Chapter 4: Sea Level Rise and Implications for Low Lying Islands, Coasts and Communities

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Executive Summary

Sea Level Change

1) Observations show that global mean sea level (GMSL) is rising and accelerating and it will continue to rise over many centuries. Glaciers and polar ice sheets are now the dominant source of sea level rise *(very high confidence[1])*. During the Last Interglacial period (LIG) 130 to 115 thousand years ago, these polar ice sheets contributed 6-9 m to sea level above present-day at a time when Earth was 0.5°C–1°C warmer than preindustrial time (*high confidence*), providing additional evidence of high sensitivity to modest warming (*medium confidence*). However, differences in incident solar radiation between the LIG and today complicate the relationship between past temperature change and sea level**.** The Mid Pliocene Warm Period (~3 million years ago) was 1.9°C–3.6°C warmer than pre-industrial, and sea level was higher than during the LIG (*high confidence*), but the maximum level remains deeply uncertain. The rate of past ice-sheet mass change and hence the rate of sea level rise during these periods remain very uncertain {4.2.2.1, 4.2.2.2, 4.2.2.6}.

2) Human activity has been the dominant cause of global mean sea level rise since 1970 (*high confidence*). Sea level rise (SLR) at the end of the 21st century will be strongly dependent on the global emission scenario followed, particularly as a result of Antarctica's contribution under RCP8.5 (*high confidence*). Greenhouse gas mitigation envisioned in low-emission scenarios (e.g., RCP2.6) sharply reduces but does not eliminate risk to low-lying coastlines and islands from SLR and extreme sea levels (ESL). Lower emission scenarios lead to slower rates of SLR resulting in a wider range of adaptation options. For the first half of the 21st century differences among the scenarios are small. Few individual ESL events or regional-to-local mean sea level changes have as yet been attributed to climate change {4.2.1.2, 4.2.2.6}.

3) Different modelling studies demonstrate that under high emissions scenarios, Antarctica will *likely*[2] contribute several tens of centimetres of sea level rise by the end of the century (*medium confidence*). Projections of global mean SLR under RCP2.6 result in 0.39 m (0.26–0.52 m, *likely* range) for the period 2081–2100, and 0.42 m (0.28–0.57 m) in 2100. Projections of global mean SLR under RCP4.5 results in 0.48 m (0.34–0.63 m, *likely* range) for the period 2081–2100, and 0.55 m (0.39–0.71 m) in 2100. Projections of global mean SLR under RCP8.5 results in 0.78 m (0.47–1.09 m, *likely* range) for the period 2081–2100, and 0.97 m (0.55–1.40 m) in 2100. The rate of SLR is estimated to be 19 mm/yr under RCP8.5 in 2100. This magnitude, rate and range for RCP8.5 are higher than earlier assessments {4.2.3.1}.

4) Processes controlling the timing of future ice-shelf collapse and a possible Marine Ice Cliff Instability (MICI) make Antarctica's contribution to future sea level rise deeply uncertain for outcomes with SLR higher than the *likely* range (Cross-Chapter Box 3 in Chapter 1). Long term evolution of the Antarctic Ice Sheet beyond the end of the 21st century remains deeply uncertain as ice sheet models lack realistic representations of some of the underlying physical processes. The few studies available addressing century to millennial timescales indicate multi-metre rise in sea level for RCP8.5 (*medium confidence*) {4.2.3.1}.

5) Due to projected global mean sea level rise, extreme sea level events that are historically rare (e.g., those that, in the past, have been associated with surges from intense cyclones), will become common by 2100 under all RCPs, leading to severe flooding in the absence of strong adaptation (*high confidence*). In RCP8.5, many small islands and megacities will experience such events annually by 2050 {4.2.3.4}.

[1] FOOTNOTE: In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence (see Section 1.9.3 and Figure 1.4 for more details).

[2] FOOTNOTE: In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: Virtually certain 99–100% probability, Very likely 90–100%, Likely 66–100%, About as likely as not 33–66%, Unlikely 0–33%, Very unlikely 0–10%, Exceptionally unlikely 0–1%. Additional terms (Extremely likely: 95–100%, More likely than not >50–100%, and Extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely* (see Section 1.9.3 and Figure 1.4 for more details).

6) Subsidence is an important contributor to future changes in relative sea level (RSL) (*high confidence*). Subsidence caused by human activities is currently the most important cause of RSL change in many delta regions. In some regions, however, changes in wave height and period currently have a larger effect on coastal flooding than RSL change (*medium confidence*). While the comparative importance of climate-driven RSL rise will increase over time, these findings on subsidence and waves imply that a consideration of local processes causing subsidence is critical for projections of sea level impacts at local scales {4.2.1.6, 4.2.2.5}.

Exposure and Vulnerability to Sea Level Rise

7) Non-climatic anthropogenic drivers, including settlement trends, have played a dominant role in increasing coastal communities' exposure and vulnerability to SLR and ESL events and will continue to have a significant impact in the future (*high confidence*). This has been confirmed by post-AR5 literature, which provides more systematic and comprehensive account of all dimensions of SLR-related coastal risk, such as improved projections of SLR and ESLs, coupling of societal and ecological dynamics, consideration of spatial and temporal dynamics of current and future exposure, and better understanding of drivers and thresholds of vulnerability (*medium evidence, high agreement)*. This suggests that risk reduction and resilience-building can be undertaken in the short- to medium-term by targeting local drivers of exposure and vulnerability, notwithstanding uncertainty about local SLR impacts in coming decades and beyond {4.3.1, 4.3.2}.

8) Although all low-lying coasts in both the northern and the southern hemisphere (including coastal cities and towns, small islands, deltas, river mouths and polar regions) are at risk in the face of sea level rise, recent analyses demonstrate that some areas will be more exposed and vulnerable than others (*medium evidence, high agreement*). Highly populated but less intensively developed regions (e.g., some populated deltas and rural coasts) and those with very climate-sensitive environments (e.g., atoll reef islands, Arctic) are on the frontline of climate change and SLR. Adaptation there will critically depend on a implementing a combination of options, particularly protection, accommodation, and retreat. Intensively developed and populated cities, including coastal megacities, face immense and escalating SLR risks. However, the feasibility and affordability of hard protective measures in such localities can significantly reduce exposure in coming decades {4.3.4.2, 4.3.3.4}.

Impacts of Sea Level Rise

9) There is increasing evidence of changes at the coast with respect to ecosystems, ecosystem services, coastal infrastructure, habitability, community livelihoods, and cultural and aesthetic values. Attribution to sea level rise, however, remains difficult due to the influence of non-climatic drivers and local processes unrelated to sea level rise (*medium confidence*). These processes include land use changes, reduced upstream sediment supply, and human-induced subsidence (*medium evidence, medium agreement*) This underscores the merit of short- to medium-term risk reduction measures that target local drivers of exposure and vulnerability {4.3.3, 4.3.4}.

Responses to Sea Level Rise

10) Coastal communities are implementing a variety of protect, accommodate, advance, and retreat measures in response to coastal risk compounded by sea level rise. The selection and sequencing of these measures can have important synergistic, complementary, or antagonistic consequences (*high confidence*). Protection can be feasible and affordable in densely populated and intensively developed areas, such as urbanized coasts, and may be necessary to protect critical infrastructure. Hence, a *likely* impact of SLR will be a diverging world, with richer and densely populated areas well protected behind dikes and poorer less densely populated areas struggling with SLR impacts, and eventually retreating from the coast (Hinkel et al. 2018). Residual risk remains regardless of protection intervention. Accommodation measures, such as warning systems, can help to reduce some of the residual SLR risk. Advance measures reconfigure the coast and associated risk, and can be used to finance protection interventions through, for example, income generated by newly created land. Retreat is the only measure that eliminates residual SLR risk locally. But SLR-driven displacement, migration and relocation can have both positive and negative impacts on those who retreat and on communities that receive them {4.3.3.2, 4.4.3, 4.4.4}.

11) For densely populated coasts, protect, accommodate and advance measures can reduce risk in the short- to medium-term, and 'buy-time' to make social choices with more clarity about the trajectory of global warming and sea level rise (*high confidence*). Incremental interventions that have minimal adverse impacts on their own can, however, result in deleterious cumulative impacts, path-dependency, lock-in, and maladaptation. Furthermore, a particular SLR response might be compelling at the city-scale, for example, but the distribution of associated costs and benefits may not be equitably shared, and locality-specific impacts may compound the exposure and / or vulnerability of some groups. SLR risk is compounded by locating new development in low-lying localities exposed to severe coastal hazards {4.4.3, 4.4.3.1.5}.

12) Ecosystem-based and hybrid (combinations of natural and built infrastructure) solutions are gaining traction worldwide and progress has been made to demonstrate their effectiveness, and quantify costs and benefits (*medium evidence, high agreement*). Vegetation (marshes/mangroves, seagrasses/kelp, mussel beds) and reefs (coral/oyster) provide protection and risk reduction benefits to those living in nearby coastal locations (*medium evidence, high agreement)*. There is *medium evidence* that ecosystem-based measures bring substantial economic benefits, but *low agreement* regarding the scale of the benefits. However, ecosystem-based measures provide multiple co-benefits (*high confidence*). Due to their space requirements, ecosystem-based measures play a smaller role in densely populated urban areas. There is *medium evidence and low agreement* regarding design considerations for ecosystem-based measures {4.4.2, 4.4.3.2, 4.4.4.2, 4.4.4.5}.

13) The societal context and prevailing governance arrangements and processes influence the nature and trajectory of social choices about sea level rise (*medium evidence, high agreement*). Choices about how to respond to SLR are made in the context of wider societal concerns about coastal habitability, livelihoods, risk, resilience and sustainability. The prevailing political economy shapes the direction of social choices about SLR, and can perpetuate patterns of exposure and vulnerability to SLR. In the face of many competing urgent needs and concerns, many communities are reluctant to incur significant short-term costs to reduce exposure to deeply uncertain SLR in the distant future. Adaptation planning is underway in many jurisdictions but translating such plans into effective action remains challenging {4.4.4.2}.

14) Despite deep uncertainty about long-term future mean and extreme sea levels, adaptation can be progressed in the short-term by applying decision-analytical methods in combination with participatory approaches, community visioning and consensus building. Realizing this potential is difficult to achieve in practice (*medium evidence, high agreement*). Decision-analytical methods range from consideration of high-level adaptation pathways approaches that can be applied in diverse contexts, to technical and costly methods of robust and flexible decision making that can be applied to assess specific, large-scale investment decisions. More integrated and systematic collaboration between researchers on SLR and decision sciences, as well as between researchers, coastal stakeholders and decision makers, has the potential to improve these methods, their application, and decisions made in the face of anticipated SLR and ESL events (*limited evidence, medium agreement*) {4.4.5.2, 4.4.5.3}.

