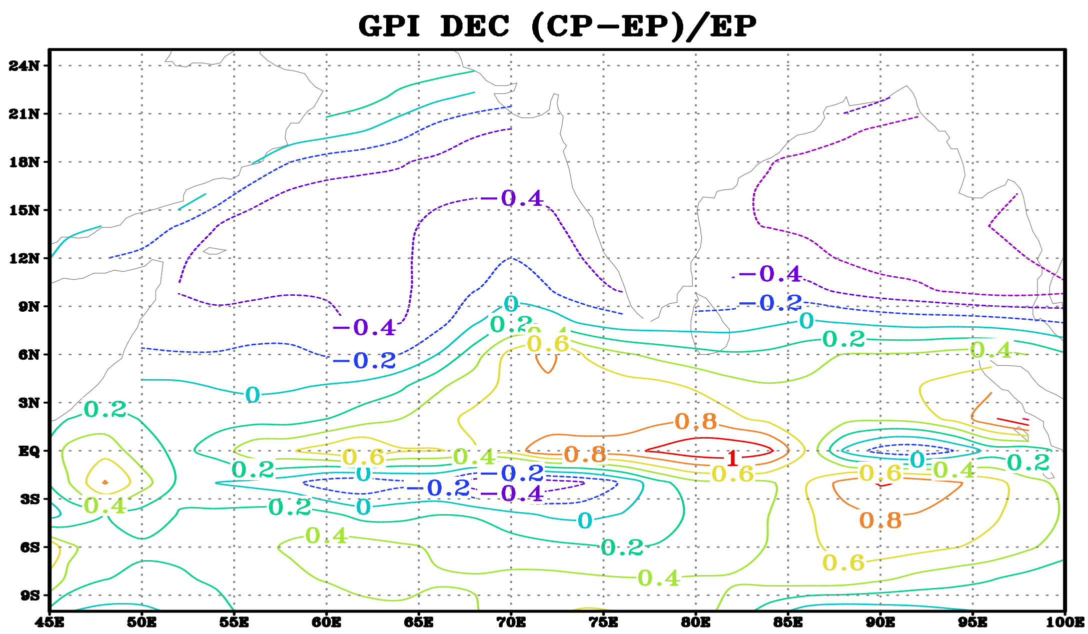


Fig. 3.4 Relative difference in the total GPI during CP years compared with that in the EP years.

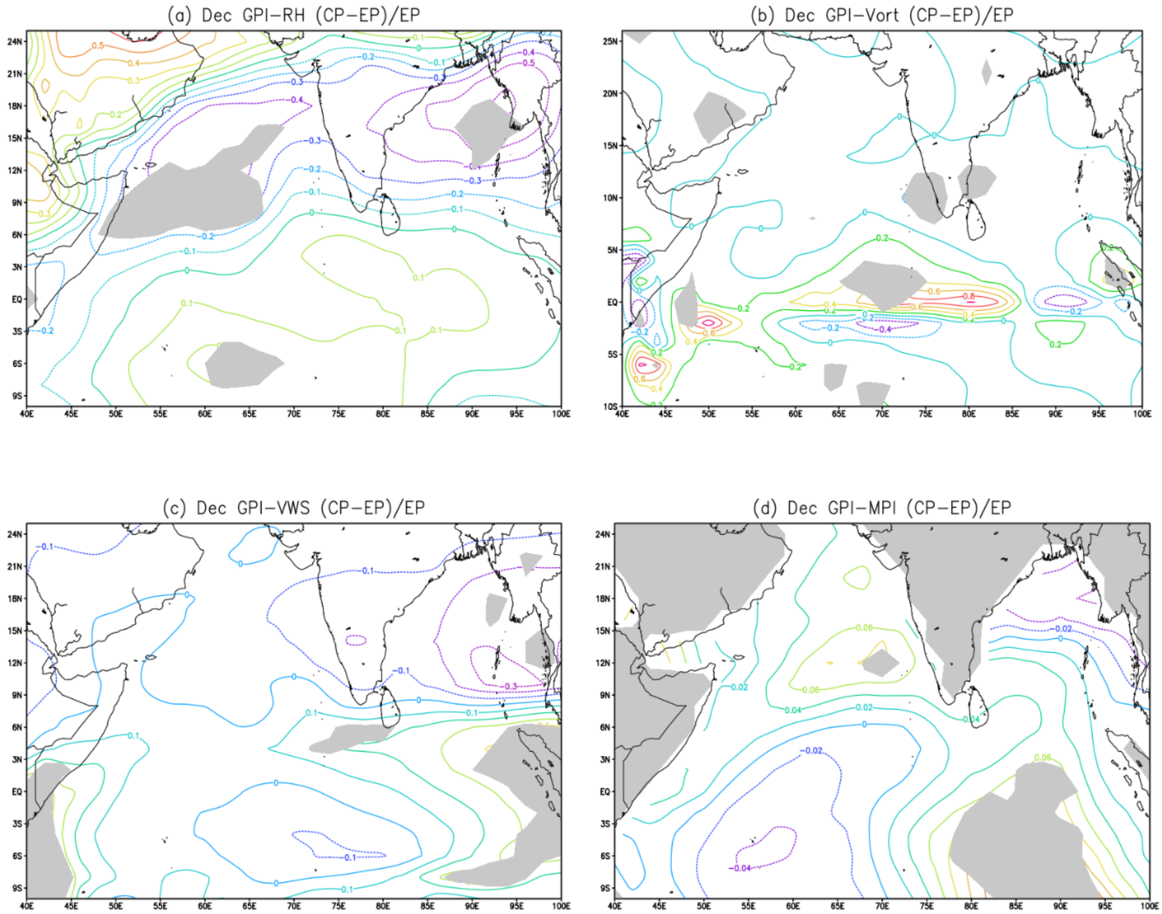


Fig. 3.5 Relative difference in the individual GPI terms of RH, relative vorticity, VWS and maximum potential intensity during CP years compared with that in the EP years. Shaded regions indicate differences that are statistically significant at 95% confidence level (land regions in (d) can be ignored).

(a)

(b)

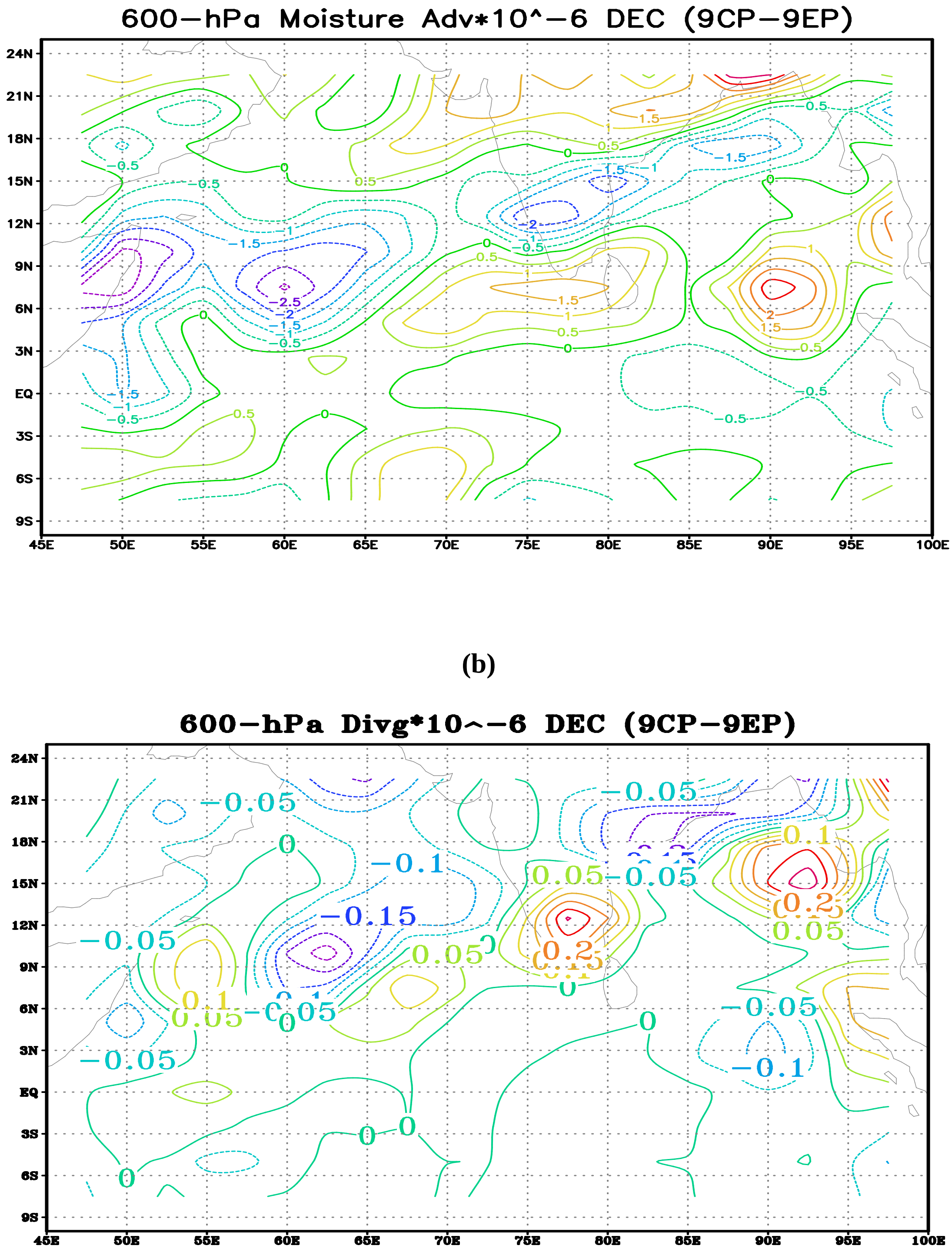


Fig. 3.6 Composite difference of the 600-hPa advection (a) and divergence (b) term in the moisture budget between the CP and EP years.

3.4 Large-scale responses to ENSO events

3.4.1 Responses to El Niño events over the Indian and Pacific Oceans

There are unique teleconnection patterns in the tropics during the two types of El Niño including the dynamical links between the NIO and Pacific Ocean, however, the processes in the latter have already been canvassed in previous studies. The difference in the post-monsoon SST pattern during the CP years from the EP years concentrates over the central Pacific (Fig. 3.7a for December). With such a difference in SST forcing, the Walker circulation responses vary. During CP, the major convection forced by SST is at the central Pacific (around the dateline). Associated with this major convection, there is subsidence to the east and this subsidence depends on the exact location of the major convection. Zhang et al. (2015b) demonstrated that the east-type CP events with maximum SST near the dateline have strong subsidence near 120°E (see their Fig. 4). Conversely, the west-type CP with maximum SST west of the dateline has weaker subsidence. Such subsidence motion would create near-surface divergence near 120°E, with easterly anomalies extending into the Indian Ocean (and westerly anomalies returning to the central Pacific).

This response in the Walker circulation explains the low-level easterlies over the tropical NIO in the composite difference between CP and EP years (Fig. 3.7b). These low-level easterlies have certain aspects relevant to TC development in the NIO. They generate anti-cyclonic relative vorticity, thus reducing the background vorticity for TC formation (see the regional plot in Fig. 3.3b). The regional analysis earlier depicts reduction in mid-level moisture mainly due to the advection process. This is likely due to the advection by these easterly anomalies during CP because they pass through the South Asia continent and would have advected dryer air into the NIO. In addition, the returning flow of the near-surface easterlies to the upper level provide westerly anomalies. This is consistent with the westerly anomalies in the 200-hPa wind composite difference between CP and EP (Fig. 3.7c). The low-and upper-level wind anomalies thus generate larger VWS especially for the southeast BoB and prohibit TC formation in it (Fig. 3.7d and the regional plots Fig. 3.3c, d).

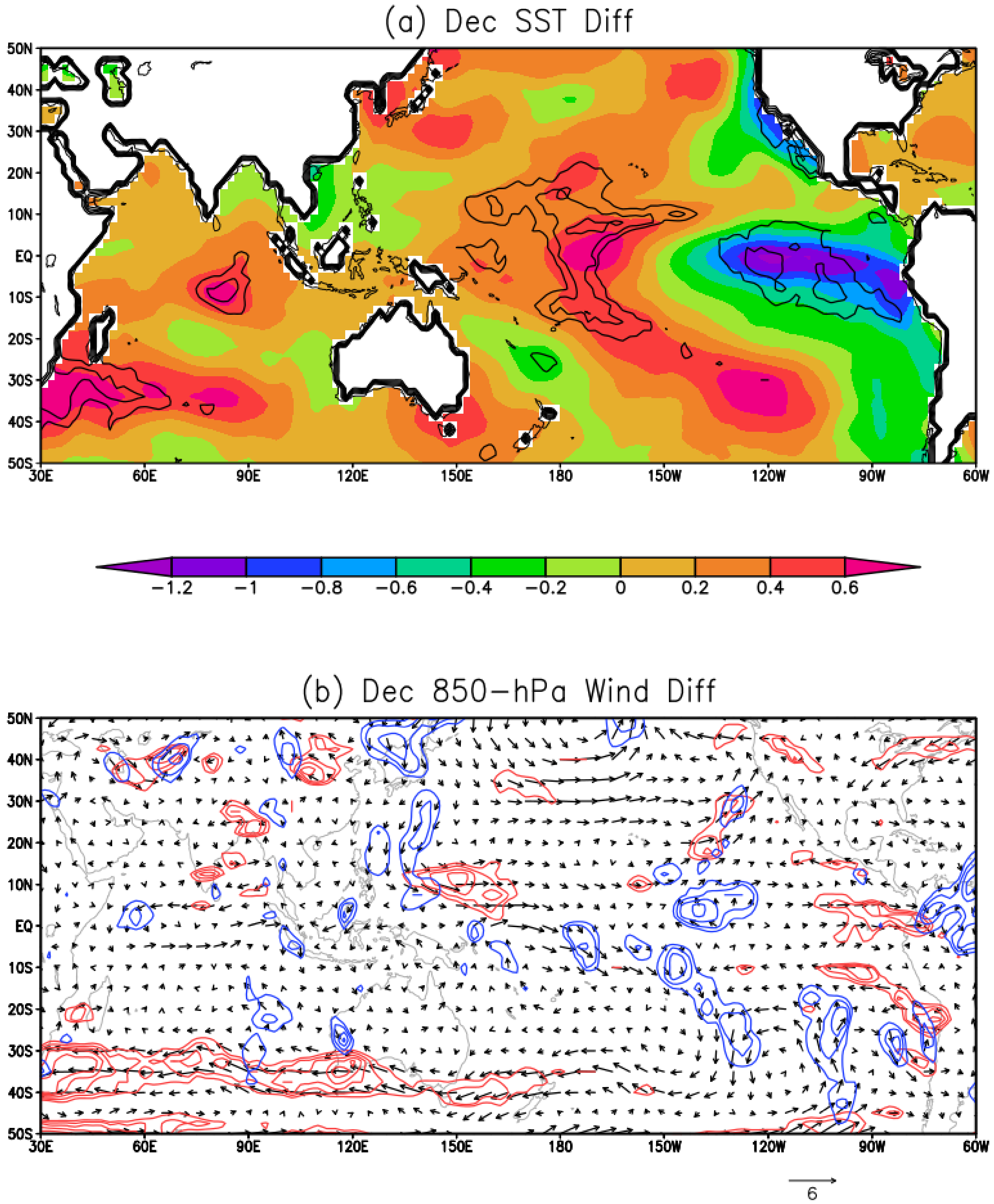
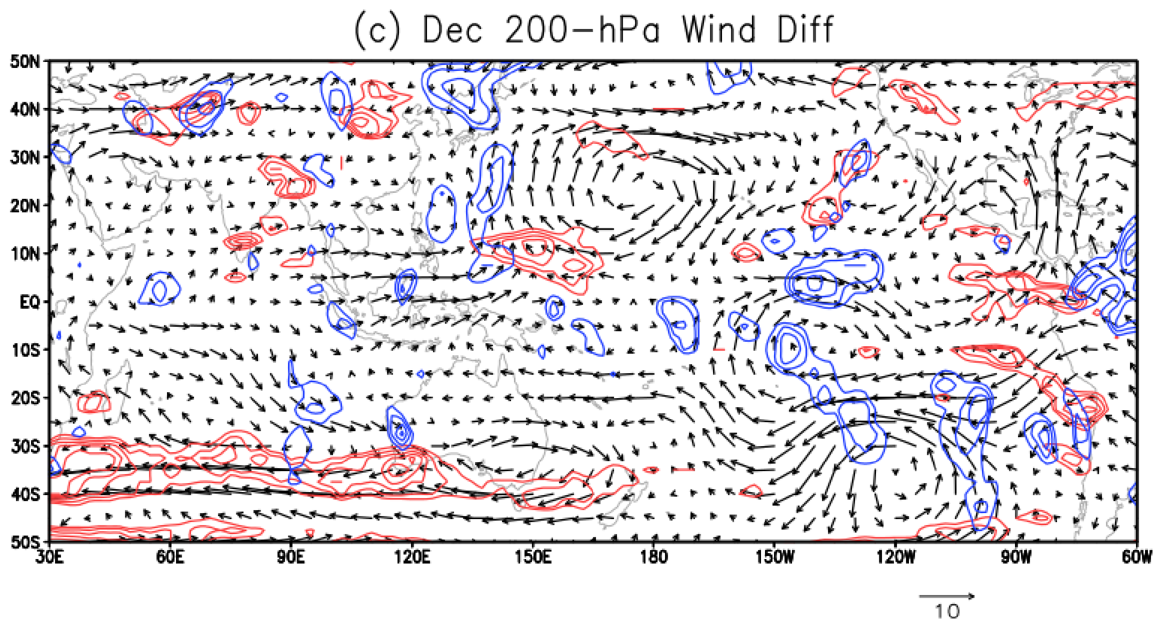


Fig. 3.7 Large-scale composite difference between the CP and EP years for (a) SST, (b) 850-hPa winds, (c) 200-hPa winds and (d) 200-850-hPa VWS magnitude. The contours indicate regions that are statistically significant at 95% confidence level (red and blue contours for zonal and meridional wind in (b) and (c), respectively).



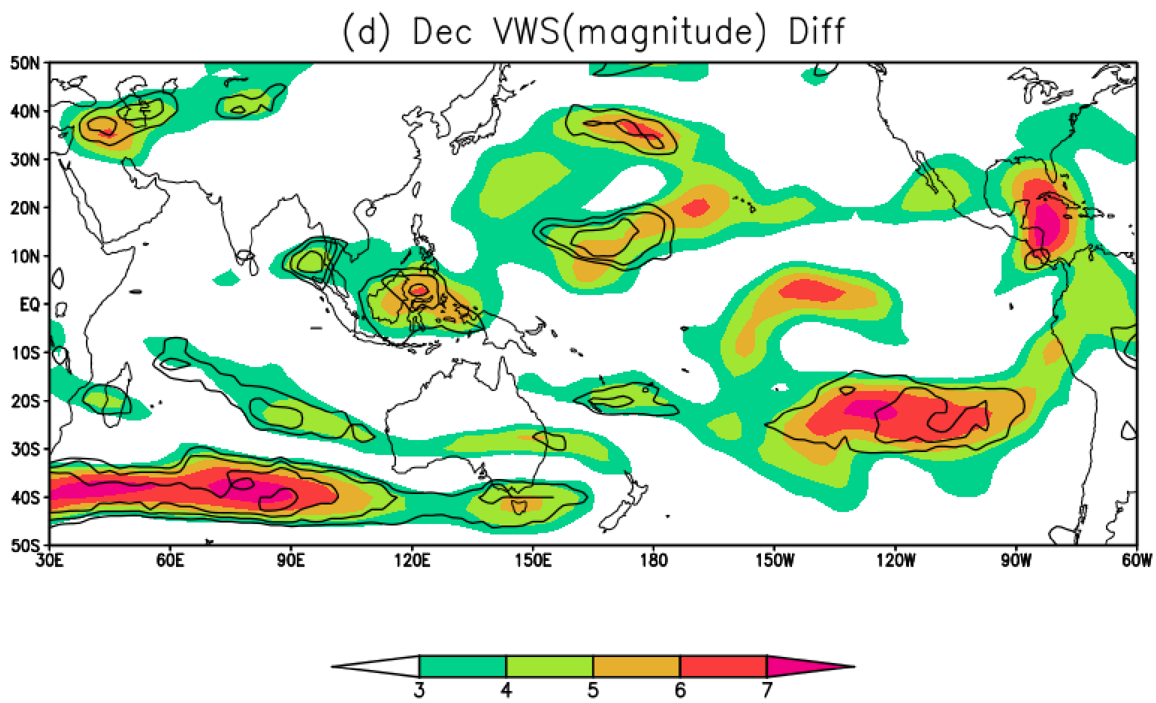


Fig. 3.7 (cont.)

Recent studies further separate different types of CP events based on the location of the maximum SST warming. As mentioned earlier, Zhang et al. (2015b) classified the east- and west-type CP event. Wu et al. (2018) classified CP-only and EP-only warming and kind of mixture of them. They identified similar responses in the Walker circulation and associated wind anomalies over the WNP, as has been discussed in Zhang et al. (2015b) and this present study extends it to the NIO here. As expected, the response is especially large in the coexisting CP and EP events defined by Wu et al. (2018) because in the extreme EP events SST warming actually has extended into the central Pacific. In this study, some major EP events, such as the years 1982, 1997 and 2015, have been included. For this reason, the contracts between the composite CP and EP events may have been influenced. The differences between the two types of El Niño should be even large if only the 'regular' events are compared.

3.4.2 Relationship to Indian Ocean Dipole development

Other than ENSO, another type of climate variability that influences TC activity in the NIO is the Indian Ocean Dipole (IOD). During the nearly biennial oscillation of the positive and negative SST anomaly over western and eastern tropical IO, the regional circulation has corresponding changes that in turn affect TC development (Yuan and Cao 2013). It is well-known that the positive IOD (PIOD, with warm SST anomalies over western IO) event suppresses TC activity over the NIO and especially the BoB. Ng and Chan (2012) also identified a significant correlation between the DMI and NIO TC number during post-monsoon. Such a correlation is largely attributed to TCs in the BoB and subsequently, it is critical that the influence from IOD in comparison with the two types of El Niño be considered.

Within the CP and EP years in this study, there were four PIOD events (1967, 1987, 1994 and 2012) coinciding with CP, and five PIOD events (1963, 1972, 1982, 1997 and 2015) coinciding with EP. Thus, the influence from IOD has contributed to both types of El Niño. During a PIOD event, there are low-level easterly anomalies over the tropical IO (Yuan and Cao 2013), quite similar to the wind anomalies in the CP composite (versus the EP composite). These easterly anomalies generate a more anticyclonic environment in the BoB and thus are unfavourable for TC development. Therefore, the suppression effect of TC activity over the

BoB during CP has been contributed by PIOD events. However, further analysis, likely with the help of numerical modelling, is necessary for quantifying the relative contribution of these two types of climate variability to TC frequency and track.

In general, ENSO and IOD events are considered independent with each other because measures of these two kinds of events usually have an insignificant correlation. However, studies on the physical linkages between ENSO and IOD have been conducted. For example, Zhang et al. (2015b) argued that the east-type CP events favour PIOD development. This is due to the large response in the form of low-level anomalous easterlies over the eastern tropical IO. These strong anomalous easterlies along the Java/Sumatra coast would activate the local Bjerknes feedback and cool the SST over that part of the IO, thus generating a PIOD SST pattern. Based on this argument, IOD and a portion of CP events are correlated and impacts on TC activity derived from CP are considered; whether the PIOD has been activated is an important factor to examine as well. In the CP years analysed in this study, 1994 and 2002 are classified as east-type CP events and the DMI values show activation of PIOD in the late monsoon or post-monsoon season (Fig. 3.8). In contrast, for most EP events the maximum SST forcing concentrates at the eastern Pacific. The responses in the IO are not as large as those in the CP events. This is consistent with the analysis by Wu et al. (2018) regarding weak EP warming events.

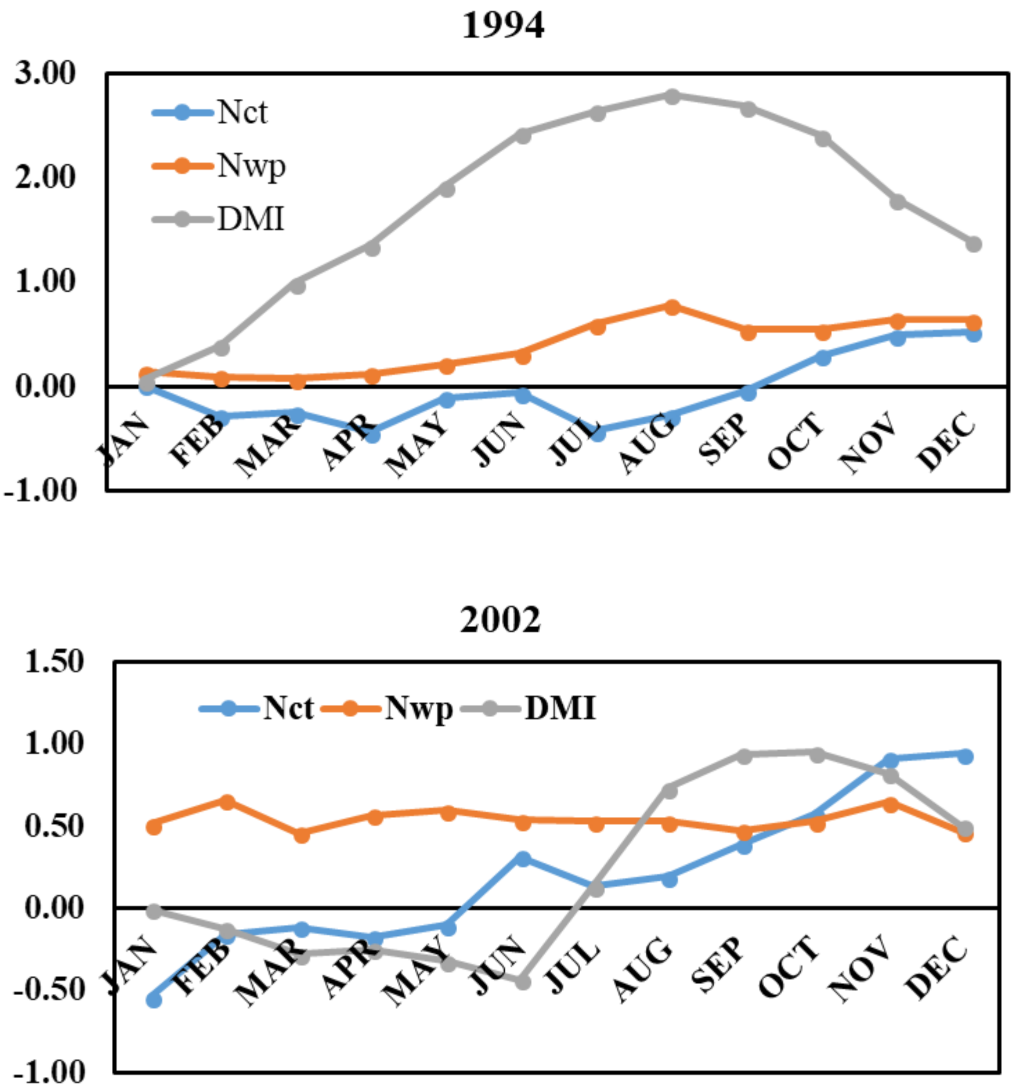


Fig. 3.8 Time series of Dipole Mode Index (DMI, grey), east-type CP event (N_{wp}, red) and EP event Index (N_{ct}, blue) during 1994 and 2002.

3.5 Conclusion

In this chapter the impact of two types of ENSO flavours, namely CP- and EP-type on TC activity over AS and BoB of NIO, has been examined intensively as these new types of ENSO flavours reported in recent studies especially for the Pacific Ocean. This study identified 9 CP years: 1977, 1986, 1990, 1991, 1994, 2002, 2004, 2009, 2012 and 2014, and 9 EP years: 1951, 1957, 1965, 1972, 1976, 1982, 1997 and 2015 during 1951-2015 and did not find significant changes of TC genesis and tracks between the identified CP and EP events.

However, a significant shutdown in the number of TCs during the CP years in particular post-monsoon seasons is found. The possible causes for TC reduction during CP events are investigated and found that both major thermodynamic and dynamic factors - particularly mid-level RH and VWS - are responsible for this. These results are consistent with those for GPI analysis. The mid-level RH and the VWS term of GPI contribute significantly to the reduction of GPI value during CP years that suppress TC genesis. The pattern of change in moisture advection is similar to that in the total change in mid-level RH. Furthermore, this study concluded that the regional change in low- to mid-level circulation is likely to be a major factor that has modified the moisture content in the NIO, and the circulation change contributes to the moisture advection more. This study also concluded that PIOD events are linked to eastern-type CP events that can suppress TC activity in the BoB region. Finally, this conclusion requires further research for confirmation.

