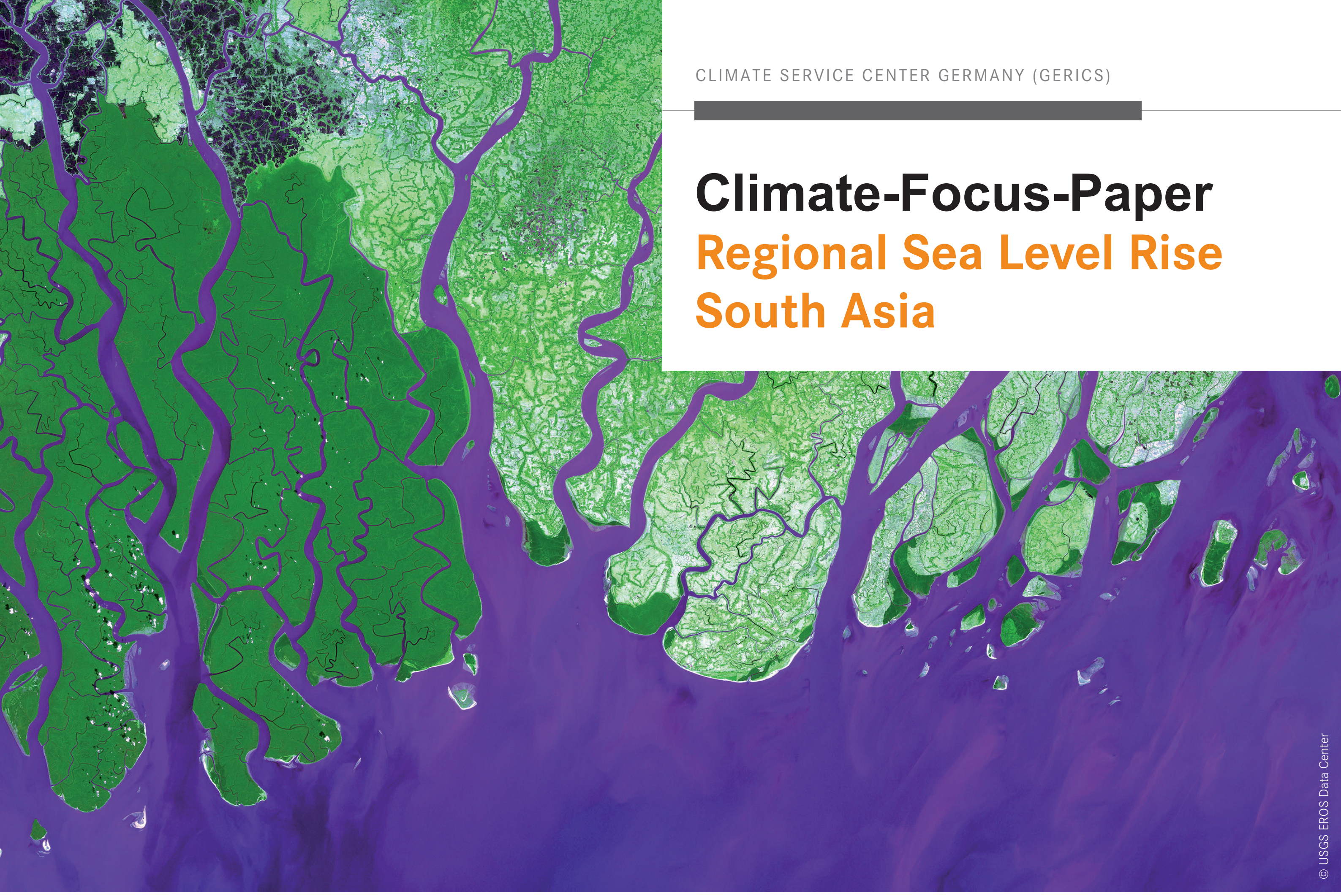
Climate-Focus-Paper
Regional Sea Level Rise South Asia



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Speed read

- South Asian countries bordering the Bay of Bengal are subject to a number of climate related hazards, chief among which is rising sea levels. Rising sea levels lead to impacts in many different economic sectors, including agriculture, water resources, and human health. As such, many economic sectors will need to adapt to the threat posed by rising sea levels.
- Successful adaptation to rising sea levels requires an understanding of the relative importance of the various drivers of change, whether these be climatic, or non-climatic factors. Understanding changes in sea level in the highly populated and low-lying south Asian region is of major importance, but is challenging because of inadequate tide-gauge, and subsidence time-series, data.
- Tide gauge observations of changes in sea level in the region show a large range of variation in linear rates of relative sea level rise (RSLR), ranging from 0.7 mm yr-1 at Chennai, to 8.2 mm yr^{-1} at Charchanga, in the Ganges delta.
- Projections of future changes in RSLR across the region, in 2080-2099, are fairly similar, with mean increases in the range 0.32 m to 0.38 m under a stringent mitigation scenario (RCP2.6), and 0.53 m to 0.58 m under a business-as-usual scenario (RCP8.5). These projections do not take account of local subsidence, however, which in some areas is a more important driver of changes in RSLR than climatic factors.
- Coastal flooding is one of the most important impacts associated with rising sea levels, and a major study shows the avoided damage costs by investing in infrastructure adaptation, i.e. dikes and sea walls, to maintain present day standards, may be as high as 1800%.