15) Community-based approaches, which involve local people directly in understanding and addressing the climate change risks they face, are increasingly used by people living in low-lying coastal areas to adapt to climate change impacts, including SLR, especially in developing countries (*medium evidence, high agreement*). Particular attention is focused on reducing local-level vulnerability and building resilience. However, unless ESL events have been experienced, or the prospect of SLR impacts is readily apparent, pressing immediate needs tend to dampen community efforts to take action to address uncertain SLR risk in the distant future. Moreover, in many settings, powerful interests prevail and vulnerable groups are marginalized in local planning and decision-making. As a result, empirically-based literature suggests that community-based adaptation is more likely to be effective when it is an integral part of more general community development efforts (*limited evidence, high agreement*). The drivers of poverty, inequity and political marginalization shape vulnerability and SLR-related coastal risk, and they are not readily addressed by ad hoc community-based adaptation projects. Hence the merit of integrating such efforts into development initiatives more generally {4.4.5.4}.

16) Adaptation pathways have emerged as an important way to frame thinking about responses to sea level rise because this approach recognizes and enables sequenced long-term decision-making in the

face of dynamic and deeply uncertain coastal risk (*medium evidence, high agreement*). Among other things, it enables incremental and transformational measures and strategies to be considered together in a potentially coherent and flexible way to address both short- and long-term challenges, notwithstanding uncertainty about the distant future {4.4.5.3, 4.4.5.4}.

17) Implementing effective responses to escalating coastal risk in the face of SLR is highly variable and context-specific, and remains elusive in many localities (*medium evidence, high agreement*). A key ingredient to reducing SLR risk and building resilience is creating meaningful opportunities for stakeholders from government, civil society, the private sector, and the scientific community, to engage in an authentic process of deliberation and conflict resolution to address the complex interplay of socio-political, economic, environmental, technical, administrative and ethical trade-offs that are inherent in adapting to climate change at the coast {4.4.5}.

18) Achieving the UN Sustainable Development Goals (SDGs) and charting Climate Resilient Development Pathways in the face of rising sea level depends mainly on how well conflicting interests are resolved. If greenhouse gas emissions continue along current trajectories, SLR at the end of the 21st century will have widespread, severe, and devastating impacts on many people living on low-lying coasts and islands. Institutionalizing transformative coastal adaptation responses will help to enable climate resilient development pathways and progress in achieving the SDGs (*limited evidence, high agreement*).

4.1 Purpose, Scope, and Structure of the Chapter

This chapter evaluates the current and future state of low-lying islands, coasts and communities in the context of sea level rise (SLR), changing characteristics of extremes of coastal high water (also called extreme sea level or ESL), and related consequences of climate change, based on an assessment of the relevant literature published since AR5. Owing to the nature and magnitude of the expected effects of sea level rise on human coastal communities and to the interlinked nature of exposure and vulnerability of human communities and coastal ecosystems, the chapter focusses on coastal socio-ecological systems and not on marine and cryosphere ecosystems. We also take cognizance of the IPCC Special Report on Global Warming of 1.5°C (SR1.5) as an additional point of departure.

For assessing coastal exposure, vulnerability, and risk to ecosystems, species, and human systems, groups, and individuals, this chapter adopts the risk framework developed in the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX; see also Cross-Chapter Box 1 in Chapter 1). This framework was applied extensively in IPCC's Fifth Assessment Report (AR5) and subsequent literature. This chapter also assesses pathways to resilience and sustainable development along the coast in the specific context of climate change and sea level rise. In each aspect, we place special emphasis on Small Island Developing States (SIDS), deltas, and coastal cities and communities.

4.1.1 Themes of this Chapter

Section 4.2 establishes the physical setting relevant to coastal hazards including dynamical coastal morphology and the numerous processes contributing to sea level rise globally, regionally, and locally. This section also assesses paleo-climate evidence, direct observations of sea level change and its acceleration, and attribution of sea level rise, and assesses previous projections in light of new literature with a particular focus on ice-sheet dynamics and uncertainties. Section 4.3 assesses the socio-economic and demographic drivers of change with an emphasis on how human and societal factors, such as urbanization, interact with the ever-changing social-ecological coastal setting to determine the dynamic pattern of coastal exposure and vulnerability for ecological and human systems. These socio-economic and demographic drivers of change interact with the changing hazards evaluated in Section 4.2 to determine risk and impacts (the manifestation of risk). We assess cultural, institutional, and ethical dimensions insofar as they both influence and are influenced by risk and impacts. Governance and the interactions across scales of governance, such as individuals' interactions with local, regional, national and transnational institutions, discussed in Section 4.4, provide an especially important focus. Also important is how risk perception affects responses to risk. This chapter furthers the development of the Reasons for Concern and the associated Burning Embers diagram, a global aggregation of risk established in the Third Assessment Report (AR3), by applying this framework to sea level rise and coastal risk at a greater level of specificity than in AR5. Section 4.4 also assesses the literature on responses, particularly on options and development pathways facilitating planning and implementing adaptation, building resilience, and facilitating transformation. The section concludes with an assessment of pathways to resilience and sustainable development in the coastal context, including measures, safety margins, limits, barriers and enablers of response.

Figure 4.1 illustrates the interconnection of this chapter's themes, including drivers of hazards associated with sea level rise and extreme sea level (Section 4.2), drivers of exposure, vulnerability, and impacts and risk related to SLR and ESL (Section 4.3), and climate resilient development, with a focus on responses to SLR and ESL (Section 4.4). We anchor our presentation with specific examples of coastal risk and individual and institutional responses to risk and its manifestation (impacts) as they evolved over time in specific, placed-based contexts and events (see Box 4.1).

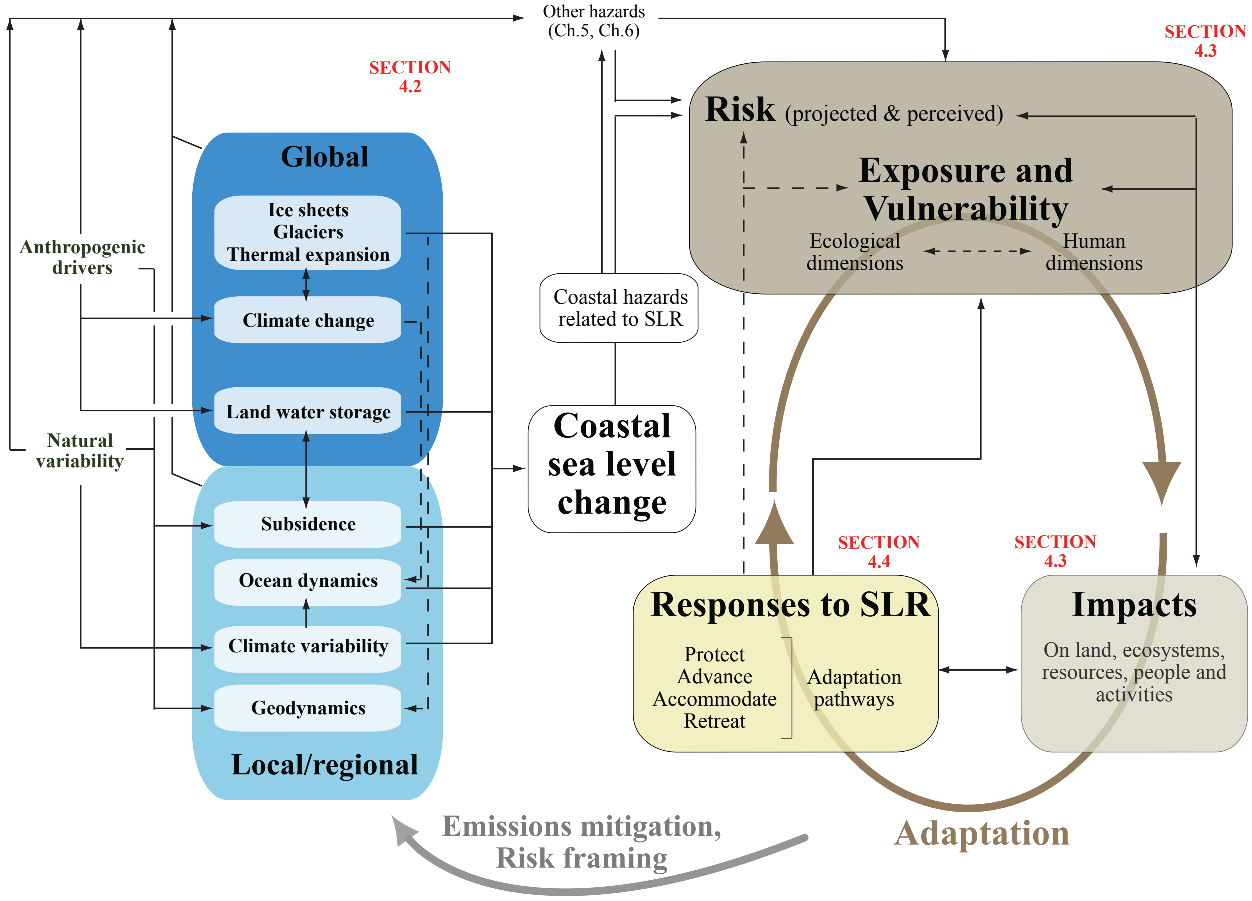


Figure 4.1: Schematic illustration of the interconnection of Chapter 4 themes, including drivers of sea level rise and extreme sea level hazards (Section 4.2), drivers of exposure, vulnerability, and impacts and risk related to sea level rise (Section 4.3), and climate resilient development, with a focus on responses to these hazards (Section 4.4).

4.1.2 Advances in this Chapter Beyond AR5 and SR1.5

Developments since AR5 lead to a different evaluation of the SLR and ESL hazard in this report compared to the previous assessment, especially from the middle of the 21st century and beyond for higher emissions scenarios (e.g., RCP8.5). SR1.5 focused on scenarios compatible with modest warming, such as RCP2.6, for which differences with this chapter are small. Noting that “sea level will continue to rise well beyond 2100 (*high confidence*)”, SR1.5 emphasized that “a slower rate of sea level rise enables greater opportunities for adaptation in the human and ecological systems of small islands, low-lying coastal areas and deltas (*medium confidence*)”, findings echoed in this report. Both AR5 and SR1.5 point to the dynamical response of the Antarctic ice sheet to warming as a key uncertainty in projecting sea level rise. Advances in ice sheet modelling since AR5 lead to an assessment of the *likely* range of 21st century SLR in this report that is both markedly higher and wider than in the previous assessment (Sections 4.1.2.1, 4.2.3). Because the effect of the dynamical response is muted for low emissions scenarios, these developments do not require significant alteration of SR1.5 findings.