Chapter 4: Active Tropical Cyclone Seasons over the Arabian Sea and Bay of Bengal

4.1 Introduction

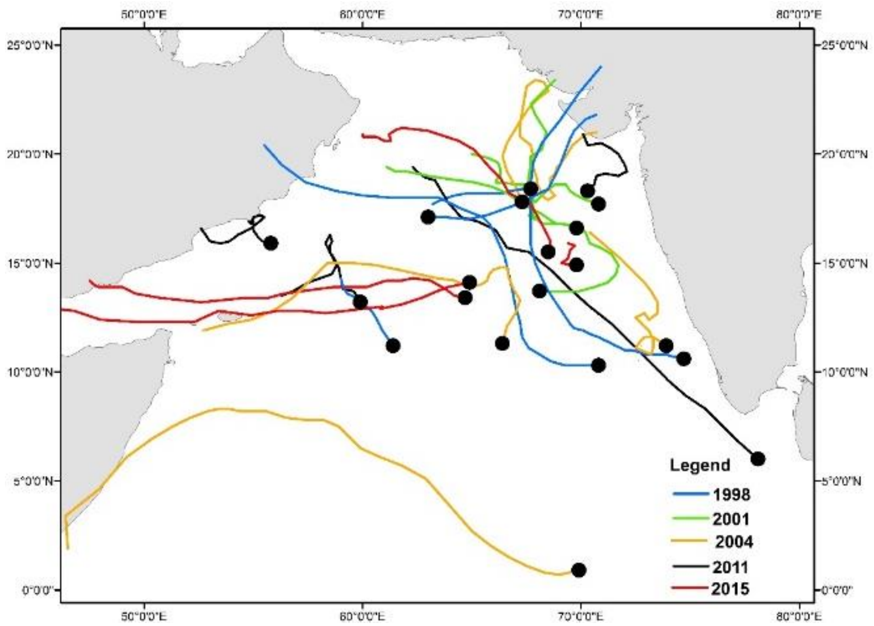
The NIO is one of the ocean basins in which TCs form, develop and make landfall. Climatological backgrounds for TC activity over the NIO have been reviewed extensively in Chapter 1. This present study identified the AS as being very active during some years in the period 1983-2015 which is the focus here. More importantly, during late October to early November of 2015, Cyclones Chapala and Megh traversed the Arabian Sea (AS) with disastrous outcomes. After Cyclone Gonu (2007), Chapala was the strongest cyclone that formed over the AS and it affected about 1.1 million people and caused about 40,000 people to be displaced and 8 deaths. Just two days after Chapala's landfall, another cyclone, Megh, formed over the AS which also caused enormous destruction of property and flooding (AccessScience 2015). The maximum intensity of these two cyclones was 135 and 110 knots (69.4 m s^{-1} and 56.6 m s^{-1}), respectively (AccessScience 2015). These two cyclones caused 26 people's deaths in all affected areas of Yemen (AccessScience 2015). According to historical records, forming two intense cyclones within one week during November is very unusual in the AS. More interestingly, for the whole of 2015 there was only one weak storm (out of total of five that year) that formed over the BoB (just south of the Bangladesh coast) and lasted for about one day. Therefore, it is worth exploring what environmental conditions make TC formation active in the AS but almost inactive in the BoB. As will be shown in the following, the opposite ever occurred. Such exceptional spatial patterns of TC activity over the NIO motivate this study in order to achieve the research objective 2: "*to identify the meteorological and climate factors that account for the exclusively active or inactive TC seasons over AS and BoB*". In other words, the focus is on those years when most NIO TCs formed in one of the basins but not the other.

4.2 Contrast between the AS and BoB

The motivation of this study is that in some years during the analysis period, TC activity concentrated in the AS or BoB, but not both. From the JTWC best tracks, such exclusively active AS years include 1998, 2001, 2004, 2011 and 2015, while the active BoB years are 1990, 1991, 2000, 2005, 2009 and 2013 (Fig. 4.1). In the six active BoB years there was no activity at all over the AS except 2009 and 2013 when only one storm formed. As in climatology, most TCs in the active AS years formed in the eastern part of the basin and they moved north or northwest. The TCs in the active BoB years formed in the central part of the basin and most of them had tracks to the northwest. In total 28 TCs formed over the NIO during the five AS active years, which are partitioned between 20 and 8 between AS and BoB, respectively. Comparatively, there were 31 TCs in the six BoB active years, 29 formed over the BoB and only 2 in the AS. These two sets of periods thus had very different regional impact patterns in the NIO caused by these storms. Below, the synoptic and climatic factors responsible for generating such east-west contrast of TC activity over the NIO are analysed.

It should be noted that these eleven years do not represent the years with the largest ACE values over the NIO, because often TCs in those years with the largest energy distributed quite evenly between AS and BoB. Examples of these years are 1992, 1996, 1999, 2007 and 2010 (Fig. 4.2). The selection criterion for the years under study is mainly based on the asymmetric TC development pattern between AS and BoB, and accordingly most of the ACE in each of these ten years concentrates in one of the basins. The identified active AS years are almost all the years during 1983-2015 in which the AS ACE is larger than that in BoB (except 1989, 1993 and 2010 in which the difference is very small). The year 2015 is definitely an extreme case in which almost the total ACE value over the NIO is from the AS, mostly derived from TC Chapala and TC Megh which developed during late October to November. In 2013 TC activity also

(a)



(b)

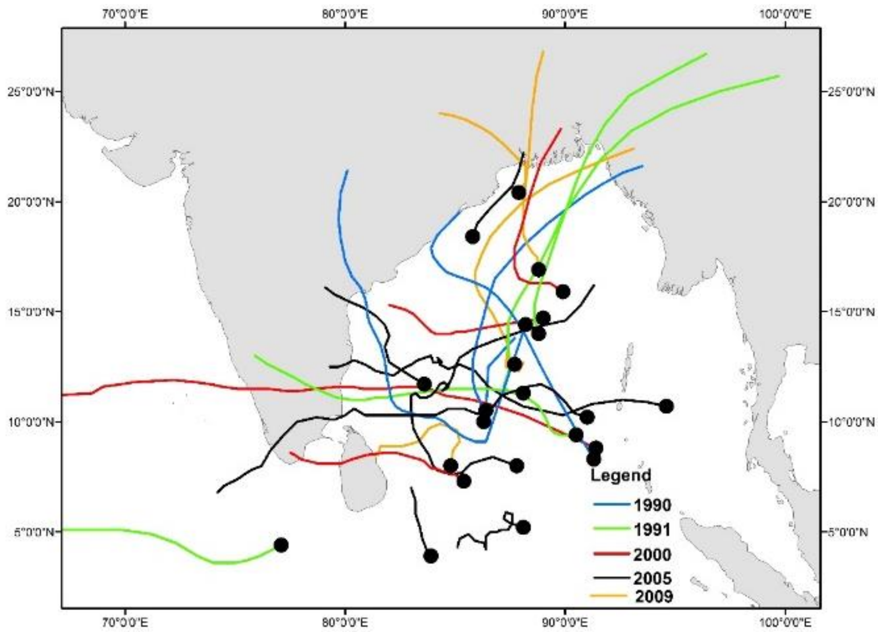


Fig. 4.1 TC best tracks for the identified (a) Arabian Sea active years (1998, 2001, 2004, 2011 and 2015) and (b) Bay of Bengal active years (1990, 1991, 2000, 2005 and 2009). Each colour represents a specific year and black solid circle indicates TC formation location.

concentrated in the BoB. This year has not been included in the analysis in order to keep the sample size the same for the AS and BoB (each with five years). Tests have been carried out to add this year in the sample for active BoB years, however, the conclusions based on the composite analyses in the following will not be changed.

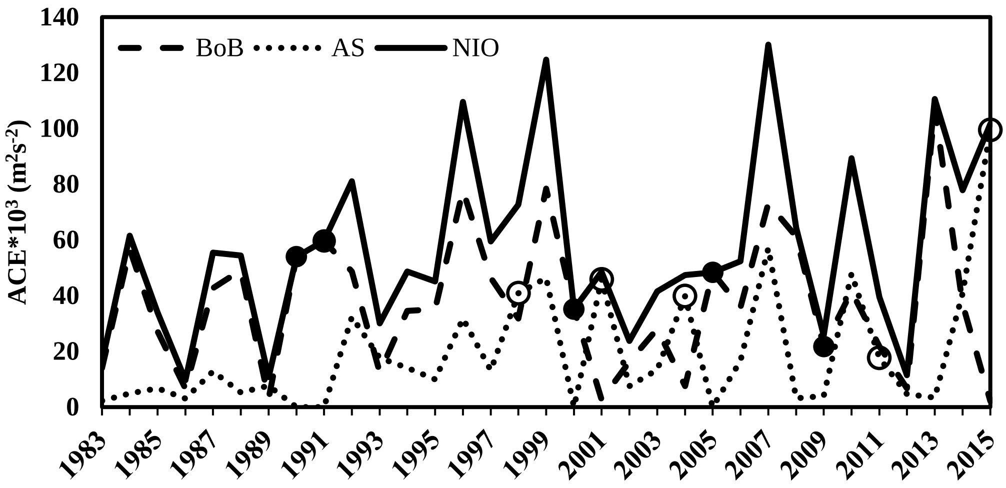


Fig. 4.2 Time series of annual accumulated cyclone energy (ACE) (103 m^2 s^{-2}) over Bay of Bengal, Arabian Sea and the entire North Indian Ocean during 1983-2015. The open (black) dots mark the active AS (BoB) seasons analysed in this study.

Examination of the monthly distribution of TCs in the five active years in AS and the other five in BoB indicates that the contrast in regional development mainly comes from the post-monsoon season (Table 4.1). This is especially true in the AS active years in which 60% - 83% of the TCs formed in that season every year. In the BoB active years, many TCs still formed during OND such as in 2000 and 2005. In other words, it is during the retreat of the South Asia summer monsoon and transition to the post-monsoon period that the environment is likely to be favourable for TC development in only one of the ocean basins. Therefore, the environmental conditions during OND are focused on in the following.

Table 4.1: Monthly distribution (only AMJ and OND are shown) of TC formation in the five AS active years and six for BoB (note that 2013 has not been included in analysis; see text for details). One storm formed in January 1991, two in January 2005, one in September 2009 and one in July 2015 not shown in the table.

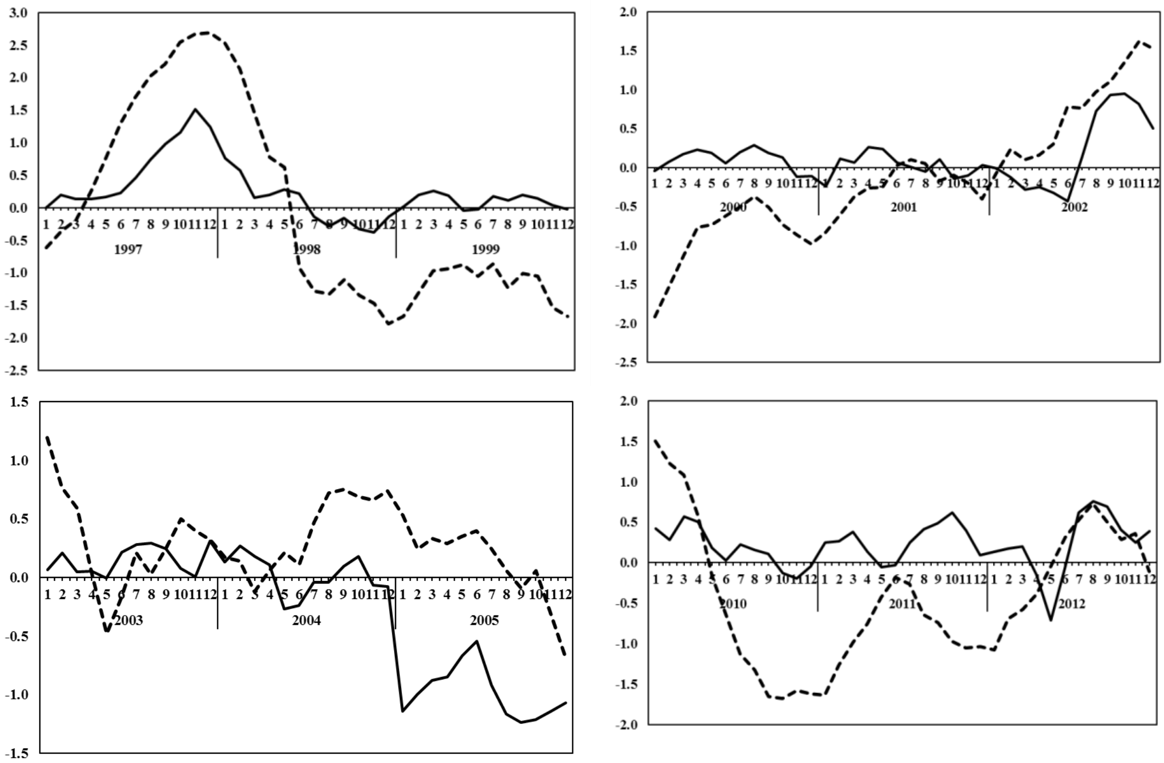
	Year	April	May	June	October	November	December
AS	1998	0	2	1	2*	2	1
	2001	0	1	0	2*	1	0
	2004	0	2	0	1	2	0
	2011	0	0	1	1	3	1
	2015	0	0	1	2	1	0
BoB	1990	1	1	0	1	0	1
	1991	1	1	0	0	1	0
	2000	0	0	0	2	1	1
	2005	0	0	0	2	1	2
	2009	1	1	0		1	1
	2013	0	1	0	1	4	1

* One of them formed in late September

4.3 Climatic and monsoonal influences

4.3.1 Are the active AS and BoB seasons due to ENSO and IOD?

Examination of the indices measuring the state of ENSO and IOD indicates that there is likely not a single climate mode of variability leading to the exclusively active AS and BoB TC seasons. For example, in the five active years over the AS, 1998 and 2011 are La Niña years, while 2004 and 2015 are El Niño years (Fig. 4.3). Given the well-known phase lock of ENSO to the seasonal cycle, these ENSO events all developed in the boreal late summer to autumn period and they should have influenced the TC activity in the NIO during OND if physical mechanisms exist. For the IOD, results are also mixed. The year 1998 is identified as NIOD, while the years 2011 and 2015 are PIOD. The other two years are neutral. It can be seen that these positive and negative IOD events developed in the second half of the year that matched the OND TCs. However, not a single phase is associated with the active TC activity in the AS. Recent studies, for example Guo et al. (2015) indicated there are different degrees where IOD events develop under the influence of ENSO, and thus it is not expected that an IOD event is always accompanied by a particular phase of ENSO.



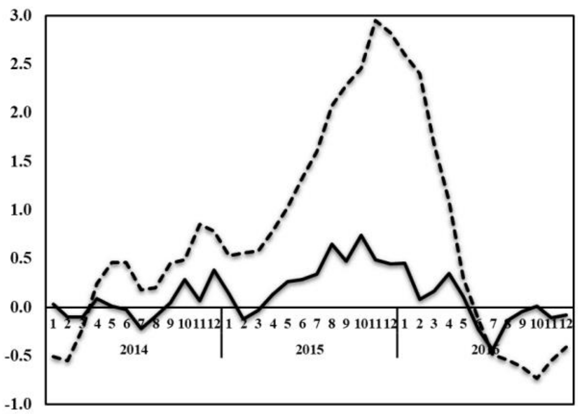
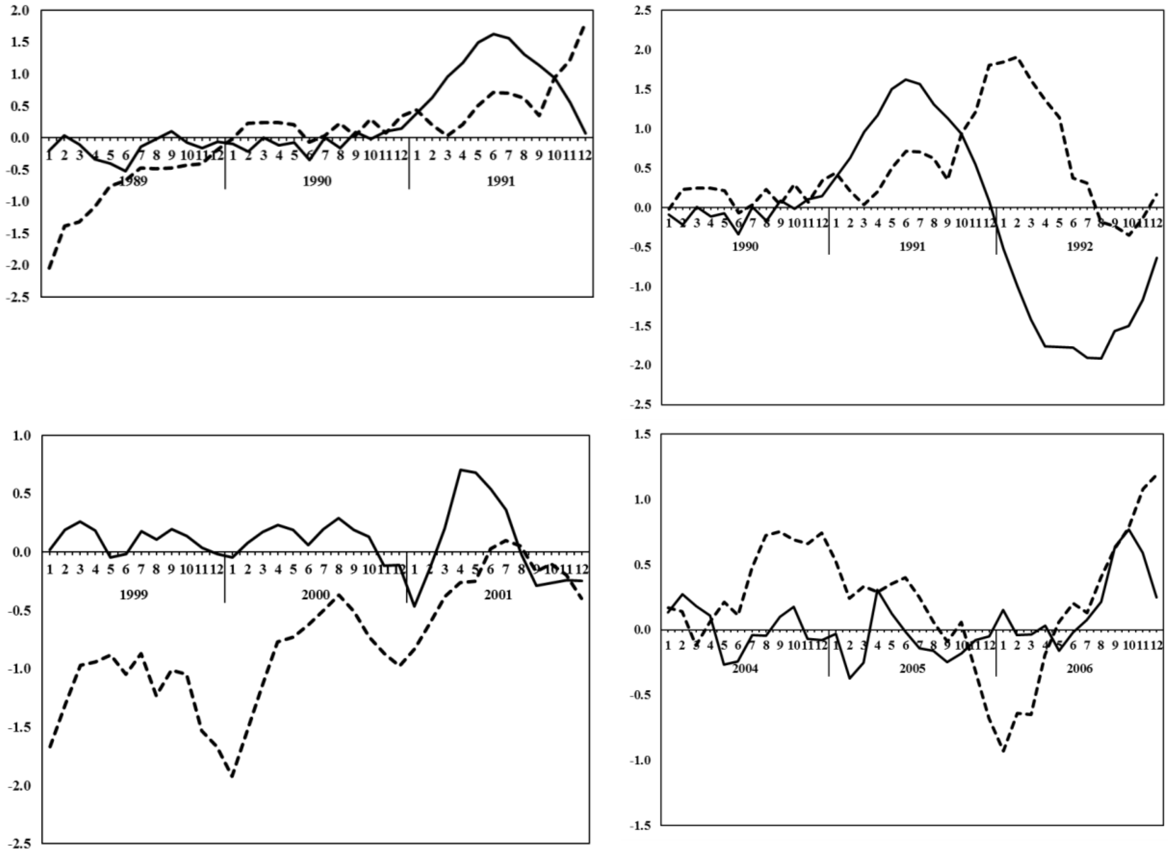


Fig. 4.3 Time series of Dipole Mode Index (DMI, solid) and Oceanic Niño Index (ONI, dash) during the active TC years in the Arabian Sea. The indices in the year before and after each active year are also shown.

Similarly mixed results apply to the active TC years over the BoB. The years 1991 and 2009 are El Niño years, but 2000 and 2005 are La Niña (Fig. 4.4). On the other hand, 1991 is a major PIOD event but the only IOD event among the five years. There is also no dominating climate mode that seems to explain the active BoB TC seasons.



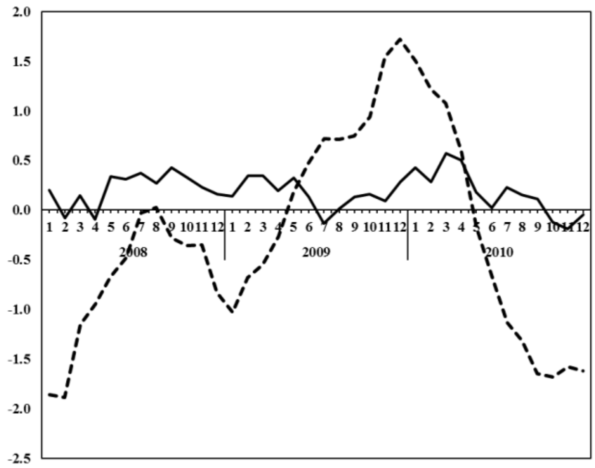


Fig. 4.4 Time series of Dipole Mode Index DMI, solid) and Oceanic Niño Index (ONI, dash) during the active TC years in the Bay of Bengal. The indices in the year before and after each active year are also shown.

The remote atmospheric responses in the NIO under ENSO and IOD support the above results from the climate indices. For instance, during El Niño events there are equatorial anomalous easterlies in the NIO (Fig. 4.5a) and the anomalies decrease with latitude to the north, which are similar to those in Fig. 4 of Girishkumar and Ravichandran (2012). Thus, although the SST anomaly over NIO is higher during El Niño than La Niña (not shown), the general anticyclonic low-level environment in the NIO does not favour TC development. Nevertheless, the easterly anomalies extend from the BoB to AS and the environment over the two basins is similar, which agrees with the historical TC activities during OND in Fig. 4.5a.

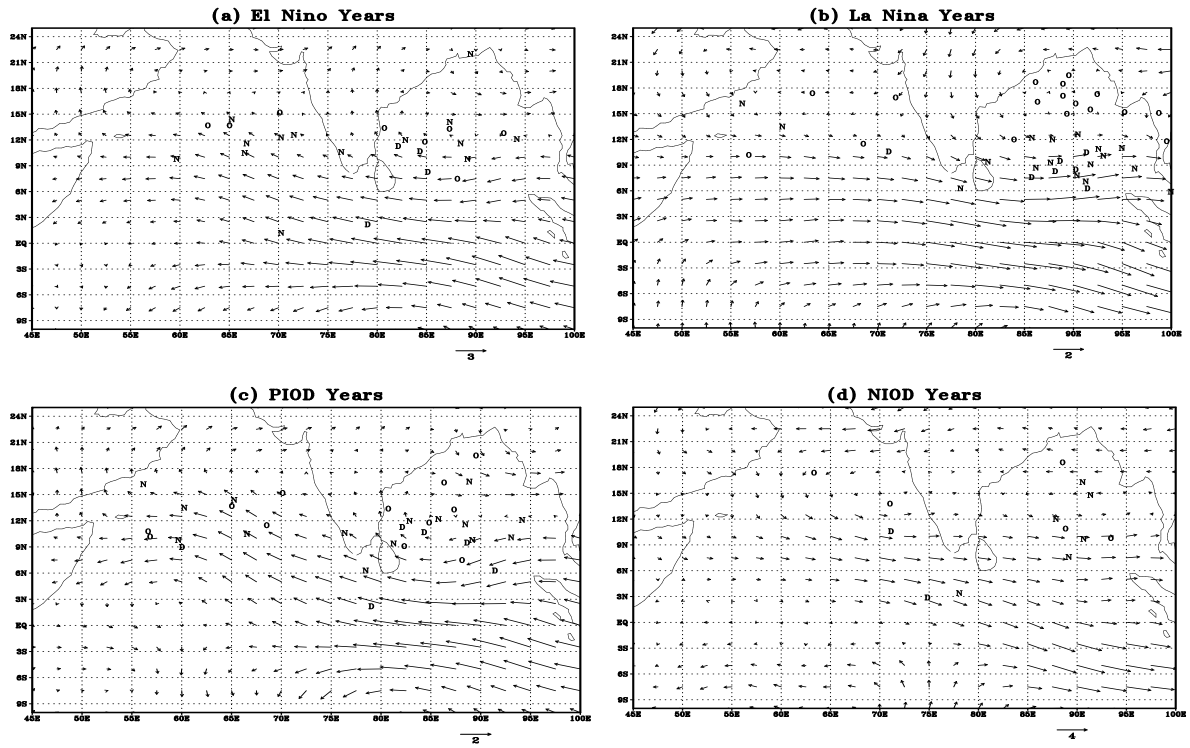


Fig. 4.5 Composite 850-hPa wind anomaly during OND in (a) El Niño, (b) La Niña, (c) PIOD and (d) NIOD years. The TC formation locations in the years for composite are marked by O, N and D which correspond to the formation months.

During La Niña years, there are equatorial anomalous westerlies instead in the NIO, and together with the climatological low-level westerlies (Fig. 4.5b) creating a cyclonic environment especially in the BoB favourable for TC development. This agrees with the observed higher number of BoB TCs during La Niña. However, AS TC activity has not completely shut down during La Niña. In both El Niño and La Niña phases, there are low VWS regions in AS and BoB (Figs. 4.6a, b, comparable with Fig. 7 of Felton et al. 2013 that is for the BoB only). Thus, ENSO does not select the AS or BoB as being more favourable for TC development.

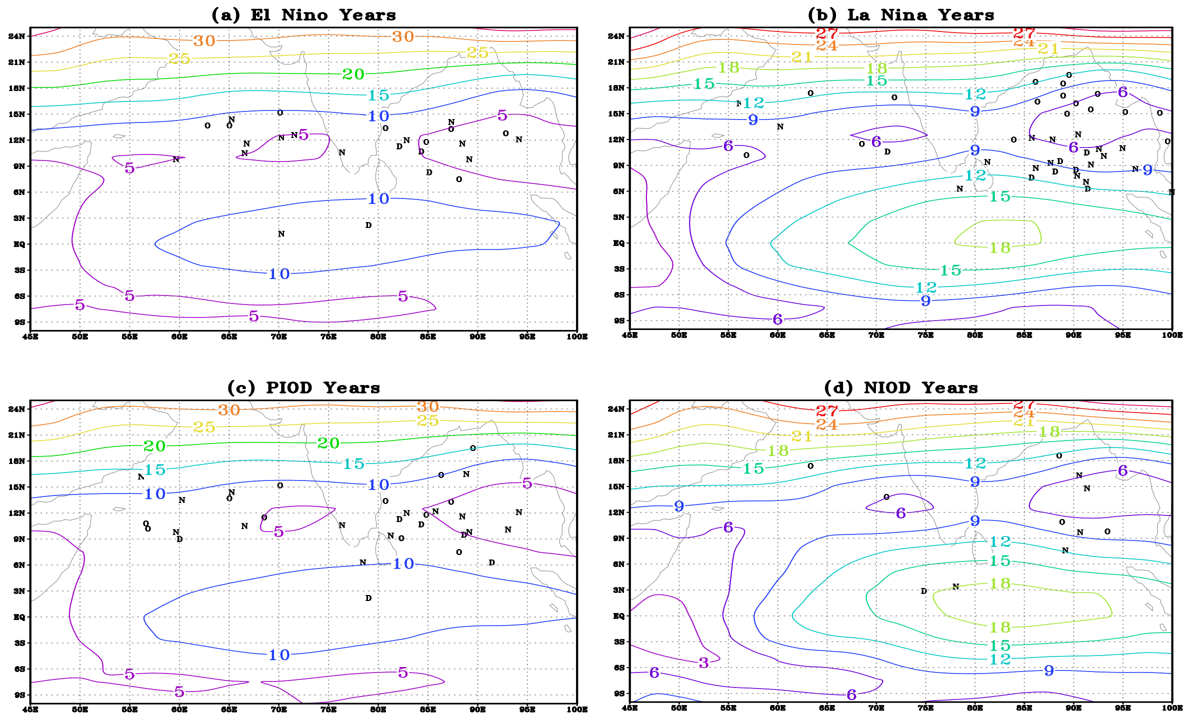


Fig. 4.6 Composite 200-850-hPa VWS magnitude during OND in (a) El Niño, (b) La Niña, (c) PIOD and (d) NIOD years. The TC formation locations in the years for composite are marked by O, N and D which correspond to the formation months.

As a SST pattern in the NIO, the IOD has evident atmospheric responses in the basin. During PIOD, warm SST is over the western IO and there are equatorial anomalous easterlies over the eastern IO (Fig. 4.5c). These anomalous easterlies originate from the Walker circulation anomaly and a low-level divergence flow over Indo-China (Yuan and Cao 2013). According to Yuan and Cao (2013), the general low-level anticyclonic environment over the BoB during PIOD suppresses the annual TC frequency and those with westward-moving tracks. However, this is not clear for OND as there is still a substantial number of post-monsoon TCs over the BoB. The anomalous westerlies going into northwest AS also generate a number of TCs over that part of the AS in the study period. During NIOD, low-latitude anomalous westerlies exist in the NIO, which generate a general low-level cyclonic environment crossing from the AS to the BoB (Fig. 4.5d). This cyclonic flow would increase the annual TC frequency during NIOD (Yuan and Cao 2013), and it can be seen that there are comparable TCs over the AS versus BoB during OND. These TCs form within the low-VWS regions in the AS and BoB, which are quite similar under either phase of IOD (Figs. 4.6c, d). Thus, neither PIOD nor NIOD generate distinct asymmetric TC distribution between the two basins.

4.3.2 Monsoonal influence

In order to identify the contrasts in the environment that result in the active AS and BoB TC seasons, composite differences between the mean during AS years and the BoB years of the relevant parameters on monthly and seasonal timescales are examined. It emerges there is little difference in SST and MSE, which are the same conducive to TC development. However, an interesting difference in the low-level circulation has been identified. During October of the active AS years, there are anomalous easterlies (note that these are against the active BoB years) flowing into the low latitudes of BoB (Fig. 4.7a). There is also a branch of anomalous easterlies south of the equator that flow northward and then northeastward into the AS. The anomalous easterlies persist in November (Fig. 4.7b), although this difference flow is not quite statistically significant. On the other hand, there are anomalous southerlies into AS and the near-equatorial anomalies become southwesterlies. Part of these anomalous southerlies/southwesterlies are statistically significant. During December, there are still clear anomalous southerlies (northerlies) over the AS (BoB).