Introduction

Changes in mean sea level are the result of the complex interplay of a number of climatic and non-climatic factors. Regional and local mean sea level may differ significantly from global mean sea level because of variation in the relative importance of the different factors across the world[1]. A Focus Paper on Global Sea Level Rise is also available which discusses these issues[2]. Particularly at the regional and local level, the importance of non-climatic factors, e.g. subsidence or uplift, may be more important drivers of sea level change, than climatic ones. As such, when developing projects and considering investment decisions that may be sensitive to changes in sea level, it is important that adequate consideration of all relevant factors has been taken, and the implications this may have for projects well understood. This Focus Paper highlights the challenge of understanding changes in sea level, and the associated impacts, for a region in south Asia, focused on the Bay of Bengal.

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Regional context

The region of south Asia is characterised by having large areas of low elevation land in the coastal zone (LECZ), that are only a few metres above sea level, together with long shallow adjacent bathymetry which exacerbates the risk from storm surges (figure 1). In addition, the region is home to a number of the world's major river deltas, including the Ganges-Brahmaputra-Meghna and the Irrawaddy. There are large population centres within the LECZ, including Chennai, Dhaka, Kolkata, and Yangon. Table 1 provides some representative figures for the populations that live within given elevation bands above sea level, and as such there are large populations exposed to the risk of coastal flooding. The influence of human activity through changes in land and river management, coupled with groundwater extraction, contributes significantly to the large observed rates of subsidence in the delta systems, such that the contribution that subsidence makes to changes in local mean sea level are often more important than the effect of climatic drivers[1]. As population growth in the region continues apace, this phenomenon is likely to increase in importance[3]. Furthermore, the region is subject to tropical cyclone activity, and associated storm surges, which typically results in large areas of the LECZ being inundated, and the risk of coastal flooding from such events is high[4,5]. Given this context, it is extremely important to understand the nature of changes in relative sea level in this region, both in the past and for the future, if human populations and physical assets are to be safeguarded and sustainable development achieved.

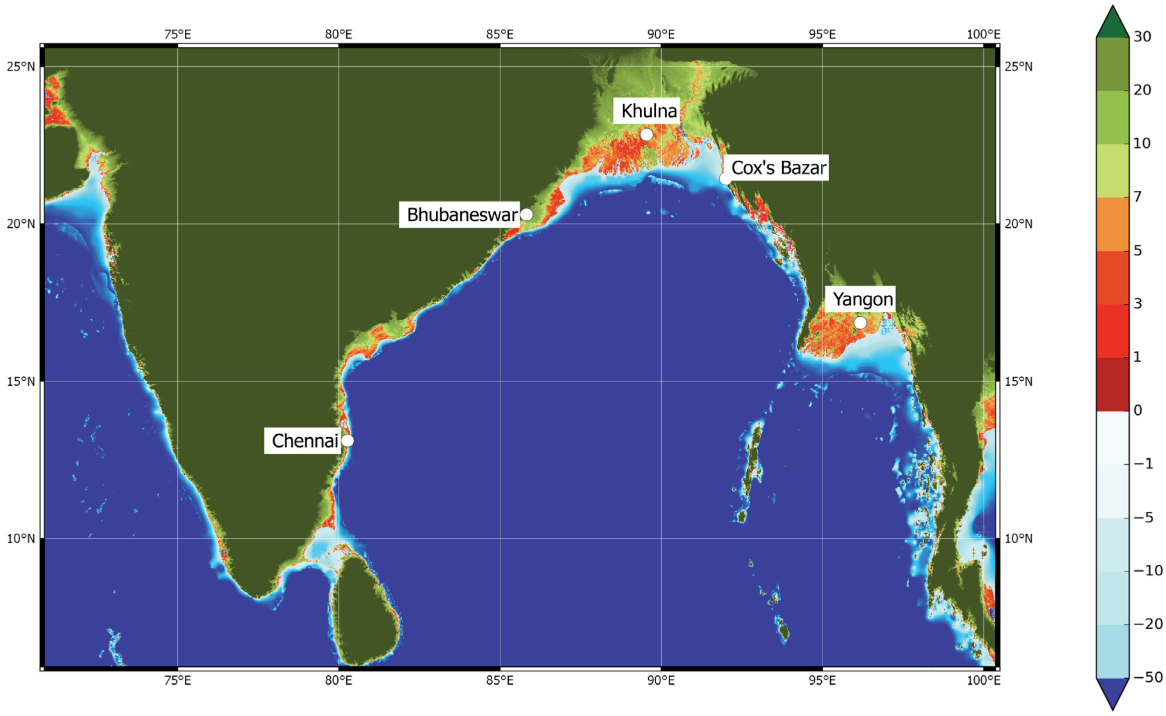

Figure 1. Elevation and bathymetry (in metres) of the south Asia coastline showing the large areas of low elevation coastal zones (below 10m a.m.s.l.), and shallow adjacent bathymetry. ***Source data*****: ETOPO[16].**

