Review of sea-level rise science, information and services in Bangladesh

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ARRCC Asia Regional Resilience to a Changing Climate

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Contents

Executive Summary

Sea level rise over the coming decades and centuries was identified in the Intergovernmental Panel on Climate Change (IPCC) fifth assessment report (AR5) as one of the most important risks facing coastal nations and communities. The low-lying islands and densely populated coastal areas of South Asia are vulnerable to the impacts of sea-level rise, such as coastal erosion and increased inundation from tropical cyclone storm surges. Those tasked with formulating and implementing coastal adaptation measures will require information about observed and projected sea-level rise, over a range of temporal-spatial scales.

As part of the Climate Analysis for Risk Information and Services in South Asia (CARISSA) project, under the Asia Regional Resilience to a Changing Climate (ARRCC) programme[1], the Met Office is working in partnership with organisations in South Asia to enhance the use of regional climate information in vulnerability assessments and adaptation planning. In order to understand the sources of future climate information available for use in the South Asia region, the Met Office has been engaging with scientists and intermediaries in the region through a series of workshops and visits. To support this work, a review has been conducted to assess studies from the last 10 years linking climate change science to changing costal risks in the region.

This report reviews the scientific literature published between 2009 and 2019 on sea-level rise and the cascading impacts of sea-level rise in Bangladesh. This includes vulnerability and risk assessments of the natural and human coastal environments, along with adaptation or mitigation responses. The report is intended to provide a baseline understanding of what is known about sea-level rise in Bangladesh along with the types of sea-level rise information being used for impact, vulnerability and adaptation assessments.

A systematic literature review process was adopted, consisting of pre-specified search protocol and eligibility criteria. Sources are categorised based on the spatial-temporal scale and geographic areas under consideration. The methodology is not specific to Bangladesh and can be applied to other nations in the South Asia region.

[1] https://www.metoffice.gov.uk/services/government/international-development/arrcc

The results reveal disparities in the number of studies covering the southwestern, central and south-eastern coastal zones. The southwest and the southeast coastal zones are respectively the most and least studied areas. Most studies focus on the impacts of sea-level rise on human and natural coastal systems, however no studies attempt to attribute impacts to relative and extreme sea-level changes.

Historical studies, based on in-situ and remote sensing data, highlight the significant influence of non-climate processes on relative sea-level rise at some locations, which are often highly localised. The studies based on tide gauge records in this review indicate that sea-level rise in Bangladesh exceeds the global average, which is likely to be partly due to the high subsidence rates observed in the delta region.

30% of studies reviewed discussed future climate and sea-level scenarios, with most using projections of global sea-level rise and only two studies use regional sea-level projections. The IPCC Special Report on Oceans and cryosphere in a Changing Climate (SROCC) states that sea-level rise varies regionally and that varying contributions to sea-level rise, from processes such as thermal expansion, ocean dynamic and land ice loss, could cause regional sea-level rise to differ by around 30% compared to the global mean sea-level. In the near-term, considering local processes, such as subsidence, is critical for projection of sea level impacts at local scales.

Sea-level response measures discussed in the reviewed publications cover protect, accommodate, advance, retreat and eco-system measures. The type of responses discussed in the publications varied with the research scale and geographic area under consideration. The review includes examples highlighting potential social conflicts and trade-offs associated with different coastal risk management options, suggesting the need for multi-scale, interdisciplinary coordination.

This review focuses on peer-reviewed scientific literature. Further work to include grey literature is needed to establish a baseline understanding of existing coastal climate services in Bangladesh. Given the lack of regional climate projections featured in the scientific publication during this period, it would be surprising to find regional and local scale projections being used extensively in coastal climate services. The key findings of this review, based on the published literature, are: i) coastal climate risks from sea-level rise impacts in Bangladesh show spatial heterogeneity due to local processes, and ii) uptake of regional or local sea-level rise information in Bangladesh is low.

1. Introduction

Sea level rise over the coming decades and centuries was identified in the Intergovernmental Panel on Climate Change (IPCC) fifth assessment report (AR5) as one of the most important risks facing coastal nations and communities. The low-lying islands and densely populated coastal areas of South Asia are vulnerable to the impacts of sea-level rise, such as coastal erosion and increased inundation from tropical cyclone storm surges. Those tasked with formulating and implementing coastal adaptation measures will require information about observed and projected sea-level rise, over a range or temporal-spatial scales.

This review aims to provide a baseline indication of the available sea-level rise information in Bangladesh, and the use of sea-level rise information for vulnerability, impact and adaptation studies. The review also aims to establish what is known about the impacts of sea-level rise in different sections of the Bangladesh coastal zone. It is intended to support the development of coastal climate services in Bangladesh, by identifying barriers preventing the use of sea-level rise information and highlighting where national or sub-national scale sea-level projections could potentially enhance coastal management or adaptation assessments. The method used in this review of Bangladesh could be applied to other coastal nations in the South Asia region, allowing for country-by-country analysis and comparison.

The rereview has the following three main objectives:

1) To establish what is known about the impacts of sea-level rise on different sections of Bangladesh Coastal Zone;

2) To identify the types of sea-level information used for assessments of vulnerability and projected exposure at the national, sub-national and local scale; and

3) To identify applications where additional sea-level rise information or sea-level rise services may have the potential to enhance vulnerability and adaptation assessments in Bangladesh.

2. Methods

A systematic literature review was conducted to identify, assess and synthesise literature on sea level rise in Bangladesh using a pre-defined search protocol and inclusion/exclusion criteria. The method will also be applied to Pakistan, as the other coastal country in the South Asia region covered by Asia Regional Resilience to a Changing Climate (ARRCC) programme. Since the aim is to generate results on a country by country basis, studies with a regional focus (i.e. covering multiple South Asian countries) are omitted (see section 2.2).