While these anomalous flows during OND would generate anomalous low-level relative vorticity, the patterns in the three months of OND do not differentiate TC formation potential in AS and BoB. In October and December there are slight decreases in relative vorticity over both the AS and BoB, while in November there is still a slight decrease over the BoB (about

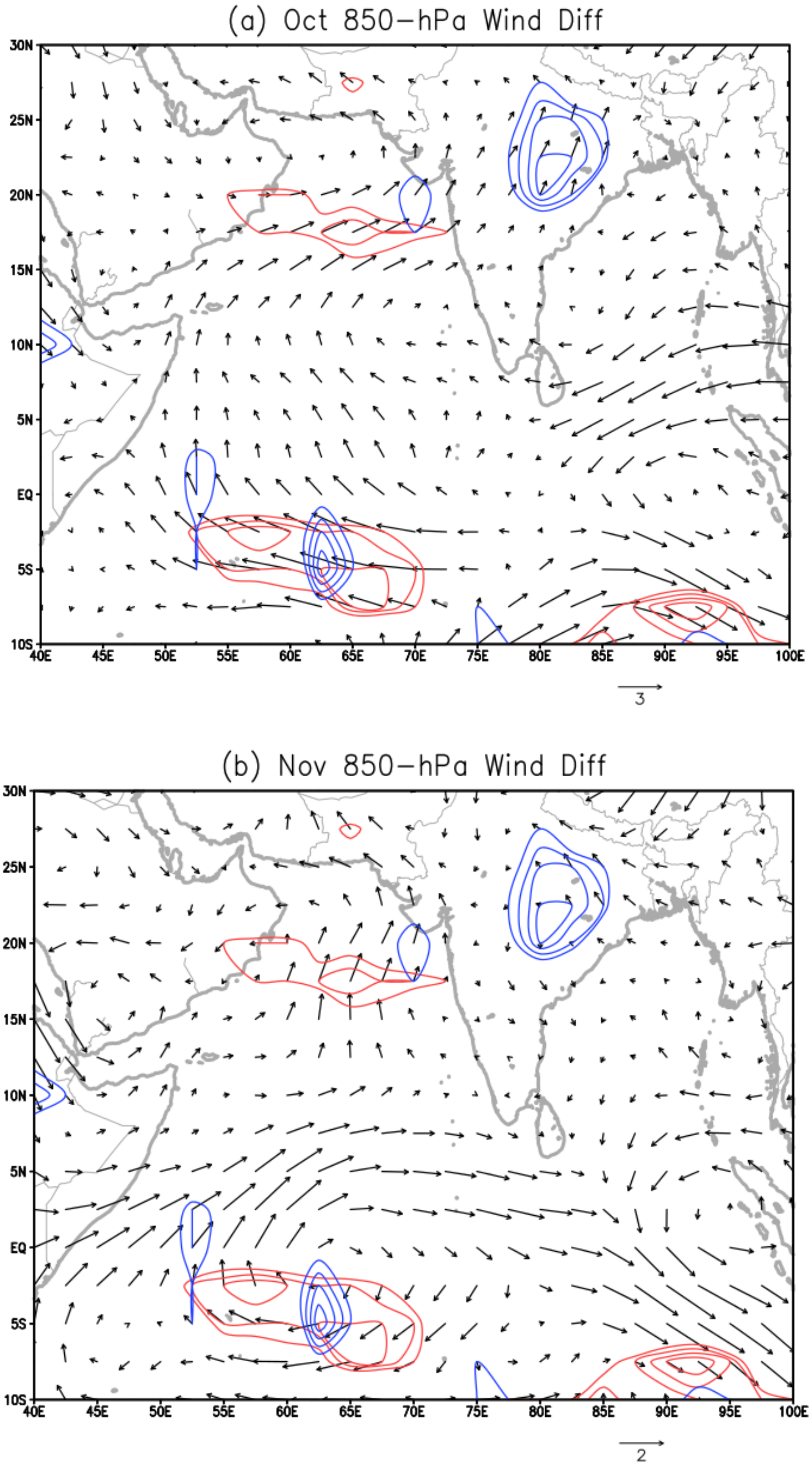


Fig. 4.7 Composite difference of 850-hPa wind (m s^{-1}) between the active AS and BoB years for (a) October and (b) November. The red (blue) contours indicate regions that pass the Wilcoxon-Mann-Whitney rank-sum significance test at 95% confidence level for the zonal (meridional) winds.

2×10^{-6} s^{-1}) but not much anomaly over the AS, thus potentially enhancing TC development there compared to the BoB. Difference in VWS also has the same sign from the AS to BoB. Generally, there is a decrease in VWS in the TC-formation latitudes during OND. A point to note concerns MSLP. There is indeed slightly higher MSLP (by less than 1 hPa) over the BoB than AS during October and over the western BoB during December, which is consistent with the analysis in Evan and Camargo (2011) that surface pressure in the BoB was higher when TCs formed in the AS. Composite differences of MSLP are negative in both the AS and BoB during November. These dynamic factors are likely to not generate the AS-BoB contrast in TC activity.

On the other hand, a basin-wide difference is identified in the composite difference of mid-to-low-level RH (Fig. 4.8). There is generally higher RH over the AS and less over the BoB, which amounts to an approximately 10% difference between the two basins. This kind of difference lasts until December. Thus, the difference in moisture may be responsible for generating the active TC post-monsoon seasons over AS while keeping the BoB quiet in storm, and vice versa in the years of active BoB post-monsoon seasons.

Similarity between the anomalous low-level flow during PIOD (Fig. 4.5c) and Fig. 4.7 may be identified due to the anomalous easterlies from low-latitude BoB and the general anomalous southerly components in the AS. In fact, when Kripalani and Kumar (2004) examined the variability of the northeast (post-summer) monsoon rainfall over India, attribution to PIOD has been concluded. In particular, when the composite low-level flow during the years with excess northeast monsoon rainfall was prepared in Kripalani and Kumar (2004; their Fig. 9), a similar pattern to Fig. 4.7 was obtained. Namely, there are general anomalous easterlies in the equatorial BoB and they flow into the AS with southerly components. Over the northern part of the BoB, northeasterlies exist. On the other hand, years with deficit rainfall have an anomalous flow pattern more like that in NIOD years. Kripalani and Kumar (2004) attributed moisture advection to the excess/deficit northeast

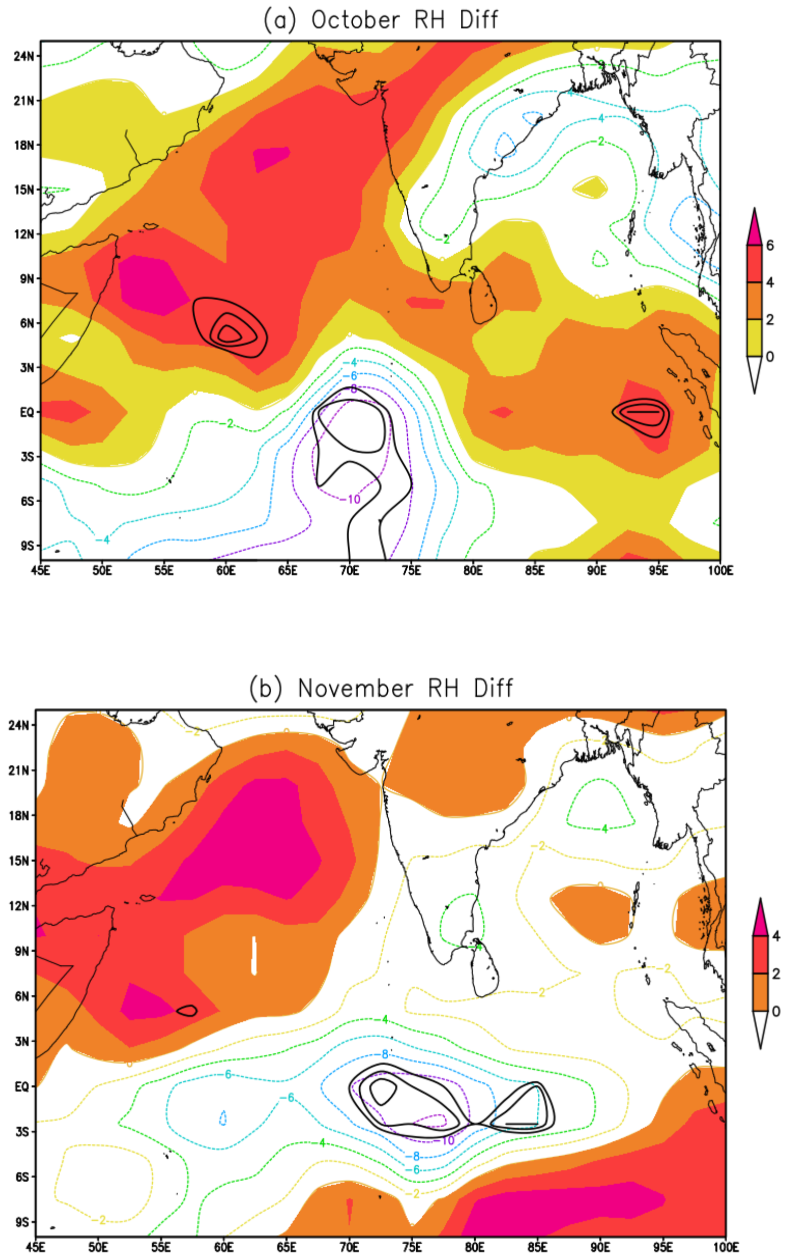


Fig. 4.8 Composite difference of 500-700-hPa RH (%) between the active AS and BoB years for (a) October and (b) November. The thick black contours indicate regions that pass the the Wilcoxon-Mann-Whitney rank-sum significance test at 95% confidence level.

monsoon rainfall over the south Indian peninsula. In the context of this study, with moisture enhancement associated with winds sourcing from the equatorial region in the AS but with dryer winds moving from land into the BoB, such a moisture effect is likely to be a major factor that results in the contrasting TC activity between the two sets of five years for AS and BoB, respectively.

Kripalani and Kumar (2004) indicated that during OND the subdivisions in south India receive most of the rainfall. To examine whether development of the northeast (post) monsoon is a factor that modulates TC activity in the AS and BoB during OND, correlation analysis is performed between the interannual time series of average rainfall over all the subdivisions and those of total ACE in the three months. In general, the correlation coefficients are not high for all subdivisions. However, it is interesting to note there is indeed difference between the AS and BoB. The only three subdivisions with a significant (at 90% confidence level) correlation during OND with AS ACE are over the western and southern Indian regions (Fig. 4.9). The highest correlation coefficient is about 0.27. In contrast, there is no subdivision that positively (and significantly) correlated with the BoB ACE during OND except one (to the far west in Fig. 4.9). However, there are three other subdivisions in the northern region that negatively correlated with BoB ACE (largest coefficient being about -0.29). Thus, excess northeast monsoon rainfall is related to active post-monsoon TC activity in the AS, but not so for TCs in the BoB.

Almost the opposite situation applies for AMJ. Only one subdivision is positively correlated with AS ACE, but there are eleven positively correlated with BoB ACE. Thus, pre-monsoon development is closely related to TC activity in the BoB. This is why when annual rainfall and ACE are analysed instead, almost the same result as in AMJ is obtained. However, it should be noted that the relationship is different for OND.

4.3.3 Dynamic Indian Monsoon Index

In order to quantify the above argument on the relationship between post-monsoon development and TC formation, the Dynamic Indian Monsoon Index (DIMI) defined by Wang and Fan (1999) is examined based on reanalysis data. The DIMI index is defined as the difference of the 850-hPa zonal wind between two regions: (5-15 °N, 40-80 °E) and (20-30 °N, 70-90 °E). Note that the DIMI has been developed with the summer monsoon in focus, however, a negative value of DIMI also indicates the strength of the northeast (post) monsoon (Murakami et al. 2017).

With respect to the OND period, the interannual variability of the DIMI is large. Since the largest difference between TC activity over the AS and BoB in the past occurred in October and November, the average DIMI anomaly in these two months is examined (Table 4.2). It can be seen that the AS active years more consistently have the larger negative values of DIMI anomaly, indicating the northeast monsoon in these years was quite intense. The years 1998 and 2001 are definitely exceptions and the former might have been influenced by the La Niña event that year. It was reported in Zubair and Ropelewski (2006) that the ENSO-northeast monsoon relationship has been quite consistent and reveals a slight strengthening trend in recent decades. Accordingly, the La Niña phase in 1998 would have weakened the northeast monsoon. For the year 2001, the DIMI index becomes more negative in December, indicating a late northeast monsoon development that year.

Table 4.2: Average value of the Dynamic Indian Monsoon Index (DIMI) anomaly during October to November for the active years in AS and BoB, respectively. The negative values indicating strong post-monsoon have been highlighted.

AS years	Oct-Nov DIMI	BoB years	Oct-Nov DIMI
1998	4.03	1990	0.46
2001	1.15	1991	**-1.0**
2004	**-1.3**	2000	0.02
2011	**-1.13**	2005	0.84
2015	**-0.75**	2009	**-0.26**

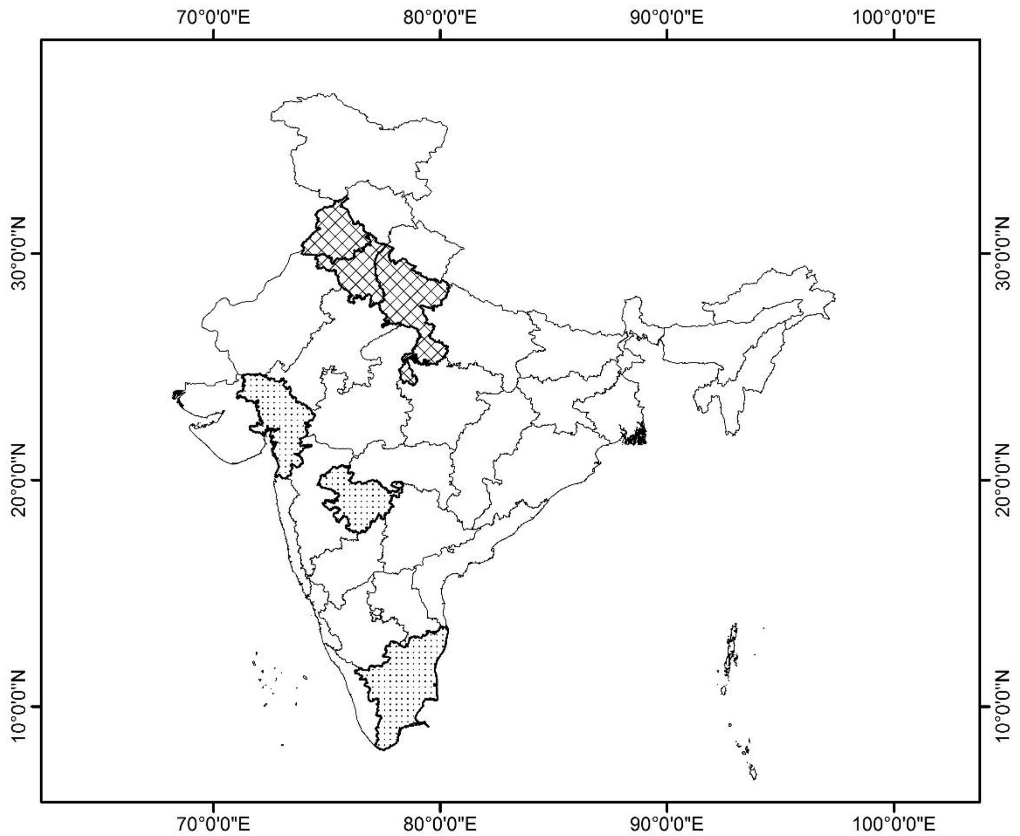


Fig. 4.9 Map of the subdivisions for the ground-based rainfall stations in the Indian region. In the dotted (gridded) subdivisions, average OND rainfall is significantly (at 90% confidence level) correlated with ACE in the same period for the AS (BoB, but negatively correlated) TCs based on variability during 1983-2013.

Nevertheless, the DIMI has been developed based on the summer monsoon regions. However, studies have shown that post-monsoon development in the NIO mainly involves strengthening of the northeasterlies over the BoB, and subsequently this is manifested as rainfall anomaly over the oceanic south BoB region and Sri Lanka. For example, based on multi-satellite rain estimate, Chang et al. (2005) defined the summer (winter) monsoon region over the oceanic north (south/southwest) BoB region. The winter monsoon is associated with persistent northeasterlies over the BoB (the period DJF was examined by Chang et al. 2005). Zubair and Ropelewski (2006) examined the rainfall at Sri Lanka and the Indian subdivision of Tamil Nadu (the southmost subdivision in Fig. 4.9) to indicate northeast monsoon development. This is consistent with our finding that the OND rainfall anomaly at Tamil Nadu is significantly correlated with TC activity over the AS, indicating post-monsoon effect over the BoB to storm development to the west of the Indian continent.

4.4 Conclusions

4.4.1 Summary

Unlike the other ocean basins, TC formations in the NIO have a clear bimodal distribution that consists of the pre-monsoon (AMJ) and post-monsoon (OND) season. In particular, the bimodal distribution is asymmetric and there are more TCs usually in the post-monsoon season. Ten years from the period 1983-2015 have been identified in this study in which most TCs developed in either the AS or BoB, but not both. It is further concluded that this contrast occurred mostly during OND when the South Asian summer monsoon ends, and the northeast monsoon develops.

There are well-known influences on TC activity in the NIO from climate variability, such as ENSO and IOD. However, when the states of ENSO and IOD based on climate indices in the five years of active AS seasons and another five for the BoB are examined, no single climate index seems able to explain the contrast between the AS and BoB. This is further supported when examining the anomalous atmospheric conditions during OND in the years of ENSO and IOD. These anomalous atmospheric conditions are conducive or prohibitive to TC development for both the AS and BoB, but not quite selective between the two ocean basins.

Composite analyses for the years with active AS seasons versus those with active BoB seasons show that it is likely the difference in moisture, which is represented by the 500-700-hPa RH, which explains the spatial patterns of TC development in these years. Such a difference in moisture between the AS and BoB is consistent with the difference in low-level circulation. The difference 850-hPa flow consists of southerly wind component advecting moisture from the equatorial IO into the AS, while northerlies go from land into the BoB that advect dry air. It is interesting to note that it is the dynamic factors, including low-level relative vorticity and VWS, which explain the higher TC activity during post-monsoon compared with pre-monsoon (e.g., the GPI analysis in Xing and Huang 2013). However, it is the RH as one of the thermodynamic parameters that is likely to generate the asymmetry between AS and BoB in some years. Examination of the low-level flow pattern between the active AS and BoB seasons indicates that active AS TC seasons are related to strong northeast monsoon development (and associated excess rainfall in south India) in the NIO. Such a relationship points to a potential forecast parameter for TC activity in the AS, and whether there will be asymmetry between the AS and BoB.

4.4.2 Discussion

While most previous studies on TCs in the NIO focused on the bimodal distribution consisting the pre- / post-monsoon activity and their asymmetry, this study has identified the spatial asymmetry of TC activity between the AS and BoB that occurred during many years in the last three decades. Since there are populated coastal regions and agricultural lands in both of these ocean basins, such a TC spatial pattern has serious implications for preparedness and disastrous impacts.

It has been identified that active TC seasons in the AS (and at the same time almost no activity in the BoB) can be explained by enhanced/reduced moisture in the AS/BoB. The enhancement and reduction in RH is within 10% and that is with respect to the average RH of about 70% in the regions of NIO where most TCs develop. The conclusion herein is mainly based on the fact that dynamic factors such as relative vorticity and VWS do not seem to have asymmetry between AS and BoB. Similar arguments apply to the atmospheric responses during ENSO and IOD. The problem is to what extent such a slight change in RH, which leads to the environment being more conducive/prohibitive to moist convection, results in the AS/BoB asymmetry. Other possibilities include increase/decrease in the number of disturbances in the two ocean basins for TC development due to other factors. Further investigations are necessary to clarify these issues, which may involve regional climate modelling studies.

One possibility of the modulation to tropical disturbances in NIO is from intraseasonal variability (Kikuchi and Wang 2010; Tsuboi and Takemi 2014; Yanase et al. 2012). Such intraseasonal variability includes the MJO and the Boreal Summer Intraseasonal Oscillation (BSISO), with variability ranging from a few days to about two months. Kikuchi and Wang (2010) wrote that both MJO and BSISO can provide seeding disturbances for TC development. However, BSISO would generate a cyclonic vorticity anomaly, thus more directly enhancing TC formation. On the other hand, the major effect from MJO is likely the wake of Rossby wave propagation which may develop into an incipient TC vortex, but that would occur after the wet phase of MJO and turning into a dry phase. Since MJO (BSISO) has an eastward (northward/northeastward) propagation direction, whether they are responsible for generating the asymmetric TC development over AS and BoB is an interesting issue that requires clarification.

Northeast (post) monsoon development is found to relate to active TC season in the AS, which opens the potential for developing seasonal forecast model for AS during post-monsoon, which is in general lacking in the literature and for operational applications. Ng and Chan (2012) developed one of the few statistical TC models for BoB during OND using the stepwise regression technique. Their model includes VWS and upper-level divergence as predictors for estimating TC number, and mainly geopotential heights for estimating ACE value. It would be highly desirable to have a seasonal model for AS during OND, and how these predictors in the model of Ng and Chan (2012) are related to northeast monsoon development in the NIO. An additional note on the measure of northeast monsoon over NIO is that the DIMI, which was developed to indicate summer monsoon development, has been examined in this study. The regions defining the DIMI do not include the strong northeasterlies over the BoB and the accompanied rainfall anomaly over south India and Sri Lanka. An alternative and improved measure for the northeast monsoon has to be developed in order to precisely indicate the processes that may be relevant to TC development on both sides of the Indian continent.

As in the other ocean basins where TC activity is evident, future projection is critical for impact assessment and designing mitigation/adaption measures, especially for the vast population in the NIO largely depending on agriculture. For example, P. Singh et al. (2000) reported an increasing trend of severe TC frequency over the NIO based on the period 1877-1998, which was mainly due to increased frequency over BoB. Muni Krishna (2009) reported a decline in the NIO tropical easterly just (and associated easterly VWS), and suggested that if the recent warming pattern in the NIO persists, TCs are expected to form even during the boreal summer when climatologically the VWS is too large for TC to form during that time. Moreover, Murakami et al. (2013) simulated future TC activity in the NIO using a Japan global model based on the Inter-governmental Panel on Climate Change Fourth Assessment Report's A1B scenario. It was estimated there will be a substantial increase (decrease) in TC frequency over the AS (BoB) under this scenario. Murakami et al. (2017) performed further experiments using a US climate model under the Representative Concentration Pathways, and a similar conclusion was obtained. If this scenario is plausible and similar projection patterns are collected from the latest assessment reports, the critical question is whether the AS/BoB asymmetry in TC activity will be further expanded in the future climate. The relationship to post-monsoon development as has been identified in this study can be applied to assess the latest climate model projections.

Chapter 5: Impacts assessment via storm surge and inundation modelling

5.1 Introduction

It is well known that TC landfall causes coastal flooding which impacts severely on populations, settlements, land cover productivity, roads, other communication routes, etc. This chapter aims to fulfil research objective 3: "*to estimate potential impacts of TCs for the rim countries of NIO for the past and future by simulating both the storm-surge and inundation patterns in the region*". Storm surge, inundation and impacts modelling have been performed followed by climatology of TC in terms of TC genesis and tracking over the NIO. It is noteworthy to mention that the inundation depth due to TC landfalls is very sensitive to changes of TC track and intensities which will ultimately affect the impacts as well (Mori et al. 2014; Takayabu et al. 2015). Since, there is no control on future TC tracks and intensities, uncertainties will always remain on the actual inundation depth and their associated impacts. Firstly, both simulated and observed TC climatology are examined for the periods 1990-2010 and 2075-2099. At the end of this chapter, impacts and minimum needs assessment against specific TC are done by using an impact assessment tool (InaSAFE) for the most vulnerable coastal zone of Bangladesh as a case study. This study found crucial information for disaster managers regarding disaster preparedness and responses.

5.2 Past and future trends of TC genesis and tracks

Murakami et al. (2013), who utilised the Japan Meteorological Research Institute general circulation model (MRI-AGCM) under the IPCC A1B warming scenario, did one of the early studies that simulated future TC activity in the NIO. More recently, Murakami et al. (2017) conducted experiments using the U.S. Geophysical Fluid Dynamics Laboratory climate model under the IPCC RCP warming scenarios also with future TC activity over the NIO in mind. As will be seen later, although there are model biases, both studies demonstrated there will be reduced (enhanced) TC frequency in the BoB (AS). In order to estimate future impacts in terms of storm surge, inundation and even social/economic aspects given such trends of TC frequency, the simulated tracks from Murakami et al. (2017) for both the historical and future periods were acquired from the authors for the following study.

Both past and future tracks were analysed for the entire NIO region. To validate the model, simulated TC tracks for the past (1990-2010) were compared with the observed TC best tracks of IMD (Fig. 5.1). During 1990-2000, IMD recorded 86 TCs for NIO basin and among these 69 and 17 formed over the BoB and AS, respectively (Fig. 5.1a). It is well demonstrated that most of the TC formed and made landfall over the BoB region. About 24% of TCs were intense having an intensity ≥ 64 knots (equivalent to hurricane category-1), which caused large numbers of human deaths and property damage. As for TC frequency, there was also contrast between AS and BoB in terms of intense TC activity. For instance, only 4 out of 20 hurricane category-1 TCs were recorded for AS and the remaining ones in the BoB region. It was also observed that the entire BoB basin mostly had northwestward and northeastward tracks. In contrast to the BoB, only the AS's eastern part close to the BoB basin had TC activity (Fig. 5.1c). During the decade 2001-2010, 58 (25) TCs were observed over the BoB (AS). Of these TCs, 9 were recorded as hurricane category-1 and only 3 were observed over the AS region. Nevertheless, TC activity over AS has increased in recent years. For example, two intense TCs formed and made landfall over the AS coast during 2015. Furthermore, TCs tracks seem to have shifted from the eastern to western region of the NIO.

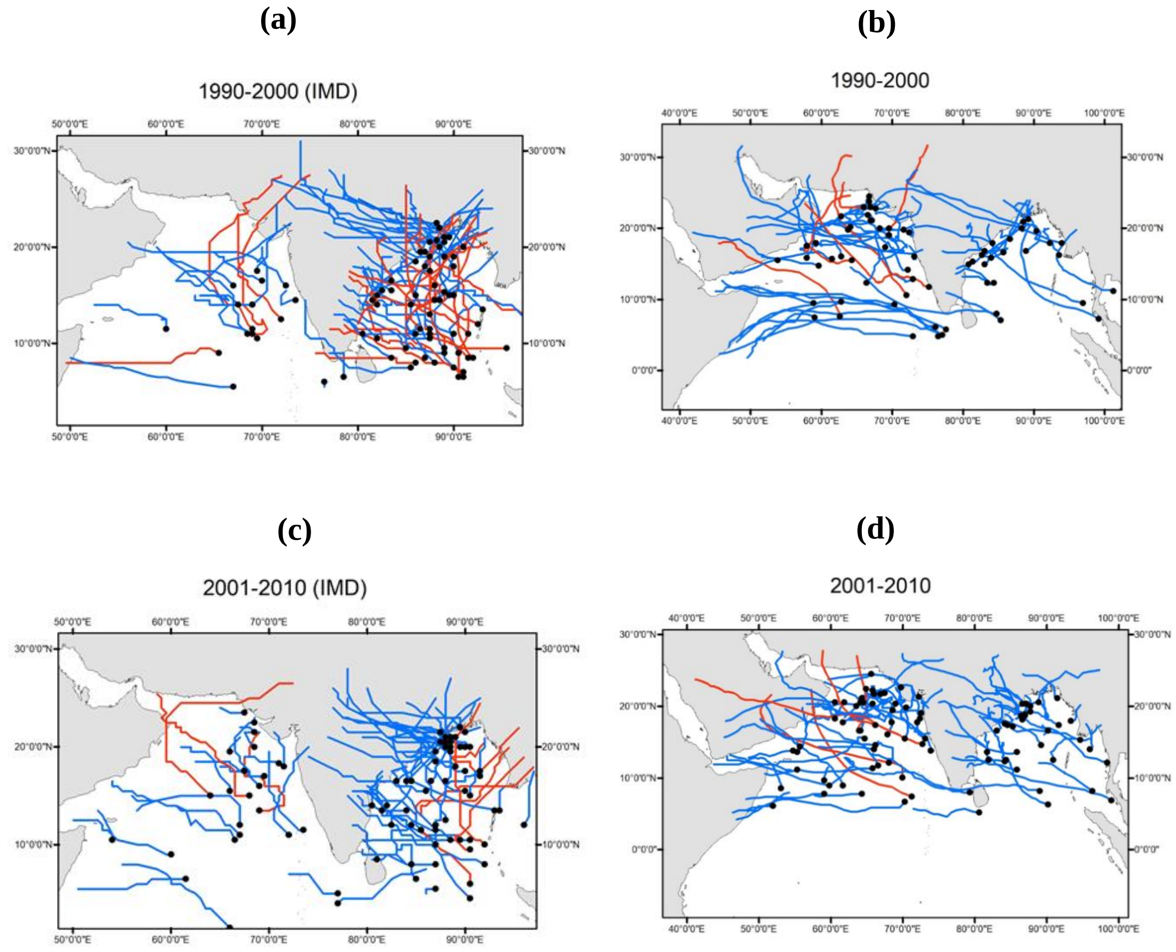


Fig. 5.1 (a) Observed versus (b) simulated TC tracks over NIO during 1990-2000. (c) and (d) are for the period 2001-2010. Black solid circles indicate TC formation locations and red tracks indicate intense TCs having intensity ≥ 64 knots.