Table 1. Cumulative population (in thousands) within different elevation bands of select cities. *Source data*: Hallegatte *et al.*[6] Population numbers relate to the year 2002.

City	0.5m	1m	3m	5m	10m
Chennai	63,660	125,301	344,713	777,520	2,948,453
Chittagong	3,217	31,663	199,288	890,244	3,075,065
Dhaka	41,925	143,433	245,717	1,013,731	7,052,987
Khulna	2,523	40,986	256,223	531,870	1,362,661
Kolkata	195,291	261,147	737,752	2,004,649	9,359,665
Visakhapatnam	11,007	15,300	37,531	95,493	396,111
Yangon	15,045	24,167	85,292	461,733	1,678,830

Note: The figures presented here are derived from a 'bathtub' approach, which assumes that all areas within a given elevation band will be uniformly affected by flooding at that level. In reality this is most unlikely to be the case, as areas need to be connected to the water for them to flood. This hydrodynamic connection is not included in the 'bathtub' approach. Nevertheless, these figures serve to provide an adequate first pass assessment of potentially exposed population.

Understanding changes in mean sea level

Changes in relative sea level at a given location are the result of contributions from four different components[8]:

$$\Delta RSL = \Delta SL_G + \Delta SL_{RM} + \Delta SL_{RG} + \Delta SL_{RLM}$$

where, ΔRSL is the change in relative sea level, ΔSLG the change in global mean sea level, ΔSLRM regional variation due to meteo-oceanographic factors, ΔSLRG changes in the earth's gravity field, and ΔSL_{RLM} changes in vertical land movement e.g. subsidence. In the current context, where it is known that subsidence is of major importance in significant parts of the Bay of Bengal, it is particularly critical to try and get a handle on the contribution from this component. Sadly, however, there is a lack of reliable, high quality, long time-series subsidence data in this region. A recent literature review[9] summarised what is known about subsidence rates in the Ganges-Brahmaputra-Meghna (GBM) delta. These results highlighted the large uncertainties associated with estimates of subsidence in the GBM delta, and results for three cities in the study are summarised in table 2. A major reason for the large uncertainty associated with estimates of subsidence is the range of different methods used, and the snapshot nature of the measurements. For a better understanding of relative sea level change in this region, long-term investment is needed in subsidence measurement and monitoring programmes.

Table 2. Estimates of subsidence (mm yr^{-1}) in three cities in the Ganges-Brahmaputra-Meghna delta. *Source*: Brown & Nicholls[9]

City	n	Minimum	Maximum	Mean	Median	Standard deviation
Kolkata	40	0.5	43.8	8.6	7.1	7.8
Khulna	15	1.0	10.0	3.5	2.9	2.4
Dhaka	13	0.4	22.0	5.9	1.0	7.3

Note: n is the sample size

Contemporary sea level change

Understanding local changes in relative sea level is best determined on the basis of continuous measurements at tide gauge stations over a long period of time, ideally 50 years or more[10]. The number of such stations in south Asia is extremely limited. Figure 2 shows time-series from representative stations in which it is clear to see that the data are not always recorded continuously, and are of varying length[11,12]. This represents a major barrier to understanding local sea level change, and more investment in the measurement and monitoring of sea levels is needed.

Linear rates of relative sea level rise display a large range of variation across the selected stations in the Bay of Bengal, with 0.7 mm yr^{-1} at Chennai, to 8.2 mm yr^{-1} at Charchanga (figure 2). The faster rates observed at stations Diamond Harbour, Charchanga, and Hiron Point are likely explained by the fact that they are all located in the Ganges-Brahmaputra-Meghna (GBM) delta, and as such subject to subsidence. The implication of these different rates means that population centres located in the GBM delta will be facing a greater risk from rising sea levels and the associated impacts, than locations on the east coast of India.