4.1.2.1 Coastal Hazards

AR5 assessed past sea level change based on the instrumental and geological record and projected a *likely* range for global mean sea level rise of 0.28–0.98 m by 2100 compared to 1986–2005 (Church et al., 2013). Importantly, AR5 also assessed regional sea level changes, and changes in extremes of high water, especially as they relate to the sources of flooding. AR5 presented IPCC’s first quantification of the dynamical contribution of the Antarctic ice sheet to sea level rise by 2100 but cautioned that, ‘Based on current understanding, only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause global mean sea level to rise substantially above the *likely* range during the 21st century. This potential additional contribution cannot be precisely quantified but there is *medium confidence* that it would not exceed several tenths of a meter of sea level rise during the 21st century' (Church et al., 2013, p. 1140). An important finding in this chapter is our assessment that advances in modelling since AR5 (Section 4.2.3) allows a characterization of the *likely* range that includes the contribution from initiation of collapse of marine-based sectors of the Antarctic ice sheet. We also progress the assessment of the upper tail or high end of the probability distribution of sea level rise (e.g., the probability of larger SLR than encompassed by the *likely* range) compared to AR5. Nevertheless our evaluation is still constrained by the deep uncertainty (i.e., ambiguous or difficult-to-quantify probabilities) that inhibits full characterization of the tail (Oppenheimer et al., 2016; Bakker et al., 2017b; Section 4.2.3.4; Cross-Chapter Box 4 in Chapter 1).

The literature since AR5 leads us to re-evaluate AR5 projections of changes in frequency of regional extremes of high water associated with coastal storms and flood events (Section 4.2.3.4). AR5 projections of regional sea level did not account for factors such as tectonics or subsidence associated with groundwater and hydrocarbon withdrawal. This approximation increased the uncertainty in the projected extremes. The AR5 projections of regional extremes of high water were also limited by the uncertainty on the projected characteristics of tropical and extratropical cyclones. Several of these uncertainties could not be removed and still limit our confidence in the updated projections of extremes for some regions and times.

4.1.2.2 Exposure, Vulnerability, Impacts and Risks

AR5 comprehensively assessed the coastal exposure and vulnerability of natural and human systems in many regional settings, finding with *very high confidence* that "Coastal systems and low-lying areas will increasingly experience adverse impacts such as submergence, coastal flooding, and coastal erosion due to the combined effect of relative sea level rise and extreme sea level." AR5 also updated the Reasons for Concern framework and the Burning Embers representation of risk to incorporate additional elements: risk for marine species impacted by ocean acidification only, by the combined effect of acidification and warming, and risk for coastal human and natural systems impacted by sea level rise (Wong et al., 2014; O'Neill et al., 2017). Ability to perform a detailed assessment of future risk was constrained by the uncertainty in regional projections of sea level change, extreme sea level, and changes in storm frequency and intensity (Sections 4.1.2.1, 4.2.3.4).

Improved hazard assessment, and a significant extension of the literature relevant to more spatially and temporally explicit current as well as future coastal exposure and vulnerability (Box 4.2, Section 4.3.2.5), allows increased confidence in the assessment of coastal risk in this chapter (Section 4.3.4). We assess the relationship between SLR risk and the risks stemming from significant social-ecological changes driven by non-climatic drivers, such as demographic and development trends, which are observed along many coastlines (Sections 4.3.2, 4.3.3). We find that low-lying coasts around the world, irrespective of their characteristics (e.g., continental vs island coasts), face escalating SLR risk on a multi-decade to centennial scale in the absence of effective adaptation (Section 4.3.3.; Cross-Chapter Box 7; *medium evidence, high agreement*). However, notwithstanding advances in post-AR5 literature, it remains difficult to isolate the SLR risk component of coastal risk from the risks due to non-climatic drivers and local non-SLR processes (Section 4.3.3.3; *medium confidence*). Our assessment highlights the important role played by compound events in shaping coastal risk, with SLR interacting with non-SLR processes and events, such as severe storm tides resulting from the compounding effect of SLR and tropical cyclones, and exacerbated flooding due to the combination of extreme precipitation and storm surge (Section 4.3.4.1). A new synthesis is provided of the risk induced by GMSLR for megacities, urban atoll reef islands, populated deltas, and Arctic coasts (Section 4.3.4.2).

4.1.2.3 Responses

'SLR responses' refers here to provisions, plans and actions taken to reduce risk, adapt, and build resilience and sustainability in the face of rising sea levels. Responses to SLR are seldom determined in isolation, and are an integral part of individual, private sector, government, community and social choices about adaptation in the face of climate, environmental and societal change. Consequently, the AR5 findings on climate change adaptation provide an important platform for this assessment, including relevant findings about adaptation in general (IPCC, 2014a), adaptation in coastal and low-lying areas (Wong et al., 2014), adaptation needs and options (Noble et al., 2014), adaptation planning and implementation (Mimura et al., 2014), opportunities, constraints and limits (Klein et al., 2014), and the economics of adaptation (Chambwera et al., 2014). In this assessment, we go beyond this adaptation literature to draw on diverse literatures pertinent to SLR responses in the short-, medium- and long-term. (From a decision making perspective, these timeframes might correspond to 1–10 years; 10–50 years; and 50 plus years respectively.) These literatures include wide-ranging governance scholarship relevant to the coast (see Cross-Chapter Box 2 in Chapter 1) and scholarship about challenges and opportunities for reducing coastal risk, and building resilience and sustainability (see Cross-Chapter Box 1 in Chapter 1).

We describe the different observed and available responses to SLR (Section 4.4.2), with attention focused on making social choices about SLR (Section 4.4.1). Importantly, this chapter extends the scope of the AR5 assessment by adding 'advance' (i.e., the creation of new land by building outwards and upwards, including land reclamation) to long-recognized responses: 'protection' (including 'hard' and 'soft' measures, and ecosystem-based adaptation), 'accommodation' and 'retreat' (including, displacement, migration and planned relocation). A variety of approaches, methods and tools are used to decide which response, or combination of responses, is appropriate for a particular locality at a particular point in time, and how best to sequence and institutionalize SLR responses over time (Section 4.4.4).

Literature since AR5 underscores the important ways in which the trajectory of SLR responses is shaped by the historical and prevailing institutional setting (Section 4.4.4.1). We highlight the range of formal and informal institutional provisions and processes in place to respond to SLR, including legal provisions to formalize SLR responses, land-use planning, efforts to align formal and informal institutional provisions, as well as the application of, among others, simulation games, futures and foresight methods, deliberation and conflict resolution processes (Section 4.4.4.2). Our assessment corroborates the AR5 finding that adaptation planning is underway in many jurisdictions but translating such plans into effective action is challenging (Section 4.4.4.2).

There have been advances in the development and use of decision-analytical (economic) approaches and tools to appraise and assess the effectiveness of alternative SLR responses, revealing, among other things, the feasibility and affordability of hard protection along densely populated and intensively developed coasts (Section 4.4.3.1). Recent literature provides new insights about how SLR responses have been applied in the past, are being applied currently, their effectiveness, costs, benefits and co-benefits, as well about for potential future responses. Such literature also shed lights on governance implications for appraising, selecting and implementing appropriate responses (Section 4.4.4.3). The selection and sequencing of context-appropriate responses can generate significant interacting complementary and / or antagonistic impacts (*high confidence*). This assessment underscores the advantages of using decision-analytical methods and other technical approaches and tools in combination with community-based approaches grounded in public participation, community visioning, and collaborative planning. Realizing these advantages is difficult in practice (Sections 4.4.4.3, 4.4.4.4; *medium evidence, high agreement*).

Since AR5, the adaptation pathways concept has become influential in thinking about how to enable long-term planning and decision-making in the face of uncertainty and change. However, translating innovations in adaptation planning, risk reduction and resilience building into local institutional reality is highly variable and context-specific, and seldom achieved in many jurisdictions (Section 4.4.5; *medium evidence, high agreement*).

While uncertainty about future SLR and ESL will pose a constant challenge for planning, three characteristics of this uncertainty can help frame the planning process. These aspects are 1) growing uncertainty in climate change farther in the future, arising from the increasing differences among the Representative Concentration Pathways (RCPs) beyond 2050; 2) growing uncertainty in global and regional sea level rise, due to uncertainty in the dynamical contribution from the Antarctic ice sheet, especially in the latter half of this century; 3) a resulting increase over time in uncertainty of projected frequency of occurrence of sea level extremes associated with tropical and extratropical cyclones and coastal flooding (4.2.3, 4.2.4). Thus, uncertainty in projections is much higher late in the 21st century and beyond than at mid-century. This finding has implications for the timing of response strategies (Section 4.4.4.3.4).

The chapter concludes with an assessment of post-AR5 literature on climate resilient development pathways at the coast, building on Denton et al. (2014). Whilst there is little literature since AR5 specifically on SLR and climate resilient development pathways, it is clear that SLR poses a fundamental challenge to low-lying coasts, and consequently, prospects for achieving the sustainable development goals. If the current trajectory of SLR continues, many people living on low-lying coasts and islands face dismal prospects over the course of this century. Institutionalizing climate resilient development pathways is consequently imperative (Section 4.4.6), especially given projected accelerating SLR (Section 4.2).

4.2 Physical Basis for Sea Level Change and Associated Hazards

As a consequence of natural and anthropogenic changes in the climate system, sea level changes (SLC) are occurring on temporal and spatial scales that can cause increased levels of risk for coastal communities, cities, and low-lying islands. Sea level in the general sense is used here as the time mean of the sea surface eliminating short duration fluctuations like waves, surges and tides. Global mean sea level (GMSL) rise is caused by volume changes of ocean water caused by thermal expansion, and by mass changes caused by loss of land ice or changes in terrestrial water reservoirs. Mass changes lead to distinct spatial patterns of regional sea level rise, often called fingerprints. These fingerprints are caused by changes in Earth's rotation and its gravitational field, and elastic deformation of its lithosphere as masses of ice and water are redistributed on the Earth's surface. Here regional sea level refers to spatial scales of around 100 km, while local sea level refers to spatial scales smaller than 10 km. In addition to gravitational and rotational effects, the solid Earth may cause sea level changes due to tectonics, mantle dynamics or glacial isostatic adjustment. These processes causes vertical land motion and sea surface height changes at coastlines, and hence a relative sea level (RSL) change defined as the change in the difference in elevation between the land and the sea surface at a specific time and location (Farrell and Clark, 1976). In most places around the world, current annual mean rates of regional and relative sea level changes are typically in the order of a few mm yr^{-1} (see Figure 4.4). Additional risk associated with changing sea level is related to individual events, superimposed on the background of these gradual changes. As a result, the gradual changes in time and space have to be assessed together with processes that lead to flooding events. These processes include storms, surges, waves, and tides or a compounded combination of these processes that can all lead to extreme sea level (ESL) events. In this section, newly emerging understanding of these different episodic and long-term aspects of sea level change are assessed, within a context of sea level changes measured directly over the last century, and those inferred for longer geological timescales. This longer-term perspective is important for contextualizing future projections of sea level and providing guidance for process-based models of the individual components of sea level rise, in particular the polar ice sheets.