2.1 Search Protocol

The review considers only peer reviewed research papers published between 2009 and 2019. Although the grey-literature could contain more information relating to the practice of coastal management and adaptation practice, these documents may not have been reviewed to the same standards as the scientific literature. The search was restricted to studies published during the previous decade, 2009-2019, to narrow the scope of the review and span the time between the last Bangladesh National Action Plan for Adaptation (NAPA) update in 2009 and the next NAPA expected in 2020.

Relevant publications from the scientific literature were identified using key word searches on Clarvirate Web of Science[2]. The Web of Science database has previously been used to gather information for development of coastal decision support systems in Australia (Leitch et al. 2019, NCCARF 2015) and reviews of climate change research in Bangladesh (Rahman et al 2018). The search protocol was adapted from a State of Play report produced as part of the Australian CoastAdapt[3] project (NCCARF 2015).

The search protocol for this review included the following key word search terms:

1. "Climate change” AND “Bangladesh” AND “coast”
2. “sea-level” AND “Bangladesh” AND “climate Change”
3. “coast AND “sea level” AND adaptation AND “Bangladesh”

The search returned 125 published articles.

[2] Web of Science: *https://apps.webofknowledge.com*
[3] https://coastadapt.com.au/

2.2 Inclusion and Exclusion Criteria

Additional criteria were used to further subset the papers returned through the search.

1. Articles peer reviewed and written in English
2. Coastal climate variability or change the primary focus of the article
3. Multi-country studies are not included in the review

Following a review of title and abstract, a total 98 articles were retained based on the inclusion-exclusion criteria.

2.3 Research scale and geographic focus

Each reference was categorised by research scale (national, sub-national or local) and timescale (case-study, historical or future). The sub-national and local studies were further categorised by the geographic location of the coastal areas under consideration. The Bangladesh Coastal Zone (BCZ) covers an area of over 47150 km^2, consisting of 19 coastal districts along a coastline of 710 km and population of approximately 38.52 million based on a 2011 census (MoEF, 2016). For the purposes of this review the coastal zone was split into three physiographic zones; The Ganges Tidal Floodplain (GTF), Meghna Estuarine Floodplains (MEF) and the Chittagong Coastal Plains (CCP) covering the western, central and eastern sections of coastline respectively. The three physiographic zones were adopted from (Brammer, 2014) but have also appeared in reports by the Bangladesh Ministry for Environments and Forests (MoEF, 2016).

The temporal scale of each study is described by three categories. Studies dealing with trends over a period of five years or more were labelled as historical. Studies dealing with results from a shorter period were labelled case studies. Studies using future projections or scenarios were designated as future. For each of the studies the stated timescales (case-study, historical or future) were also recorded for further analysis. Review articles covering work from multiple timescale were assigned to a fourth category called review. The temporal scale classification was intended to help identify sources of information about past, present and future sea-level rise available in Bangladesh, along with information about changing coastal hazards or risks.

A grey-literature review may provide a better indication of the types of sea-level rise used by policy makers and coastal management practitioners but typically this information can be traced to peer-reviewed literature. A lack of peer reviewed studies based on global or regional climate projections for example, could suggest that information from sea-level projections is not available for use by decision makers or that the sources information being used are not based on peer-reviewed science.

2.4 Qualitative Analysis: Research scope and relevance

For each paper we sought to answer the following set of questions.

1. What problems or questions does the paper seek to address?
2. What were the main findings or outputs?
3. What limitations were identified by the authors?
4. What research requirements and information needs were identified?
5. What gaps in the literature have been identified?

3. Results and discussion

3.1 Research scale: National, sub-national and local trends

National level studies account for 26 of the 98 reviewed articles, sub-national studies make up the majority with 66 studies, and there were a further 8 local studies – see table 1. In terms of temporal scale, 12 of national studies were classified as historical, with 7 of these being review papers. There were 12 national studies that included some form of projection, extrapolation or prediction and where classified as future.

Research scale			
National Level Studies	Sub-national studies	Local studies	Total
24	66	8	98
Geographic focus			
Coastal Zone	Sub-national studies	Local studies	Total
Ganges Tidal Floodplain (GTF)	46	8	54
Meghna Estuarine Floodplain (MEF)	8	0	8
Chittagong Coastal Plains (CCP)	2	0	2

Table 1 – Publication research scales and geographic focus areas

In some studies, future sea-level estimates were based on global or regional sea-level projections from the IPCC fourth assessment report (AR4) and AR5, as in Adams and Kay (2019) and Nicholls et al. (2016). In others, empirical methods were used to extrapolate future sea-level changes from observed or reconstructed tide gauge records, such as Bhuiyan and Dutta (2012). Studies cover future climate impacts on national resources, for example water (Hoque. et al. 2016, Dasgupta et al. 2017) and power (Adams and Kay 2019), and key sectors like agriculture and aquaculture (Ahmed and Diana 2015). There are also national studies on the link between coastal climate risks and migration (Angus et al. 2009, Chen and Mueller 2018, Davis et al. 2018).

The national level studies referencing tide gauge data note that the observed sea-level trends in Bangladesh are larger compared to the global average, as in Lee (2013). Sea-level changes in deltaic regions are influenced by vertical land motion processes like sediment accretion and subsidence. According to a report by the Bangladesh Task Force approximately 10% of any sea-level change in Bangladesh in due to subsidence (Lee, 2013). National level studies reveal large variations in magnitude and sign of vertical land motion along the coastal zone, with changes to the dominant processes during the observation period (Sarwar and Woodroffe 2013). This could suggest that tide gauge records from a single location are not representative of the entire coastline and local changes to vertical land motion processes should be considered when interpreting sea-level projections extrapolated from tide gauge records. Vertical land motion processes are also influenced by local-scale land-use changes, along with changes to river flow due to upstream infrastructure projects.