Compared to the observed TC activity, overall the model simulated lower TC frequency (67) during 1990-2000 whereas 86 TCs were observed during this time (Fig. 5.1b). Furthermore, the model overestimated (underestimated) TC frequency as well as intensity for the AS (BoB) basin. During this time, no intense TC were simulated for the BoB, although 26 intense TCs were recorded by IMD. Similarly, for the period 2001-2010, the model estimated TC frequency of 35 (52) for BoB (AS) basins in the NIO (Fig. 5.1d). Similar to the observed tracks, the model simulated mostly westward TC tracks. The model significantly underestimates TC frequency as well as intensity for the BoB but not for the AS. During 1990-2010, 11 intense TCs were hindcasted for AS and none of them for the BoB, although the number of intense TCs observed over it during 1990-2010 was six times higher than in the AS. It is worth noting that the AS basin was very active in 2015 compared to the BoB and this trend continued in 2016 and 2017. Overall, the model overestimates about 30% of total TC frequency during 1990-2010 for the NIO. Given this bias and also the slight emphasis of the model for TC formation in the AS basin, the model's performance is still considered reasonable and can be used for estimating future storm activity in the NIO, as has been applied in Murakami et al. (2017).

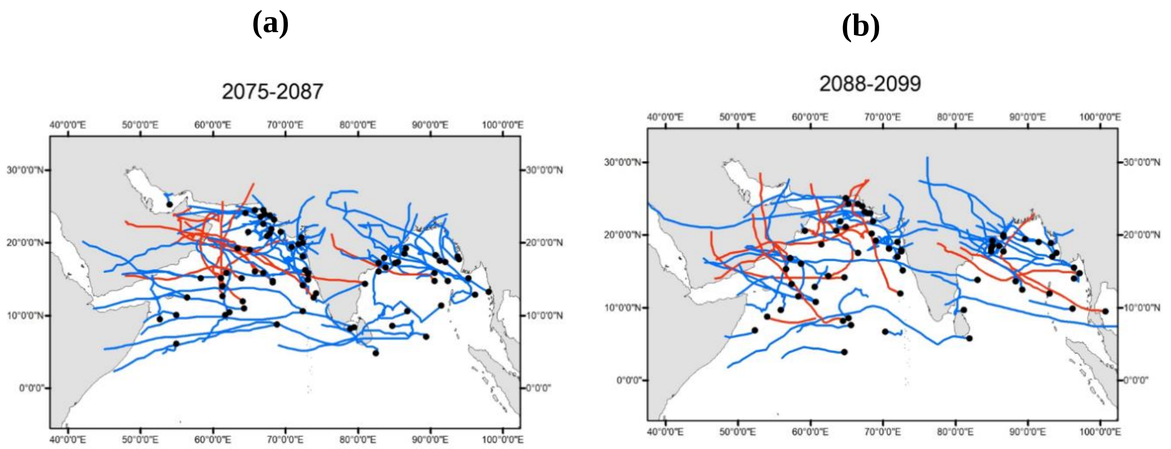
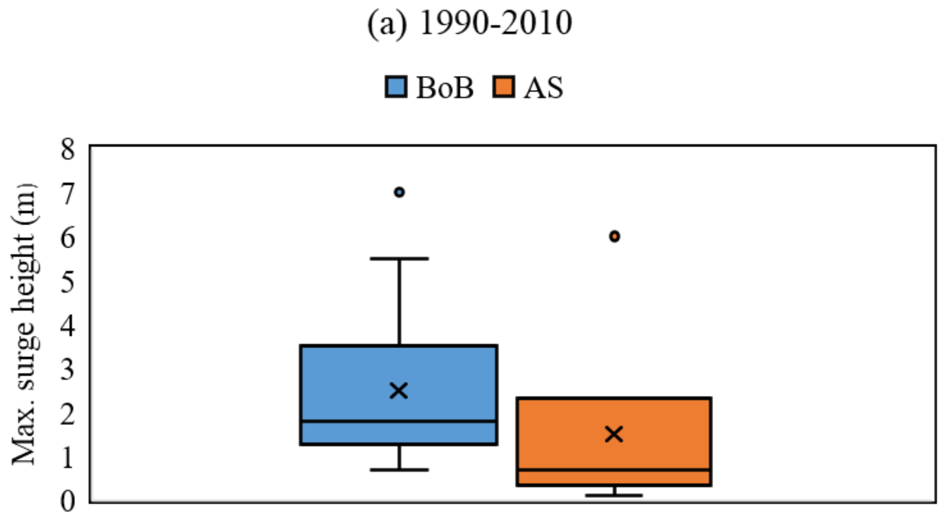


Fig. 5.2 Future projection of TC tracks over the NIO during (a) 2075-2087 and (b) 2088-2099. Black solid circles indicate TC genesis location and red colour indicates intense TC tracks having an intensity ≥ 64 knots.

Future projections of TC formations and tracks for NIO showed enlarged contrast between the AS and BoB in terms of TC frequency and intensity (Fig. 5.2). There will be higher TC activity over the AS compared to the BoB by the end of this century. The model projected TC frequecy for the AS basin almost double that in the BoB for both 2075-2087 and 2088-2099. The model also predicted 5 (19) intense TCs (intensity ≥ 64 kt) out of 143 TCs for BoB (AS). The results suggest that future TCs tracks will be towards the western part of the BoB and AS basin and there will be many TC formations in the coastal regions of the northeast AS. These results clearly demonstrated the potential shifting of TC activity from the eastern to western part of BoB and AS. It is expected that the AS basin will be more active in terms of TC formation, development and landfall.

5.3 Past and future trends of maximum surge height

The simulated TC tracks reported in Murakami et al. (2017) were applied as input to the JMA/MRI storm surge model. No tidal cycle was activated in the storm surge model, and thus only waves generated by the storms have been simulated. The climatology of maximum surge height associated with TCs that reach intensity at least 64 kt both for the past (1990-2010) and future (2075-2099) period have been analysed. Maximum surge has been computed for each intense TC for 48 hours while the TC approaches the coastal areas and makes landfall afterwards. During this period, the TC will cause major damage and there is a great risk of surface inundation. The box plot of all the simulated maximum surge levels for the hindcast period (1990-2010) is illustrated in Fig. 5.3a. The average maximum surge was estimated at around 2 m and 1 m for the BoB and AS, respectively. During this period, two extreme cases were identified: one for each basin where the estimated surge height was 7 m for the BoB and 6 m for the AS. When all cases are considered, the mean value of the maximum surge (middle line in Fig. 5.3) for the BoB was estimated to be almost double of that for the AS.



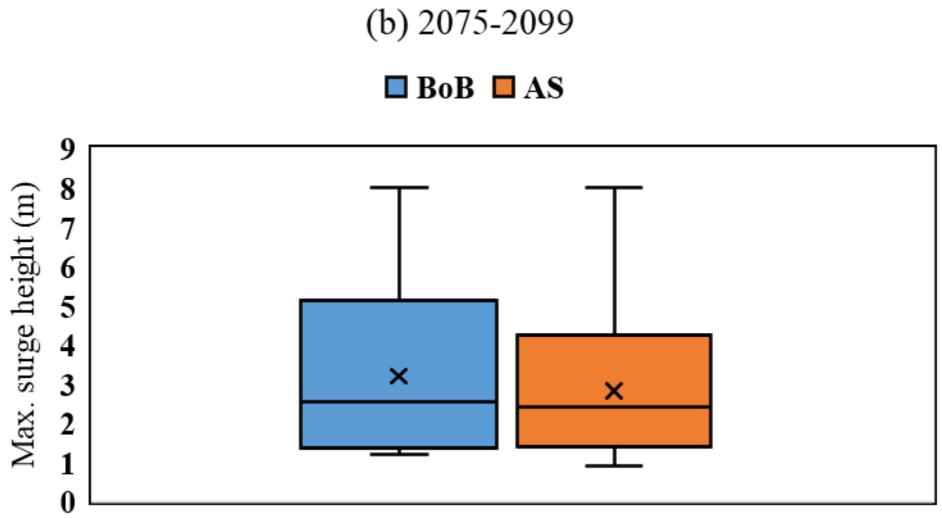
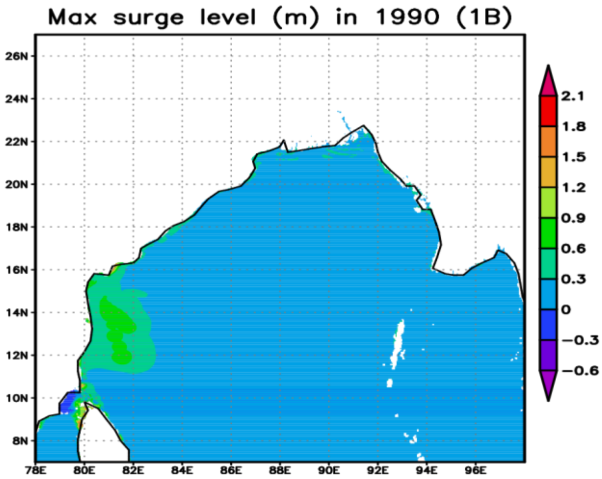


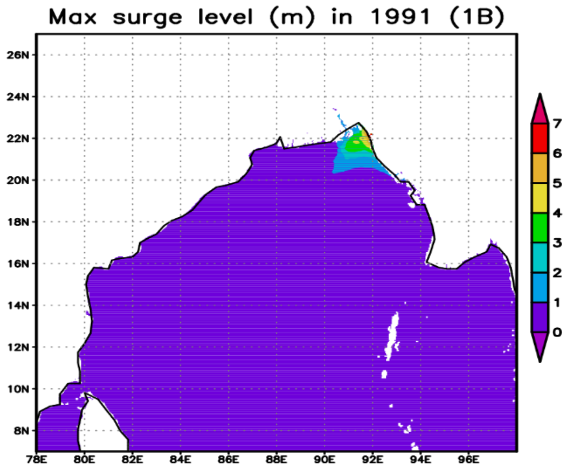
Fig. 5.3 Box plot of the simulated maximum surge height (m) for 48-hour period before and after landfall of TCs having an intensity > 64 kt during (a) 1990-2010; and (b) 2075-2099 over AS and BoB. The sample is 6 and 22 for AS and BoB for the past, respectively, while this is 17 and 10 for the future concerning the AS and BoB, respectively.

For the future TC scenario, there is a significant increase in estimated surge height especially for the AS basin (Fig. 5.3b). Mean surge level is about 2.5 m for both basins, while the two extreme cases are both about 8 m in surge height. There is consequently a clear increase in future surge level for AS compared to the climatology period. For the BoB, the mean surge height only increases slightly, however, the spread toward the high extreme surge levels has also been increased.

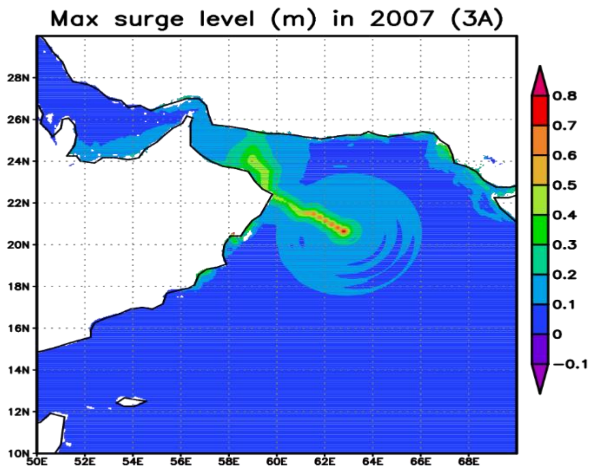
(a) 127 kt wind intensity



(b) 127 kt wind intensity



(c) 127 kt wind intensity



(d) 105 kt wind intensity

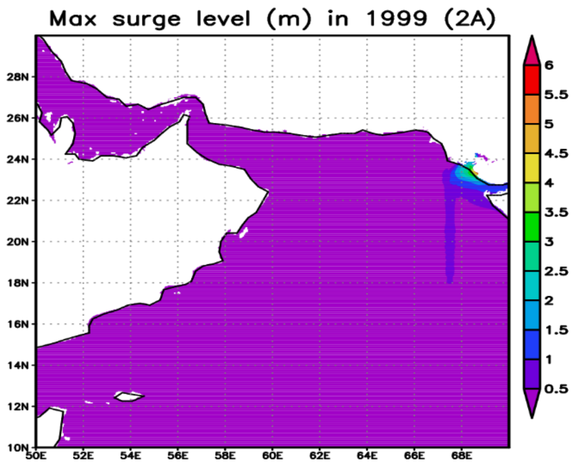


Fig. 5.4 Spatial differences of surge levels for the AS and BoB basins.

It is also important to note that the surge level varies spatially over the NIO because of its topography and tidal effects (the latter not simulated in this study). TCs with similar intensities will result in different surge levels due to their formation and landfall locations. In the future scenario it is expected that surge height increases in the eastern part of AS and BoB (including the Bangladesh coast of BoB) according to the simulated tracks. For instance, two TCs with similar intensity are compared: one made landfall to the western part and another made landfall close to Bangladesh (Figs. 5.4a, b). These two cases resulted in very differrent surge levels (with maximum surge of about 2.1 m versus 7 m, respectively).

Similar cases can be identified for the AS basin as well. TC 3A (Gonu) had intensity 127 kt during 2007 before making landfall over western part of AS, and the TC caused only 0.8 m surge height (Fig. 5.4c). In contrast, TC 2A during 1999 had lower intensity of 105 kt while making landfall over the eastern part of the AS coast, and it generated a maximum surge height of about 6 m (Fig. 5.4d). It can be seen that similar track types like these two cases over the AS can be identified in future climate scenarios. Further studies are necessary for elucidating the factors behind the spatial differences of storm surge height, such as topography, landfall direction and astronomical effects.

5.4 Impact assessment for Bangladesh

There are 4 and 1 intense TCs with landfall within the study area identified for the analysis periods 1990-2010 and 2075-2099, respectively. First, inundation depth was estimated for each identified TC by using the RISC-KIT. For this chapter super cyclone Sidr (2007) is selected as the extreme event while TC 4631 (2090) is chosen for the future scenario. The estimated inundation depths resulting from these two TCs are presented in Fig. 5.5. The impacts of the identified TC strike were estimated using the inundation map layers as a flood event, which is a practice applied in the Coastal Inundation and Flood Demonstration Project - Bangladesh (CIFDP-B). The current version of RISC-KIT applied here only has the digital elevation for the Bangladesh region. Results showed that the future TC has larger and more widely-spread inundation potential compared to the past event. Nonetheless, this analysis was conducted only as a case study, which will be extended to all simulated TCs for the entire NIO when the digital elevation model in RISC-KIT is extended.

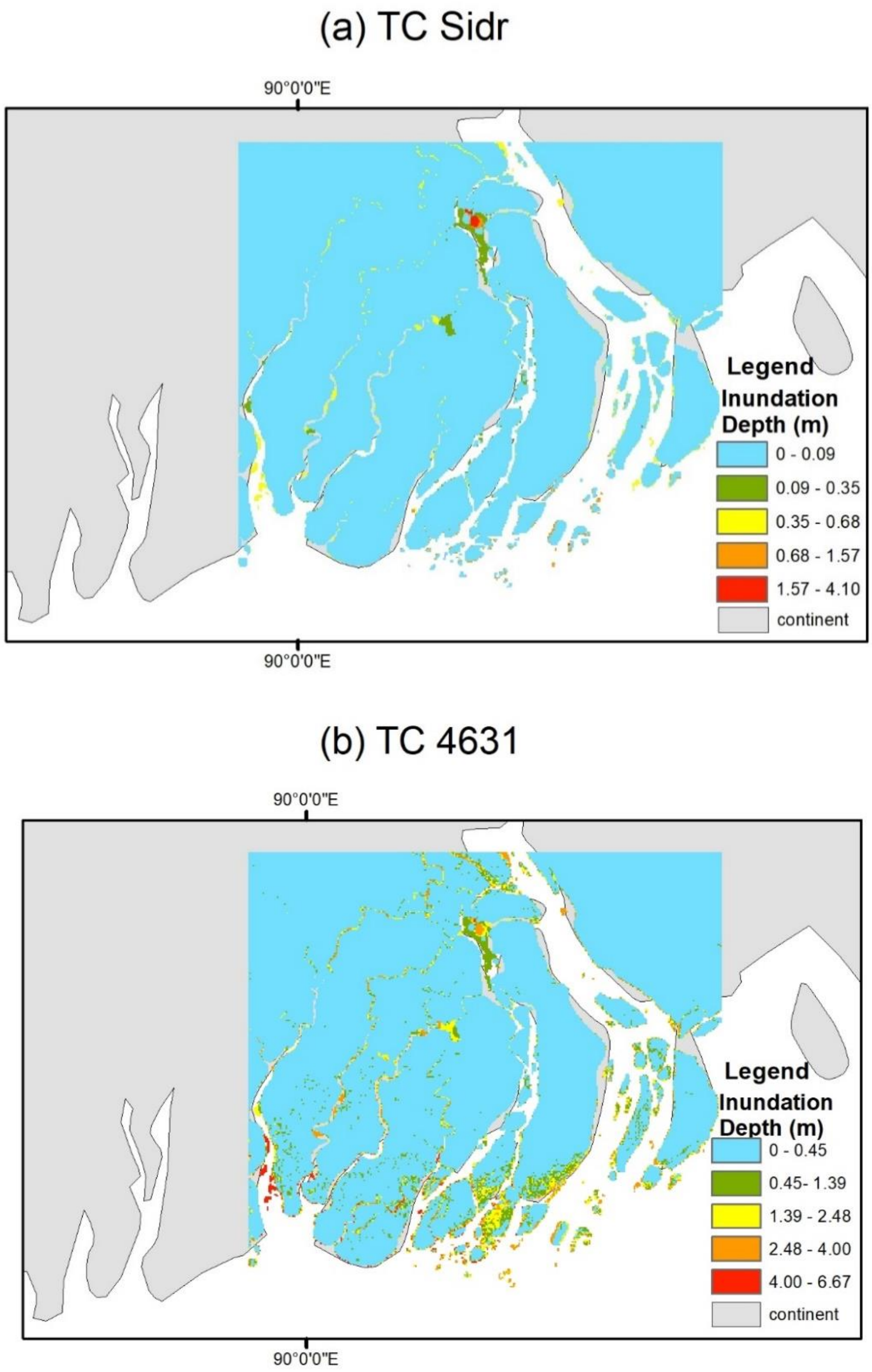


Fig. 5.5 Maps of the RISC-KIT estimated inundation depth (m) for (a) TC Sidr (2007) and (b) the future event in 2090 over the CIFDP-B study area.

For assessment of impact, surface inundation due to TC landfall has been categorised into three hazard zones, namely, high (inundation depth > 3 m); medium (inundation depth 2-3 m); and low (inundation ≤ 2 m). Impacts and needs assessment for TC Sidr, which hit the coast of Bangladesh in 2007, were analysed in terms of impacts on population, buildings, land uses and roads using the InaSAFE tool. To assess future effects, assessment for TC 4631 (2090) was estimated by assuming no change in the exposure components regarding the study area. The InaSAFE tool produces a comprehensive impact report for each case. Furthermore, it also produces a check list in terms of what things disaster managers and policy-makers will need to be considered for preparation and responses. It is worth mentioning that the quality of this report depends heavily on the quality of input data. For demonstration purposes, some of these results are described in the following paragraphs. The tool makes the following assumptions while calculating inundation impacts on populations, buildings, roads and other exposure variables:

- The extent and severity of the mapped scenario or hazard zones may not be consistent with future events.
- The impacts on roads, people, buildings and land-covers elements may differ from the analysis results due to local conditions such as terrain and infrastructure type.
- The analysis extent is limited to the aggregation layer or what is being examined. Hazard and exposure data outside the analysis extent are not included in the impact layer, impact map or impact reports.

5.4.1 Impacts on population

InaSAFE defined exposed people who are present in a hazard zone and they include those subjected to potential losses and inhabitants exposed within the extent of the hazard. This tool considered affected people who are affected by a hazardous event directly or indirectly. Affected people may experience short-term or long-term consequences to their lives, livelihoods or health and in terms of economic, physical, social, cultural and environmental assets. People who are killed during the event are also considered to be affected. This tool considered displaced people as those who, for different reasons and circumstances because of risk or disaster, have to leave their place of residence. In InaSAFE, demographic and minimum needs reports are based on displaced / evacuated people. The impacts of TC Sidr on population are presented in Table 5.1. Results shows around 200,000 people are exposed and among these only 10,500 people are affected while 10,500 people are displaced. The detailed report provides information for different age groups, gender, disability, etc., which is not shown. In the detailed report, about 50% of these displaced people are female and around 1000 are infants. Furthermore, there are 260 and 280 women found to be pregnant and lactating women, respectively. It estimates there are 1600 disabled people. All this information is necessary for better planning and responses.

Table 5.1: Estimated affected people per hazard zone for past and future TC scenarios.

Hazard Zone	TC Sidr in 2007	TC 4631 in 2090
	Count	Count
High	1,200	48,500
Medium	9,400	108,000
Low	177,000	587,000
Total Exposed	187,000	744,000
Population	**Count**	**Count**
Affected	10,500	157,000
Not Affected	177,000	587,000
Not Exposed	8,906,000	8,364,000
Displaced	10,500	157,000

Future TC 4631's (2090) impacts on population have been estimated and the results indicate much more damage being done in comparison to TC sidr (Table 5.1). For example, the selected future TC will affect more than 150 thousand people which is more than 10 times the impact of TC Sidr. Similarly, there are many more people to deal with, including infants, pregnant and lactating women, disabled people, adults, etc., in the future TC scenario. Over time in Bangladesh, having more people will lead to an increase in exposure elements for this study area. These results are consistent with the above maximum storm surge analysis.

Since more people are expected to be affected by future TC scenarios, much more than minimum requirements for displaced people for the future case have been estimated. InaSAFE calculates the minimum requirements for displaced people and these are presented in Table 5.2. Results reveal that more than 500 toilets will be required for the evacuated people in the TC Sidr case, whereas about 8 thousand toilets are needed for TC 4631 in 2090. More interestingly, it also estimates how much food, drinking water, family kits and hygiene packs will be required. It is estimated that around 30 thousand kg of rice and about 200,000 litres are necessary per week for the displaced people in the TC Sidr situation. About 15 times more rice and drinking water are estimated for the future TC case. Exposed population varies according to time (day or night, weekends, holidays, etc.) of inundation, for instance, if it happens at night then it will have much greater impacts compared to day time. Such variations are not included in the analysis. Numbers reported for population counts have been rounded to the nearest 10 people if the total is less than 1,000; nearest 100 people if more than 1,000 and less than 100,000; and nearest 1,000 if more than 100,000. Rounding is applied to all population values, which may cause discrepancies between subtotals and totals. Furthermore, if displacement counts are 0, no minimum needs and displaced related post-processors are shown. These needs will vary according to the resources available for affected areas. More importantly, affected areas’ adaptive capacity has an effect on resources requirements.

Table 5.2: Estimated minimum needs for displaced people for past and future TC scenarios.

Relief items to be provided single	TC Sidr in 2007	TC 4631 in 2090
	Total	Total
Toilets	530	7,900
Relief items to be provided weekly	Total	Total
Rice [kg]	29,400	438,000
Drinking water [l]	184,000	2,732,000
Clean water [l]	703,000	10,459,000
Family kits	2,100	31,300
Hygiene packs	4,200	61,500
Additional rice [kg]	1,500	21,200

5.4.2 Impacts on buildings

Table 5.3: Estimated impacts on buildings for past and future TC scenarios.

Hazard Zone	**TC Sidr in 2007**	**TC 4631 in 2090**
	Count	Count
High	0	278
Medium	15	965
Low	1,100	11,300
Total Exposed	1,100	12,500
Structures	**Count**	**Count**
Affected	15	1,300
Not Affected	1,100	11,300
Not Exposed	160,000	149,000

Both past and future impacts of TCs on different types of structures are estimated and results are illustrated in Table 5.3. The tool estimates extremely higher impacts on buildings for future scenarios compared to a past event. About 10 times more buildings are expected to be impacted in the future TC case compared to the past TC scenario. Nevertheless, the tool may underestimate the impacts in terms of inundation on different types of building. This is because the tool considers the inundation depth when calculating impacts. The lack of information on buildings in the building layers input data is the main reason for underestimating actuall impacts on buildings. It estimates 1100 exposed buildings and of these only 15 were affected in the TC Sidr scenario.

5.4.3 Impacts on roads

Past and future TCs impacts of roads are summarised in Table 5.4. Results clearly demonstrated higher impacts under future TC scenarios. Total exposed road lengths are estimated to be 43 km and 532 km for the past and future TC cases, respectively. The past TC has the potential to affect only less than 1 km of road, whereas this is more than 90 km for the future TC case. This means that most roads will be inundated and this problem will ultimately interrupt responses and evacuation processes.

Table 5.4: Estimated impacts on roads for past and future TC scenarios.

Hazard Zone	TC Sidr in 2007	TC 4631 in 2090
	Length (m)	Length (m)
High	0	17,300
Medium	354	73,400
Low	42,800	441,000
Total Exposed	43,100	532,000
Roads	Length (m)	Length (m)
Affected	354	90,700
Not Affected	42,800	441,000
Not Exposed	7,707,000	7,219,000

5.4.4 Impacts on land use

Similar to other exposure components, higher impacts on landcover are estimated under future TC scenarios which are shown in Table 5.5. Although no impacts on land use for past TC case are assessed, areas that are 1400 ha in size are estimated for the future TC case which may have landfall in 2090. Moreover, landcover is changing over time and this estimation is based on present landcover scenarios. More damage is expected to be done on landcover in the future.

Table 5.5: Estimated impacts on landcover for past and future TC scenarios.

Hazard Zone	TC Sidr in 2007	TC 4631 in 2090
	Area (ha)	Area (ha)
High	0	452
Medium	0	947
Low	645	3,700
Total Exposed	645	5,100
Land cover	**Area (ha)**	**Area (ha)**
Affected	0	1,400
Not Affected	645	3,700
Not Exposed	46,600	42,100

5.5 Conclusions

5.5.1 Summary

Climatology of the simulated intense TCs over the NIO has been analysed for the period 1990-2010 and 2075-2099. Results indicate more intense TCs over the BoB in the past, however, simulated results show a rising number of intense TC over the AS in the future climate scenario. The mean maximum surge will be twice the size in the future and especially over the AS. The general TC track will also shift from the eastern part to the western part of both basins. Furthermore, spatial variation of surge height has been demonstrated through case studies. A large difference in surge level is found for TC cases making landfall over the eastern part of the NIO versus the western part. However, further study is necessary to explain such spatial variation in the surge level. In conclusion, it is expected that higher maximum surge level over the NIO especially over the AS basin will occur if the projected TC activity is robust.

Impacts and needs assessment for TC landfall are performed for both past and future TC scenarios by using the RISC-KIT inundation model and the InaSAFE tool. Results clearly demonstrated the increasing TC impacts and minimum needs for future TC events. In conclusion, it is highly recommended to incorporate this tool into disaster management systems in Bangladesh for building a more resilient coastal community. This can be done by minimising the hazards by providing realistic risk information.

5.5.2 Discussion

In this chapter , intense TCs (hurricane category-1 with intensity > 64 kt) in the climatology and future periods simulated by a climate model have been applied as inputs to a storm surge model. Results clearly demontrated that maximum surge height will be higher over the NIO in the future. Compared to the BoB, the increasing surge level over the AS is more remarkable, which is more than double compared to the past. These results are consistent with the study by Murakami et al. (2013, 2017) who predicted the occurrence of more intense TCs over the NIO and especially over the AS basin. The uniqueness of this study is that model-simulated TC information has been applied for generating inundation depth while some other studies used synthetic TC tracks for estimating inundation depth. For instance, Sahoo and Bhaskaran (2018) used synthetic TC tracks for analysing inundation due to TC activity for India's east coast. Another study by Dasgupta et al. (2013) used an estimated inundation risk map for Bangladesh for the year 2050. They took climate change into account and reported an inundation depth of more than 6 m for some regions including Bhola and Hatiya island. This study found similar results for the year 2090.

As demonstrated earlier, the InaSAFE tool has been applied for calculating realistic impacts and minimum needs assessment for two cases: one in the past and one in the future. This tool gives a wealth of information usable for CRR and it is a tool that can be incorporated into the the real time TC forecasting systems of BMD. The results can then be provided to emergency managers for planning disaster preparedness and responses. The main limitation of this study is the lack of updated and compatable exposure data for this tool. Nonetheless, it is able to generate realistic and informative reports for disaster managers.