4.2.1 Processes of Sea Level Change

Sea level changes have been discussed throughout the various IPCC assessment reports as sea level rise is a key feature of climate change. In the early 1990s, observed changes in the polar ice sheets covering Greenland and Antarctica were small, and the general understanding, based in part on numerical ice sheet models (e.g., Huybrechts, 1994) estimating global ice volume changes, was that they would not provide a major contribution to future sea level on decadal or even century timescales. In fact, it was assumed that increased snow accumulation rates in Antarctica in response to a warming polar atmosphere would contribute a small net drop in sea level and was the dominate process for ice sheet changes on these timescales. Complex interactions between the oceans and ice sheets were not yet recognized as important drivers of processes that can lead to rapid dynamical changes in the ice sheets. Understanding of ice calving processes and glacial hydrological processes was also limited. The view on the potential role of ice sheets in future sea level rise changed by the time of AR4 (Lemke et al., 2007), following the first convincing signs of increased ablation rates in Greenland and increased rates of ice discharge into the ocean around Antarctica. Projections of future sea level were presented with the caveat that dynamical ice-sheet processes were not accounted for, as our physical understanding of these processes was too rudimentary and no literature could be assessed (Bindoff et al., 2007). This implied that processes related to changes in the atmospheric conditions affecting the surface mass balance were captured, but the adjustment of ice dynamics to the changed environmental conditions were not. In AR5 (Church et al., 2013) a first attempt was made to quantify the dynamic contribution of the ice sheets, although still with limited physics, relying mainly on an extrapolation of existing observations and a single process based case study. Furthermore, AR5 provided improved insight into local and regional patterns of sea level change. These two advances provide the basis for this chapter, where the focus is on sea level changes around coastlines and low-lying islands, rather than global mean sea level rise. We explain the mechanism driving past and contemporary sea level changes and episodic extremes of sea level and assess confidence in regional projections of future sea level over the 21st century and beyond. A combination of approaches using information from geological sea level records, the global network of tide gauges, and satellite data have substantially advanced our understanding of sea level change over the past century and earlier (Section 4.2.2). The addition of ocean mass from the loss of land ice has begun to outpace thermal expansion as the dominant contributor since around 2005 (Table 4.1). A combination of tide gauge and satellite-based estimates consistently indicate an increase in the rate of GMSL rise, with the rate of sea level rise accelerating (Hay et al., 2015; Watson et al., 2015; Chen et al., 2017; Dieng et al., 2017; Nerem et al., 2018).

4.2.1.1 Ice Sheets and Ice Shelves

The polar ice sheets on Greenland and Antarctica contain most of the fresh water in the cryosphere. As a consequence, they have the greatest potential to cause changes in sea level. Figure 4.2 illustrates the size of land ice reservoirs and the most important processes that drive mass changes of ice sheets. The total mass of an ice sheet is controlled by the surface mass balance (SMB), the sum of accumulation and ablation controlled by atmospheric processes. Ice sheets also lose mass through contact with warm ocean water below ice shelves, and by calving (iceberg discharge) at marine-terminating ice margins. Changes in the SMB, discharge, and melting forced by the ocean will lead to a dynamical adjustment of the ice sheet.

Ice sheets drive changes in sea level mainly through the loss or gain of land ice above flotation, which is the ice thickness above local sea level, corrected for the density difference between water and ice. The Greenland Ice Sheet is currently loosing mass at roughly twice the pace of the Antarctic Ice Sheet (Table 4.1). However, Antarctica contains eight times more ice above floatation than Greenland. Furthermore, a substantial fraction of Antarctic glacial ice rests on bedrock below sea level, making the ice sheet responsive to changes in ocean melt and possibly vulnerable to marine ice sheet and marine ice cliff instabilities (see Section 4.2.3.1, Chapter 3 and Cross-Chapter Box 3 in Chapter 1). Ice shelves, the floating extensions of glacial ice flowing into the ocean (Figure 4.2) do not directly contribute to sea level, but they play an important role in the dynamics of ice sheets by providing resistance to the seaward flow of the grounded ice upstream (Fürst et al., 2016). Ice shelves gain mass through the inflow of ice from the ice sheet and from precipitation. If surface melt is substantial, ice shelves not only lose mass, they can collapse from flexural stresses caused by the movement of the meltwater and the deepening of water-filled crevasses (Banwell et al., 2013; Macayeal and Sergienko, 2013; Kuipers Munneke et al., 2014). Ice shelves can also thin from below (Paolo et al., 2015), through ocean-driven melt, controlled by complex ice-ocean interactions involving circulation, temperature, and salinity of the water (Dinniman et al., 2016). Iceberg formation at marine-terminating ice margins or ice-shelf calving fronts is governed by complex ice-mechanical processes, the internal strength of the ice, and interaction with ocean waves and tides (Benn et al., 2007; Bassis, 2011; Massom et al., 2018).

Our understanding of ice sheets has progressed substantially since the AR5, although deep uncertainty (Cross-Chapter Box 4 in Chapter 1) remains with regard to their potential contribution to future sea level rise on long time scales. This is particularly true for Antarctica (Cross-Chapter Box 3 in Chapter 1).

4.2.1.2 Glaciers

Glaciers outside of the Greenland and Antarctic ice sheets are important contributors to sea level change (Figure 4.2). They gain mass by accumulation (mainly snowfall) and lose mass by ablation (mainly melt) or calving in lakes or the ocean. Because of their specific accumulation and ablation rates, which are often high compared to those of the ice sheets, they are sensitive indicators of climate change and respond fast to change in the climate system, with a response time scale in the order of decades (Jóhannesson et al., 1989). As a consequence, glaciers have added more mass to the ocean than the Greenland and Antarctic ice sheets during the past century EG (Gregory et al., 2013). However, the volume of ice in this land ice reservoir is small by comparison, equivalent to only between 0.31 and 0.53m mean sea level rise if all the world's glaciers were lost (Vaughan et al., 2013). In some areas, the loss of glaciers has been interrupted by periods of increased precipitation or regional cooling (Mackintosh et al., 2017), but on multidecadal and longer time scales, the impact of global temperature tends to dominate, contributing to ongoing glacial melt (e.g., Marzeion et al., 2015).

4.2.1.3 Ocean Processes

The warmer the ocean water, the lower its density and therefore the larger its volume per unit of mass ("thermal expansion"). Thus, warming leads to a higher sea level even when the ocean mass is constant. Over at least the last 1500 years the sea level was coupled to the global mean temperatures (Kopp et al., 2016), partly because of ice mass loss, and partly because of thermal expansion. Models indicate that over the last decades, more than 90% of the increase in energy in the climate system has been stored in the ocean. Climate change and sea level are thus intimately related and thermal expansion provides insight in our understanding of the climate system and climate sensitivity (Church et al., 2013). Findings from these two viewpoints are consistent (Otto et al., 2013). As the thermal expansion coefficient is temperature-dependent, heat uptake by a warm region has a different impact on sea level rise than heat uptake by a cold region. This contributes to regional changes, which are also caused by the ocean dynamics and salinity changes (e.g., Lowe and Gregory, 2006; Suzuki and Ishii, 2011).

4.2.1.4 Terrestrial Reservoirs

Global sea level is also affected by changes in terrestrial reservoirs of liquid water (Wada et al., 2017). Withdrawal of groundwater and storage of fresh water through man-made dam construction contributes to GMSL (Chao et al., 2008; Fiedler and Conrad, 2010). In the earlier parts of the 20th century the terrestrial contribution was dominated by the storage component, but in recent decades, land water depletion, related to domestic, agricultural and industrial usage, has begun to dominate. Changes in terrestrial reservoirs may also be related to climate variability: In particular, the El Nino Southern Oscillation (ENSO) has a strong impact on precipitation distribution and temporary storage of water on continents (Boening et al., 2012; Cazenave et al., 2012; Fasullo et al., 2013).

4.2.1.5 Geodynamic Processes

Land ice and thermal expansion dominate GMSL change on decadal and longer time scales, but other processes are relevant for regional-to-local sea level changes. Regional patterns in sea-level change are modified from the global average by changes in ocean currents, salinity, and trends in atmospheric pressure (Yin, 2012).

Changing distributions of water mass between land, ice, and ocean reservoirs cause nearly instantaneous changes in the Earth's gravity field and rotation, producing patterns of sea level change, called fingerprints (Mitrovica et al., 2001; Mitrovica et al., 2011). Proximal to an ice sheet loosing mass to the ocean, relative sea level falls despite a rise in GMSL. Far from the ice sheet loosing mass, these gravitational-rotational effects can enhance the rise in relative sea level by as much as 25% compared to the global average. On longer timescales, redistributions of water and ice cause time-dependent, visco-elastic deformation of the Earth. This is observed in regions previously covered by ice during the Last Glacial Maximum (LGM), including much of Scandinavia and parts of North America (Lambeck et al., 1998; Peltier, 2004). In these regions, glacio-isostatic adjustment (GIA) is causing uplift and a lowering of relative sea level that continues today. In other locations, proximal to the previous ice load and where a glacial forebulge once existed, the relaxing forebulge can contribute to a relative sea level rise. The loading of ocean crust by melt water can also cause uplift of land areas near continental margins, far from the location of previous ice loading (Mitrovica and Milne, 2003; Milne and Mitrovica, 2008). Rates of modern vertical land motion associated with these post-glacial processes are generally on the order of a few mm/yr or less.

Vertical land motion from tectonics and dynamic topography associated with viscous mantle processes are important for reconstructing ancient sea-levels based on geological indicators (Austermann and Mitrovica, 2015). However, tectonics and dynamic topography are generally not considered in projections of sea-level change on decadal-to-century timescales.

4.2.1.6 Sea Level Extremes

Superposed on gradual changes in RSL, tides, storm surges, waves and wave run-up (being the sum of wave set-up and wave swash) and other high-frequency processes (Figure 4.2) can be important locally. Understanding the localized impact of such processes requires detailed knowledge of bathymetry, erosion and sedimentation, as well as a good description of the temporal variability of the wind fields generating storm surges. The potential for compounding effects (Section 4.3.4.1), like storm surge and high SLR, are of particular concern as they can contribute significantly to flooding risks and extreme events (Little et al., 2015a). These processes can be captured by hydrodynamical models (see Section 4.2.3.5).