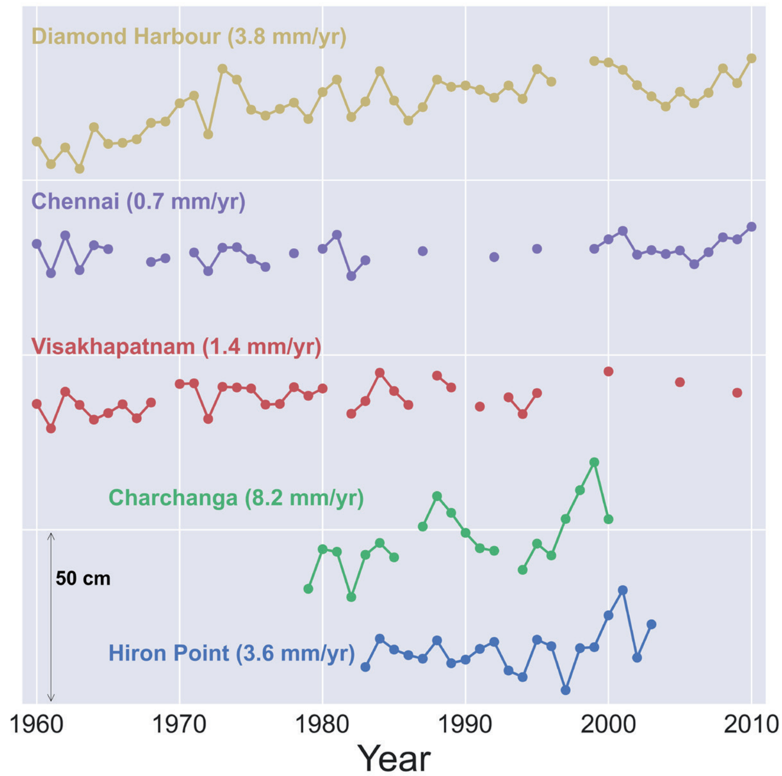

Figure 2. Relative sea level change for five selected tide gauge stations in the Bay of Bengal, over the period 1960-2010. Data from the individual stations are offset for visual clarity. *Source data*: PSMSL[11], Holgate *et al.*[12]

Future sea level change

Project and investment decisions that will be effective for many years into the future need to consider possible future changes in relative sea level. Figure 3 provides a regional overview of projected changes in relative sea level, under a business-as-usual (RCP8.5) scenario, from the IPCC AR5[13, 14]. Of perhaps more importance and relevance to adaptation investment decision making is the temporal evolution of relative sea level rise over the 21st century. Figure 4 shows the temporal evolution of regional sea level rise for five selected cities in the region, under the RCP2.6 and RCP8.5 scenarios. In addition, projected changes in relative sea level in 2080-2099 for the five selected cities, under these two emissions scenarios, are provided in table 3.

Overall, figure 4 shows – and table 3 confirms – that the projected mean rise in sea level is broadly similar for all five cities under both emissions scenarios. It is only at the top end of the 90% confidence interval that more significant differences are seen between cities, with around 10 cm difference between the lowest and highest values. These projections thus depict a different picture of relative sea level rise than that presented by the tide gauge observations. It is important to state, however, that the projections from climate models do not include the effects of local subsidence, and this explains the broad regional symmetry found in the projections. This issue serves to highlight the fact that, when planning projects in low lying coastal areas, it is important to fully understand all the issues involved and that the use of climate projection data to inform adaptation decision making needs careful consideration and appropriate application in the context of risk management[14].

Depending on the path along which global carbon emissions develop, the region could be in for around 20 cm more sea level rise under the business-as-usual RCP8.5 scenario than if carbon emissions are reduced dramatically under a RCP2.6 scenario. It is also important to note that, regardless of the path along which future global carbon emissions develop, the region will have to contend with sea level rise for centuries to come, owing to the slow oceanic response to global warming[15].

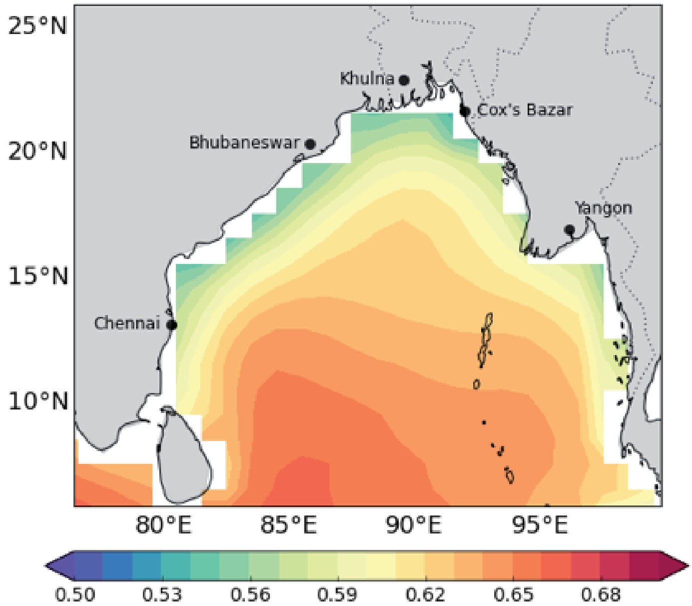

Figure 3. **Ensemble mean relative sea level rise in 2080-2099 under the RCP8.5 scenario, relative to the reference period (1986-2005).** ***Source data*****: ICDC, University of Hamburg[13].**

A note on the representative concentration pathway (RCP) emissions scenarios: RCP2.6 represents a stringent mitigation scenario, where carbon emissions are significantly reduced, whereas RCP8.5 represents a business-as-usual case.