Chapter 6: Tropical cyclone risk analysis: a case study from Bangladesh

6.1 Introduction

Since risk perception plays a very important role in formulating and implementing any DRR policy, present scenarios in terms of TC risk and CRR for the coastal areas of Bangladesh are investigated. After analysing climatological aspects of TC activity as well as its potential impacts over the coastal areas of the NIO, a case study has been conducted to analyse the TC risk both from expert and household perspectives. Research objective 4: "*to explore cyclone risk reduction strategies for coastal Bangladesh both from households and experts perspectives*" is considered in this chapter. Three specific research objectives have been formulated under research objective 4 and these are:

i. analyse actual versus perceived cyclone risk at the household level in the coastal community of Bangladesh
ii. investigate experts' perceptions of cyclone risk by people in the community
iii. explore risk reduction strategies by comparing experts and community peoples' actions and desires to reduce the cyclone risk

6.2 Methodology

6.2.1 Study area and data collection

In this study, the areas investigated here were identified followed by sampling procedures that took 4 stages to complete. First, 3 districts, specifically, Patuakhali, Satkhira and Khulna out of 19 coastal districts of Bangladesh were chosen. Secondly, 3 upazila's known as Kalapara, Shyamnagar, and Koyra are identified, one from each chosen district. In the third stage, three unions Lalua, Burigoalini, and Koyra union each from the identified upazila's, respectively - were selected (Fig. 6.1). Finally, a mixture of villages were chosen, these being: Charipara, Soto 5 No., Nawpara, Munsipara, 11 No. Hawla, Chawdhuri Para, Boro 5 No. and Dhangu Para from Lalua union; Burigoalini, Vamia, Durgabati, Parakatla, Datinakhali, Kalbari, Nildumur and Arpangasia from Burigoalini union; and Madinabath, 1 No. Koyra, 2 No. Koyra, 3 No. Koyra, 4 No. Koyra, 5 No. Koyra, Gobra, Harinkhola and Ghatakhali from Koyra union. The selected villages have varied geographical environments, for example, adjacent or not adjacent to rivers, dams, etc., and a diversity of participants in terms of gender, age, income, farm size, occupation, education, experience with past cyclones, etc. (Table 6.1) since these factors can influence or trigger their risk perceptions and actions (Ho et al. 2008; Kellens et al. 2011; Mills et al. 2016; Peacock et al. 2005; Wachinger et al. 2013). These three study areas were badly affected by the two recent severe cyclones, namely, Super Cyclone Sidr in 2007 and Cyclone Aila in 2009 which caused about 3,500 and 191 deaths, respectively, with massive destruction and losses of households, infrastructure, livestock, agricultural production, etc., in coastal Bangladesh. It was reported that in Burigoalini union, Cyclone Aila caused 15 deaths with 5,914 fully and 4,868 partially damaged households (Kumar et al. 2010). In Koyra union, 6,204 households were affected with 50% damage and 5 deaths or missing persons during Cyclone Aila (UNDP 2009).

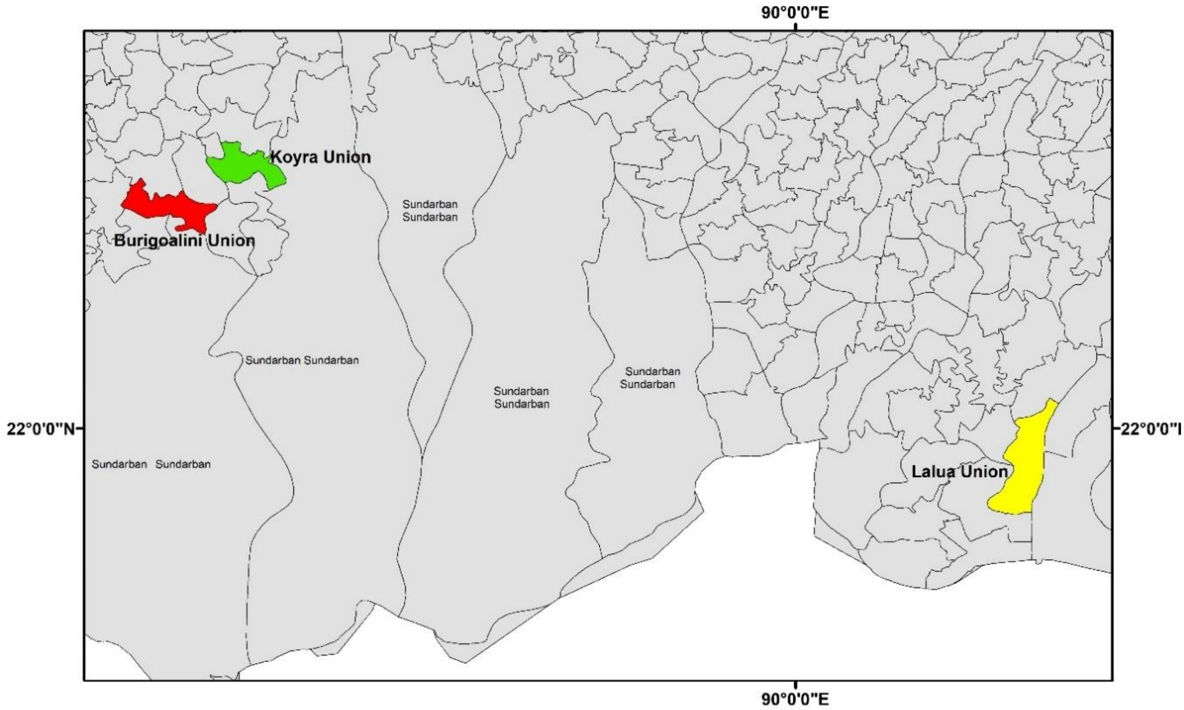


Fig. 6.1 Study areas in Bangladesh: Lalua Union (yellow), Burigoalini Union (red) and Koyra Union (green) from Patuakhali, Satkhira and Khulna districts, respectively.

In this study, the following equation served to determine sample size at 95% confidence level, 0.5 degree of variability and 10% level of precision as proposed by Sam et al. (2017) and based on Yamane (1967):

$$n = \frac{N}{1+N(e)^2}. \quad (6.1)$$

where

n = sample size,

N =population size (total number of households in the study areas), and

e = level of precision.

The total number of households for Lalua, Burigoalini and Koyra unions are 5313, 5760, and 7788, respectively (BBS 2014) and by applying the above equation the calculated sample size for these three unions are 98.15, 98.29, and 98.73, also respectively. Therefore, to assess households' actual and perceived cyclone risk as well as their risk reduction preferences, the first author together with two research assistants conducted surveys among 300 households; 100 households for each study site during 1-19 March 2017 (Macquarie University ethics approval number#5201600982). The research team chose face-to-face verbal interactions for each participant separately since this method is the one most likely to get trustworthy results (Anderson 2003).

Table 6.1: Socio-economic profiles of the participants at the household level.

Socio-economic Characteristics		Lalua Frequency	%	Burigoalini Frequency	%	Koyra Frequency	%
Age	<=30	20	6.7	30	10.0	22	7.3
	31-45	32	10.7	35	11.7	37	12.3
	46-60	29	9.7	21	7.0	25	8.3
	>60	19	6.3	14	4.7	16	5.3
Farm Size (in acres)	<5.0	90	30.0	100	33.3	100	33.3
	5.0-10.0	9	3.0	0	0.0	0	0.0
	>10.0	1	0.3	0	0.0	0	0
Monthly Income (in Bangladeshi Taka)	<5,000	20	6.66	54	18.0	46	15.3
	10,000-5,000	38	12.7	33	11.0	39	13.0
	15,000-10,000	21	7.0	5	1.7	6	2.0
	20,000-15,000	9	3.0	0	0	2	0.7
	>20,000	12	4	8	2.7	7	2.3
Educational Attainment/ Qualification	Not attended	22	7.3	30	10	38	12.7
	Primary	36	12	29	9.7	36	12.0
	Middle	19	6.3	23	7.7	15	5.0
	High	16	5.3	11	3.7	6	2.0
	College/University	7	2.3	7	2.33	5	1.7
Occupation of household's head	Government Service	2	0.7	7	2.33	8	2.7
	Trade and Commerce	18	6.0	13	4.3	6	2
	Agriculture	68	22.6	36	12.0	26	8.66
	Daily Wage Earner	7	2.3	44	14.6	60	20.0
	Unemployed	5	1.7	0	0.0	0	0

Furthermore, 50 experts' opinions about overall coastal people's perceptions of cyclone risk were collected. These experts worked as GOs, NGOs, academicians, scientists and practitioners from Bangladesh and understand what is required in terms of disaster management. The opinions were gathered during March-April 2017. Experts' prescriptions for cyclone risk reduction are obtained to compare and contrast to households' preferences. It is assumed that the common strategies or interventions from both experts and households' can be the first cyclone risk reduction priority for governments and/or other donor organisations to implement.

6.2.2 Theoretical framework

There are various methodologies and frameworks for quantifying risk (Fuchs et al. 2012). For instance, UNISDR (2009) defined risk assessment "is a methodology to determine the nature and extent of risk by analysing potential hazards and evaluating existing conditions of vulnerability that together could potentially harm exposed people, property, services, livelihoods and the environment on which they depend". Furthermore, risk assessment is considered to be a basic component in deciding group risk as well as in defining the risk condition (Shaw et al. 2013). Risk discernment and concern is not quite the same as individuals, groups, districts and regions vary in their considerations, opinions, feelings and preferred activities. Risk can be defined as "the potential disaster losses, in lives, health status, livelihoods, assets and services, which could occur to a particular community or a society over some specified future time period" (UNISDR 2009). Some studies calculated risk as a function of hazard and vulnerability (Saha 2014; Zhou et al. 2015). Recently, it has been defined as the function of hazard, vulnerability and capacity and this definition is widely accepted by the scientific community (Bollin et al. 2016; USAID 2011). Accordingly, risk can be represented as:

$$\text{Risk} = \frac{\text{Hazard} * \text{Vulnerability}}{\text{Capacity or Manageability}}. \quad (6.2)$$

Here,

Risk = Likelihood of harm and loss,

Hazard = Potentiality of geographical, social, environmental, and physical impact of a disturbance, Vulnerability = Lack of capacity of a community to prepare and tackle a hazard, and

Capacity = Community resources that reduce community vulnerability.

Vulnerability can be explained as a function of exposure, sensitivity and adaptive capacity in the recent integrated approach adopted from the Intergovernmental Panel on Climate Change (IPCC) framework for measuring vulnerability (Birkmann et al. 2013; Hahn et al. 2009). Exposure can be defined as the presence of elements, for instance, households' locations, assets, properties, etc., that may be exposed to a hazard causing damage or loss (IPCC 2012). However, all exposed elements are not equally vulnerable in terms of damage and loss, which can be explained through the concept of sensitivity. Beccari (2016) defined sensitivity as a tendency for elements at risk to come to harm as a result of the hazard. In this study, equation (6.3) below has been adopted to quantify actual cyclone risk at the household level for coastal Bangladesh (Rana and Routray 2016).

$$\text{Risk (R)} = \frac{\text{Hazard (H)} * \text{Exposure (E)} * \text{Sensitivity (S)}}{\text{Capacity (C)}}. \qquad (6.3)$$

The components of risk are influenced by different factors such as social income, social bonding, occupation, wind speed, duration, frequency, location of house, etc. The following factors were considered during the construction of the questionnaire:

a) **Socio-economic:** Social bonding, income, occupation, education, loans, house rent, savings, insurance, access to tube-well for drinking water, access to an improved toilet, access to electricity, access to electronic media, access to public transport, food shortages and preserved some dry foods.

b) **Environmental:** Intensity, frequency, duration and magnitude of cyclone.

c) **Physical:** Type of house, building materials and infrastructure.

d) **Geographical:** Location of house, location of agricultural field and distance to nearest medical facility.

e) **Psychological:** Mental disorder, chronic illness, pregnancy or disability, suicide attempt rate, sexual harassment, depression and anxiety and substance abuse (addiction).

f) **Demographic:** Population, gender and type of family.

6.2.3 Actual and Perceived Risk Index

Fifty-nine indicators/questions: 11, 12, 19 and 17, respectively, for hazard (H), exposure (E), sensitivity (S) and capacity (C) component of risk were constructed that cover the aforementioned factors to assess actual risk of cyclone at the household level (see Appendix B1 for detail about the selected 59 indicators). This is based on people's previous experience of extreme cyclones within the last ten years. Then, perceived risk (PR) from the household and expert perspectives was assessed. To assess perceived risk, 10 indicators/questions were asked. The indicators are: likelihood of TC occurrence; how much dread/fear they have; potential of the TC to threaten their lives; likelihood of everything being destroyed or damaged; how much adaptive capacity they have to cope for a future TC; possibility of interruptions in supplies of water, electricity, necessary food, etc.; how much adapting capacity people have if their livelihood options are destroyed; deterioration in relationships as a consequence of future TC; extent of knowledge about mitigation actions; and how much they agree with existing government policies for CRR. To compute the H, E, S, C and PR composite indices, a composite of all the questions for each component were taken, which is similar to that applied in recent studies (Gain et al. 2015; Haitham Bashier and Jayant 2014; Rana and Routray 2016).

$$CI = \frac{W_1 + W_2 + W_3 + \cdots W_n}{n} = \sum_{i=1}^{n} \frac{Wi}{n}, \qquad (6.4)$$

where

CI = the composite index,

W_1 to W_n = the respective weights employed to indicators, and

n = the number of indicators/questions used to compute the CI.

By following the general principle of the computing composite index, the Hazard Index (HI), Exposure Index (EI), Sensitivity Index (SI) and Capacity Index (CAI), and Perceived Risk Index (PRI) were computed and defined as follows:

$$Hazard\ Index\ (HI) = \frac{\sum_{i=1}^{11} HW_i}{n},$$

$$Exposure\ Index\ (EI) = \frac{\sum_{i=1}^{12} EW_i}{n},$$

$$Sensitivity\ Index\ (SI) = \frac{\sum_{i=1}^{11} SW_i}{n},$$

$$Capacity\ Index\ (CAI) = \frac{\sum_{i=1}^{11} CW_i}{n},$$

$$Perceived\ Index\ (PRI) = \frac{\sum_{i=1}^{11} PW_i}{n},$$

$$Actual\ Risk = \frac{HI*(EI*SI)}{CAI}. \qquad (6.5)$$

After computing these indices, actual risk index was calculated by using equation (6.5).

6.3 Results

6.3.1 Actual risk assessment at household level

The present study quantifies actual risk indices for Lalua, Burigoalini, and Koira unions based on past experience with extreme cyclone at the household level, shown in Fig. 6.2. Results show that of these three locations, Koyra union has the highest mean risk index (0.42) and the lowest risk index (0.32) is in Lalua union whereas 0.38 was reported for Burigualini union. These variations can be explained by the nature of damage done and people's agricultural practices in these areas. During Cyclone Aila that ravaged both Koyra and Burigoalini unions, the embankments in these areas were fully or partially damaged in some parts and triggered increasing amounts of saline water throughout the agricultural lands and people's homes. These problems created much long-term suffering for many people. Many participants mentioned that after Cyclone Aila they could not rear cattle or goats due to the scarcity of drinking water. Furthermore, Cyclone Aila hit so suddenly that people had virtually no time to prepare. Respondents explained that if Cyclone Aila had occurred during night time, human casualties would have been extremely high. Compared to Burigoalini and Koyra unions, the saline water problem in Lalua union is less and likely due to the actual risk index being lower. Although this study did not find significant differences in average actual risk indices among the study areas, it is noticed significant differences among individuals. Therefore, it can be concluded that the impact or risk of a hazard is not the same for each household even in the same community since impact depends on various socio-economic and geographical factors.

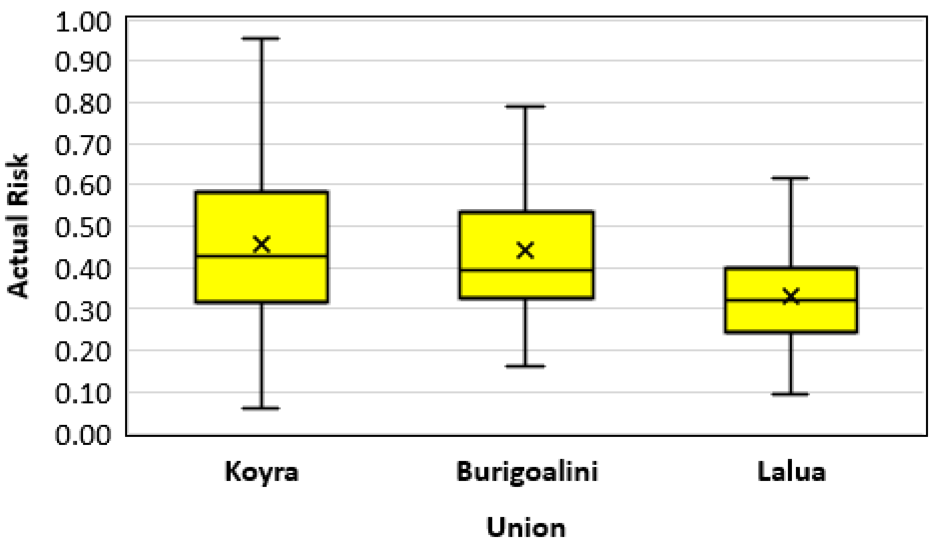


Fig. 6.2 Index of actual risk for the three study areas (Lalua, Burigoalini and Koyra unions).

Furthermore, the correlation between actual risk and some socio-economic factors, for instance, occupation, income, education, and farm size, are elucidated and results are

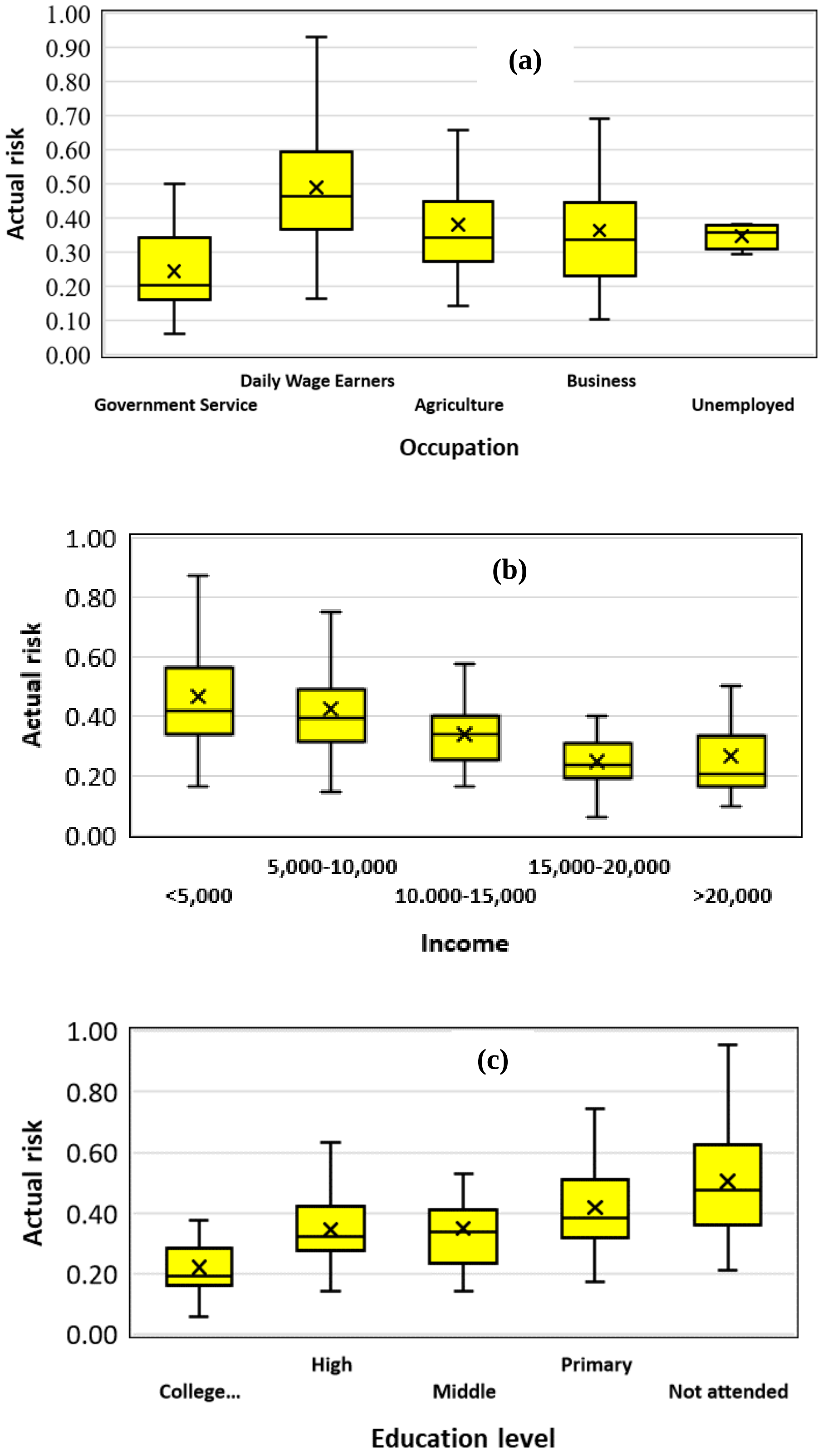


Fig. 6.3 Dependence of actual cyclone risk (household level) on occupation, income in Bangladeshi Taka and education achievement/qualification.

represented in Fig. 6.3. These results clearly indicate that positive correlation of actual risk with the status of participants' occupation (government service to unemployed) (Fig. 6.3a). Since government jobs are permanent and other jobs including agricultural production are precarious in Bangladesh, government employees perceived lower cyclone risk. However, it is found that with increases of income, education level and farm size (not shown), the actual risk value decreases (Figs. 6.3b, c). Participants who have higher incomes and larger farms must have a higher capacity to tackle any kind of disasters, so this results in less risk. Similarly, educated people will generally have more knowledge of early warning systems as well as CRR strategies to help them through an actual risk situation.

6.3.2 Perceived risk analysis

6.3.2.1 Perceived risk assessment at household and expert level

This study assesses communities' perceptions as well as those of experts regarding future cyclone risk (Fig. 6.4). Results indicate that the perceived cyclone risk is more or less the same in the three study areas (Fig. 6.4a). The average perceived risk of the three study sites is 0.72 whereas this value is 0.68 based on experts' opinions about what coastal communities think about overall cyclone risk perceptions, which is slightly lower than the actual community's perception.

Also, this study analyses differences in risk perception from the gender perspective (Fig. 6.5). Results indicate similar perceived cyclone risk values from male and female respondents from ordinary households in the three sites or at the expert level. However, female respondents perceived a slightly higher risk than males at the household level but the opposite results are found for the expert level. Since these three areas are severely affected by many cyclones and all participants had experiences with cyclone attack, these kinds of results are expected. The three study districts have experienced similar frequencies of cyclone in the past (Barua et al. (2016). Therefore, risk perceptions in these areas may be quite similar.

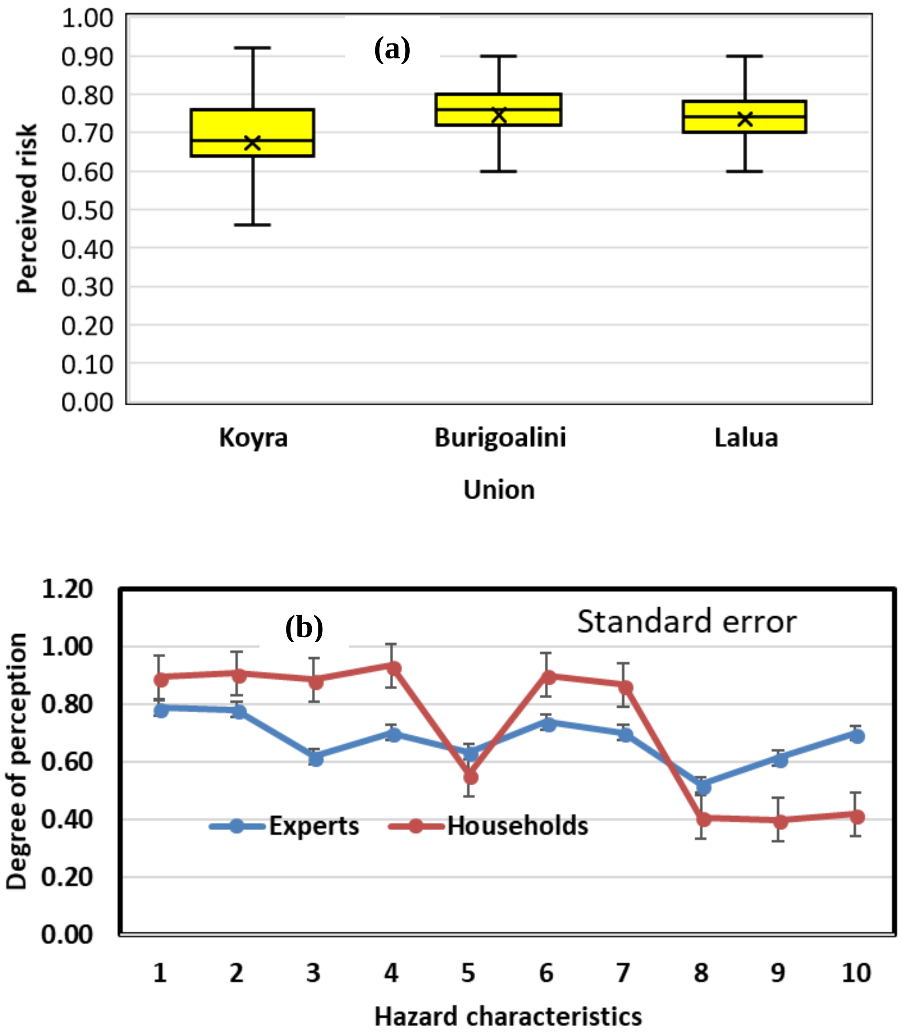


Fig. 6.4 Perceived risk index from household perspectives in the three study areas (Lalua, Burigoalini and Koyra) (a). The same index from households vs experts, standard error bars have been added to those for households (b). The hazard characteristics 1 to 10 indicate: 1= Likelihood, 2= Dread/Fear, 3= Threatening Life, 4= Likelihood of damage, 5= Ability to cope, 6= Interruption of supplies, 7= Adapting lifestyles, 8= Altering relationships, 9= Knowledge about mitigation actions, and 10= Agree with policies, corresponding to the 10 survey questions for perceived risk.

6.3.2.2 Factor affecting perceived risk at household level

There are various factors that influence risk perception of hazards. It has been reported that gender, education level, income, farm size, occupation, past experience with hazard and

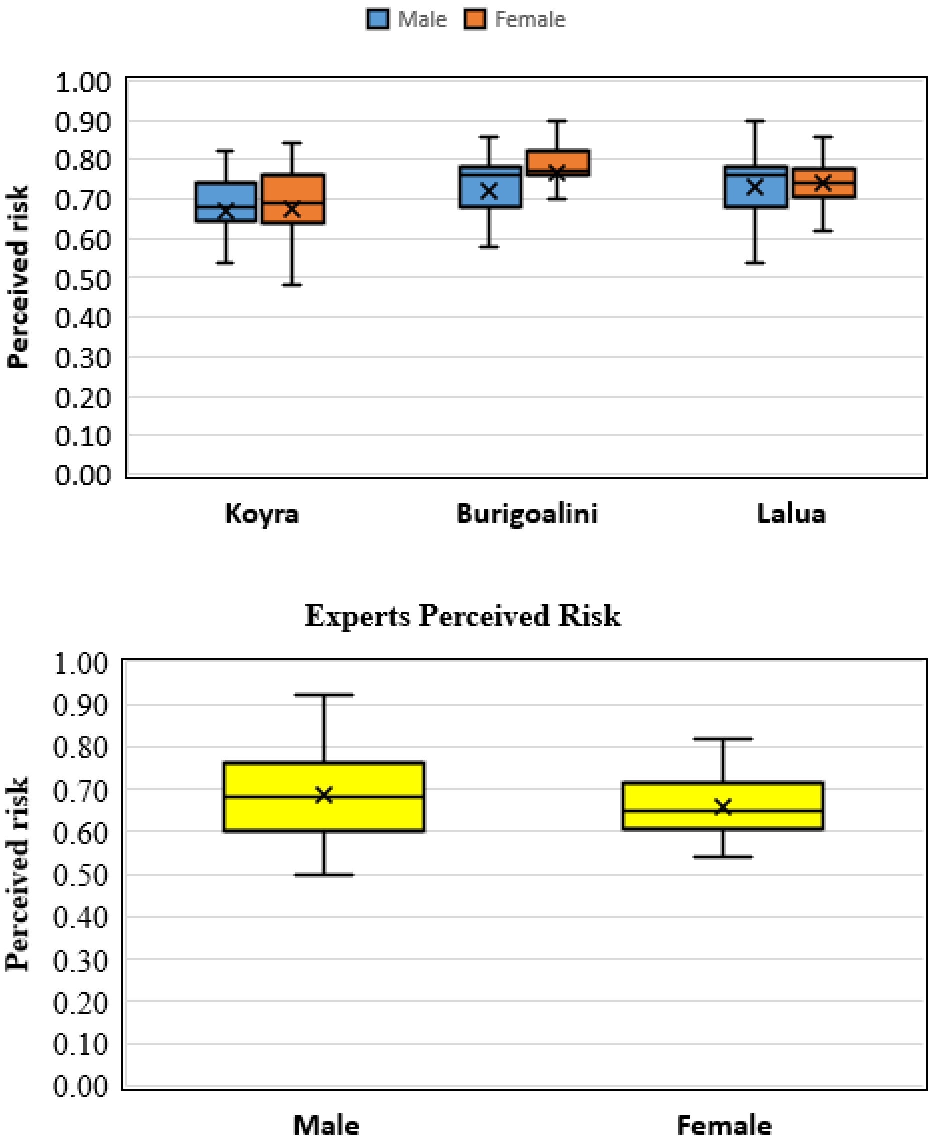


Fig. 6.5 Risk perceptions from gender perspectives for households (above) and experts below).

geographical locations are the predominant factors affecting risk perception (Ho et al. 2008; Kellens et al. 2011; Mills et al. 2016; Peacock et al. 2005; Wachinger et al. 2013). Rana and Routray (2016) revealed that perceived risk increases when the actual risk perceptions of people also increase. This study first analyses the relationship between actual and perceived risk. It emerged that through a Pearson two-tailed correlation analysis there is no relationship between the two (Fig. 6.6). Thus, it can be said that the factors determining cyclone risk make very different contributions to perception and actual risk. This can be illustrated when the dependence of perceived risk on the socio-economic parameters, as in the analysis of actual risk, is examined.