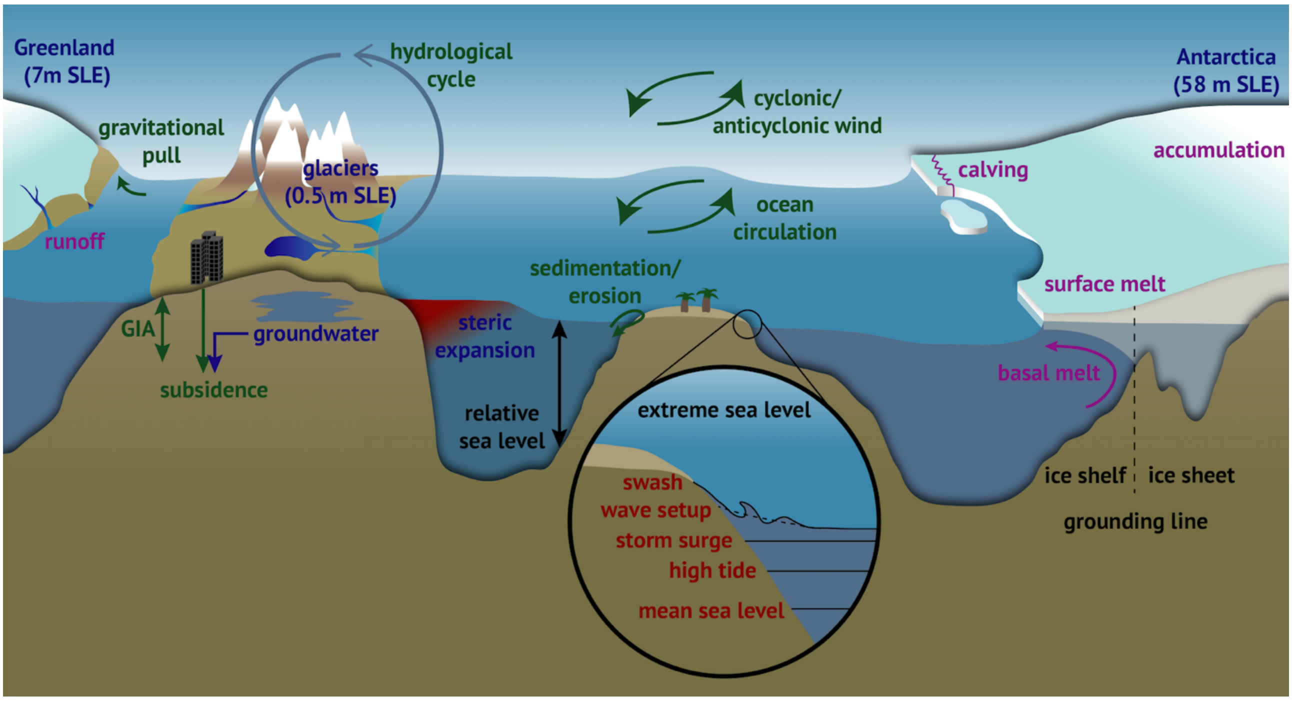


Figure 4.2: A schematic illustration of the climate and non-climate driven processes that can influence global, regional (green colours), relative and extreme sea level (red colors) along coasts. Major ice processes are shown in grey and general terms in black. SLE stands for Sea Level Equivalent and reflects the increase in GMSL if the mentioned ice mass is melted completely and added to the ocean.

4.2.2 Observed Changes in Sea Level (Past and Present)

Past changes in sea level are important as they provide information on the size of the major ice sheets in climates different from today. Past climate intervals warmer than today are of particular interest, because they can be used to test and calibrate process-based ice sheet models. These include the Mid Pliocene Warm Period (MPWP) around 3 Myrs ago, when global mean temperature was warmer than today. A second period of interest is the Last Interglacial (LIG) or Eemian around 130–115 Kyr ago, when global mean temperatures were slightly higher than today's. Reconstructions from proxy data indicate sea levels substantially higher than present-day during those warm periods, although considerable uncertainty remains.

In Section 4.2.2.1, we summarize recent advances in reconstructing these time periods in terms of climate, sea level maxima, and rates of sea level rise, and implications for the future evolution of the ice sheets. In addition to periods with elevated sea level relative to modern, we consider the last deglaciation as a period of substantial and rapid ice loss. In Section 4.2.3 we discuss more recent observation of sea level changes.

4.2.2.1 Paleo Sea Level

4.2.2.1.1 Mid-Pliocene Warm Period or Mid-Piacenzian Warm period

The Mid-Pliocene Warm Period (MPWP) is far beyond the limit of ice cores, but several geochemical techniques have been developed to reconstruct Pliocene carbon dioxide concentrations from sediment archives and fossil leaves (Zhang et al., 2013; O'Brien et al., 2014; Martínez-Botí et al., 2015), with recent estimates ranging from 300 to 500 ppmv, except the stomata based estimate by Hu et al. (2015), which finds evidence for values below 300 ppmv. Despite these relatively modest CO_2 concentrations, temperature peaked between 1.9°C to 3.6°C degree above pre-industrial (Haywood et al., 2016). Most sea-level estimates for this period are considerably higher than at present. A recent compilation by Dutton et al. (2015) argues that GMSL was at least 6 m higher, but with few constraints on the maximum. AR5 (Masson-Delmotte et al. et al., 2013) assessed the maximum to be 14 m, with *high confidence* that it did not exceed 20 m. Correcting Pliocene shoreline observations for glacial isostatic adjustment (GIA; Raymo et al., 2011), and new insights regarding the role of dynamic topography, the vertical movement of the Earth's surface in response to mantle dynamics, Rovere et al. (2014) questioned interpretations of the sea level high stand.

During the MPWP obliquity paced variations of up to 30 m have been reconstructed based on marine $\delta^{18}O$ data (Naish and Wilson, 2009), but sea level changes associated with orbital forcing are likely not important for assessing the current changes on a shorter time scale. A sea-level record based on a combination of geochemical data and a water-exchange/salinity model of the Mediterranean Sea (Rohling et al., 2014) also supports tens of meters of Pliocene sea level variability and peak levels >30 m above present. Updated oxygen isotope mass balance calculations, comparing the isotopic composition of the modern and Pliocene ocean (Winnick and Caves, 2015), suggest Pliocene sea level was only ~9–13.5 m above modern, with a relatively small ~2–4.5 m contribution from the East Antarctic Ice Sheet in addition to the WAIS and Greenland. However, the isotope approach relies on the average of multiple isotope records (Lisiecki and Raymo, 2005) with limited (~3 kyr) temporal resolution that might not represent the full range of Pliocene isotope and sea level variability. Subsequent work, using isotope-enabled climate and ice sheet models to constrain the isotope mass balance problem concluded a Mid Pliocene Antarctic ice mass loss equivalent to as much as 13 meters is consistent with isotope records (Gasson et al., 2016). This higher estimate implies that almost 10 m of sea level rise was contributed by East Antarctica, in line with interpretations of marine sediment cores from the East-Antarctic margin, indicating substantial ice sheet variability in deep East Antarctic basins (Cook et al., 2013). Higher than present-day sea levels are also supported by sediment data (De Schepper et al., 2014), suggesting ice-free conditions in the Northern Hemisphere and Patagonia. A global ice-sheet modelling study by de Boer et al. (2017) suggests that the ice sheets in Greenland and Antarctica responded out of phase as a consequence of precessional orbital forcing, with a total maximum contribution of 13.3 m. The potential for interhemispheric antiphasing of Pliocene ice volume (Raymo et al., 2006; de Boer et al., 2017) is an important emerging issue, but little work has been done on this topic. For example, the expansion of ice in Greenland during a MPWP high stand, would consequently require a larger contribution from Antarctica than the global average rise in GMSL.

Recent Antarctic ice sheet modelling studies of maximum, mid-Pliocene ice loss (Austermann and Mitrovica, 2015; Pollard et al., 2015; Yamane et al., 2015; DeConto and Pollard, 2016) range widely, between 5.4 and 17.8 m sea-level equivalent. An intercomparison experiment (de Boer et al., 2015) indicates that the largest uncertainty in modelling the MPWP is related to the mass balance forcing of the Antarctic ice sheet models. An ice sheet model including new, but uncertain parameterizations of ice sheet processes including the influence of surface meltwater on crevasse penetration and calving of marine-terminating ice cliffs (MICI; see Cross-Chapter Box 3 in Chapter 1) demonstrates the potential for considerable mass loss in East Antarctica, in addition to West Antarctica (Pollard et al., 2015; DeConto and Pollard, 2016). Another modelling study demonstrated that ocean melt at grounding lines is capable of causing Pliocene ice retreat in East Antarctica (Golledge et al., 2017). In this case, the model used a sub-grid melt scheme that applies melt under partially grounded grid cells. This approach increases the sensitivity of the model to ocean forcing, although its validity is unproven (Yu et al., 2017).

Given the ongoing uncertainties in Pliocene data interpretations and dynamical ice sheet modelling, we have *low confidence* in MPWP sea-level as a future analogue, consistent with the assessment of AR5.

4.2.2.1.2 Last Interglacial

Dutton et al. (2015) present a revised review of Eemian sea level based on geological indicators, indicating that global mean sea level was 6 to 9.3 m higher than today. This is in line with an earlier estimate by Kopp et al. (2009) and close to the range reported by AR5, but slightly higher than AR5's central estimate of 6 m. Austermann et al. (2017) compared a compilation of last interglacial (LIG) sea level indicators with dynamic topography simulations. They found that vertical surface motions driven by mantle convection can produce several meters of uncertainty in LIG sea level estimates, but their mean and most probable estimates of 6.7 m and 6.4 m, respectively are broadly in line with other estimates. In light of these updated findings, we find it *unlikely* that peak LIG sea level exceeded 10 m above present, in agreement with AR5.

Due to ongoing uncertainties in GIA and dynamic topography corrections of LIG sea-level indicators (Dutton et al., 2015) and the wide range of model estimates of Greenland and Antarctic ice-sheet response to LIG climate conditions discussed below, relative contributions of the Greenland and Antarctic Ice Sheets to LIG sea level remain uncertain, as does the exact timing of peak sea level within the interglacial. In particular, there is controversy on the shape of the sea-level curve throughout the Eemian (Rovere et al., 2016). Kopp et al. (2013) argue for a double peak in GMSL within the LIG, whereas Dutton and Lambeck (2012) suggest that part of the double peak shape may be caused by uncertainties in the GIA corrections. Solving this dispute may improve understanding of relative contributions to LIG sea level rise from Antarctica and Greenland, and in turn, the potential for future changes in ice sheets. Marine cores from the Antarctic Margin also suggest ice retreat into the Wilkes Subglacial Basin in East Antarctica, during multiple Pleistocene interglacials, including the LIG (Wilson and Forsyth, 2018). The WAIS is assumed to have collapsed during the LIG based on GIA-corrected sea level estimates (Dutton et al., 2015), but the evidence is indirect. Isotopic evidence in Antarctic ice cores combined with atmospheric modelling have been used to infer the loss of WAIS during the LIG (Steig et al., 2015), but those results are in conflict with other studies, albeit using course-resolution models (Holloway et al., 2016). We stress that definitive geological evidence of the extent and volume of WAIS retreat during the LIG has yet to be uncovered.