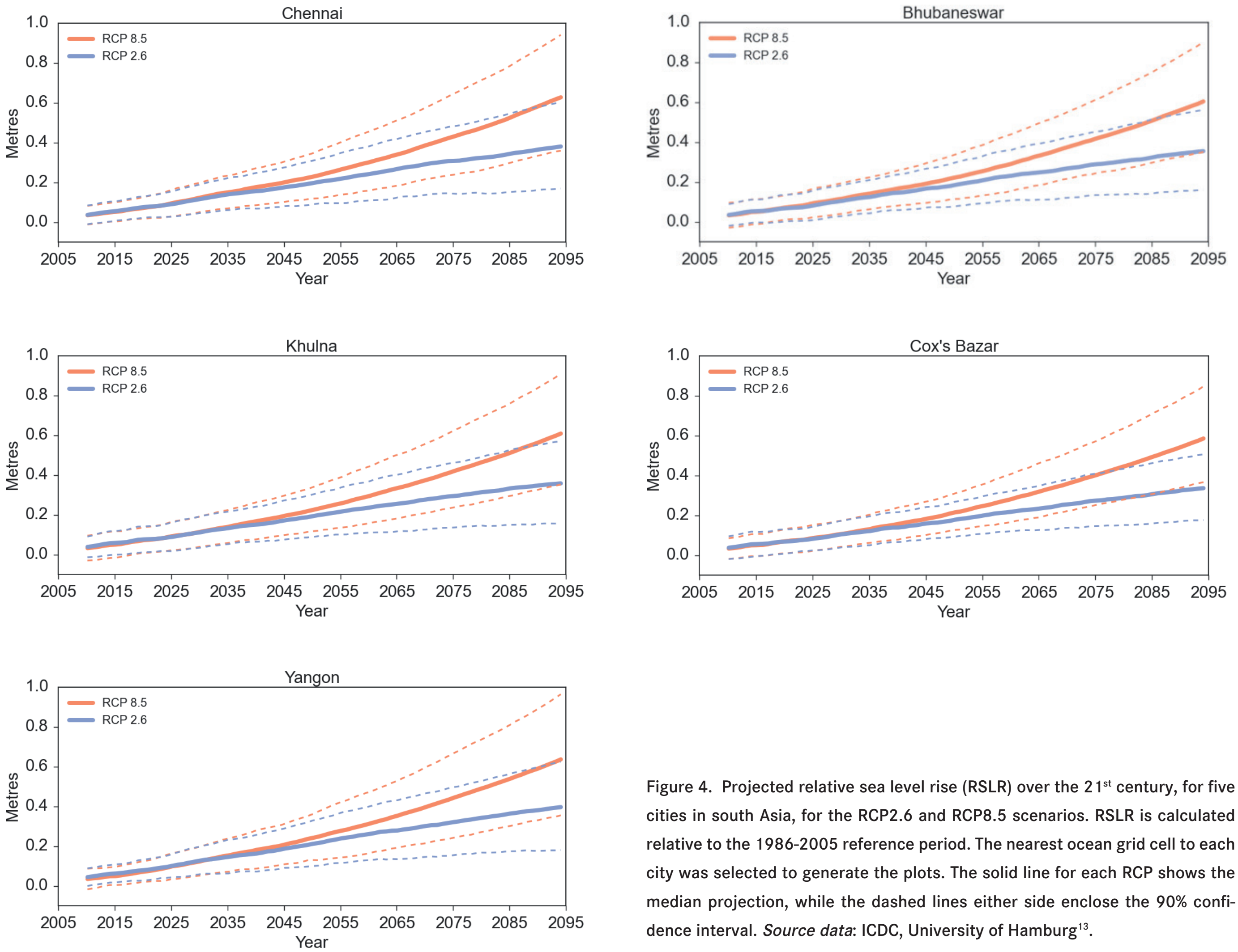

Figure 4. Projected relative sea level rise (RSLR) over the 21^{st} century, for five cities in south Asia, for the RCP2.6 and RCP8.5 scenarios. RSLR is calculated relative to the 1986-2005 reference period. The nearest ocean grid cell to each city was selected to generate the plots. The solid line for each RCP shows the median projection, while the dashed lines either side enclose the 90% confidence interval. *Source data*: ICDC, University of Hamburg[13].