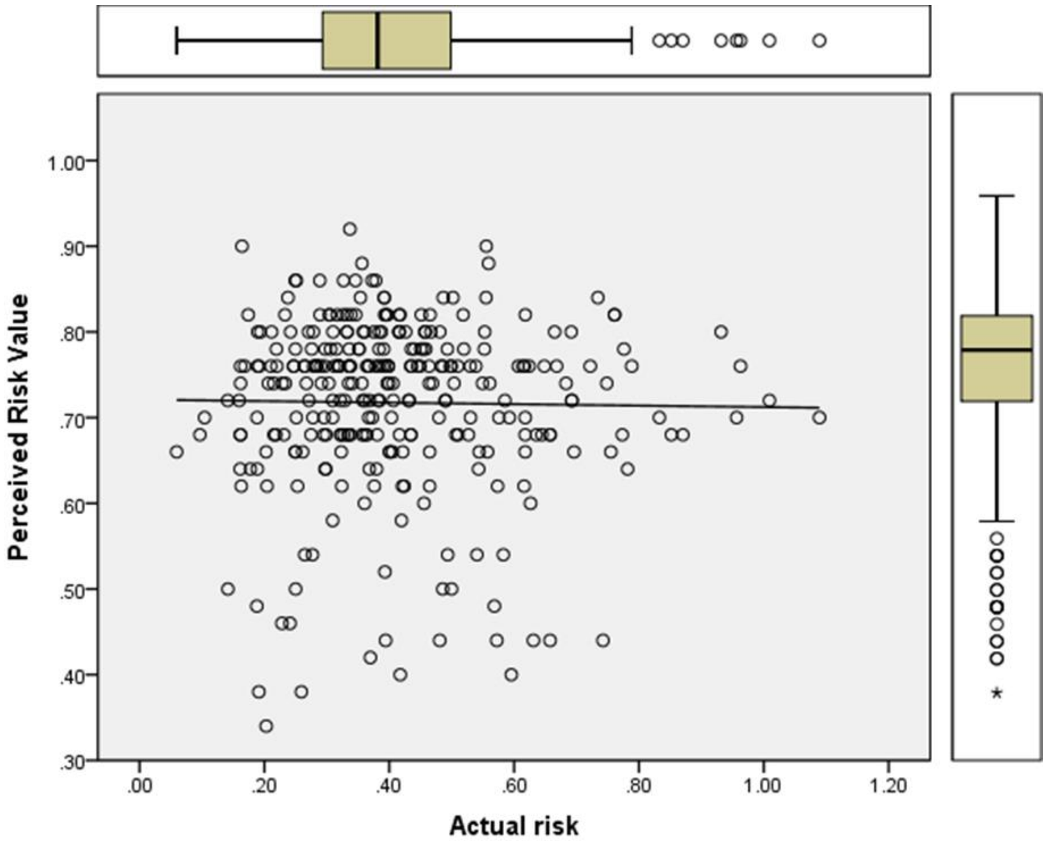


Fig. 6.6 Correlation between actual and perceive risk at household level.

Referring to the relationship between perceived risk and some socio-economic parameters (occupation, income, education and farm size) of the respondents, this study found similar trends concerning actual risk, except for the relationship between perceived risk and farm size. Results indicate a positive trend line for the relationship between perceived risk and farm size, whereas a negative relationship has been identified in actual risk.

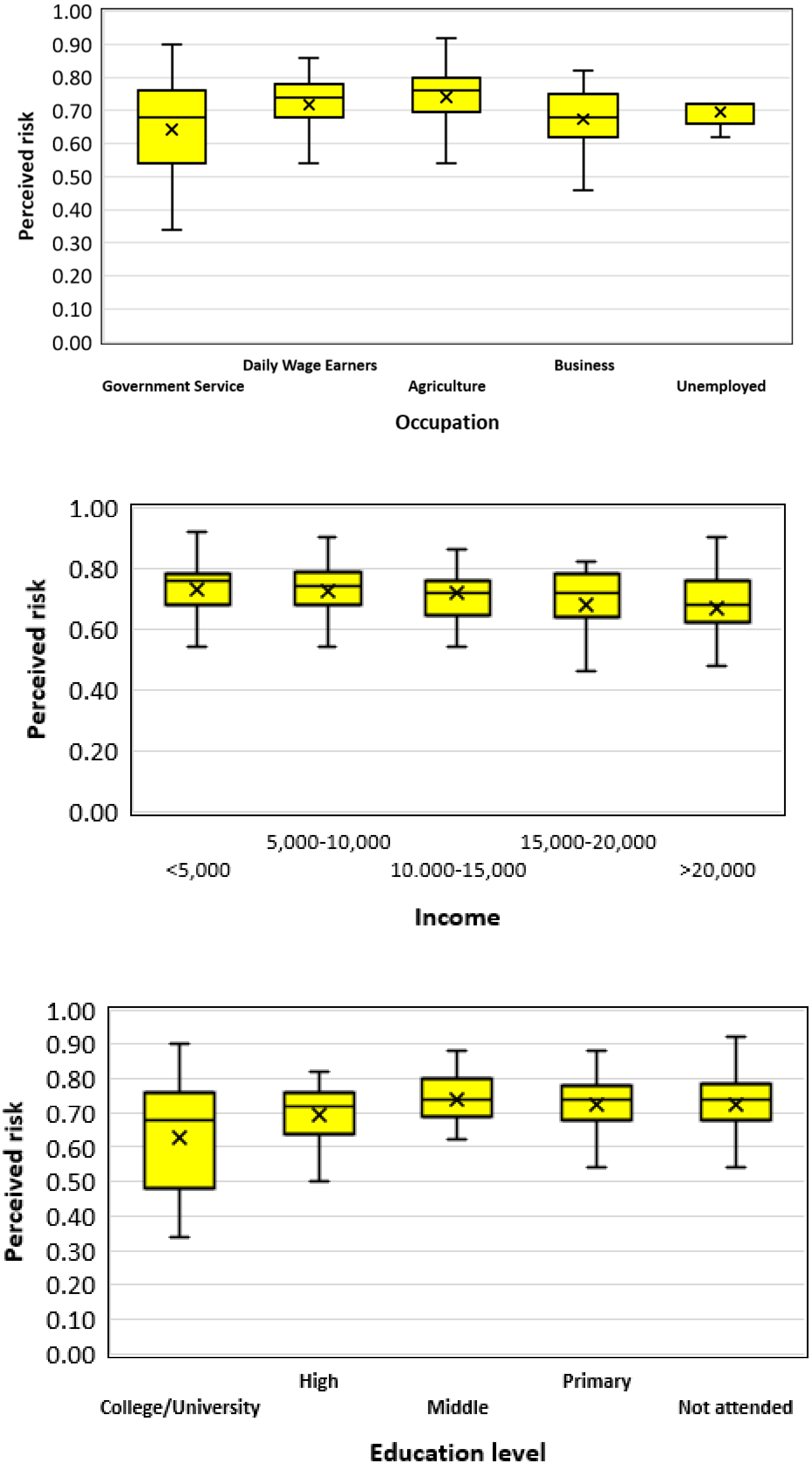


Fig. 6.7 Dependence of perceived cyclone risk (household level) on occupation, income in Bangladeshi Taka and education level.

6.3.3 Cyclone risk reduction (CRR) strategies in coastal Bangladesh

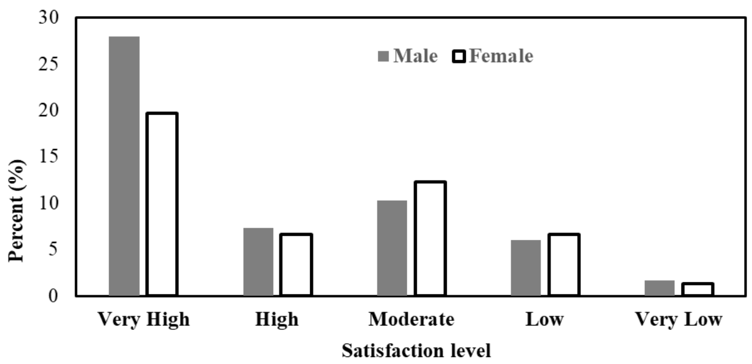
6.3.3.1 Current status of CRR strategies for Bangladesh

Despite Bangladesh being a developing country that is highly populated and still generally poor, it has gained global recognition for better natural disaster management, particularly tropical cyclone management. This country is considered as a role model for natural disaster management in some aspects. The government took the initiative to minimise damage and losses, especially to reduce human casualties and the destructive aftermaths of catastrophic cyclones in 1970 and 1991. These included many programs, for example: the implementation of the Cyclone Preparedness Program (CPP) with the Red Crescent Society in 1972, emergence of the Disaster Management Approach in the 1980s and 1990s, Disaster Management Bureau (DMB) in 1993 and now named the Department of Disaster Management (DDM), drafting of the Standing Orders on Disaster (SOD) in 1997 (revised in 2010 for the National Plan for Disaster Management (NPDM), Comprehensive Disaster Management Programme (CDMP-I & II) in 2004 and 2009, revised the Standing Orders on Disaster (SOD), and the Disaster Management Act 2012. The Bangladeshi government together with foreign donors took both structural and non-structural measures to make natural disaster management effective (Haque et al. 2012; Islam et al. 2013; Mallick and Rahman 2013). In the case of cyclone management, early warning systems, training given to volunteers, practitioners as well as community people, search-rescue operations, providing relief, etc., are the major non-structural measures. On the other hand, the common structural measures are to build embankments, cyclone shelters, roads, etc. It has been observed some structural measures in the study areas which are shown in Fig. 6.8 and it was found some community people who had been trained on disaster management. School cum cyclone shelter is the most effective and popular structural measure for CRR (Figs. 6.8a, b). Furthermore, pond sand filters (PSF) and rain water harvesting tanks are used in Burigoalini and Koyra unions (Figs. 6.8c, d). Outcomes from the above-mentioned activities can be seen from the comparison of the scenarios of the 1991 cyclone and the 2007 cyclone (Sidr). The 1991 cyclone hit coastal Bangladesh with a maximum wind speed of 225 km/hr and the death toll was 138,882. Conversely, Cyclone Sidr struck coastal Bangladesh with a maximum wind speed 240 km/hr and its death toll was 3500 (Paul 2009). Government initiatives and in particular the application of an early warning system and building cyclone shelters in the coastal areas reduced the possible death toll and damage.

Fig. 6.8 Some representative pictures showing adaptation and mitigation measures: (a-b) school cum cyclone shelter; (c) Pond Sand Filter (PSF) for drinking water; and (d) Rain water harvesting tank.

The recognition of government initiatives and actions for disaster risk reduction (DRR) and climate change adaptation (CCA) are reflected by the respondents' opinions. In this study, 300 households and 50 experts were asked the following question: "how much do you agree with govt. policies for DRR and CC?" and the results are represented in Fig. 6.9. They suggest that about 50% and 25% households have a very high and moderate satisfaction level regarding government initiatives, respectively. Only less than 2% of households expressed a very low satisfaction level and this may be due to their bitter experiences during any kind of disaster. For instance, Islam et al. (2016) reported that although the government provides good support in terms of distribution of relief, providing livelihood assistance and reconstruction of community services, bribery and political bias work against the principles of equity and ensuring proper services for all. Similarly, the majority of experts expressed a moderate to high satisfaction level towards government responses (Fig. 6.9b). It is interesting to note that in general, female respondents are less happy than males both from the households and experts levels.

(a)



(b)

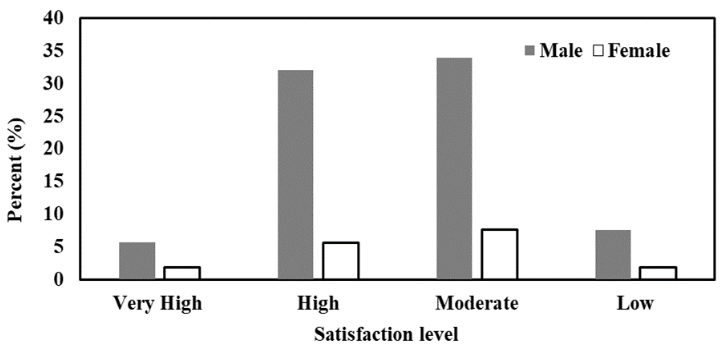


Fig. 6.9 Households' (a) and experts' (b) satisfaction levels towards government responses to DRR and CCA.

6.3.3.2 CRR strategies from household perspectives

This study explored local people's experiences regarding the impacts of cyclones and what they can do for themselves, and what the government can do for cyclone risk reduction in coastal Bangladesh. Results revealed that people are mostly concerned about the impacts of cyclones on people's lives, houses and then their properties and assets. To assess households' preferences and capacities for CRR, it is asked a hypothetical question, "*Suppose, the government gives you BDT 30,000 for risk reduction and you must use this money only for risk reduction, what you will do with this money*?". The study found that in total 33 opinions from 300 respondents (for details see Appendix C1) were broached on this topic. More than 50% of respondents wanted to build a cyclone resilient house and the second preference was to increase plinth height of houses (26%) and do business (25%). It is clearly evident that most actions are related to people's socio-economic status.

These opinions can play an important role when government policies are being formed and implemented, since the results reflect capacity as well as what local people prefer. Later on, another hypothetical question was asked: *"Suppose the government has a big project for cyclone risk reduction for the coastal community; what sorts of support will you want from the government to minimise your household risk for pre-cyclone, during a cyclone and post-cyclone (at least 3 for each phase)*?". The study documented 40 suggested prescriptions and among these the top ten are and in terms of frequency (%):

a. Build more cyclone shelters (48.3%)
b. Provide adequate dry food during a cyclone (48.3%)
c. Help to build cyclone resilient houses (45%),
d. Improve and repair roads (40.7%)
e. Improve embankments in the coastal areas (30.3%)
f. Provide pure drinking water during a cyclone (22%)

g. Install more Pond Sand Filters (11.3%)

h. Provide safe latrines (7.7%)

i. Supply clothes ((7.7%) and

j. Supply medicines during a cyclone (6.3%).

6.3.3.3 CRR strategies from expert perspectives

Experts' prescriptions for people in the community and the government's CRR strategy were explored in the present study. Experts were asked about what community people can do for CRR and elicited 24 suggestions, of which the top then were with frequency (%): preserve food (30.2%); go to a cyclone shelter (28.3%); help CPP volunteers and family members to reach a cyclone shelter (22.6%); regular meetings and training (18.9%); participate in an awareness programme (15.1%); build cyclone resilient houses (15.1%); follow early warnings (9.4%); participate in rescue operations (7.5%); rehabilitation (7.5%); and preserve pure drinking water (7.5%). Nevertheless, only a few experts mentioned some important suggestions, for instance, formation of properly funded formal community organisations, strengthening emergency and first aid knowledge, formation of youth volunteer groups who can offer practical help, etc. These suggestions are important for CRR in coastal Bangladesh.

Similar to the households' level, a hypothetical question was asked to experts: *"Suppose the government has a big project for cyclone risk reduction for coastal communities; what sorts of measures would you prescribe to minimise your household risk for pre-cyclone, during a cyclone and post-cyclone*?". In total 37 measures were obtained from them (for details see Appendix C3). Experts are mostly concerned with building cyclone shelters (26.7%), fostering awareness programmes in the communities (22.6%), a trustworthy Early Warning Message (EWM) system and building safe embankments (18.9 %), and helping to build cyclone resilient houses along the coastal areas. Furthermore, they prescribed some measures for saving the environment, distributing relief and rehabilitation as well as offering development opportunities to coastal people. It is worth noting that experts and local people agree that any innovations or technology implemented in the coastal areas must be user-friendly and particularly for older people.

6.3.3.4 Proposed CRR strategies for Bangladesh

This study proposed an integrated bottom-up and top-down approach for analysing tropical cyclone risk reduction (CRR) which is presented in Fig. 6.10. It is well-known that any differences in risk perceptions in terms of preparedness and adoption of policies, procedures, innovative measures, etc., will be evident between experts and local people. For this reason present study considered opinions and suggestions both from groups aiming to make CRR more effective and fruitful. The proposed framework consists of 4 stages and the first 3 steps concern both the expert and household level. The first step is to assess actual cyclone risk and taking into account hazard potential, vulnerability both from the exposure and sensitivity point of view, and ability to face and overcome the hazard both from the community and household levels. This is to be done as actual risk triggers the future risk perceptions which ultimately affects CRR attitudes. Furthermore, before going for accepting CRR, it is important to know the actual impacts of a cyclone based on people's previous experiences. Secondly, to assess perceived risk the focus should be on probability of loss and damage caused by a future cyclone. The first two steps give a complete scenario of overall risk perceptions. The next step is to explore and collect CRR strategies/measures from local people and relevant experts and practitioners. The final step is to analyse the CRR measures and prepare and prescribe a list consisting of clearly articulated CRR plans and actions. After implementing this CRR analysis framework for the three coastal study sites in Bangladesh, this study prescribes some CRR measures for before, during, and post-cyclone scenarios and these are listed below:

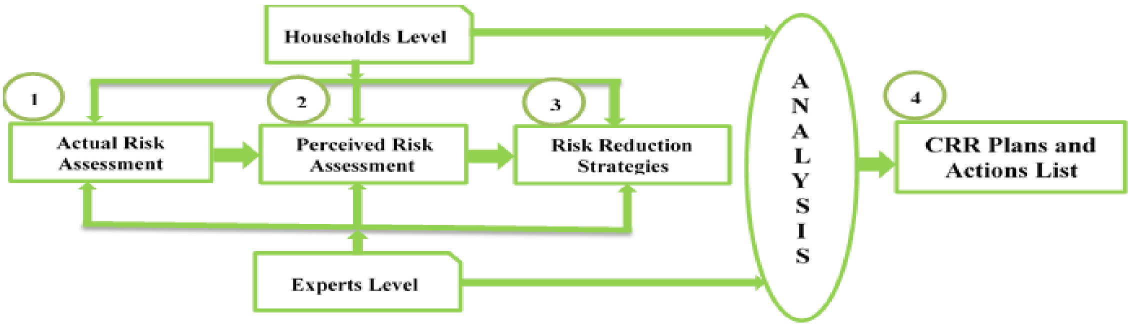


Fig. 6.10 Conceptual framework for cyclone risk reduction (CRR) analysis.

Pre-cyclone:

1. Build more cyclone shelters
2. Build private cyclone resilient houses
3. Develop or improve embankments and sluice gates, and polders
4. Develop or improve roads
5. Restore mangrove forests and suitable tree plantations in the coastal areas
6. Trustworthy cyclone warning and forecasting systems
7. Awareness raising and training programs
8. Community managed cyclone warning centres
9. Increase the number of volunteers who can offer practical assistance
10. Professionalisation of the Department of Disaster Management (DDM)
11. Provide user-friendly innovations that can help the community
12. Increase the plinth level of houses and ponds
13. Install Pond Sand Filters (PSF) to ensure pure drinking water for all
14. Supply electricity to all areas so that they can use TV, radio, internet, etc.
15. Open more medical centres to ensure timely health services
16. Formation of well-funded community-based formal organisation to tackle any hazards and help people facing disaster

17. Develop region-wise risk profiling and risk reduction plans by engaging people in the communities
18. Supply lifesaving materials, for instance, life jackets, hand-mikes, boats, first aid kits, radios, torches, etc.

During cyclone:

1. Disseminate up-to-date warning messages to all
2. Provide adequate food and drinking water supplies as relief that must be managed centrally to avoid any overlap or duplication of effort
3. Fostering assistance to older people, children, women and disabled people to reach cyclone shelters
4. Ensure safety and security in the cyclone shelters
5. Supply clothes and medicines where necessary
6. People in the communities to participate in search and rescue operations

Post-cyclone:

1. Help to repair damaged houses and infrastructure
2. Provide relief and healthcare where necessary
3. Provide financial support to poor people and those who have lost everything
4. Supply materials, for instance agricultural seeds, livestock, poultry, silai machines, etc., to improve or restore people’s livelihoods
5. Create employment opportunities for the affected people
6. Follow-up relief distribution strategies

6.4 Discussion

Cyclones represent an unexpected climatic event that can severely damage or destroy the communities of poorer people living along the coast in Bangladesh. Results revealed that most people's houses cannot resist tropical cyclones (Fig. 6.11b). Secondly, this study identified that there are not enough cyclone shelters in convenient locations to accommodate a large number of people. This problem has been noted elsewhere (Dhakal and Mahmood 2014; Mallick 2014; Mallick et al. 2011). Furthermore, the communication system throughout Bangladesh is very poor generally, and there is a great risk in going to a cyclone shelter. Vulnerable roads close to a cyclone shelter are common, as shown in Figs. 6.11a, c and d. These depictions clearly illustrate how vulnerable these are and particularly when they and their immediate environs are inundated. One anonymous participant from Lalua union of Patuakhali began to cry during the interview, stating that his old father died while trying to reach a cyclone shelter due to improper roads. This tragedy occurred during Cyclone Sidr in 2007. Experts suggested building more cyclone shelters in suitable and convenient locations regardless of political or economic sensitivities, and recently, they advocated the erection of private cyclone resilient houses financed by the government for the most vulnerable communities. Furthermore, embankments play a vital role in protecting coastal people and their properties and assets during a cyclone (Ataur Rahman and Rahman 2015; Dasgupta et al. 2013). It is observed that the height and structure of the embankments with their sluice gates in Lalua, Burigualini, and Koira unions are not strong enough to combat a storm surge. As a result, thousands of hectares of croplands were damaged in Lalua union, while shrimp farms were destroyed in Burigualini and Koira unions during Cyclones Sidr and Aila, respectively. Moreover, most people of Nawpara, Patuakhali, built their houses close to the Ramnabad channel (embankment), which was breached by a storm surge (Fig. 6.11a shows embankment). Among the three study sites, it is observed that severe pure drinking water scarcity in both Burigoalini and Koira unions. Also, it is noticed that only two water purification systems, these being one saline water removing filter (Fig. 6.8c) and one Pond Sand Filter (Fig. 6.8d) in Burigoalini union which is simply not enough for the community. Hence, it is needless to say that many

Fig. 6.11 Photographs showing vulnerable, fragile and high-risk structures near a cyclone shelter in the study areas: wood and bamboo bridge (a, c and d); fragile house (b); fragile and partially damaged embankment (e); and unmanaged.

communities are facing many problems regarding safe drinking water. It is also noticed a rain water harvesting tank, which is provided to some people by the organisation Islamic Relief Bangladesh. However, it is not sufficient to supply water to a great number of people.

It is worth noting that this study found as the same and differing opinions regarding CRR from household and expert perspectives. Some commonly held CRR strategies actually demand the building of resilient coastal communities in Bangladesh. The common CRR measures are: building cyclone resilient houses and cyclone shelters; improving embankments; and providing relief. Furthermore, a few innovative ideas emerged from both the household and expert groups. The bulk of most CRR measures/strategies prescribed here have also been noted in other studies as well (Bisson 2012; Dasgupta et al. 2013; Shaw et al. 2013). Therefore, this study firstly recommends that agreed-to CRR strategies be implemented by the government or donor organisations to reduce cyclone risk. Secondly, it advocates CRR measures as prescribed by households and experts be constantly developed to improve cyclone resistance.

6.5 Conclusion

This study was conducted in the coastal areas of Bangladesh and explored risk perceptions as well as risk reductions strategies regarding cyclones. The perspectives of both households and experts were considered. Face-to-face questionnaire survey and site observation methods were employed to reach the research objectives. Unlike the study by Rana and Routray (2016), It did not find any relationship between actual risk and perceived risk. Results indicate that the average level of perceived cyclone risk is high both from household and expert level since cyclones constitute a continuing natural disaster and Bangladesh has much experience of them. Risk perceptions vary greatly from individual to individual and it does not vary among the three study sites. However, female participants perceive slightly higher risk than males.

Furthermore, income, occupation, farm size and education attainment or qualification influence risk perception to some extent.

Results reveal that past cyclones created the most damage in Koira union through persistent salinity intrusion compared to Lalua and Burigoalini unions. Nevertheless, government responses to natural disaster and in particular cyclone management are acknowledged by many people as well as the experts as steadily improving. Yet there is still many more things to do to minimise risk. This study introduced a new framework for CRR (Fig. 6.10) and after implementing this, this study advocates some CRR measures in order to build a cyclone resilient community along coastal Bangladesh. The most important CRR measures are to build more cyclone shelter; build cyclone resilient private house; build or improve embankment and polders; build or improve roads; preserve dry food; supply adequate food and pure drinking water; and improve the quality of early warning message. Finally, this study concludes that risk perception assessment is prerequisite for implementing any risk reductions plan or strategies. Furthermore, this study advocates to integrate bottom-up and top-down approaches for CRR plans and actions.

Chapter 7: Synthesis, conclusions and implications

7.1 Introduction

The NIO is one of most important breeding places for TC formation and landfall, and cyclones have caused a huge number of human casualties and property damage and losses. Unlike the other ocean basins, TC formations in the NIO have a clear bimodal distribution that consists of the pre-monsoon (AMJ) and post-monsoon (OND) season. While many studies focused on climatology of TC in terms of large-scale environmental parameters as well as interannual climate variability such as ENSO and IOD for NIO, this dissertation has adopted an interdisciplinary and integrated approach to examine TC impacts, which include climate variability analysis, future impact assessment and TC risk perception. This dissertation consists of three major parts, namely: (i) climatological aspects of TC activity over NIO including impact from the central Pacific El Niño and comparing AS and BoB in terms of TC climatology; (ii) past and future TC impacts for the NIO; and (iii) TC risk perception analysis in Bangladesh using a case study approach. Results from these three sections are summarised with concluding remarks and future directions of research below.

7.2 TC climatology for NIO

After completing an extensive literature review regarding TC activity over the NIO (Chapter 1), climatological aspects of TC genesis, development and landfall are critically analysed in this dissertation. After revisiting climatology of TC in terms of large-scale environmental parameters as well as interannual climate variability, this study intensively examines the impact of two types of ENSO flavours, namely, CP- and EP-type with the focus on how CP-ENSO influences TC activity in the NIO. This study identifies 9 CP years: 1977, 1986, 1990, 1991, 1994, 2002, 2004, 2009, 2012 and 2014, and 9 EP years: 1951, 1957, 1965, 1972, 1976, 1982, 1997 and 2015 during 1951-2015. The results indicate there are no significant changes in TC formation locations and tracks between the identified CP and EP events. For AMJ, mostly westward (northeastward) TC tracks are found over the AS (BoB). During OND, most of the tracks of the BoB still remain northwestward in all years.

However, this study reveals a noticeable reduction in the number of TCs during the CP years especially during the post-monsoon season over the BoB. TC frequency in the CP years has decreased by more than double in June compared with that in EP years (0.33 versus 0.78). Mechanisms behind this TC frequency reduction are examined and results clearly show that the major thermodynamic and dynamic factors, namely mid-level RH and VWS, are responsible for this. To confirm these findings, Genesis Potential Index (GPI) analysis is performed. The mid-level RH and the VWS term of GPI contribute significantly to the reduction of GPI value during that CP years and means that TC formation potential is suppressed. In particular, the pattern of change in moisture advection is similar to that in the total change in mid-level RH. Furthermore, this study concluded that changes in humidity and vertical wind shear are due to the large-scale circulation pattern originating from the Pacific Ocean in response to the CP event. This study also found that PIOD events are linked to eastern-type CP events and thus the IOD phase has played a role in some CP events.

This study has identified the spatial asymmetry of TC activity between the AS and BoB that occurred in many years during the last three decades. Although about 70% TCs formed over the BoB and the rest over the AS during 1983-2015, this study identifies ten years from this period in which most of the TCs developed in either the AS or BoB, but not both. Such exclusively active AS years include 1998, 2001, 2004, 2011 and 2015, while the active BoB years are 1990, 1991, 2000, 2005 and 2009. It was assumed that the well-known climate variability such as ENSO and IOD may govern these TC variabilities for the AS and BoB. Nevertheless, results of these climate indices indicate that no single mode can explain these variations. Instead, it is found that variability of the northeast (post) monsoon is an important factor responsible for the difference between the two basins. Excess moisture is available over the AS due to anomalous low-level flow from the equatorial Indian Ocean in the years in which there are more TCs in that basin, and dryer conditions are characteristic of the BoB. However, intraseasonal variability, which can provide the seeding disturbances for TC development, may also influence TC frequency in the AS and BoB with variations. Such shorter time-scale variability has not been analysed in this study but it is a potential future research direction. Further investigations may involve regional climate modelling studies to clarify these problems. Since climate models project more intense TCs in the AS but less for the BoB in the future, the critical question is whether the AS/BoB asymmetry in TC activity will be further expanded in future climate scenarios. The relationship to monsoon development as identified in this study can be applied to assess the latest climate model projections.

7.3 TC impacts and storm surge modelling

Climatology of the simulated TCs from a climate model with the focus on the intense TCs (intensity > 64 kt) is analysed for past (1990-2010) and future (2075-2099) periods. A storm surge model simulates the surge level for all cases, and for demonstration purposes the Resilience-Increasing Strategies for Coasts Toolkit (RISC-KIT) is applied to estimate coastal inundation. Potential coastal area inundations due to TC landfalls are analysed for past and future TC scenarios. Results clearly show that almost all the intense TCs in the past made landfall around the BoB region, however, climate model projection simulated more intense TCs over the AS. The storm surge model and RISC-KIT estimate an average of 3-5-meter inland flooding depending on TC intensity and topography, and more high-impact cases will be shifting to the AS. Since the projected TCs are on average more intense compared to previous events, a higher level of storm surge height is estimated, which indicates larger and more destructive TCs especially around the coastal areas of the AS. An impact assessment tool, InaSAFE, has been applied to assess the social and economic outcomes for the

Bangladesh region. This tool is able to provide crucial information that can be used for short- and long-term disaster preparation and in general CRR strategy.