Simulations with coupled climate-ice sheet models of Greenland indicate a Greenland contribution to LIG sea-level rise of only up to 50 mm SLC per century (Helsen et al., 2013), a total contribution to LIG sea level of as little at 0.75 m (Quiquet et al., 2013), and not likely more than 2.5 m (Helsen et al., 2013; Stone et al., 2013; Colleoni et al., 2014). Moreover, modelling studies indicate a late peak for the Greenland contribution around 123–122 ka BP EG (Helsen et al., 2013; Quiquet et al., 2013; Goelzer et al., 2016; Yau et al., 2016), implying an Antarctic-dominated meltwater source early in the LIG (130–125 ka). Greenland ice cores and internal ice layer imaging by radar (Dahl-Jensen et al., 2013) do not indicate major LIG ice loss. However, ice core temperature reconstructions indicating a large increase in summer temperatures are not compatible with limited Greenland ice retreat from models (Dahl-Jensen et al., 2013; Landais et al., 2016; Yau et al., 2016). This suggests the Greenland Ice Sheet was either insensitive to LIG temperature changes or the temperatures inferred from ice core oxygen isotope records are overestimated. The contribution of thermal expansion to LIG GMSL rise was modest (0.35–0.4 m) (McKay et al., 2011; Goelzer et al., 2016; Hoffman et al., 2017) lending additional evidence that Antarctica contributed to the LIG high-stand, particularly early in the interglacial before the Greenland Ice Sheet was a major sea-level contributor (Goelzer et al., 2016; Yau et al., 2016).

Bierman et al. (2016) used cosmogenic 10Be and 26Al of marine sediments to argue that large ice caps have persisted in east Greenland during the last 7.5 Myr. Data from 10Be and 26Al measurements of sediments below the ice suggest extensive, episodic ice-free conditions in Greenland's interior (Schaefer et al., 2016), but the duration and frequency of such events are unknown. Whether these geological findings are compatible strongly depends on the extent and thickness of the ancient LIG ice sheet, which remain poorly constrained due to uncertainties in past mass balance. Spatial patterns of retreat vary strongly among the existing model studies using different mass balance forcings (Colleoni et al., 2014).

In summary, we have *high confidence* that sea level high stands were higher than present-day during the LIG, but ongoing uncertainties in the observational evidence and ice sheet models continue to hamper conclusions regarding the rates of sea level rise, or the relative contributions from the loss of Greenland versus Antarctic ice.

4.2.2.1.3 Deglaciation

Sea level rise during the Last Deglaciation (~19–11 ka) was mainly driven by the retreat of Laurentide and Fenno-Scandinavian ice sheets that no longer exist. However, there is substantially more evidence available for this period than for the LIG or MPWP, and it is the last period in the geological past when ice sheets melted rapidly. Therefore, data from this period may reveal information on the physical processes causing the ice sheet retreat, which may be difficult to retrieve from present-day observations. For example, recent evidence of keel-plough marks on the sea-floor indicate that large scale calving (see Section 4.2.3.1) plays a role in the deglaciation of Pine Island Bay, Antarctica (Wise et al., 2017).

During the last deglaciation, some sudden jumps in the pace of sea level are recorded in several sea-level curves. They were first described in Barbados (Bard et al., 1990) and later recorded in Tahiti and elsewhere.

During melt-water pulse 1A (14,300-11,000 yrs BP) the sea level rose approximately 20 m (Carlson, 2009). The meltwater pulse 1B occurred about 11,000 years BP (Bard et al., 1990). Some references suggest that this contribution originates from the Laurentide Ice sheet (Carlson, 2009) although other studies suggest that it was from the Ross Sea (Licht, 2004). Regarding the sea-level fluctuation during the Mid Holocene (about 6000 years BP), new studies conducted in the Great Barrier Reef (Leonard et al., 2018), Southern China (He et al., 2018), and South Korea (Song et al., 2018) confirm these fluctuations, although the vertical changes vary from site to site.

However, it is important to note that the retreat of ice sheets during the Holocene occurred during climatic conditions generally colder than today with different orbital conditions, so the mechanisms of retreat maybe be different from those that will dominate the future.

4.2.2.2 Global Mean Sea Level Changes During the Instrumental Period

Sea level observations on more recent timescales have mostly relied on tide gauge measurements. This record, beginning around 1700 in some locations, provides insight into historic sea level trends. Since 1992, the emergence of precise satellite altimetry has advanced our knowledge considerably through a combination of near global ocean coverage and high spatial resolution and more detailed monitoring of ice mass changes. Since 2002, high precision gravity measurements provided by the GRACE mission (Gravity Recovery and Climate Experiment) show the loss of land ice in Greenland and Antarctica (e.g., Velicogna and Wahr, 2005; Velicogna and Wahr, 2006), confirming independent assessments of ice sheet mass changes based on satellite altimetry and InSAR measurements (Shepherd et al., 2012; The Imbie team, 2018), combined with regional climate models to calculate the surface mass balance (Thomas et al., 2006; Rignot et al., 2008). Since 2006, when the array of Argo profiling floats (which measures the ocean temperature) reached a near-global coverage, it has been possible to get an accurate estimate of the ocean thermal expansion and test the closure of the sea level budget. In addition, the combined analysis of the different observing systems that are available since 2006, has improved significantly the understanding of the magnitude and relative contributions of the different processes causing sea level change. In particular, important progress has been achieved since AR5 on estimating and the understanding the increasing contribution of the ice sheets to sea level rise.

4.2.2.2.1 Tide gauge records

The number of tide gauges has increased over time from only a few, in northern Europe in the 18th century, to more than 2000 today along the world coastlines of continents and islands. Because of their location and limited number, tide gauges sample the ocean sparsely and non-uniformly, with a bias towards continental coastlines (only a small number of them are located on islands) and the Northern Hemisphere. In general, tide gauge records lack long term records and have significant gaps. In addition, tide gauges are grounded on land and are affected by the vertical motion of Earth's crust caused by both natural processes (e.g., GIA, tectonics and sediment compaction; Wöppelmann and Marcos (2016)) and anthropogenic activities (e.g., groundwater depletion, dam building or settling of landfill in urban areas; Raucoules et al., 2010). When estimating the GMSL due to the ocean thermal expansion and land ice melt from tide gauge records, tide gauges must be corrected for the vertical land motion (VLM). Stations of the Global Positioning System (GPS) network when they are co-located with tide gauges provide measurements of the local VLM. This approach enables correcting some tide gauge records for the VLM over recent decades (Santamaría-Gómez et al., 2017). However, the estimation of past VLM, on longer time scales remains difficult (Riva et al., 2017). Church et al. (2013) summarized the different strategies developed to account for both the inhomogeneous space and time coverage of tide gauge data and the corrections for VLM. On this basis, they estimated the sea level trend and acceleration over the period 1900–2010. Church et al. (2013) concluded that it is *very likely* that the long-term trend in GMSL from tide gauge records is 1.7 (1.5 to 1.9) mm yr^{-1} between 1900 and 2010 with a *likely* average acceleration over the 20th century between -0.002 to 0.019 mm yr^{-2}.

Since AR5 two new approaches have been developed to estimate the GMSL from tide gauge records. The first one uses a new statistical approach with a Kalman smoother which combines tide gauge records with spatial fingerprints of ocean dynamics, GIA and ice melting to account for the inhomogeneous distribution of tide gauges (Hay et al., 2015). The second approach uses ad hoc corrections to tide gauge records with an additional fingerprint from the changes in terrestrial water storage to account for the inhomogeneous distribution in tide gauges (Dangendorf et al., 2017) and it accounts for VLM using both GPS measurement and a new method based on a comparison between tide gauge records and satellite altimetry (Wöppelmann and Marcos, 2016; Santamaría-Gómez et al., 2017). Both methods lead to GMSL increase rates that are significantly lower than previous estimates over the first half of the 20th century leading to long-term trend since 1900 that are smaller than previous estimates by 0.4 mm yr^{-1} (see Figure 4.3). Different arguments including biases in the tide gauge datasets (Hamlington and Thompson, 2015), biases in the averaging technique and biases in the VLM correction (Dangendorf et al., 2017) have been proposed to explain these differences with earlier AR5 estimates. These arguments for the difference do not rule out the more recent GMSL estimates or previous AR5 estimates. They rather show that the uncertainty in GMSL reconstructions is larger than previously thought and is still poorly understood from a tide gauge observational perspective. Hence, on the basis of this we conclude that it is *very likely* that the long-term trend in GMSL estimated from tide gauge records is 1.6 (1.1–2.1) mm yr^{-1} between 1902 and 2010 for a total sea level rise of 0.17 (0.12–0.23) m. In addition, we conclude with *high confidence* that sea level has accelerated over the 20th century as four of five reconstructions extending back to at least 1900 show an acceleration (Jevrejeva et al., 2008; Church and White, 2011; Ray and Douglas, 2011; Hay et al., 2015; Dangendorf et al., 2017). The estimates of the acceleration ranges between -0.002–0.019 mm yr^{-2}. The range is large and could be improved (Watson, 2016).

4.2.2.2.2 Satellite altimetry

High precision satellite altimetry started in October 1992 with the launch of the TOPEX/Poseidon and Jason series of spacecraft. Since then, 11 satellite altimeters have been launched providing nearly global sea level measurement (up to ±82° latitude) at different temporal sampling (from 3 to 35 days) over more than 25 years. Unlike tide gauges, altimetry measures sea level relative to a geodetic reference frame and thus is not affected by vertical land motion. But altimetry measurement can be affected by instrumental biases, in particular in the early altimetry era when TOPEX/Poseidon was flying alone. Since AR5, several studies using two independent approaches based on tide gauge records (Watson et al., 2015) and the sea level budget closure (Chen et al., 2017; Dieng et al., 2017) identified a drift of 1.5 (0.4–3.4) mm yr^{-1} in TOPEX A over the period January 1993 to December 1998. Accounting for this drift leads to a revised rate of the global MSL from satellite altimetry of 3.0 mm yr^{-1} (2.4–3.6) over the period 1993–2015 instead of 3.3 mm yr^{-1} (2.7–3.9) as stated in the AR5. Hence, a revised estimate of the satellite altimetry GMSL record now shows an acceleration of 0.084 (0.059–0.090) mm yr^{-2} over 1993–2015 (Watson et al., 2015; Nerem et al., 2018). This acceleration is mostly due to an increase in Greenland mass loss since the 2000s (Chen et al., 2017; Dieng et al., 2017) and a slight increase in all other components probably partly due to the recovery from the Pinatubo volcanic eruption in 1991 (Fasullo et al., 2016) and partly due to the increased GHG concentrations (e.g., Slangen et al., 2016).

4.2.2.3 Contributions to Global Mean Sea Level Change During the Instrumental Period

In this section, we review the estimations of the observed contributions to the GMSL rise and we assess the closure of the sea level budget. In addition, we compare observational estimates of contributions with results derived from climate model experiments of Climade Model Intercomparison Project Phase 5 (CMIP5; Taylor et al., 2012). We compare the observations with experiments beginning in the mid-19th century, forced with past time-dependent anthropogenic changes in atmospheric composition, natural forcings due to volcanic aerosols and variations in solar irradiance (Taylor et al., 2012) (the period since the mid-19th century and these simulations are referred to as 'historical'). The objective of this section is first, to assess our understanding of the causes of observed sea level changes and second, to evaluate the ability of climate models to reproduce past observed sea level changes. It enables to evaluate the confidence we have in current climate models that form the basis of future sea level projections.