Table 3. Projections of relative sea level rise in 2080-2099, for five selected cities in the south Asia region, under RCP2.6 and RCP8.5. Values shown are the multi-model mean, and the 90% confidence interval (C.I.), in metres, calculated relative to the reference period (1986-2005). Source data: ICDC, University of Hamburg[13]

	RCP2.6		RCP8.5	
City	*Mean*	*90% C.I.*	*Mean*	*90% C.I.*
Chennai	0.36	0.16 – 0.57	0.57	0.33 – 0.86
Bhubaneswar	0.34	0.15 – 0.53	0.55	0.32 – 0.82
Khulna	0.34	0.15 – 0.54	0.56	0.32 – 0.83

Impacts of sea level rise

Rising sea levels pose a major problem for a range of activities in coastal and low lying areas, including effects on the incidence and extent of coastal flooding, freshwater supplies, agriculture, tourism, biodiversity, and wetlands[16]. Chief among these impacts is the risk of coastal flooding. As sea levels rise, the frequency and magnitude of coastal flooding and associated infrastructure damage, as well as assets at risk, may increase[4]. The most damaging coastal flooding in this region is typically associated with tropical cyclones and accompanying storm surges. Water heights associated with storm surges are driven by low pressure and very strong winds, superimposed upon mean sea level and tidal conditions. As such, storm surges are not simply related to changes in mean sea level. While there is no strong evidence to indicate how the magnitude and frequency of tropical cyclones may change in south Asia[17], rising sea levels will clearly change the background mean sea level. Under an assumption of no change in the magnitude and frequency of tropical cyclones, water levels associated with storm surges would be expected to increase over the 21st century[4].

To illustrate the large areas that may be inundated as a result of a storm surge, figure 5 shows areas of the Irrawaddy delta, Myanmar, that were inundated by the surge associated with tropical cyclone Nargis in May 2008. Figure 5 also shows very clearly the overlap between areas of low elevation (at or less than 7 m above mean sea level), and those affected by the flooding[5]. Moreover, figure 5 serves well to illustrate that it is not just areas directly along the coast that are at risk from coastal flooding, but areas much further inland that are hydrodynamically connected to the surge. For project managers, this should heighten awareness of potential risk zones where projects and assets may be exposed.

Clearly, if countries in the region are to continue to develop and reduce opportunity costs, in addition to human suffering associated with coastal flooding, adequate planning and investment in adaptation measures needs to be a major motivation for public policy. There are three main classes of adaptation response to sea level rise, these are:

1. **Planned retreat:** where sea level rise is allowed to happen and, through careful spatial planning, exposed assets are either relocated, and/or possibly compensated for losses.
2. **Accommodation:** sea-level rise is allowed to happen, and is accommodated for by making infrastructure more resilient to the impacts, for example, through raising buildings and insurance schemes. Accommodating sea level rise may also require careful spatial planning.
3. **Protection:** here sea level rise is combated through the use of hard and soft engineering solutions, such as, and the construction of dikes and sea walls, or storm surge barriers, and beach nourishment [18].

To try and inform this policy discussion, we present summary results from a recent scenario based impact assessment of the incidence of coastal flooding associated with sea level rise and subsidence, from Hallegatte et al.[7] Their analysis deals with protective adaptation options of raising dikes and maintaining sea walls, and considers changes in sea level and subsidence, which for a pessimistic scenario assumes 20 cm, 40 cm, and 50 cm of subsidence, and sea level rise of 20 cm, 40 cm, and 70 cm, in the years 2030, 2050, and 2070, respectively. In addition, they consider three adaptation options:

1. **No adaptation (NoA):** simply no adaptation is considered.
2. **Maintain defence standards (PD):** this option assumes that coastal defences will be raised by the same amount as relative sea level rise.
3. **Maintain relative risk (PL):** this option assumes that, even though over time there will be more exposed assets with population growth and wealth accumulation, there is a desire to maintain relative mean annual financial losses as a result of coastal flooding, at the current level. In practice this means that coastal defences will be raised by more than the level of relative sea level rise.

Table 4 presents results from this analysis for cities within the Bay of Bengal region. It is clear from table 4 that the aggregated annual losses (AAL) in million US$ are much reduced by implementing adaptation measures of raising dikes and maintaining sea walls. For example, in Kolkata in 2070, the PD option leads to a reduction of ~1800% in AAL, compared to no adaptation.