National level studies on tropical cyclone impacts, focused on how sea-level rise could lead to increases in flood inundation, from tropical cyclone storm-surges. The papers in this sample, used reanalysis data from tropical cyclones Sidr in 2007 and Alia in 2009, which both made landfall in the west of Bangladesh and so discussions around impacts focus on the southwest coastal zone (Jisan et al. 2018, Rahman et al. 2019). Climatologically the eastern coastal zone experiences more tropical cyclones, for example Alam and Dominey-Howes (2014) produced an extended record of landfalling cyclones from archival sources, covering a period from 1000-2009. The authors identify the Chittagong Coastal Plains as the coastal zone that experienced the most tropical cyclones. Tropical cyclone landfall is more frequent in the CCP but storm-surges are less severe compared to storms making landfall in the GTF.

The national level studies also include estimates for coastal erosion and accretion processes. In Sarwar and Woodroffe (2013) erosion and accretion rates for the period 1989-2009 were estimated based on LandSat imagery and Digital Shoreline Analysis System (DSAS) in ArcGIS. The DSAS compares the position of the shoreline in satellite images from different periods along transects perpendicular to the coastline. The net erosion and accretion rates were calculated for six sections of mainland coastline and four of the larger islands. The study highlights the dynamic and heterogenous nature of the erosion and accretion processes that influence relative sea-level rise along the Bangladesh coastline.

All the review articles were at the national-scale (7 in total) and were more policy oriented than other articles. Saline intrusion from sea-level rise, has been linked to contamination of coastal freshwater resources and groundwater, causing adverse impacts on coastal agriculture and human health (Rahman 2018). Rahman (2018) reviewed work linking climate change to health impacts in Bangladesh, including the health impacts of saline intrusion. The findings and recommendations could be generalised to other sectors; i) credible best available science summaries on sea-level rise health impacts, ii) research-practitioner coordination, to ensure grey-literature findings are made available and subjected to peer-review, iii) Exchange of sea-level, salinity and health datasets, iv) use of performance indicators to monitor the effectiveness of saline intrusion mitigation measures.

In another sector-focussed review, Shahid (2012) discussed the potential impacts of climate change on national energy production, energy demand and security. Several recommendations are made, the most relevant for coastal climate services is that, water supply and storm exposure must be considered when scoping infrastructure locations.

3.2 Geographic focus

Sub-national and local studies mostly focussed on the GTF in the southwest, the next most common study area being from the central coastal areas in the MEF, with just a couple of studies from the eastern coastal zone CCP (see table 1). Nearly all the local studies are based in Khulna and Barisal areas of the GTF.

3.2.1 Ganges Tidal Floodplain (GTF)

The Khulna district in the GTF is home to the Sundarbans, the world's largest mangrove forest, which is known to provide a natural defence against storm-surges and coastal erosion. The IPCC Special Report on the Ocean Cryosphere in a Changing Climate (SROCC 2019) highlights the trend towards including natural and ecosystem-based adaptation approaches, alongside traditional hard-structures (e.g. seawalls and dikes). For example, Chow (2018) evaluated the effectiveness of the mangrove plantations established by the Bangladesh Government to prevent erosion and stabilise coastal areas. The results indicated that mangrove plantation areas experienced greater rates of accretion relative to erosion, compared to the non-plantation areas.

Dasgupta et al. (2019) quantified protective of capacity of the mangrove forests against tropical cyclone storm surges, by reducing storm surge height and water flow velocity. The study used a hydrodynamic model to simulate how mangrove forests of varying width and density, could modify the surge height and flow velocity, based on the tropical cyclone Sidr (2007) storm surge. The study also estimated variations in protective capacity from different mangrove species, using different roughness parameters depending on the mangrove species composition at four different sites. The results showed significant reduction in flow velocity (29-92%) and a small reduction in surge height (4.0-16.5 cm). The authors suggest the protective capacity of mangroves should be considered when setting the design parameters of embankment projects adjacent to mangrove forests. The authors also state the importance of anticipating future environmental stresses, such as sea-level rise and future storm surges when planning mangrove-based adaptation projects.

Dasgupta et al. (2017) assessed potential changes to the composition of mangrove species in mangrove forests due to changing climate and soil-salinity by 2050, using global mean sea-level projections from IPCC AR4 (27 cm for scenario B1, 32 cm for A1B and A2) from three global circulation models. This were combined with estimated subsidence rates of 2mm, 5mm and 9mm per year. The results indicated varied patterns of gain and loss across the 14 mangrove types but significant reductions (median decline of 58 %) for the mangrove species highest timber value.

Ghosh et al. (2019) assess the impact of sea-level rise on mangrove species due to increases in inundation. This study used three sea-level scenarios for 2100 based on regional sea-level projections for Haldia in West Bengal from Pachauri et al. (2014). The three different scenarios were for 0.46m, 0.75m and 1.48m respectively, relative to the 1986-2005 baseline. The results indicate that for a net subsidence rate of -2.5 mm/year, the mangrove forest area will be reduced by 1.78 km^2/year, 3.76 km^2/year and 14 km^2/year for the three sea-level scenarios respectively. The study also indicated that erosion may be the dominant mechanism for area loss, rather than inundation from sea-level rise

The Sundarbans mangrove forests are all an important area for biodiversity, home to the globally endangered Bengal Tiger species. Mukul et al. (2019) assessed the potential Bengal Tiger habitat loss due to climate change and sea-level rise in the Sundarbans. The study used global sea-level projections from IPCC AR5, with RCP6.0 and RCP6.0 to produce sea-level scenarios for 2050 and 2070, with a 1986-2005 baseline period. The projected sea-level changes were 30 cm and 40 cm by 2050, with 60 cm and 80 cm by 2070, for RCP6.0 and RCP8.5 respectively. The study used a statistical model with based on nine bioclimate parameters[4] to assess the contributions from bioclimate and sea-level change on habitat loss. The study found a dramatic decline for suitable Bengal tiger habitats under both RCP6.0 and RCP8.5, with larger contributions from bioclimate change compared to sea-level rise. By 2070 the model indicated there would be no remaining areas suitable for the Bengal tiger's habitat in Bangladesh Sundarbans. Sea-level rise alone contributed to 28.5% and 48.9% reductions in habitat by 2070 for RC6.0 and RCP8.5 respectively.