4.2.2.3.1 Thermal expansion contribution

Ocean thermal expansion is a major contribution to the rate of global mean sea level rise (GMSLR), about 0.5 to 1.1 mm yr^{-1} for 1971–2010 and 0.8 to 1.4 mm yr^{-1} for 1993–2010 (Church et al., 2013; Rhein et al., 2013). It is caused by the heat taken up by the ocean as the climate is warming. The ocean heat uptake is *very likely* due to anthropogenic GHG emissions (Bindoff et al., 2013; Church et al., 2013; Rhein et al., 2013; Slangen et al., 2014b; Gleckler et al., 2016).

Thermal expansion is estimated from in situ ocean observations and also through ocean syntheses that rely on assimilation of data into numerical models EG (Storto et al., 2017). Full-depth, high-quality and unbiased ocean temperature profile data with adequate metadata and spatio-temporal coverage are required to estimate thermal expansion and to understand drivers of variability and long-term change. The global ocean observing system, however, is not ideal (Abraham et al., 2013; Good, 2017). Estimates of global thermal expansion are fundamentally limited by the availability of in situ ocean temperature measurements. While sampling of the upper 700 m is reasonable from the late 1960s, the deeper layers are only observed through a sparse network of hydrographic sections, prior to Argo observations becoming available in the early 2000. In addition several factors can introduce uncertainty (Palmer et al., 2010), such as the inhomogeneous time and space sampling of in situ measurements, the changes in measurement instrumentation, the systematic errors in measurements (in particular in expandable bathythermograph—XBT- and mechanical bathythermograph—MBT), the changes in the quality control of the data and the mapping method of the in situ records. The largest sources of uncertainty are the choice of mapping methods for estimates in the upper 700 m during the 1970s (Boyer et al., 2016) and the correction of the bias in XBT instruments (see Section 5.2.1.2 for more details).

The thermal expansion contribution estimated from observations, ranges from 24% to 42% of the GMSL rise rate for 1993–2015, depending on the XBT bias correction used. If we consider bias-corrected contributions including all recommended factors (National Centers for Environmental Information, 2017), the results lie in the upper-range (~40%). Further coordinated evaluation/refinement of mapping methodologies and XBT bias corrections (e.g., Cheng et al., 2016a; Palmer et al., 2018) will help to reduce uncertainty.

Greater agreement among estimates is found for more recent data from 2006–2007, when the array of Argo profiling floats reached its targeted near-global (60ºN to 60ºS) coverage in the upper 2000 m (Roemmich et al., 2015; Riser et al., 2016; von Schuckmann et al., 2016; Wijffels et al., 2016). For 2005–2015, the data indicates a global ocean heat gain of 0.50–0.65 W m^{-2} (with an additional 0.15 W m^{-2} due to deep ocean warming and ocean areas not sampled by Argo), equally divided between 0–500 m and 500–2000 m, with a broad maximum between 700–1400 m. Most of this decadal heat gain (75% to 98%) occurred in the Southern Hemisphere, with a zonally-averaged maximum at 40ºS (Roemmich et al., 2015; Wijffels et al., 2016), largely due a volumetric increase of subtropical mode waters (Desbruyères et al., 2017).

Since AR5, based on a full-depth 13-member ensemble global mean thermal expansion timeseries, linear rates are 1.34± 0.4 mm yr–1 for 2005–2015 and 1.36 ± 0.4 mm yr^{-1} for 1993–2015 (Cazenave et al., 2018). While the relative contribution of the upper 300 m did not change (~70%), the 700–2000 m contribution increased by 10% over the Argo decade, when observations for that depth interval soared. The linear rate for 1970–2015 is 0.89 ± 0.05 mm yr^{-1}. It is estimated from a smaller ensemble of 4 estimates in which we assume no thermal expansion below 2000m before 1993 because of lack of data. After 1993, for each estimate of the ensemble, the thermal expansion below 2000m is calculated as the mean between the thermal expansion estimate from Purkey and Johnson (2010) and the one from Desbruyères et al. (2017).

Historical GMSL rise due to thermal expansion simulated by CMIP5 models is shown in Table 4.1. For models that omit the volcanic forcing in their control experiment, the imposition of the historical volcanic forcing during the 20th century results in a spurious time mean negative forcing and a spurious persistent ocean cooling related to the control climate (Gregory, 2010; Gregory et al., 2013).

The magnitude of this effect is estimated from historical simulations forced by only natural radiative forcing, and then used to correct the historical simulations forced with the complete 20th century forcing including both the anthropogenic and natural forcing (Slangen et al., 2016; Slangen et al., 2017b). This approach is a refinement of the methodology used in AR5 where a constant correction of 0.1 mm yr^{-1} was applied to all the model results. The model spread in thermal expansion is larger than the observational uncertainties (Cheng et al., 2016b; Gleckler et al., 2016). This spread is essentially due to uncertainty in radiative forcing and uncertainty in the modelled climate sensitivity and ocean heat uptake efficiency (Melet and Meyssignac, 2015). The ensemble mean of model thermal expansion provides a good fit to the observations within the uncertainty ranges of both models and observations (Roemmich et al., 2015; Riser et al., 2016; von Schuckmann et al., 2016; Wijffels et al., 2016; Slangen et al., 2017a). The improved observed and modelled estimates of thermal expansion, the good agreement between both estimates, and the improved understanding of the spread between modelled estimates give *high confidence* in the simulated thermal expansion using climate models. It also provides *high confidence* in the ability of climate models to project future thermal expansion.

4.2.2.3.2 Ocean mass observations from GRACE

Since 2002, it is possible to estimate directly the ocean mass changes with space gravimetry data from the Gravity Recovery and Climate Experiment (GRACE) mission. The ocean mass changes correspond to the sum of land ice and terrestrial water storage changes so the direct measurement from GRACE provides an independent estimate of the sum of these contributions. Since AR5, GRACE-derived ocean mass rates show increased consistency among different estimates (Cazenave et al., 2018) because of the extended length of GRACE observations (over 15 years now), the improved understanding of data and methods for addressing GRACE limitations (e.g., noise filtering, leakage correction and low-degree spherical harmonics estimates), and the improved knowledge of geophysical corrections (e.g., GIA). Recent estimates (Dieng et al., 2015c; Reager et al., 2016; Rietbroek et al., 2016; Chambers et al., 2017; Blazquez et al., 2018) report a global ocean mass increase of 1.7 (1.4 to 2.0) mm yr^{-1} over 2003–2015. The associated uncertainty arises essentially from differences in the inversion method to compute the ocean mass (Chen et al., 2013; Jensen et al., 2013; Johnson and Chambers, 2013; Rietbroek et al., 2016), uncertainties in the geocenter motion and uncertainty in the GIA correction (Blazquez et al., 2018). The consistency between estimates of the global mean ocean mass on a monthly time scale has also increased since AR5, the biggest differences between monthly estimates being now of the order of 5 mm while the typical month to month variations are of the order of 10 mm.

4.2.2.3.3 Glaciers

To assess the mass contribution of glaciers to sea level change, global estimates are required. Recent updates and temporal extensions of estimates obtained by different methods continue to provide *very high confidence* in continuing glacier mass loss on the global scale and show increased agreement on rates of mass loss during the 20th century, compared to earlier estimates reported by Vaughan et al. (2013). Rates of early 21st century glacier mass loss on the global scale were found to be unprecedented during the observed period (Zemp et al., 2015). Here, we discuss global estimates of glacier mass change. More detailed discussions on regional estimates can be found in Section 2.2.3 concerning low and mid latitude glaciers, and in Section 3.3.2 concerning high latitude glaciers.

Updates of three long-term global time series were presented in Marzeion et al. (2015): First, an update of the compilation of Cogley (2009) which combines geodetic and direct measurements of glacier mass change resulting in slightly lowered mass loss rate estimates, particularly within the first decade of the 21st century. Second, the method of Leclercq et al. (2011) and Leclercq et al. (2014), which is based on glacier length records, was revised by including the extended glacier length database presented in Leclercq et al. (2014), and recalibrated using the mass change update of Cogley (2009) mentioned above. Third, based on forcing a glacier model with gridded climate observations, the estimate of Marzeion et al. (2012) was revised by updating the glacier inventory used for initialization (Pfeffer et al., 2014) from version 1.0 to version 4.0, and the gridded climate observations used as forcing (Harris et al., 2014) from version 3.0 to version 3.22. All these three long-term time series are now agreeing with each other, within their respective uncertainties, for their entire common periods, on the global scale. Zemp (in review) present a new global estimate of glacier mass change to sea level rise combining geodetic and in-situ observations, in order to obtain high resolution both in time and space. Their results indicate slightly higher mass loss rates of glaciers than previous estimates, particularly in the beginning of the 21st century.

Gravimetric estimates of glacier mass loss are available since 2002. Their uncertainty is mostly related to the difficulty of attributing observed mass changes to glaciers and other sources of mass change (such as regional land hydrology and Solid Earth signals) which is exacerbated by their small size relative to the resolution of the measurement and by their spatially heterogeneous distribution. The strong temporal variability of glacier mass change rates in combination with the still relatively short gravimetric time series and diverse periods of assessment complicates the comparison of the different estimates (Chen et al., 2013; Schrama et al., 2014; Dieng et al., 2015a; Reager et al., 2016; Rietbroek et al., 2016). However, these estimates tend to result in lower glacier mass change rates than those based on direct and geodetic observations, and glacier modelling. This difference might be explained by meltwater retained on land (Zhang, 2003; Haeberli and Linsbauer, 2013; Zhang et al., 2013; Neckel et al., 2014; Kääb et al., 2015; Brun et al., 2017).

Because global estimates of glacier mass change are necessary for quantifying their contribution to sea level rise, and because of the relatively high uncertainty of estimates based on gravimetry, particularly in vicinity to the ice sheets, we here rely on the results of Zemp (in review) for the second half of the 20th century, and Marzeion et al. (2015) for the entire 20th century (Table 4.1). See Sections 2.2.3 and 3.3.2 for more details.

While the agreement between observational estimates of glaciers' mass changes (in particular in the first half of the 20th century) has increased since AR5, and while historical model results (Slangen et al., 2017b) are more consistent with observational estimates, the confidence in the use of glacier models to reconstruct sea level change remains medium because of the still limited number of well-observed glaciers to validate models on long time scales, and because of the small number of model-based global glacier reconstructions.