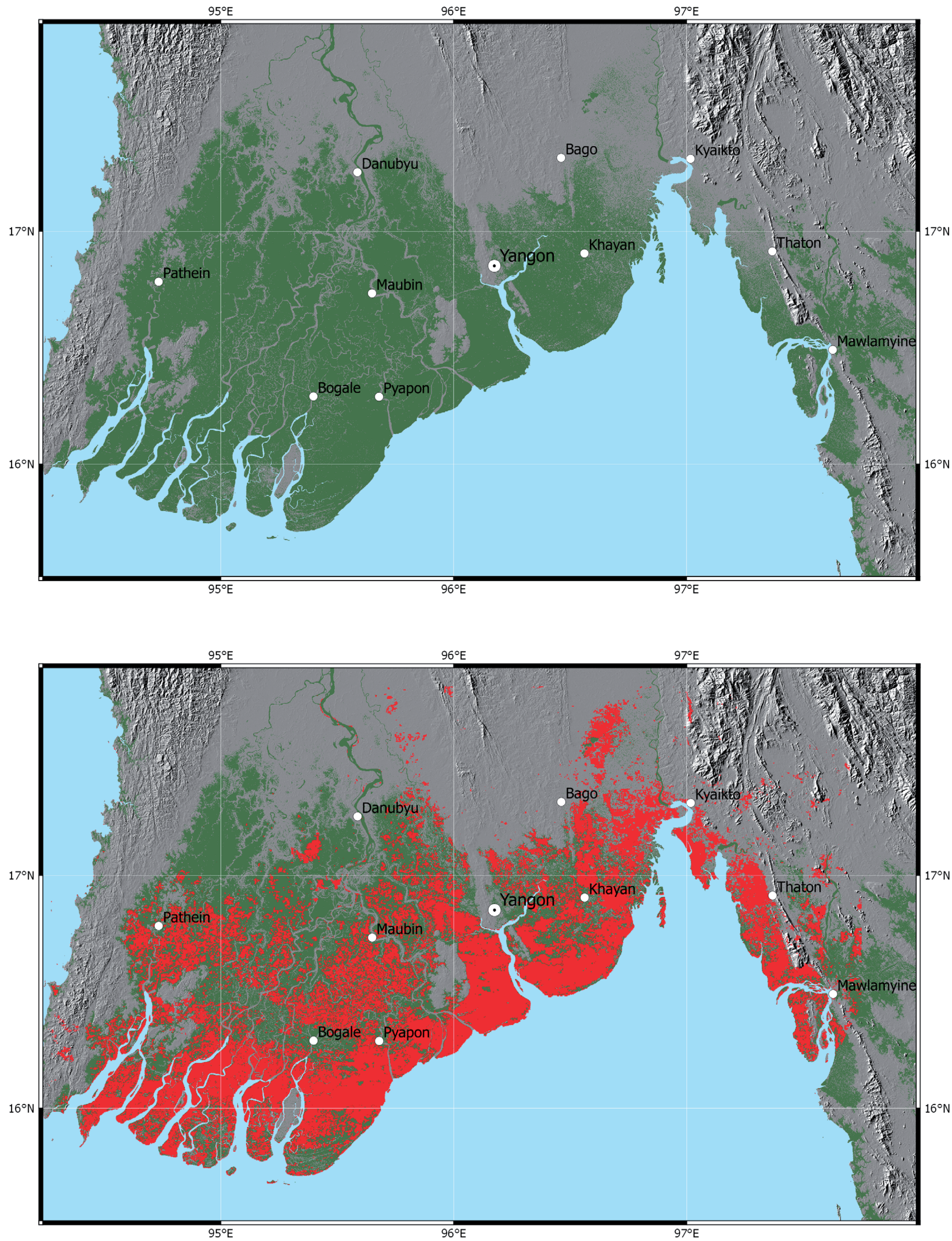

Figure 5. Storm surge flood inundation associated with tropical cyclone Nargis, along the Irrawaddy Delta, Myanmar. The top image shows areas in green where elevation is at or below 7 m above mean sea level, while the red areas in the bottom image show the May 5 2008 MODIS flood inundation data overlaid on top. *Source data*: MODIS Flood Maps, GLCF, University of Maryland. Elevation data set is SRTM version 3.

Table 4. **Aggregated annual losses (million US$), in 2030, 2050, and 2070, from a pessimistic scenario of sea level rise, and three adaptation responses: no adaptation (NoA), adaptation that maintains present defences and constant flood probability (PD), and adaptation that maintains relative risk (PL).** *Source*: Hallegatte *et al.*[7]

	2030			2050			2070		
City	*NoA*	*PD*	*PL*	*NoA*	*PD*	*PL*	*NoA*	*PD*	*PL*
Chennai	2,504	318	279	9,347	1,028	826	24,147	2,578	1,877
Chittagong	216	52	49	2,934	171	154	8,178	479	378
Dhaka*	1,014	189	175	9,219	524	451	18,896	1,055	856
Khulna*	1,019	117	95	6,851	459	295	21,342	1,344	728
Kolkata*	10,936	1,175	1,007	60,930	3,515	2,704	126,616	6,974	4,982
Visakhapatnam	382	41	58	1,242	131	163	3,110	571	388
Yangon*	596	68	37	1,942	211	110	5,108	327	250

*denotes cities that are susceptible to subsidence.