In the GTF the Ganges river is the major source of dry season water for maintaining navigable rivers, fisheries, irrigation system, reducing salinity and maintaining ecosystems (Rahman and Rahman 2018). The Farakka barrage constructed up-stream of the India-Bangladesh border by India in 1976 has significantly reduced monthly, average and minimum discharges in February-May, December-May and

[4] annual mean temperature, isothermality, temperature seasonality, maximum temperature of warmest month, minimum temperature of coldest month, mean temperature of warmest quarter, Annual precipitation, precipitation of warmest quarter, vegetation type

February-April respectively (Rahman and Rahman 2018). Due to the reduction in Ganges flow post Farakka the GTF in south-west Bangladesh has been suffering from environmental degradation (Rahman and Rahman 2018). The inland intrusion of saline water is regulated by the upstream fresh-water flow from rivers but since construction of Farakka, salinity has increased 380 μΩ/cm during the pre-diversion period in 1974 to about 29,500 μΩ/cm in 1992 (Rahman and Asaduzzaman 2010).

Saline intrusion is likely to increase in future due to further reduced river flows and longer-term climate change-induced decreases in dry-season rainfall and sea-level rise (Szabo et al. 2016). The Bangladesh Climate Change Resilience Fund (BCCRF) management committee highlighted saline intrusion in coastal areas as a critical issue for adaptation (Dasgupta et al. 2015). Among the selected publications Saline intrusion has been linked to adverse impacts on coastal agriculture (Szabo et al. 2016, Alam et al. 2017) , biodiversity (Hossain et al. 2017a, Mehva et al. 2019) aquaculture (Alam et al. 2017, Fernandes et al. 2016, Dasgupta et al. 2015) and human health (Kahn et al. 2014, Rasheed et al. 2014).

Clarke et al 2013, produced projections of on-farm salinity for coastal Bangladesh for 2098, using a soil deficit model with a 17-member ensemble from HadRM3P (PRECIS), dynamically downscaled from HadCM3 under the SRES A1B Scenario. The study found that once dry season irrigation goes above 5ppt the monsoon rainfall is no longer able to leach dry season salt deposits, reducing farm productivity by up to 50%. The study mentions saline intrusion of aquifers from sea-level rise as a likely cause of increased salinity but no sea-level information was used to generate the salinity projections. Similarly, Dasgupta et al. 2015 produce salinity projections for 2050 compared to 2001-2009 using an econometric model, finding a median increase of 39% at the 41 soil monitoring stations but did not include any information on sea-level rise.

3.2.2 Meghna Estuarine Floodplain (MEF)

The Meghna Estuarine floodplain has been described as one of the world's most dynamic estuaries (Islam et al. 2015a), which may explain the focus on sediment transport and Vertical Land Motion (VLM) processes, in the publications for this area. The other common research themes were Disaster Risk Management and storm-surge studies. Some studies include elements from all these research themes, as in Islam et al. (2015a) which assessed the relative contributions from coastal slope, relative sea-level rise, tidal-range, shoreline erosion vs accretion, population size, bathymetry and flood frequency to coastal vulnerability. The study developed a coastal vulnerability index based on these eight parameters, which were ranked from 1-5 on their contribution to physical changes on the coast as sea-level rises. The CVI was calculated as the square root of the product of the ranked parameters, divided by the total number of parameters. The sea-level contribution was based on relative sea-level changes at Daulatkhan tide gauge station over a 30-year period (1960-2011). The authors note that the derived sea-level rise rate of 14 mm/yr seems to be an overestimation if compared to the 4.0-7.8 mm/yr assessment by Singh (2002) but within 10-15 mm/yr range estimated by Choudhury et al. 1997. The 14 mm/yr rate is taken to be representative of the whole study region and all areas are assigned the highest rank of 5 for the contribution from sea-level rise. Similarly, all areas were assigned the rank of 4 for the contribution from tidal range, based on the 2.05 m tidal range observed at Daulatkhan tide gauge station. The calculation was performed for 263.87 km of coastline on Bhola island in the Bhola district of Barisal division. According the vulnerability index 22% of coastline (57.23 km) is under very high risk, another 29% (75.26 km) is under high risk, 25% (67.69 km) at moderate risk and 24% (63.69 km) at low risk. The most vulnerable sections were along the western coast of Char Fasson and northern and southwestern coasts of Bhola Sadar. Since uniform sea-level rise and tidal-range ranking were used for all areas, these variables cannot explain variations in vulnerability as measured by the CVI at different locations.