The striking point of this analysis is that it provides a comprehensive picture of spatial differences of future TCs with their associated impacts over the NIO. More importantly, this is the first study for Bangladesh that estimates the realistic impacts of TCs on populations, buildings, land uses and roads by using the InaSAFE tool. It is highly recommended to incorporate this tool into disaster management systems in Bangladesh for building a more resilient coastal community. However, the main limitation of this analysis is that the digital elevation model within RISC-KIT needs to be extended and there is a lack of updated exposure data for this study area. Further studies should be conducted to extend this analysis to all coastal areas of all the rim countries along the BoB and AS.

7.4 TC risk perception analysis for Bangladesh

This field study measured the perceived and actual risk of TC impact in the southern coastal areas of Bangladesh by using an extensive survey that consisted of face-to-face questionnaire surveys and site observations. Results indicate that the average level of perceived risk is high both at the household and expert level. Female participants perceive slightly higher risk than males in the communities along coastal Bangladesh. Moreover, income, occupation, farm size and education attainment influence people's risk perceptions to some extent. This survey advocates some cyclone risk reduction (CRR) measures: build more cyclone shelters; build cyclone resilient private houses; build or improve embankments and polders; build or improve roads; preserve dry food; supply adequate food and pure drinking water; and improve the quality of early warning messages. This study concludes that risk perception assessment is a prerequisite for implementing any risk reduction plan or strategy, and it is critical to integrate bottom-up and top-down approaches for CRR plans and actions so that they work effectively.

The salient feature of the study is that this is the first one for Bangladesh which assesses both actual and perceived TC risk simultaneously at the household level, while CRR is explored from both the household and expert levels. The government of Bangladesh can use this study's findings and proposed CRR framework to implement and monitor DRR interventions. Finally, this kind of interdisciplinary and comprehensive analysis can play a vital role in building a cyclone resilient coastal community in an increasingly important part of the world.

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Appendices

Appendix A0: Ethics Clearance Certificate

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(Research)

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MACQUARIE University
SYDNEY · AUSTRALIA

20 March 2017

Dear Dr Cheung

Reference No: 5201600982

Title: *Cyclone risk perceptions, impacts and adaptations in coastal Bangladesh: households and experts' perspectives*

Thank you for submitting the above application for ethical and scientific review. Your application was considered by the Macquarie University Human Research Ethics Committee (HREC (Human Sciences & Humanities)).

I am pleased to advise that ethical and scientific approval has been granted for this project to be conducted by:

- Macquarie University

This research meets the requirements set out in the *National Statement on Ethical Conduct in Human Research* (2007 – Updated May 2015) (the *National Statement*).

Standard Conditions of Approval:

1. Continuing compliance with the requirements of the *National Statement*, which is available at the following website:

http://www.nhmrc.gov.au/book/national-statement-ethical-conduct-human-research

2. This approval is valid for five (5) years, subject to the submission of annual reports. Please submit your reports on the anniversary of the approval for this protocol.

3. All adverse events, including events which might affect the continued ethical and scientific acceptability of the project, must be reported to the HREC within 72 hours.

4. Proposed changes to the protocol and associated documents must be submitted to the Committee for approval before implementation.

It is the responsibility of the Chief investigator to retain a copy of all documentation related to this project and to forward a copy of this approval letter to all personnel listed on the project.

Should you have any queries regarding your project, please contact the Ethics Secretariat on 9850 4194 or by email ethics.secretariat@mq.edu.au

The HREC (Human Sciences and Humanities) Terms of Reference and Standard Operating Procedures are available from the Research Office website at:

http://www.research.mq.edu.au/for/researchers/how_to_obtain_ethics_approval/human_research_ethics

The HREC (Human Sciences and Humanities) wishes you every success in your research.

Yours sincerely

Dr Karolyn White
Director, Research Ethics & Integrity,
Chair, Human Research Ethics Committee (Human Sciences and Humanities)

This HREC is constituted and operates in accordance with the National Health and Medical Research Council's (NHMRC) *National Statement on Ethical Conduct in Human Research* (2007) and the *CPMP/ICH Note for Guidance on Good Clinical Practice*.

Appendix A1: Consent form for households and experts interview

Department of Environmental Sciences
Faculty of Science and Engineering
Macquarie University, NSW 2109
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Chief investigator's Name and Title: Dr. Kevin Cheung, Senior Lecturer, Email: kevin.cheung@mq.edu.au

Student Researcher: Md. Abdus Sattar, PhD Candidate (Email: md-abdus.sattar@students.mq.edu.au)

Title of the research: "Cyclone risk perceptions, impacts and adaptations in coastal Bangladesh: households and experts' perspectives. Ethics Approval Reference Number: 5201600982"

Participation information and consent form

Introduction
As a part of Mr. Sattar's PhD research project, this study attempts to collect information about tropical cyclone risk and adaptations based on households' and experts' opinions and experiences. There is no and/or minimal risk involve in this study. You will be asked about your age, gender, occupation, income, family; your past experience with cyclone and your perceptions towards cyclone risk and government policy. Some of the questions might cause distress and upset, if so please find necessary contact details at the bottom of the page. The entire survey will take around 90.00 and 30:00 minutes for households and experts, respectively and it will take place at your convenient time and place.

Benefits
There is no direct benefit to the participants. However, this study will advocate to governments or other organizations for building cyclone resilient community by identifying risk, mitigation and adaptation measures from households as well as experts' perspectives.

Confidentiality

All data obtained from participants will be kept confidential and will only be reported in an aggregate format (by reporting only combined results and never reporting individual ones). Data will be archived anonymously as per department rules. All questionnaires will be concealed, and only investigators listed below will have access to them.

Participation

Participation in this research study is completely voluntary. You have the right to withdraw at any time or refuse to participate entirely without jeopardy to your status. If you desire to withdraw, inform the investigator as you leave.

Questions about the Research

If you have questions regarding this study, you may contact Dr. Kevin Cheung, Senior lecturer, Macquarie University at kevin.cheung@mq.edu.au or Md. Abdus Sattar, PhD Candidate, Macquarie University at md-abdus.sattar@students.mq.edu.au

Practical instructions

- Please switch off your mobile phones
- Please give your opinions with honesty and sincerity
- Do not hesitate to ask any question, if you do not understand

Contact details of health services:

1. Bilkis Akhtar, Community Health Care Provider, Koira Union, phone: +8801929618864
2. Konoktala Rani, Burigoalini Union, phone: +8801788323390
3. Md. Sagir Hossain, Lalua Union, Phone: +8801727019461
4. Upazila health complex, Kalapara, Patuakhali, Phone: 0442556333
5. Jasnabala Mallik, Shyamnagar, Satkhira, Phone: +8801718857085
6. Mrs. Mumtaz Begum, Koira, Khulna, Phone: +8801717235763
7. National Institute of Mental Health, Mirpur Rd, Dhaka, Bangladesh, Phone: +880 2-9118171.

Participant's consent **Date: ……./……./2017**

I, ……………………………….. agree to participate in this survey for Mr. Sattar's PhD research project of Macquarie University on my own will and can leave this survey at any time. I know that my participation is completely voluntary and I will not get monetary benefits.

Signature of the participant ________________________

Name and Designation of the Investigator: ________________________

Signature of the Investigator: ________________________

Appendix A2: Questionnaire for experts

Cyclone risk perceptions, impacts and adaptations in coastal Bangladesh: households and experts' perspectives

Questionnaire- 2017

[Answer the following questions by writing or circling the most appropriate answer]

Expert Information (EI)			Date:
Sex	Male	Female	Age:………………(years)
Organization			
Designation			

Perceived risk information from Expert perspectives:

1. What do you think is the chance for future cyclone occurrence?

Very High (1 in a year)	High (1 after 2 years)	Moderate (1 after 3 years)	Low (1 after 4 years)	Very Low (1 in after 5 years)

2. How much are you afraid of cyclones considering you as a coastal community member of Bangladesh?

Very much Afraid (>80%)	Afraid (50-80%)	Neutral (30-50%)	Slightly afraid (10-20%)	Not afraid (0%)

3. What do you think are the chances of loss of coastal people lives in cyclones?

Very High (>80%)	High (50-80%)	Moderate (30-50%)	Low (10-30%)	Very Low (<10%)

4. What is the likelihood of future damages by cyclones?

Very High (>80%)	High (50-80%)	Moderate (30-50%)	Low (10-30%)	Very Low (<10%)

5. What do you think about people capability to cope with future cyclone?

Very High (>80%)	High (50-80%)	Moderate (30-50%)	Low (10-30%)	Very Low (<10%)

6. What are the chances of supplies (e.g., electricity, drinking water, goods, etc.) interruption during cyclones?

Very High (>80%)	High (50-80%)	Moderate (30-50%)	Low (10-30%)	Very Low (<10%)

7. What are the chances that cyclone will change coastal people?

Very High (-Severe depression and anxiety -Higher substance abuse (addiction) -Severe loss of assets and infrastructures -Severe loss of household income -Overall >80% changes)	High (-Higher depression and anxiety -Substance abuse (addiction) -Higher loss of assets and infrastructures -Higher loss of household income -Overall 50-80% changes)	Moderate (-Depression and anxiety -Substance abuse (addiction) -Loss of assets and infrastructures -Loss of household income to some extents -Overall 30-85% changes)	Low (-No depression and anxiety -No substance abuse (addiction) -Loss of assets and infrastructures to some extents -Loss of household income to some extents -Overall 10-30% changes)	Very Low (-No depression and anxiety -No substance abuse (addiction) -Negligible loss of assets and infrastructures -No loss of household income -Overall <10%

8. What are the chances that cyclone will change coastal people relationships?

Very High (>80% relationship	High (50-80% relationship with	Moderate (30-50% relationship	Low (10-30% relationship	Very Low (<10% relationship	

with neighbors becomes worse)	neighbors becomes worse)	with neighbors becomes worse)	with neighbors becomes worse)	with neighbors becomes worse)	

9. What is the level of understanding emergency protocols?

Very Poor	Poor	Average	Good	Very Good
(-Don't know emergency protocols -No ideas about mitigation actions -Good to go cyclone shelter)	(-Poor knowledge of emergency protocols -No ideas about mitigation actions -Good to go cyclone shelter)	(-Good knowledge of emergency protocols -Few ideas about mitigation actions -Good to go cyclone shelter)	(-Clear knowledge of emergency protocols -Good ideas about mitigation actions -Good to go cyclone shelter)	(-Very clear knowledge of emergency protocols -Very good ideas about mitigation actions -Good to go cyclone shelter)

10. How much do you agree with govt. polices for DRR and CC?

Very High	High	Moderate	Low	Very Low
(-Govt. took very good steps for DRR and CC for our community -Govt. improved infrastructures -Govt. provides early warning and training to community effectively -Search-rescue-relief operations are very good -Overall >80% satisfactory level)	(-Govt. took good steps for DRR and CC for our community -Govt. improved infrastructures -Govt. provides early warning and training to community but not so effective -Search-rescue-relief operations are good -Overall 50-80% satisfactory level)	(-Govt. took steps for DRR and CC for our community and needs more steps -Govt. improved infrastructures to some extents -Govt. provides early warning and training to community but not sufficient -Search-rescue-relief operations are good to some extents -Overall 30-50% satisfactory level)	(-Govt. took very few steps for DRR and CC for our community and needs more steps -No improvement of infrastructures -Govt. provides early warning and no training to community -Search-rescue-relief operations are bad -Overall 10-30%)	(-Govt. took no steps for DRR and CC for our community -No improvement of infrastructures -Govt. provides early warning and no training to community -Search-rescue-relief operations are very bad -Overall <1 0%)

11. What can community do to help reduce the impacts of tropical cyclones for pre-cyclone, during cyclone and post-cyclone?

1. **pre-cyclone:**
2. **during cyclone:**

3. **post-cyclone:**

12. Suppose, government has a big project for cyclone risk reduction for coastal community; as an expert, what sorts of measures you will prescribe to minimize household risk for pre-cyclone, during cyclone and post-cyclone?

1. **pre-cyclone:**
2. **during cyclone:**

3. **post-cyclone:**

Appendix A3: Questionnaire for households

Cyclone risk perceptions, impacts and adaptations in coastal Bangladesh: households and experts' perspectives
Household Survey Questionnaire- 2017

[Answer the following questions by writing or circling the most appropriate answer]

Date:

1. Household Information (HI)			
Sex	Male	Female	Age:……………………(years)
Household Address	Village/ Mouza)		Union: ………………….. Upazila:…………………….
Farm size including cultivable and non-cultivable land:……………………………. (in acres)			

2. Hazard Component of Disaster Risk:

2.1 Which is the extreme cyclone that experienced by your household?

Sidr	Aila	Mahasen	Roanu

2.2 How often has a cyclone hit your home during the last 10 years?

0	1-2	3-4	5-6	>6

2.3 What is the maximum height of flood measured above the ground floor during the extreme cyclone (e.g. in Haths)?

0	1-2	3-4	5-6	>6

2.4 What is the maximum height of flood measured above the local roads during the extreme cyclone (e.g. in Haths)?

0	1-2	3-4	5-6	>6

2.5 What is the maximum duration of cyclonic winds (in days) during the extreme cyclone?

No days	< 1	1-3	3-5	5-7	> 7

2.6 What is the maximum duration of flood due to the extreme cyclone (in days)?

No days	1-5	5-10	10-15	15-20	> 20

2.7 What is the intensity of peak wind speed in the previous extreme cyclone?

Very Low	Low	Moderate	High	Very High

2.8 What is the highest magnitude of damages and losses of houses by the extreme cyclone?

Very Low (<10%)	Low (10-30%)	Moderate (30-50%)	High (50-80%)	Very High (>80%

2.9 What is the highest magnitude of damages and losses of agricultural crops production by the extreme cyclone?

Very Low (<10%)	Low (10-30%)	Moderate (30-50%)	High (50-80%)	Very High (>80%

2.10 What is the highest magnitude of damages and losses of livestock by the extreme cyclone?

Very Low (<10%)	Low (10-30%)	Moderate (30-50%)	High (50-80%)	Very High (>80%

2.11 What is the highest magnitude of damages and losses of poultry by the extreme cyclone?

Very Low (<10%)	Low (10-30%)	Moderate (30-50%)	High (50-80%)	Very High (>80%

3. Exposure (Vulnerability) Component of Disaster Risk:

3.1 Where is your most of the agricultural field location?

Upland	Floodplain	Adjacent to river

3.2 What is the family type?

Joint	Nucleus	Single

3.3 How many members got injury and took medical supports in your households in previous extreme cyclone?

0	1	2	3	>4

3.4 How many members caused death in your households in previous extreme cyclone?

0	1	2	3	>4

3.5 Where is your home location?

Upland	Floodplain	Adjacent to river

3.6 What is your building/house height (number of stories)?

Triple	Double	Single

3.7 What is the age of house (in years)?

<2	2-5	5-7	>7

3.8 Which materials are used to build your houses?

Pacca (Brick, Cement)	Katcha (Adobe, Mud)

3.9 What is your level of understanding of the national cyclone warning signals?

Very High (know meanings of all signals)	High (know meanings of almost all signals)	Moderate (know meanings of few signals)	Low (know meanings of few signals but not clear)	Very Low (don't know the meanings of signals)

3.10 What is your children (below 18 years old) level of understanding of the national cyclone warning signals?

Very High (know meanings of all signals)	High (know meanings of almost all signals)	Moderate (know meanings of few signals)	Low (know meanings of few signals but not clear)	Very Low (don't know the meanings of signals)

3.11 What is your spouse level of understanding of the national cyclone warning signals?

Very High (know meanings of all signals)	High (know meanings of almost all signals)	Moderate (know meanings of few signals)	Low (know meanings of few signals but not clear)	Very Low (don't know the meanings of signals)

3.12 Did your household's receive warnings about the extreme cyclone?

Yes	No

4. Sensitivity (Vulnerability) Component of Disaster Risk:

4.1 How many dependents do you have in your household?

<1	1-2	2-3	3-4	>4

4.2 What is the ratio of female to males above the age of 5 (Female/Male)?

<1	1-2	2-3	3-4	>4

4.3 Did any family members suffer from chronic illness/pregnancy or disability?

0	1	2	>2

4.4 How long has the household been living in the community (in years)?

>40	30-40	20-30	10-20	<10

4.5 What is the average monthly household's income (in Bangladeshi Taka)?

>20,000	20,000-15,000	15,000-10,000	10,000-5,000	<5,000

4.6 What is the occupation of household head?

Government Service	Trade and Commerce	Agriculture	Daily Wagers	Unemployed

4.7 Has the households have taken out loans in last ten years?

No	Yes

4.8 Is the family living in rented or other people's house?

No	Yes

4.9 What is the distance to nearest medical facility (in kilometers)?

<1	1-5	5-10	>10

4.10 Does the household have access to tube-well for drinking water?

Yes	No

4.11 Does the household have access to an improved toilet?

Yes	No

4.12 Does the household have access to electricity?

Yes	No

4.13 Does the household have a TV?

No	Yes

4.14 Does the household have a Radio?

No	Yes

4.15 Does the household have a mobile phone?

No	Yes

4.16 Does the household have access to public transportation (e.g. bus or train or tuk-tuk, etc.)?

No	Yes

4.17 Are there any formal community organizations to deal any kinds of disasters including cyclone?

Yes	No

4.18 Were there food shortages during the extreme cyclone? Yes or no? and if so how bad these?

Very High (>80%)	High (50-80%)	Moderate (30-50%)	Low (10-30%)	Very Low (<10%)

4.19 Were you impacted by any violence you experienced during the extreme cyclone?

Very High (-Higher suicidal attempt rate due to conflict with neighbors -Extreme sexual harassment -Extreme discrimination of govt. supports -Overall >80% violence experienced)	High (-Lower suicidal attempt rate due to conflict with neighbors -Higher sexual harassment -Higher discrimination of govt. supports -Overall 50-80% violence experienced)	Moderate (-Very low suicidal attempt rate due to conflict with neighbors -Moderate sexual harassment -Lower discrimination of govt. supports -Overall 30-50% violence experienced)	Low (-No suicidal attempt due to conflict with neighbors -Lower sexual harassment -Lower discrimination of govt. supports -Overall 10-30% violence experienced)	Very Low (-No suicidal attempt due to conflict with neighbors -No sexual harassment -Almost no discrimination of govt. supports -Overall <10% violence experienced)

<u>5. Capacity Component of Disaster Risk:</u>

5.1 What is the household head's education level?

College/University	High	Middle	Primary	Not attended

5.2 Has your household experienced cyclones before?

Yes	No

5.3 Can all family members swim?

Yes	No

5.4 Does any family member have knowledge of first aid?

Yes	No

5.5 How many sources of income do you have in your household?

>2	2	1	0

5.6 How many earning members do you have in your household?

>2	2	1	0

5.7 Does the household have any kind of savings (Bank, Gold, and Silver)?

Yes	No

5.8 What is the average monthly household's savings (in Bangladeshi Taka)?

>10,000	6,000-10,000	2,000-6,000	<2,000	No Saving

5.9 Does the household have insurance (Life or Health)?

Yes	No

5.10 Do you reserve some dry foods for unexpected calamities?

Yes	No

5.11 Does the household have land/house outside the flood prone community?

Yes	No

5.12 Does your household have relatives outside the village?

Yes	No

5.13 Does any family member in your household employed outside cyclone prone area?

Yes	No

5.14 What is the strength of community cooperation in disaster response?

Very Good	Good	Moderate	Poor	Very Poor

5.15 Does household aware emergency shelter?

Yes	No

5.16 Does household communicate to their local government for any kind of assistance in the past 12 months?

Yes	No

5.17 What is the frequency of public awareness programs/drills attended by household's member (in number)?

2	1	0

6. Perceived risk information

6.1 What do you think is the chance for future cyclone occurrence?

Very High (1 in a year)	High (1 after 2 years)	Moderate (1 after 3 years)	Low (1 after 4 years)	Very Low (1 in after 5 years)

6.2 How much are you afraid of cyclones?

Very much Afraid (>80%)	Afraid (50-80%)	Neutral (30-50%)	Slightly afraid (10-20%)	Not afraid (0%)

6.3 What do you think are the chances of loss of lives in cyclones?

Very High (>80%)	High (50-80%)	Moderate (30-50%)	Low (10-30%)	Very Low (<10%)

6.4 What is the likelihood of future damages by cyclones?

Very High (>80%)	High (50-80%)	Moderate (30-50%)	Low (10-30%)	Very Low (<10%)

6.5 What do you think is your capability to cope with future cyclone?

Very Low (<10%)	Low (10-30%)	Moderate (30-50%)	High (50-80%)	Very High (>80%)

6.6 What are the chances of supplies (e.g., electricity, drinking water, goods, etc.) interruption during cyclones (Households thinking in likelihood about supplies will be interrupted in cyclones)?

Very High (>80%)	High (50-80%)	Moderate (30-50%)	Low (10-30%)	Very Low (<10%)

6.7 What are the chances that cyclone will change your lifestyles (Probability of changing their lifestyle because of the cyclones)?

Very High	**High**	**Moderate**	**Low**	**Very Low**
(-Severe depression and anxiety -Higher substance abuse (addiction)	(-Higher depression and anxiety -Substance abuse (addiction)	(-Depression and anxiety -Substance abuse (addiction)	(-No depression and anxiety -No substance abuse (addiction)	(-No depression and anxiety -No substance abuse (addiction)

-Severe loss of assets and infrastructures -Severe loss of household income -Overall >80% changes)	-Higher loss of assets and infrastructures -Higher loss of household income -Overall 50-80% changes)	-Loss of assets and infrastructures -Loss of household income to some extents -Overall 30-85% changes)	-Loss of assets and infrastructures to some extents -Loss of household income to some extents -Overall 10-30% changes)	-Negligible loss of assets and infrastructures -No loss of household income -Overall <10%

6.8 What are the chances that cyclone will change your relationships?

Very High	**High**	**Moderate**	**Low**	**Very Low**
(>80% relationship with neighbors becomes worse)	(50-80% relationship with neighbors becomes worse)	(30-50% relationship with neighbors becomes worse)	(10-30% relationship with neighbors becomes worse)	(<10% relationship with neighbors becomes worse)

6.9 What is the level of understanding emergency?

Very Poor	**Poor**	**Average**	**Good**	**Very Good**
(-Don't know emergency protocols -No ideas about mitigation actions -Good to go cyclone shelter)	(-Poor knowledge of emergency protocols -No ideas about mitigation actions -Good to go cyclone shelter)	(-Good knowledge of emergency protocols -Few ideas about mitigation actions -Good to go cyclone shelter)	(-Clear knowledge of emergency protocols -Good ideas about mitigation actions -Good to go cyclone shelter)	(-Very clear knowledge of emergency protocols -Very good ideas about mitigation actions -Good to go cyclone shelter)

6.10 How much do you agree with govt. polices for DRR and CC (HH agreeing with government response to climate change and DRR policies)?

Very Low	**Low**	**Moderate**	**High**	**Very High**
(-Govt. took no steps for DRR and CC for our community -No improvement of infrastructures -Govt. provides early warning and no training to community -Search-rescue-relief operations are very bad -Overall <10%)	(-Govt. took very few steps for DRR and CC for our community and needs more steps -No improvement of infrastructures -Govt. provides early warning and no training to community -Search-rescue-relief operations are bad -Overall 10-30%)	(-Govt. took steps for DRR and CC for our community and needs more steps -Govt. improved infrastructures to some extents -Govt. provides early warning and training to community but not sufficient -Search-rescue-relief operations are good to some extents -Overall 30-50% satisfactory level)	(-Govt. took good steps for DRR and CC for our community -Govt. improved infrastructures -Govt. provides early warning and training to community but not so effective -Search-rescue-relief operations are good -Overall 50-80% satisfactory level)	(-Govt. took very good steps for DRR and CC for our community -Govt. improved infrastructures -Govt. provides early warning and training to community effectively -Search-rescue-relief operations are very good -Overall >80% satisfactory level)

7. Past and future measures for cyclone risk adaptations and mitigations households' perspective

7.1 What are the major loss and damaged your household experienced due to cyclone in the past?

7.2 What do you and your community does to help reduce the impacts of tropical cyclones for pre-cyclone, during cyclone and post-cyclone?

4. pre-cyclone:

5. during cyclone:

6. post-cyclone:

7.3 Suppose, government has a big project for cyclone risk reduction for coastal community, what sorts of support you will want from government to minimize your household risk for pre-cyclone, during cyclone and post-cyclone (at least 3 for each phase)?

1. pre-cyclone:

2. during cyclone:

3. post-cyclone:

7.4. Suppose, government gives you BDT 30,000 for risk reduction and you must use this money only for risk reduction, what you will do with this money?

1.

2.

3.

4.

5.

7.5 Is there any other information you need to be better prepared for a tropical cyclone?

1.

2.

3.

4.

5.