Implementing adaptation strategies to respond to sea-level rise may require some significant investment, and ideally we would be able to put a cost on these options. However, because adaptation in each individual city will take place in a different context, it is extremely difficult to do so. For this reason, Hallegatte *et al.*[7] do not provide estimates of the costs of raising dikes and sea walls; they do however give an indication of the height to which dikes would need to be raised in order to implement adaptation strategy PL. These figures are provided in table 5 and, while they are not monetary values, they do provide an insight into what the size of the engineering challenge may be.

There are, however, some estimates of the costs of constructing and maintaining a range of hard and soft adaptation options available in the literature[18]. Costs for selected options are provided in table 5. As can be seen, there is a large range in some of the cost estimates, and this is due to the challenges of implementing projects in different countries, such as the availability of natural resources, the cost of labour, and the complexity of the planning process.

Table 5. **Increase in dike height (in cm) required to achieve adaptation strategy PL (maintaining relative risk).** *Source:* Hallegatte *et al.*[7]

City	**2030**	**2050**	**2070**
Chennai	21	42	73
Chittagong	21	42	74
Dhaka*	42	84	125
Khulna*	44	88	131
Kolkata*	43	85	126
Visakhapatnam	43	84	126
Yangon*	21	41	72

*denotes cities that are susceptible to subsidence.

Table 6. **Estimates of unit costs of various adaptation options for responding to sea level rise.** *Source*: Jonkman *et al.*[18]

Adaptation option	**Cost at 2009 price levels (in EURO €)**
Construction of sea dike 1m high	0.6M/km, with maintenance 1.0M/km
Raising sea dikes by 1m in urban areas	15.5M–22.4M/km
Beach nourishment	4.9–9.7/m^3
Raising industrial areas and harbours by 1m	20M/km^2

Note: M means million

A note on the Hallegatte et al. analysis: It is important to state that the figures presented in tables 3 and 4 are not predictions. Rather, they provide an indication of the level of economic losses that may be associated with sea level rise, and highlight the need for investments in adaptation.

Conclusions

- → Understanding changes in relative sea level requires adequate consideration of the various contributory factors. In the Bay of Bengal region of south Asia, this task is complicated by inadequate recording and measurement of changes in relative sea level at tide gauge stations, together with a lack of high quality long-term monitoring of subsidence across the region.
- → There is a large range of variation in measured relative sea level rise across the region, largely due to the local importance of the human-induced factor of subsidence, which is a major factor in deltas in the region.
- → Projections of future sea level rise are broadly similar across the region, but these do not consider subsidence.
- → When investing in adaptation projects in the context of coastal risk management, allowance needs to be made for both the human-induced and climatic drivers of changes in relative sea levels.
- → While there is large uncertainty in the absolute level of future sea level rise, it is virtually certain that sea level will continue to rise in the region over the next century and more. There is a pressing need for an intelligent, long-term investment and planning strategy to help adapt to future changes, and make cities and population centres more resilient in the face of sea level rise and the associated impacts.

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December 2015

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1. The contents of the Climate-Focus-Paper and the underlying data were processed and carefully checked according to the current state of science and technology. HZG did not generate the data on which the Climate-Focus-Paper is based on. HZG shall not assume any liability for the topicality, correctness, completeness or quality of the provided information. HZG also assumes no liability for any decisions and their consequences, which are based on the use of the Climate-Focus-Paper.

2. Any liability claims which refer to damages of material or immaterial nature caused through the use or disuse of the presented information or through incorrect and incomplete information shall be excluded, except for any intentional or gross negligence.

3. HZG expressly reserves the right to change parts of the website or the entire offer without prior notice and to amend, delete or cease the publication of the Climate-Focus-Paper.

4. An obligation of HZG to third parties is not permitted. HZG shall not be liable for any damage of any kind arising from the assignment and processing of the Climate-Focus-Paper. The user shall indemnify HZG against any liability of any damaged third party.

5. If any discrepancy should be noticed while using the Climate-Focus-Paper, please do not hesitate to contact HZG.

6. All limitations of liability shall not apply to damages arising from injury of life, body or health and in the case of the absence of guaranteed conditions.

III. Miscellaneous:

1. Modifications and additions to these terms of use shall be made in writing. Writing includes text form according to § 126 b BGB (German Civil Code) also fax and email.

2. The court of exclusive jurisdiction shall be the registered place of business of HZG.

3. If any provision contained in these terms of use should be unenforceable, it shall be assumed that the remaining provisions are intended to remain in force. In such a case, however, the unenforceable provision shall be replaced retroactively by one which comes closest in its result to that which was intended by the unenforceable provision.