Sarker et al. (2011) investigate the effectiveness of sediment practices in this coastal zone, claiming that rates of sediment accretion will generally keep pace with sea-level rise in the estuary, but sediment transport will be restricted in polder areas, which will be more prone to subsidence. Remote sensing studies for the MEF coastal zone indicate large spatial variation in subsidence rates. For example, Higgins et al. (2014) estimated subsidence rates for Dhaka of 0-10 mm/yr and rates for areas surrounding Dhaka of 0-18 mm/yr, as well as identifying three hotspots with subsidence in excess of 18 mm/yr in 1) Lakshmipur and Noakhali districts, 2) Comilla and Chadpur districts and 3) south-eastern Kishoergani district. The subsidence rates are in line with estimates from an earlier study (Syvitski et al. 2009) of 8-18 mm/yr for the Ganges Delta, although the lack of supporting ground-based data has been questioned by

Brammer 2013. The large subsidence rates highlight the importance of non-climate contributions to local sea-level rise, since 1m of sea-level by 2100 compared to the present day (2020) would correspond to an average rate of around 12.5 mm/yr, the same order as the subsidence rates. In the near-term, sea level rise (SLR) rates are expected to be smaller, with projections indicating a non-linear increase accelerating in the mid to late 21st century.

3.2.3 Chittagong Coastal Plains (CCP)

Chittagong Coastal Plains (CCP), was the least studied coastal zone in this review, with just two studies on this area. The coastal zone is home to the Chittagong megacity, the major port terminal of the Bay of Bengal. The city was identified as a "hot spot" area of vulnerability from climate change (Islam 2016). Both the studies discuss the impacts of groundwater contamination from saline intrusion. As with the studies discussed for the GTF, Rasheed et al. (2014) assessed the salt consumption among a sample of the coastal adult population, to assess potential links between consumption of saline water and health problems like hypotension. The study did not investigate the causes of saline intrusion but referenced an earlier study (CEGIS 2006) estimating that sea-level rise and other climate effects have put 20 million people in the coastal belt at risk from environmental exposure to sodium. Fatema et al. (2018) assessed the potential impact of the tourism sector on ground-water contamination during the dry-season. They suggest saline contamination of ground water is exacerbated by unregulated groundwater extraction at hotels in the coastal tourist area of Cox's Bazar. As discussed in relations to publications for the GTF, groundwater salinization is typically more of an issue during the dry season, but since this coincides with the tourist season, local tourism can amplify the problem. The study mentioned that "*sea-level rise is reducing the gradient between the hydraulic head of the groundwater and the sea-level*" based on previous studies (Minhar et al. 2013, Bhiyan and Dutta 2011, Yu et al. 2010) but does not investigate the contribution of sea-level rise to salinization of ground-water.

3.3 Temporal Scale: Sea-level projection use and uptake

The number of publications by temporal scale for each coastal zone are shown in table 2. National level studies cover the entire Bangladesh Coastal Zone (BGZ). The types of sea-level projections used by studies focussing on future period are described in table 3.

3.3.1 Sea-level projections from Global Climate Models

The IPCC fifth assessment report (IPCC AR5) provided regional sea-level projections for nine locations, including Haldia in West Bengal India (see figure 1) From the publications included in this review, approximately 30% discussed future climate projections or scenarios. Only a small fraction of these used regional sea-level projections, generally global sea-level rise projections from IPCC assessment reports are treated as being representative of sea-level rise in the Bay of Bengal.

	Historical	**Case-study**	**Future**	**Review**
All	16	45	29	2
	Historical	**Case-study**	**Future**	**Review**
BGZ (National)	5	N/A	12	2
GTF	9	32	14	0
MEF	2	4	0	0
CCP	0	2	0	0

Table 2 – Number of publications by temporal scale for: All publications, National studies for the Bangladesh Coastal zone (BGZ) and the three sub-national coastal zones.

Kebede et al. (2018) developed a framework for applying the global Representative Concentration pathways (RCP), Shared Socio-economic Pathways (SSPs) and Share Climate Policy Assumptions (SPA) scenarios at the sub-national scale as part of the DECCMA project. The framework was applied for three deltas across the world, including the Ganges-Brahmaputra Meghna delta. Regional sea-level projections from IPCC AR5 under RCP8.5 were used to develop future climate scenarios, with sea-level rise of 17-38 cm for 2045-2065 and 26-82 cm for 2081-2100 relative to the 1986-2005 baseline period.

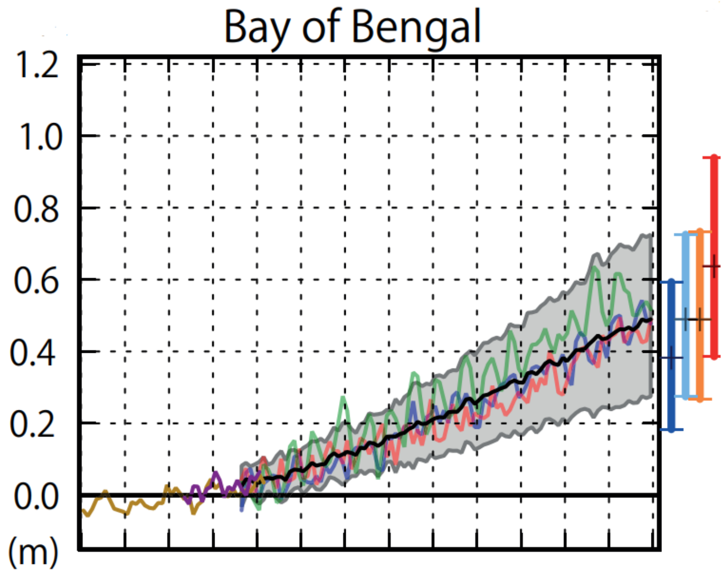

Figure 1 – Regional sea-level projections for West Bengal (IPCC AR5 WG1 Chapter 13 pp 1198)