Appendix B1: Selected indicators for actual risk assessment

SL NO	Indicators	Classes	Weights	Explanations	Source
Hazard Component of Disaster Risk					
1	The extreme cyclone that experienced by household	Mahasen (50 knots) Roanu (55 knots) Aila (65 knots) Sidr (140 knots)	0.25 0.50 0.75 1.00	Higher the sustained wind speed means more severity in terms of damages and losses. Aila and Sidr were the extreme cyclones that experienced by households in this study	JTWC
2	Frequency of cyclone hit the house during the last 10 years (in number)	0 1−2 3−4 5−6 > 6	0.00 0.25 0.50 0.75 1.00	Past cyclone events indicates that both three study areas are prone to cyclone hazard	
3	Height of flood measured from residence ground floor during the extreme cyclone (in haths)	0 1−2 3−4 5−6 > 6	0.00 0.25 0.50 0.75 1.00	In general, severity of damage and loss increases with the increases of flood height	(Barua et al. 2016; Hossain et al. 2015; Rana et al. 2010; Roy et al. 2015)
4	Height of flood measured from the local roads during the extreme cyclone (in haths)	0 1−2 3−4 5−6 > 6	0.00 0.25 0.50 0.75 1.00		(Kappes et al. 2012)
5	Duration of cyclonic wind during the extreme cyclone (in days)	No days <1 1-3 3-5 5-7 >7	0.00 0.20 0.40 0.60 0.80 1.00	Longer duration of cyclonic wind shows the higher magnitude of damage and loss potential	
6	Duration of flood during the extreme cyclone (in days)	No days 1-5 5-10 10-15 15-20 >20	0.00 0.20 0.40 0.60 0.80 1.00	Longer duration of flood shows the higher magnitude of damage and loss potential as longer exposure	(Powell and Reinhold 2007)
7	Intensity of peak wind speed in the previous extreme cyclone	Very Low Low Moderate High Very High	0.20 0.40 0.60 0.80 1.00	Higher the wind intensity means more severity, and resultant damages	(Boruff 2009; Wisner et al. 2004)
8	Magnitude of damages and losses of houses by the extreme cyclone	Very Low (<10%) Low (10-30%) Moderate (30-50%) High (50-80%) Very High (>80%)	0.20 0.40 0.60 0.80 1.00	Higher the damages of previous cyclone shows severity of cyclone and its higher risk	(Saha 2015)
9	Magnitude of damages and losses of agricultural crops production by the extreme cyclone	Very Low (<10%) Low (10-30%) Moderate (30-50%) High (50-80%) Very High (>80%)	0.20 0.40 0.60 0.80 1.00		(Burton et al. 2005)

10	Magnitude of damages and losses of livestock by the extreme cyclone	Very Low (<10%) Low (10-30%) Moderate (30-50%) High (50-80%) Very High (>80%)	0.20 0.40 0.60 0.80 1.00		
11	Magnitude of damages and losses of poultry by the extreme cyclone	Very Low (<10%) Low (10-30%) Moderate (30-50%) High (50-80%) Very High (>80%)	0.20 0.40 0.60 0.80 1.00		
1	Location of the agricultural field	Upland Floodplain Adjacent to river	0.33 0.67 1.00	Vulnerability of agricultural fields increases from upland to adjacent to rivers as their exposure to hazard varies accordingly	Exposure (Vulnerability) Component of Disaster Risk
2	Family type	Joint Nucleus Single	0.33 0.67 1.00	Vulnerability of family type increases from joint to single as their access to community resources and isolation vary accordingly	
3	Households members got injury who took medical supports in the previous extreme cyclone	0 1 2 3 >4	0.00 0.25 0.50 0.75 1.00	Households with injuries in previous cyclone means that they are more exposed and vulnerable.	(Flanagan Barry et al. 2011)
4	Households members caused death in the previous extreme cyclone	0 1 2 3 >4	0.00 0.25 0.50 0.75 1.00	Households with deaths in previous cyclone means that they are more exposed and vulnerable	(Hahn et al. 2009a)
5	Location of the house	Upland Floodplain Adjacent to river	0.33 0.67 1.00	Vulnerability of house increases from upland to adjacent to rivers as their exposure to hazard varies accordingly.	(Hahn et al. 2009a)
6	Building/house height (number of stories)	Triple Double Single	0.33 0.67 1.00	Vulnerability of house increases from single to triple stories as their exposure to hazard varies accordingly.	(Cutter et al. 2000)
7	Building/house age (in years)	<2 2-5 5-7 >7	0.25 0.50 0.75 1.00	Older buildings/houses are more vulnerable than those of new as resistance power against cyclone as well as construction technologies varies.	(Birkmann et al. 2013; Fedeski and Gwilliam 2007)
8	Building/house construction materials	Pacca (Brick, Cement) Katcha (Adobe, Mud)	0.00 1.00	Construction materials for building/house can have various impacts of exposure and vulnerability to cyclone	(Fedeski and Gwilliam 2007)

9	Respondent's level of understanding national cyclone warning signals	**Very High** (know meanings of all signals) **High** (know meanings of almost all signals) **Moderate** (know meanings of few signals) **Low** (know meanings of few signals but not clear) **Very Low** (don't know the meanings of signals)	0.20 0.40 0.60 0.80 1.00	Household members who understand national cyclone warning system will be less exposed as they know about the coming cyclone and what to do to avoid damage and loss.	(Fedeski and Gwilliam 2007)
10	Children (below 18 years old) level of understanding national cyclone warning signals	**Very High** (know meanings of all signals) **High** (know meanings of almost all signals) **Moderate** (know meanings of few signals) **Low** (know meanings of few signals but not clear) **Very Low** (don't know the meanings of signals)	0.20 0.40 0.60 0.80 1.00		(Ahsan and Warner 2014)
11	Respondent's spouse level of understanding national cyclone warning signals	**Very High** (know meanings of all signals) **High** (know meanings of almost all signals) **Moderate** (know meanings of few signals) **Low** (know meanings of few signals but not clear) **Very Low** (don't know the meanings of signals)	0.20 0.40 0.60 0.80 1.00		
12	Household's received warning about the extreme cyclone	Yes No	0.00 1.00	There is a small probability to not to get warning message for the future cyclone as they didn't receive it for the last one.	
Sensitivity (Vulnerability) Component of Disaster Risk					
1	Number of household dependents	<1 (1) 1-2 (2) 2-3 (3) 3-4 (4) >4 (>4)	0.20 0.40 0.60 0.80 1.00	Higher number of dependents (e.g., infant, children, older people, etc.) indicates more risk than young and adult as they are less mobile and need special assistance.	(Cutter et al. 2000; Cutter et al. 2003b; Flanagan Barry et al. 2011; Khan 2012;

					Phung et al. 2016)
2	Female male ratio above the age of 5	<1 1-2 2-3 3-4 >4	0.20 0.40 0.60 0.80 1.00	Female are more vulnerable than male due their physical strengths and socio-economic factors	
3	Households having family members with chronic illness/pregnancy or disability	0 1 2 >2	0.00 0.33 0.67 1.00	Households members with special needs are more at risk during emergency and evacuation especially it hinders to move safe place.	(Alam and Collins 2010; Cutter et al. 2000; Cutter et al. 2003b; Kulatunga et al. 2014; Phung et al. 2016)
4	Household living in the community (in years)	>40 30-40 20-30 10-20 <10	0.20 0.40 0.60 0.80 1.00	Households living longer period can be familiar to cyclone shelter, evacuation route and geography of the locality, therefore, can have lower risk.	(Ahsan and Warner 2014; Balica et al. 2012; Birkmann et al. 2013; Flanagan Barry et al. 2011)
5	Average monthly household's income (in Bangladeshi Taka)	>20,000 15,000-20,000 10,000-15,000 5000-10,000 <5000	0.20 0.40 0.60 0.80 1.00	Vulnerability decreases with the increases of households income and vice-versa as rich family can recover from disaster quickly.	(Birkmann et al. 2013; IPCC 2012)
6	Occupation of household head	Government Service Trade and Commerce Agriculture Daily Wagers Unemployed	0.20 0.40 0.60 0.80 1.00	Vulnerability has a correlation with type of income source. It increases/decreases with unstable/stable source of income from particular occupation.	(Khan 2012)
7	Households who have taken out loans in last ten years	No Yes	0.00 1.00	Households which took loan from others, are more vulnerable as it means they faced economic challenges to maintain expenses.	(Cutter et al. 2003a)
8	Households living in rented houses	No Yes	0.00 1.00	Tenant doesn’t have the responsibility and rights to repair, reinforce and maintain their building/house against cyclones and it totally depends on the wish of owner.	(Hahn et al. 2009c)
9	Distance to nearest medical facility (in kilometres)	<1 1-5 5-10 >10	0.25 0.50 0.75 1.00	Vulnerability increases with the increases of the distance of health centre from residence as it requires longer time to reach for health	(Cutter et al. 2003a; Khan 2012)

				support during emergency.	
10	Households have access to tube-well for drinking water	Yes No	0.00 1.00	Households having access to safe drinking water indicate lower risk.	(Hahn et al. 2009c)
11	Households have access to improved toilet	Yes No	0.00 1.00	Households having access to improved toilet indicate lower risk.	(Ahsan and Warner 2014; Hahn et al. 2009c; Zhou et al. 2015)
12	Households have access to electricity	Yes No	0.00 1.00	Households having access to electricity means lower vulnerability.	(Ahsan and Warner 2014)
13	Households have TV	Yes No	0.00 1.00	Households having access to various communication means indicate lower vulnerability and risk.	(Ahsan and Warner 2014)
14	Households have Radio	Yes No	0.00 1.00		(Ahsan and Warner 2014)
15	Households have Mobile	Yes No	0.00 1.00		
16	Households have access to public transportation (bus or train or tuk-tuk/auto rickshaw	Yes No	0.00 1.00	Households having access to public transportation indicate lower risk.	
17	Existence of any formal community organization to deal any kind of disaster including cyclone	Yes No	0.00 1.00	Community organization indicates the strength of the community and lower vulnerability.	(Flanagan Barry et al. 2011; Kaźmierczak and Cavan 2011)
18	How bad was the food shortages during the extreme cyclone	Very Low (<10%) Low (10-30%) Moderate (30-50%) High (50-80%) Very High (>80%)	0.20 0.40 0.60 0.80 1.00	Households with experienced in food shortages during cyclone indicate vulnerability and risky.	(Duijsens and Faling 2014; Karim and Thiel 2017)
19	Households impacted by any violence during the extreme cyclone	**Very Low** (-No suicidal attempt due to conflict with neighbors -No sexual harassment -Almost no discrimination of govt. supports -Overall <10% violence experienced) **Low** (-No suicidal attempt due to conflict with neighbors -Lower sexual harassment -Lower discrimination of govt. supports -Overall 10-30% violence experienced) **Moderate**	0.20 0.40 0.60	Households impacted by violence during the extreme cyclone means less social security and higher risk.	(Kulatunga et al. 2014)

		(-Very low suicidal attempt rate due to conflict with neighbors -Moderate sexual harassment -Lower discrimination of govt. supports -Overall 30-50% violence experienced) **High** (-Lower suicidal attempt rate due to conflict with neighbors -Higher sexual harassment -Higher discrimination of govt. supports -Overall 50-80% violence experienced) **Very High** (-Higher suicidal attempt rate due to conflict with neighbors -Extreme sexual harassment -Extreme discrimination of govt. supports -Overall >80% violence experienced)	0.80 1.00		
Capacity Component of Disaster Risk					
1	Household head's education level	College/University High Middle Primary Not attended	1.00 0.80 0.60 0.40 0.20	Higher literacy means higher capacity of households' and vice-a-vice as it increases the access to information and resources.	(Ahsan and Warner 2014; Gain et al. 2015; Hahn et al. 2009c; Nhuan et al. 2016; Zhou et al. 2015)
2	Households who have experience with cyclone	Yes No	1.00 0.00	Households having experience with past cyclone means higher capacity as they will be more familiar with what is coming and what to do forehand.	(Nhuan et al. 2016)
3	Households having all family members who can swim	Yes No	1.00 0.00	Swimming is a good indicator for capacity against flood and cyclone disaster as it can help save lives and household assets.	
4	Households having family member who has first aid knowledge	Yes No	1.00 0.00	Households having first aid knowledge can help injured households and save lives and ultimately increases households capacity.	(Jonkman and Kelman 2005)
5	Households having multiple sources of livelihood options	>2 2 1 0	1.00 0.67 0.33 0.00	Multiple sources of livelihood increases capacity as it increases the survival capacity.	(Wisner et al. 2004)

6	Number of earning members in household	>2 2 1 0	1.00 0.67 0.33 0.00	Higher number earning persons indicates higher households capacity as even if one income is cut off due to cyclone, households can survive on another.	(Hahn et al. 2009c; Nhuan et al. 2016)
7	Households having any kind of savings (Bank, Gold, Silver)	Yes No	1.00 0.00	Savings can be used during the bad days and it increase capacity to cope cyclone and helps to early recovery.	(Nhuan et al. 2016)
8	Average monthly households savings (in Bangladeshi Taka)	>10,000 6,000-10,000 2,000-6,000 <2,000 No saving	1.00 0.75 0.50 0.25 0.00		(Browne and Hoyt 2000; Wisner et al. 2004)
9	Households having insurance (Life, Health)	Yes No	1.00 0.00	Households having insurance indicate higher coping capacity and quick recovery after cyclone.	
10	Households who preserve dry foods for unexpected calamities	Yes No	1.00 0.00	Preserving dry food can be used during and/or post cyclone that increases coping capacity.	(Birkmann et al. 2013; Browne and Hoyt 2000; Nhuan et al. 2016)
11	Households having land/house outside the flood/cyclone prone community	Yes No	1.00 0.00	Households having land/house outside cyclone prone areas indicate higher capacity as they can move there and recovery easily.	
12	Households having relatives outside the village	Yes No	1.00 0.00		(Boon 2014; Wisner et al. 2004)
13	Households with family member employed outside cyclone prone area	Yes No	1.00 0.00	Family members who employed outside cyclone prone areas means lower vulnerability and higher capacity.	
14	Strength of community cooperation in disaster response	Very good Good Moderate Poor Very poor	1.00 0.80 0.60 0.40 0.20	Cooperation strength indicates mutual helping among community members that increases households capacity to cope cyclone/disasters.	(Hahn et al. 2009c)
15	Households aware emergency shelter	Yes No	1.00 0.00	Awareness about emergency shelter helps to reach shelter safely during cyclone.	(Flanagan Barry et al. 2011; Nhuan et al. 2016)
16	Household communicate to their local government for	Yes No	1.00 0.00	Households which asked for help means they are not capable to	(Amini Hosseini et al. 2014;

	any kind of assistance in the past 12 months			cope with cyclone by themselves.	Wisner et al. 2004)
17	Frequency of public awareness programs/drills attended by households member (in number)	2 1 0	1.00 0.67 0.33	Drills and trainings program increase coping capacity against cyclones or any kind of disasters.	(Mwale et al. 2015)

Appendix B2: Selected indicators for experts Perceived Risk about coastal households

SL NO	Indicators/Questions	Classes	Weights	Explanations	Source
1	What do you think is the chance for future cyclone occurrence?	**Very High** (1 in a year) **High** (1 after 2 years) **Moderate** (1 after 3 years) **Low** (1 after 4 years) **Very Low** (1 in after 5 years)	1.00 0.80 0.60 0.40 0.20	Likelihood of cyclone: Believing in possibility higher number of future occurrence of cyclone means higher risk perceptions.	(Armaş and Avram 2009; Ho et al. 2008; Miceli et al. 2008; Qasim et al. 2015)
2	How much are you afraid of cyclones considering you as a coastal community member of Bangladesh?	Very much Afraid (>80%) Afraid (50-80%) Neutral (30-50%) Slightly afraid (10-20%) Not afraid (0%)	1.00 0.80 0.60 0.40 0.20	Dread/Fear: Higher feeling afraid of cyclone means higher risk perception.	(Armaş and Avram 2009; Ho et al. 2008; Miceli et al. 2008; Qasim et al. 2015)
3	What do you think are the chances of loss of coastal people lives in cyclones?	Very High (>80%) High (50-80%) Moderate (30-50%) Low (10-30%) Very Low (<10%)	1.00 0.80 0.60 0.40 0.20	Threaten Life: Believing in higher threat to life by cyclone means higher risk perception	(Ho et al. 2008; Miceli et al. 2008)
4	What is the likelihood of future damages by cyclones?	Very High (>80%) High (50-80%) Moderate (30-50%) Low (10-30%) Very Low (<10%)	1.00 0.80 0.60 0.40 0.20	Likelihood of Damages from cyclone: Feeling higher damage potential means higher risk perception.	(Li 2008; Peacock et al. 2005; Saunders and Senkbeil 2017; Zhang et al. 2017)
5	What do you think about people capability to cope with future cyclone?	Very Low (<10%) Low (10-30%) Moderate (30-50%) High (50-80%) Very High (>80%)	1.00 0.80 0.60 0.40 0.20	Ability to cope: Believing in higher capability to cope cyclone means less risk perception and vice-versa.	(Alam and Collins 2010; Bishawjit et al. 2017; Ho et al. 2008; Terpstra and Gutteling 2008)
6	What are the chances of supplies (e.g., electricity, drinking water, goods,	Very High (>80%) High (50-80%) Moderate (30-50%)	1.00 0.80 0.60	Supplies interruption: Thinking in more	(Miceli et al. 2008)

	etc.) interruption during cyclones (Households thinking in likelihood about supplies will be interrupted in cyclones)?	Low (10-30%) Very Low (<10%)	0.40 0.20	likelihood about supplies will be interrupted in cyclone means higher risk perception	
7	What are the chances that cyclone will change coastal people?	**Very High** (-Severe depression and anxiety -Higher substance abuse (addiction) -Severe loss of assets and infrastructures -Severe loss of household income -Overall >80% changes) **High** (-Higher depression and anxiety -Substance abuse (addiction) -Higher loss of assets and infrastructures -Higher loss of household income -Overall 50-80% changes) **Moderate** (-Depression and anxiety -Substance abuse (addiction) -Loss of assets and infrastructures -Loss of household income to some extents -Overall 30-85% changes) **Low** (-No depression and anxiety -No substance abuse (addiction) -Loss of assets and infrastructures to some extents -Loss of household income to some extents -Overall 10-30% changes) **Very Low** (-No depression and anxiety -No substance abuse (addiction) -Negligible loss of assets and infrastructures -No loss of household income -Overall <10%	1.00 0.80 0.60 0.40 0.20	Adapting lifestyles: Higher probability of changing their lifestyle because of the cyclones means higher risk perception and vice-versa.	(Armaş and Avram 2009)
8	What are the chances that cyclone will change coastal people relationships?	**Very High** (>80% relationship with neighbors becomes worse) **High** (50-80% relationship with neighbors becomes worse) **Moderate** (30-50% relationship with neighbors becomes worse) **Low** (10-30% relationship with neighbors becomes worse)	1.00 0.80 0.60 0.40	Altering relationships: Higher the probability to become worse relationship with neighbour due to cyclone indicates higher risk perception and vice-versa.	(Armaş and Avram 2009)

		Very Low (<10% relationship with neighbors becomes worse)	0.20		
9	What is the level of understanding emergency?	**Very Poor** (-Don't know emergency protocols -No ideas about mitigation actions -Good to go cyclone shelter) **Poor** (-Poor knowledge of emergency protocols -No ideas about mitigation actions -Good to go cyclone shelter) **Average** (-Good knowledge of emergency protocols -Few ideas about mitigation actions -Good to go cyclone shelter) **Good** (-Clear knowledge of emergency protocols -Good ideas about mitigation actions -Good to go cyclone shelter) **Very Good** (-Very clear knowledge of emergency protocols -Very good ideas about mitigation actions -Good to go cyclone shelter)	1.00 0.80 0.60 0.40 0.20	Knowledge about Mitigation Actions: Higher knowledge of the mitigation actions/emergency procedures for cyclones indicates lower risk as they know what to do.	(Ho et al. 2008; Terpstra and Gutteling 2008)
10	How much do you agree with govt. polices for DRR and CC (HH agreeing with government response to climate change and DRR policies)?	**Very Low** (-Govt. took no steps for DRR and CC for our community -No improvement of infrastructures -Govt. provides early warning and no training to community -Search-rescue-relief operations are very bad -Overall <10%) **Low** (-Govt. took very few steps for DRR and CC for our community and needs more steps -No improvement of infrastructures -Govt. provides early warning and no training to community -Search-rescue-relief operations are bad -Overall 10-30%) **Moderate** (-Govt. took steps for DRR and CC for our community and needs more steps -Govt. improved infrastructures to some extents	1.00 0.80 0.60	Agree with policies: Agreeing with government response to climate change and DRR policies reflects higher risk perception	(Yu et al. 2013)

		-Govt. provides early warning and training to community but not sufficient -Search-rescue-relief operations are good to some extents -Overall 30-50% satisfactory level) **High** (-Govt. took good steps for DRR and CC for our community -Govt. improved infrastructures -Govt. provides early warning and training to community but not so effective -Search-rescue-relief operations are good -Overall 50-80% satisfactory level) **Very High** (-Govt. took very good steps for DRR and CC for our community -Govt. improved infrastructures -Govt. provides early warning and training to community effectively -Search-rescue-relief operations are very good -Overall >80% satisfactory level)	0.40 0.20		

Appendix B3: Selected indicators for households Perceived Risk

SL NO	Indicators/Questions	Classes	Weights	Explanations	Source
1	What do you think is the chance for future cyclone occurrence?	**Very High** (1 in a year) **High** (1 after 2 years) **Moderate** (1 after 3 years) **Low** (1 after 4 years) **Very Low** (1 in after 5 years)	1.00 0.80 0.60 0.40 0.20	Likelihood of cyclone: Believing in possibility higher number of future occurrence of cyclone means higher risk perceptions.	(Armaş and Avram 2009; Ho et al. 2008; Miceli et al. 2008; Qasim et al. 2015)
2	How much are you afraid of cyclones?	Very much Afraid (>80%) Afraid (50-80%) Neutral (30-50%) Slightly afraid (10-20%) Not afraid (0%)	1.00 0.80 0.60 0.40 0.20	Dread/Fear: Higher feeling afraid of cyclone means higher risk perception.	(Armaş and Avram 2009; Ho et al. 2008; Miceli et al. 2008; Qasim et al. 2015)

3	What do you think are the chances of loss of lives in cyclones?	Very High (>80%) High (50-80%) Moderate (30-50%) Low (10-30%) Very Low (<10%)	1.00 0.80 0.60 0.40 0.20	Threaten Life: Believing in higher threat to life by cyclone means higher risk perception	(Ho et al. 2008; Miceli et al. 2008)
4	What is the likelihood of future damages by cyclones?	Very High (>80%) High (50-80%) Moderate (30-50%) Low (10-30%) Very Low (<10%)	1.00 0.80 0.60 0.40 0.20	Likelihood of Damages from cyclone: Feeling higher damage potential means higher risk perception.	(Li 2008; Peacock et al. 2005; Saunders and Senkbeil 2017; Zhang et al. 2017)
5	What do you think is your capability to cope with future cyclone?	Very Low (<10%) Low (10-30%) Moderate (30-50%) High (50-80%) Very High (>80%)	0.20 0.40 0.60 0.80 1.00	Ability to cope: Believing in higher capability to cope cyclone means less risk perception and vice-versa.	(Alam and Collins 2010; Bishawjit et al. 2017; Ho et al. 2008; Terpstra and Gutteling 2008)
6	What are the chances of supplies (e.g., electricity, drinking water, goods, etc.) interruption during cyclones (Households thinking in likelihood about supplies will be interrupted in cyclones)?	Very High (>80%) High (50-80%) Moderate (30-50%) Low (10-30%) Very Low (<10%)	1.00 0.80 0.60 0.40 0.20	Supplies interruption: Thinking in more likelihood about supplies will be interrupted in cyclone means higher risk perception	(Miceli et al. 2008)
7	What are the chances that cyclone will change your lifestyles (Probability of changing their lifestyle because of the cyclones)?	**Very High** (-Severe depression and anxiety -Higher substance abuse (addiction) -Severe loss of assets and infrastructures -Severe loss of household income -Overall >80% changes) **High** (-Higher depression and anxiety -Substance abuse (addiction) -Higher loss of assets and infrastructures -Higher loss of household income -Overall 50-80% changes) **Moderate** (-Depression and anxiety -Substance abuse (addiction) -Loss of assets and infrastructures	1.00 0.80 0.60 0.40	Adapting lifestyles: Higher probability of changing their lifestyle because of the cyclones means higher risk perception and vice-versa.	(Armaş and Avram 2009)

		-Loss of household income to some extents -Overall 30-85% changes) **Low** (-No depression and anxiety -No substance abuse (addiction) -Loss of assets and infrastructures to some extents -Loss of household income to some extents -Overall 10-30% changes) **Very Low** (-No depression and anxiety -No substance abuse (addiction) -Negligible loss of assets and infrastructures -No loss of household income -Overall <10%	0.20		
8	What are the chances that cyclone will change your relationships?	**Very High** (>80% relationship with neighbors becomes worse) **High** (50-80% relationship with neighbors becomes worse) **Moderate** (30-50% relationship with neighbors becomes worse) **Low** (10-30% relationship with neighbors becomes worse) **Very Low** (<10% relationship with neighbors becomes worse)	1.00 0.80 0.60 0.40 0.20	Altering relationships: Higher the probability to become worse relationship with neighbour due to cyclone indicates higher risk perception and vice-versa.	(Armaş and Avram 2009)
9	What is the level of understanding emergency?	**Very Poor** (-Don't know emergency protocols -No ideas about mitigation actions -Good to go cyclone shelter) **Poor** (-Poor knowledge of emergency protocols -No ideas about mitigation actions -Good to go cyclone shelter) **Average** (-Good knowledge of emergency protocols -Few ideas about mitigation actions -Good to go cyclone shelter) **Good** (-Clear knowledge of emergency protocols -Good ideas about mitigation actions -Good to go cyclone shelter) **Very Good** (-Very clear knowledge of emergency protocols	1.00 0.80 0.60 0.40 0.20	Knowledge about Mitigation Actions: Higher knowledge of the mitigation actions/emergency procedures for cyclones indicates lower risk as they know what to do.	(Ho et al. 2008; Terpstra and Gutteling 2008)

		-Very good ideas about mitigation actions -Good to go cyclone shelter)			
10	How much do you agree with govt. polices for DRR and CC (HH agreeing with government response to climate change and DRR policies)?	**Very Low** (-Govt. took no steps for DRR and CC for our community -No improvement of infrastructures -Govt. provides early warning and no training to community -Search-rescue-relief operations are very bad -Overall <10%) **Low** (-Govt. took very few steps for DRR and CC for our community and needs more steps -No improvement of infrastructures -Govt. provides early warning and no training to community -Search-rescue-relief operations are bad -Overall 10-30%) **Moderate** (-Govt. took steps for DRR and CC for our community and needs more steps -Govt. improved infrastructures to some extents -Govt. provides early warning and training to community but not sufficient -Search-rescue-relief operations are good to some extents -Overall 30-50% satisfactory level) **High** (-Govt. took good steps for DRR and CC for our community -Govt. improved infrastructures -Govt. provides early warning and training to community but not so effective -Search-rescue-relief operations are good -Overall 50-80% satisfactory level) **Very High** (-Govt. took very good steps for DRR and CC for our community -Govt. improved infrastructures -Govt. provides early warning and training to community effectively	1.00 0.80 0.60 0.40 0.20	Likelihood of cyclone: Believing in possibility higher number of future occurrence of cyclone means higher risk perceptions.	(Armaş and Avram 2009; Ho et al. 2008; Miceli et al. 2008; Qasim et al. 2015)

		-Search-rescue-relief operations are very good -Overall >80% satisfactory level)			

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Appendix C1: What community people can do for cyclone risk reduction if financial support provided to them?

Sl No.	Measures/Strategies	Frequency	Percent
1	Build cyclone resilient house	157	52.3
2	Increase plinth level of house	77	25.7
3	Do business	75	25.0
4	Buy livestock	29	9.7
5	Buy food	21	7.0
6	Tree plantation	20	6.7
7	Deposit money	10	3.3
8	Buy tube-well for drinking water	10	3.3
9	Buy poultry	9	3.0
10	Buy latrine	9	3.0
11	Take health service	5	1.7
12	Build bathroom	5	1.7
13	Buy land	4	1.3
14	Increase plinth level of pond	3	1.0
15	Buy boat	3	1.0
16	Buy dress	3	1.0
17	Buy water tank	3	1.0
18	Buy agricultural seeds for cultivation	2	0.7
19	Buy life jacket	2	0.7
20	Cultivate fish	2	0.7
21	Buy van	2	0.7
22	Relocate house in a safe place	1	0.3
23	Shrimp culture	1	0.3
24	Buy furniture	1	0.3
25	Buy radio	1	0.3
26	Buy silai machine	1	0.3
27	Buy milk	1	0.3
28	Take education for children	1	0.3
29	Repair furniture	1	0.3
30	Repair roads	1	0.3
31	Buy first aid box	1	0.3
32	Buy hand mike	1	0.3
33	Build sila (high house)	1	0.3

Appendix C2: Local people prescriptions to government for cyclone risk reduction

Sl. No.		Frequency	Percent
1	Cyclone Shelter	145	48.3
2	Dry food during cyclone	145	48.3
3	cyclone resilience house	135	45.0
4	Repair roads	122	40.7
5	Embankment	91	30.3
6	Pure drinking water during cyclone	66	22.0
7	Pond Sand Filter	34	11.3
8	Safe latrine	23	7.7
9	Cloth	23	7.7
10	Medicine during cyclone	19	6.3
11	Livestock	16	5.3
12	Tree plantation	16	5.3
13	Rescue service team	14	4.7
14	Life jacket	11	3.7
15	Boat	10	3.3
16	Bathroom	9	3.0
17	Clinic	9	3.0
18	Poultry	7	2.3
19	Tanning	7	2.3
20	Culvert	6	2.0
21	Education facilities	5	1.7
22	Hospital	5	1.7
23	Solar Panel	4	1.3
24	Electricity	4	1.3
25	Water tank	4	1.3
26	Torch light	3	1.0
27	Proper distribution of relief	3	1.0
28	Ambulance	3	1.0
29	Improve EWS	2	0.7
30	Asylum for old people	2	0.7
31	Radio for news	2	0.7
32	Van	2	0.7
33	First aid box	2	0.7
34	Business	2	0.7
35	Sluice gate	1	0.3
36	River Dredging	1	0.3
37	Separate room for pregnant women	1	0.3
38	Wheelchair for disable people	1	0.3
39	Hand mike	1	0.3
40	Doctor	1	0.3

Appendix C3: Experts suggestions to community people for cyclone risk reduction

SL No.	Measures/suggestions	Frequency	Percent
1	Preserve food	16	30.2
2	Go to cyclone Shelter	15	28.3
3	Helping CPP volunteers and family members to reach CS	12	22.6
4	Regular meeting and training	10	18.9
5	Participate in awareness programme	8	15.1
6	Build cyclone resilient house	8	15.1
7	Follow early warning	5	9.4
8	Participate in rescue operation	4	7.5
9	Rehabilitation	4	7.5
10	Preserve pure drinking water	4	7.5
11	Mock drillings	2	3.8
12	Knowing emergency knowledge	2	3.8
13	Livestock safe	2	3.8
14	Use first aid	2	3.8
15	Tree plantation	2	3.8
16	Form preparedness committee	1	1.9
17	Medicine	1	1.9
18	Formal organization formation	1	1.9
19	Sanitation	1	1.9
20	Make killa for livestock	1	1.9
21	Liaison with govt. DRR project	1	1.9
22	Raise homestead area	1	1.9
23	CBO fund form	1	1.9
24	Make volunteer by youth	1	1.9

Appendix C4: Experts suggestions to government for cyclone risk reduction

SL N	Govt. Measures	**Frequenc**	**Perce**
1	Build cyclone shelter	14	26.4
2	Cyclone awareness programme	12	22.6
3	Build embankment	10	18.9
4	Disseminate EWM	10	18.9
5	Build cyclone resilient house	8	15.1
6	Food distribution	8	15.1
7	Ensuring community's time respond	7	13.2
8	Relief	6	11.3
9	Tree plantation	4	7.5
10	Pure drinking water	4	7.5
11	Region specific risk reduction plan	4	7.5
12	Long-term sustainable development initiations	4	7.5
13	Ensuring shelter for most vulnerable group	3	5.7
14	Cluster cyclone risk zones through risk or vulnerability map	3	5.7
15	Strengthening CPP and EWS	3	5.7
16	Community based disaster profile development	3	5.7
17	Short-term training on DRR	3	5.7
18	Strengthening emergency operation centre	2	3.8
19	Aware about women and children safety	2	3.8
20	Medical service	2	3.8
21	Ensuring strong communication among all govt. and NGOs organization	2	3.8
22	Make equipped search and rescue team	2	3.8
23	Set up tube-well	2	3.8
24	Protecting household resource	1	1.9
25	take household rescue map	1	1.9
26	application of widely used global satellite monitoring	1	1.9
27	Ensure information law	1	1.9
28	Inclusion of environmental friendly adaptation technology	1	1.9
29	Provide radio and television for news	1	1.9
30	Electricity and power supply	1	1.9
31	Proper drainage facility	1	1.9
32	Hazard profiling	1	1.9
33	Proper evacuation	1	1.9
34	Build PSF with low cost technology and user friendly for elderly people	1	1.9
35	Community involvement in DRMA	1	1.9
36	Build audit system for relief	1	1.9
37	Repair roads	1	1.9