Observed and projected relative sea level change at Haldia: 22.0°N, 88.1°E. The observed, in situ relative sea level from the tide gauges record (since 1970) is plotted in yellow. Satellite record (since 1993) is plotted in purple. The projected range from 21 CMIP5 RCP4.5 scenario runs (90% uncertainty) is shown by the shaded region for the period 2006–2100, with the bold line showing the ensemble mean. Coloured lines represent three individual climate model realizations drawn randomly from three different climate models used in the ensemble. Vertical bars at the right side of the panel represent the ensemble mean and ensemble spread (5 to 95%) of the likely (medium confidence) sea level change for the location at the year 2100 inferred from RCPs 2.6 (dark blue), 4.5 (light blue), 6.0 (yellow) and 8.5 (red)

Rahman et al. (2019) assessed future changes to inundation from tropical cyclones in Ganges-Brahmaputra-Meghna delta. The Delft3D model was used to simulate changes to storm-surges from tropical cyclones Roanu (2015), Alia (2009) and Sidr (2007) under different sea-level scenarios, based on projection from IPCC 2013. For tropical cyclone Roanu the inundated increased from 676 km^2 to 2912 km^2, 7832 km^2 and 12,550 km^2 for sea-level rise of 0.5m, 1.0m and 1.5m respectively. For tropical cyclone Alia the inundated increased from 1999 km^2 to 4226 km^2, 6216 km^2 and 7497 km^2 for sea-level rise of 0.5m, 1.0m and 1.5m respectively. For tropical cyclone Sidr the inundated increased from 1484 km^2 to 3380 km^2, 5777 km^2 and 7588 km^2 for sea-level rise of 0.5m, 1.0m and 1.5m respectively. Interestingly, the sensitivity of inundation area to sea-level rise for the Roanu case is non-linear, while the other two storms show an approximately linear response. Roanu storm passed through the Chittagong region, considered the business capital of Bangladesh. The results could suggest that tropical cyclone risk assessments and impact assessments for this area could be also be more sensitive to the sea-level rise projections used.

Using the same surge model, Jisan et al. (2018) with a larger cyclone event set with data from additional ten tropical cyclones, and varied the storm intensities (by ±10%) and the phasing of landfall time with the tidal cycle. The study used the future sea-level scenarios from Kay et al. (2015) based on the regional sea-level projections IPCC AR5 for Haldia in West Bengal (India). For 0.26 m of sea-level rise by the mid-century, the area inundated from a tropical cyclone like Sidr (2007) would increase by 31%, while for 0.54 m of sea-level rise by 2100, the inundated area would increase by 53%. The associated storm surge level at Char Changa station would increase 14% and 29% for under sea-level rise for the middle and end of the century respectively. For tropical cyclone Alia (2009) the storm surge height at Barisal station would increase by 22% for 0.26 m of SLR by mid-century, reaching 52% for 0.54m of SLR by 2100. For tropical cyclone Sidr the response of storm-surge height at Barisal and Char Changa was approximately linear, with similar percentage increases for both stations. In contrast for storm Alia, with 0.26m SLR the surge height increased by 112% at Barisal station and 219% at Char Changa. However, the authors attribute the much larger increase at Char Changa to "*an artificial effect due to the coarse resolution of the model grid near the station*".

The results from Rahman et al. (2019) and Jisan et al. (2018) show that even if tropical cyclone intensities remain the same over the 21st century, projected changes in sea-level rise will lead to increased inundation (Rahman et al. 2019, Jisan et al. 2018) from storm surges and increased storm-surge height (Jisan et al. 2018).

3.3.2 Empirical sea-level projections

The other regional or local SLR projections in the sampled publications, were based on statistical extrapolation of tide gauge records or expert elicitation. For many of the tide gauge stations in Bangladesh, the records contain significant gaps. In some cases, the instruments have been relocated and the changes have not been recorded or information on the station history is not available. Lee (2013) used 32-year hourly tide gauge records from 13 stations to assess SLR and changes to storm-surge heights. Hiron Point station, was used to reconstruct records at the other stations. This instrument was relocated at some unspecified time, with the impact on observations unknown. Partial records from Hiron point were reconstructed with using a hydrological model. Statistical analysis indicated, the station was relocated in March 1990. SLR trends either side of this date were markedly different 8.04 mm/yr and 4.46 mm/yr respectively. The study projected 34cm of SLR over the period 2009-2050, at a rate of 7.67 mm/yr. Extreme Value Analysis (EVA) was used to estimate future extremes from storm surges. The resulting 30, 50 and 100-year return levels were 1.59m, 1.66m and 1.75, which combined with the projected SLR produces 100-year return level of 2.09m at the 95% confidence level from 1.91-2.48m.

3.3.3 Historical Trends

Some authors have suggested that relative mean sea-level (RMSL) trends could be misleading in estuaries where the tidal range is changes. Pethick and Orford (2013) suggested that for areas experiencing tidal-range amplification, RMSL may be a poor indicator for changes to mean high water. The authors note the observed increase in tidal range at coastal and inland water stations, which they attribute partly to estuary channel constriction by embankment. Instead of RMSL rise the, authors suggest using the rate of increase in high water maxima which they term Effective Sea Level Rise (ESLR). For the Khulna in the GTF coastal zone, over half ESLR was attributed to non-climate anthropogenic factors, such as dredging and embankments. Removal of the embankments would likely cause catastrophic flooding in areas of reclaimed land. Navigation is already an issue for waterways in the area and reducing dredging would have significant economic impacts.

Publication	Projected SLR cm (year)	Baseline	Projection type	Source
Mukul et al. 2019	30 cm (2050) 60 cm (2070)	1986-2005	Global RCP6.0	IPCC 2013
	40 cm (2050) 80 cm (2070)	1986-2005	Global RCP8.5	IPCC 2013

Rahman et al. 2019	50 cm (2040) 100 cm (2100)	1986-2005	Regional RCP8.5	IPCC 2013
Jisan et. al 2018	26 cm (2050) 54cm (2100)	1986-2005	Regional	Kay et al. 2015, IPCC 2013
Kebede et al. 2018	17-38 cm (2045-2065) 26-82 cm (2081-2100)	1986-2005	Regional RCP8.5	DECMMA, IPCC 2013
Lee 2013	34 cm (2009-2050)	1990-2009	Empirical, single location Hiron Point	Lee 2013

Table 3 – Sea level projections used in the reviewed publications

4. Coastal risk assessments and risk reduction

The coastal hazards and impacts discussed by the publications in this review cover the six main concerns identified for low-lying coasts in SROCC: (i) permanent submergence of land by mean sea levels or mean high tides; (ii) more frequent or intense flooding; (iii) enhanced erosion; (iv) loss and change of ecosystems; (v) salinization of soils, ground and surface water; and (iv) impeded drainage. These are referred to as “the main cascading effects of sea-level rise” in SROCC. None of the publications reviewed attributed observed impacts, directly to climate change and sea-level, which can be difficult to disentangle from natural and local anthropogenic factors operating at different spatial scales. The salinization of soils in the GTF coastal zone has linked to the construction of the Farakka Barrage in West Bengal, while the salinization of groundwater in Cox’s Bazaar in the CCP has been influenced unregulated groundwater use within the coastal tourist area. These examples highlight the potentially significant influence of human activities on coastal impacts. While there have been numerous studies on coastal impacts in GTF coastal zone, few studies have been published on coastal impacts in the other coastal zones during the review period.

The factors influencing the exposure and vulnerability of human populations and ecosystems discussed by the publications in this review, were partly influenced by the research scale under consideration (see section 3). Local studies were more likely to emphasise the human factors such as socioeconomic status, level of education, livelihood and gender. Hossain 2015, analysed the vulnerability of households to tropical cyclones and sea-level extremes from storm surges, finding households with lower levels of education or income have less access to weather forecasts and disaster training. This would suggest that widening access to weather and climate information could potentially reduce vulnerability at the household levels.

The studies addressing aspects of vulnerability and projected exposure in this review were mostly conducted at the sub-national and local scale. This is also generally true for studies of climate change and sea-level rise impacts. In both cases, there are mismatches between the spatial of the future climate information being used and the research scale under consideration. For near-term projections of exposure and vulnerability, empirical methods can be used to bridge the scale divide, by providing location specific information derived from observations (as in Lee 2018). For longer time-horizons the assumption of statistical stationarity becomes more problematic, since contributions from non-climate processes to sea-level rise such as subsidence rates, vary temporally as well as spatially. Brammer 2014, implies that satellite-based subsidence rate estimates 18 mm/yr from Syvitski et al 2009, cannot representative of long-term subsidence over GTF zone, since plinth level measurements from historical sites in the region suggest subsidence rates of 1–2.5 mm/yr. The statistical stationarity assumption is also a feature of the extreme sea-level and storm-surges featured this review. No studies in this review considered future changes to tropical cyclone frequency, intensity and track, when assessing future storms-surge inundation or surge height.

The reviewed publications featured examples of different ways of responding to the threat from relative and extreme sea-level rise, covering the six categories identified in SROCC (see figure 2).The type of responses to coastal risk discussed varied with the research scale under consideration. Sub-national and local studies discussed migration as a possible response to local sea-level rise impacts, such as increased salinization and loss of available land. Similarly, ecosystem-based responses were discussed in sub-national or local studies focussing on the Sundabans in the GTF. There were studies assessing the effectiveness of recent ecosystem-based responses at reducing coastal erosion and enhancing sediment accretion. In contrast, the examples of protect, accommodate and advance were often from previous interventions, that were poorly maintained and exacerbating other coastal impacts, such as subsidence and reduced drainage. Historic national-level coastal management infrastructure in the form of polders, combined both the advance and protect responses but have been linked to adverse impacts at the sub-national and local scale (Ali and Syfullah 2017, Alam et al. 2017).

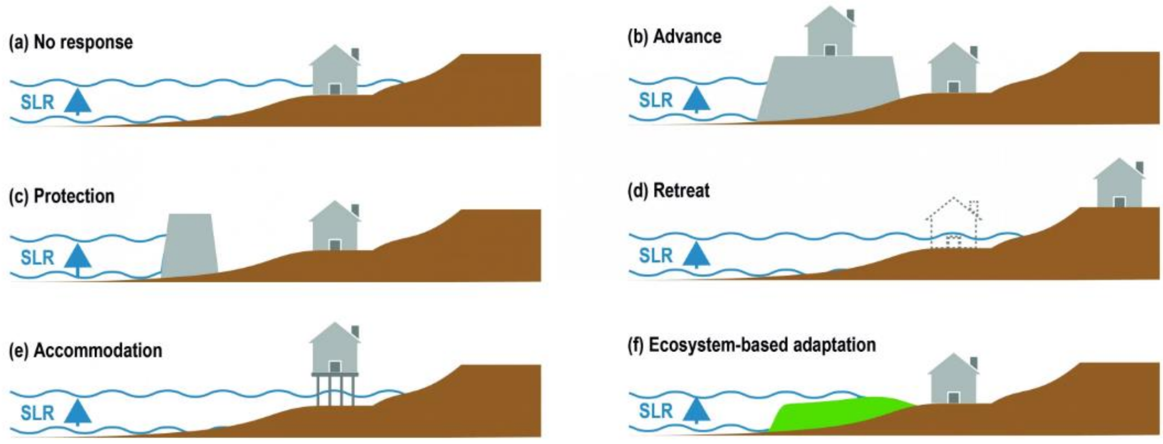

Figure 2 - Different types of responses to coastal risk and sea level rise (SLR).

5 Conclusions

Over the period 2009-2019, the scientific literature on sea-level rise in Bangladesh and the impacts of sea-level rise on the Bangladesh coast has grown in both volume and variety. The degree of disciplinary diversity depends on the temporal-spatial scale of the research, increasing from the sub-national level to the local level. Most publications in this review focussed on the sub-national and local level. In contrast, the uptake of sea-level rise projections during this period has been low and largely restricted to global scale sea-level projections. While no studies attribute specific impacts to sea-level rise, there are examples of different methods for managing risks from sea-level rise. This would suggest decisions about how to respond to sea-level rise are already being made. Over the coming decades as investment in coastal management and adaptation increases, these decisions will continue to be made and increasingly scrutinised. From this perspective, it is important to identify the sources of sea-level rise information that are available for decision makers in Bangladesh, at least in principle.

This report aimed to answer to three specific questions (see section 1). Here we take each of these questions in turn and discuss our conclusions based on the review.

- *What is known about the impacts of sea-level rise in different sections of the Bangladesh coastal zone?*

Section 3.2 discusses disparities in the degree of scholarly attention received by the southwestern, central and south-eastern coastal zones. The southwest and the southeast coastal zones are respectively the most and least studied areas. Most studies focus on the possible impacts of sea-level rise on the coastal environment, however none of these studies attempt to directly attribute impacts to relative and extreme sea-level changes. The publications for the GTF zone, feature examples of nearly all coastal hazards identified in SROCC as potential ‘cascading impacts’ of sea-level rise. From these hazards, salinization is the most widely discussed but none of the studies attempted to quantify the contribution from sea-level rise to salinization changes, which are strongly influenced by non-climate drivers.

Section 3.3 discussed historical studies, based on in-situ observations and remote sensing, also highlighting the significant influence of non-climate processes on relative sea-level rise at some locations. However, these non-climate contributions are often highly localised in both time and space. The satellite-based subsidence rate estimates for some locations an order of magnitude larger than the expected rate of sea-level rise from climate change. The studies based on tide gauge records in this review indicate that sea-level rise in Bangladesh exceeds the global average, which could be partly due to high subsidence rates in the delta region.

- *What types of sea-level information are used for assessments of vulnerability and projected exposure at the national, sub-national and local scale?*

Section 4 discusses the vulnerability and adaptation assessments featured in this review, identifying mismatches between the spatial resolution of the future climate information being used and the research scale under consideration. Few publications use sea-level projections of any form. For the publications that do feature sea-level projections, these are generally global projections from the IPCC reports. Only two publications use regional sea-level projections, which can both be traced to IPCC AR5. Given the lack of regional climate projections featured in the scientific publication during this period, it would be surprising to find regional and local scale projections in the grey literature. Table 3 summarised the projections used by publications in this review.

- *For what applications could additional sea-level rise information or sea-level rise services have the potential to enhance vulnerability and adaptation assessments in Bangladesh*?

Most vulnerability assessments in featured in this review were based on global sea-level rise projections, which may not be representative of sea-level change over the Bangladesh coastal zone. Moreover, these assessments omit the contribution to relative sea-level rise from local non-climate processes such as subsidence. For assessments for shoreline erosion, Sarwar et. al. 2013 highlight the need for "*more focused local-scale studies that quantify the pattern of change in relation to the needs of communities"* and *"Information at finer scales can form the basis for the formulation of coastal management plans"*.

Section 4 revealed a range of approaches have been taken to managing coastal risks in Bangladesh, from large-scale infrastructure projects to community based or autonomous adaptation. These approaches involve different kinds of decisions and require different forms of sea-level information. At the national scale, the polders provide an example of the 'protect' approach through large-scale infrastructure projects. The relevant organisations routinely make decisions about how to prioritise repairs on existing structures, which are categorised according to vulnerability (Alam et al, 2017). These decisions will be partly based on expectations of sea-level change and the range of sea-level extremes, over the near to medium term at different locations in the Bangladesh coastal zone. Empirical projections (as in Lee 2013) can provide the relevant location-specific information but only for the few locations where lengthy tide gauge records are available. Islam et al 2015 state that, "*more tide gauge stations are desired for computing the exact rate of sea level rise and mean tide range for large scale vulnerability mapping*"*.* Anticipating rising sea-level and storm-surge heights, these organisations also see the need to raise the existing polders as well as to build additional new ones (Ali and Syfullah, 2017). This suggests the need for location-specific sea-level information over the longer term, particularly information on extreme sea-level because the design height of protective structures against storm surge is significantly governed by the maximum surge height (Hussain and Tajima 2017).

None of the storm-surge assessments in this review used global or regional climate models to estimate future storm-surge heights. Statistical approaches, based on past storms, are limited to case studies of recent high-profile storms. Pethick and Orford (2013) provide evidence that the relative sea-level and high-water level at some locations are changing at different rates, due hydrological interventions that have changed the volume of the tidal prism. Projections of relative sea-level rise may not be the best indicator of changes to high water and thus tidal extremes, at locations where anthropogenic activities such the construction of new embankments and ongoing dredging are expected alter the geometry of coastal channels.

National scale coastal interventions and river management decisions could potentially increase the risk of sea-level rise impacts at the sub-national and local scale. Rogers and Irina, 2017 warn that "*infrastructure designed to reduce the risk of devastating floods on the delta's surface also restricts sediment deposition on coastal floodplains"*. Future coastal management and adaptation projects may also involve trade-offs, reducing the risk from some coastal hazards but potentially increasing the risk or impact from other hazards. Sub-national and local scale information on future changes to relative sea-level and extreme level, is required the potential benefits and costs of risk reduction responses.

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