4.2.2.3.4 Greenland and Antarctic ice sheets

Frequent observations of ice sheet mass changes have only been available since the advent of space observations. In pre-satellite era, mass balance has been geodetically reconstructed only for the Greenland ice sheet (Kjeldsen et al., 2015). This geodetic reconstruction empirically constrains Greenland ice sheet contribution to sea level rise between 1900 and 1983 to 17.2 ± 6.5 mm SLE (Kjeldsen et al., 2015). During the satellite era, three aproaches have been developped to estimate ice sheet mass balance. 1) Mass loss is estimated by direct measurements of ice sheet height changes with satellite laser or radar altimetry in combination with climatological/glaciological models for firn density and compaction. 2) The input–output method combines measurements of ice flow velocities estimated from satellite (Synthetic aperture radar or optical imagery) across key outlets with estimates of net surface balance derived from ice thickness data; 3) space gravimetry data yields direct estimate of the mass changes by inversion of the anomalies in the gravity field (see Section 4.2.2.3.2). Vaughan et al. (2013) concluded that the three space-based methods give consistent results. They agree in showing that the contribution of the Greenland and Antarctic ice sheets has increased since the early 1990s. Since AR5, up-to-date observations confirm this statement (Cazenave et al., 2018). Over 2002–2015 when all space technics are available, observations indicate a Greenland and Antarctica mass loss of 279 ± 25 Gt yr^{-1} for Greenland (including peripheral ice caps) (Bamber et al., 2018), and 148 ± 44 Gt yr^{-1} for Antarctica (The Imbie team, 2018), corresponding respectively, to a global mean sea level rise of 0.77±0.07 and 0.42±0.1 mm yr^{-1}. A significant acceleration in mass loss rate is found for Antarctica (McMillan et al., 2014) and Greenland (Enderlin, 2014; van den Broeke et al., 2016). In Greenland, where substantial interannual variability in mass balance has been common throughout the satellite record, a swing between extreme melting and accumulation events from 2012 to 2013–2014 (Tedesco et al., 2016) is consistent with large recorded mass loss followed by a temporary abatement. In Greenland, the accelerated mass loss is caused by a decrease in SMB and an increasing flow and retreat of outlet glaciers (van den Broeke et al., 2016). In contrast, Antarctica's recent increase in mass loss is not through surface melt, but is instead mostly related to the increasing flow and retreat of outlet glaciers in the Amundsen Sea region of West Antarctica (Mouginot et al., 2014; Rignot et al., 2014). Warming ocean temperatures resulting from changes in the ocean circulation are thinning ice shelves triggering a dynamic response of the grounded ice upstream (Rignot et al., 2014). In Antarctica, compared to the 0.42 ± 0.1 mm yr^{-1} value above, individual years driven by surface mass balance processes vary between -0.4 and +0.7 mm yr^{-1} (Cazenave et al., 2018). The largest uncertainty in trend estimates by GRACE is caused by the uncertainty in the GIA correction (Blazquez et al., 2018). All space techniques indicate a consistent mass loss from the Antarctic Peninsula and West Antarctica. For East Antarctica the signal is small compared to the uncertainties (The Imbie team, 2018). These recent estimates confirm that the mass loss of Antarctica accelerated over the last 10 years with respect to earlier periods (The Imbie team, 2018) (see Table 4.1).

So far, there are no climate model estimates of the 20th century ice sheet dynamics changes that are available for comparison with observations. This is different for ice sheet surface mass balance. Modeled changes in Antarctica and Greenland SMB are obtained from regional climate models or downscaled global climate models. Since AR5, global climate models are downscaled with new regional statistical techniques which account for the non-uniform distribution of SMB changes over Greenland and Antarctica (Noël et al., 2015; Favier et al., 2017; Meyssignac et al., 2017a). There are no direct observational time series of Greenland and Antarctica SMB over the 20th century, but observational estimate can be obtained using atmospheric reanalysis data to force regional climate models. The contribution of Greenland and Antarctica SMB changes to GMSL estimated from global climate model amounts is given in Table 4.1. For Greenland, the climate model based estimates agree with reanalyses-based estimates and direct observations in showing an abrupt increase in SMB contribution to GMSL since 1990 (Van Angelen et al., 2014). Before 1940 the reanalysis-based Greenland SMB estimates show a significantly larger contribution to GMSL than the climate model based estimates. As for glaciers, it is attributed to an increase in air temperatures in and around Greenland over the period 1900–1940, which led to increased melt in Greenland (Bjørk et al., 2012; Fettweis et al., 2017) and surrounding glaciers. This difference may be due to internal climate variability that is not supposed to be captured by climate models, or a bias in atmospheric circulation in climate models (Fettweis et al., 2013), or an issue with the spatial pattern of the historical aerosol forcing. For Antarctica, reanalyses-based estimates are reliable only since 1979 (Favier et al., 2017). Over 1979–2015 climate model based estimates of Antarctica SMB agree with reanalyses-based and observation based estimates showing an insignificant contribution to GMSL rise (Frezzotti et al., 2013; Wang et al., 2016; Agosta et al., 2018).

4.2.2.3.5 Contributions from water storage on land

Water is stored on land not only in the form of ice but also in the form of snow, surface water, soil moisture, and groundwater. Temporal changes in land water storage, defined as all forms of water stored on land excluding land ice, contribute to observed changes in ocean mass and thus sea level on annual to centennial timescales (Döll et al., 2016; Reager et al., 2016; Wada et al., 2017). They are caused by both climate variability and direct human interventions, at the decadal to centennial time scales. Over these time scales the main cause for land water storage changes are the groundwater depletion and impoundment of water behind dams in reservoirs (Döll et al., 2016; Wada et al., 2016). An impact of climate change on land water storage has not yet been detected. While the rate of groundwater depletion and thus its contribution to sea level rise increased during the 20th century until today (Wada et al., 2016), its effect on sea level was more than balanced by the increase in land water storage due to dam construction between 1950 and 2000 (Wada et al., 2016). Since about 2000, the combined effect of both processes is a positive contribution to sea level rise (Wada et al., 2016). Decreased water storage in lakes, wetlands and soils due to human activities are less important for ocean mass changes (Wada et al., 2016). Overall, the integrated effects of the direct human intervention on land hydrology have likely reduced land water storage during the last decade, increasing the rate of sea level rise by 0.15–0.24 mm yr^{-1} (Wada et al., 2016; Wada et al., 2017; Cazenave et al., 2018; Scanlon et al., 2018). Over periods of less than 2–3 decades, land water storage is affected strongly by climate variability (Dieng et al., 2015b; Reager et al., 2016; Dieng et al., 2017). Net land water storage change driven by both climate and direct human interventions can be determined based on GRACE observations and global hydrological modeling. They indicate different estimates of sea level rate. Over the period 2002–2014 GRACE based estimate of the net TWS change (i.e., not including glaciers) show a negative contribution to sea level of -0.33 mm yr^{-1}. Covering 60% of the global land area, Scanlon et al. (2018) identified, for the same time period, also a negative contribution of land water storage change to sea level rise based on GRACE observations, while hydrological models determined a slightly positive one. The reasons for this difference between both estimates is not elucidated. There is scientific consensus that uncertainties of both net land water storage contribution to sea level and its individual contributions remain high (Cazenave et al., 2018). The differences in estimates and the lack of multiple consistent studies give *low confidence* on the TWS contribution to the current sea level rise.

4.2.2.3.6 Budget of global mean sea level change

Drawing on previous sections, the budget of GMSL rise (Table 4.1, Figure 4.3) is assessed over different periods. As in Church et al. (2013), we assess the budget with models and observations. We consider 4 periods: 1901–1990 (which corresponds to the period in 20th century that is prior to the increase in ice-sheet contributions to GMSL rise), 1970–2015 (when ocean observations are sufficiently accurate to estimate the global ocean thermal expansion and when glacier mass balance reconstructions start), 1993–2015 (when precise satellite altimetry is available) and 2005–2015 (when Argo and GRACE data are both available in addition to satellite altimetry). The periods 1993-2015 and 2005–2015 are only 23 and 11 years long respectively and so can be affected by internal climate variability, which is not externally forced. Therefore, observations over these periods are not expected to be precisely reproduced by climate model historical experiments. This can explain part of the discrepancy between the observed and the model GMSL rise budget over this period. For the contribution from land water storage, we use the estimated effect of direct human intervention, neglecting climate-related variations until 2002. From 2002 on, we use the total land water storage estimated with GRACE. Before 2002 climate-related variation are not taken into account because of poor knowledge on the amplitude of their contribution to sea level. The few literature available points to an unsignificant contribution to sea level rise at 50 year time scales (Ngo-Duc et al., 2005). In general, historical simulations of climate models end in 2005. Historical simulations were extended to 2015 using the RCP8.5 scenario. The choice for RCP8.5 was based on availability, as most models are available for RCP8.5, and less for RCP2.6, 4.5 and 6.0. This is not critical to the modelled sea level, as the different scenarios only start to diverge significantly after the year 2030 (Church et al., 2013).

For 1993–2015 and 2005–2015, the observed GMSL rise is consistent within uncertainties with the sum of the estimated observed contributions. Over the period 1993–2015 the two largest terms are the ocean thermal expansion (accounting for 42% of the observed GMSL rise) and the glacier mass loss (accounting for a further 22%). Compared to AR5 the extended observations allow us now to identify an acceleration in the observed sea level rise over 1993–2015 and to attribute this acceleration mainly to Greenland ice loss with also a small acceleration in Antarctica ice loss (Velicogna et al., 2014; Harig and Simons, 2015; Chen et al., 2017; Dieng et al., 2017). Since 2005, land ice, collectively from glaciers and the ice sheets, is now becoming the most important contributor to GMSL rise over the thermal expansion with mountain glaciers and ice caps contributing 21% and ice sheets 34% (Cazenave et al., 2018). Over the periods 1993–2015 and 2005–2015 sea level components are also consistent within uncertainties at monthly-scales with the total observed sea level with significantly smaller uncertainties during the period 2005–2015 when Argo data have global distribution and GRACE data are available. This agreement at monthly time scales represents a significant advance since the AR5 in physical understanding of the causes of past GMSL change. It provides an improved basis for the evaluation of models. Given these elements we have *high confidence* that the current ocean observing system is capable of resolving changes in sea level and its components of >0.5 mm yr^{-1} at 10 years to longer time scales. However, despite this advance since AR5 there is still no comprehensive observations of ocean thermal expansion below 2000 m, in under-ice regions and marginal seas. The understanding of glacier mass loss can be improved at regional scale and the understanding of the land water storage contribution is still limited. Thus, for smaller changes in sea level of the order of a few tenth of mm yr^{-1} at decadal time scales we have *medium confidence* in the capability of the current observing system to resolve them.

Before 1990, observations are not sufficient to confidently estimate the ice sheet mass balance; before 1971, the space and time sampling of ocean observations are not sufficient to estimate the global ocean thermal expansion. For these reasons, it is difficult to assess the closure of the GMSL rise budget over 1901–1990 and 1971–2015 (Church et al., 2013; Gregory et al., 2013).

For the period 1970–2015, the thermal expansion of the ocean represents 43% of the observed GMSL rise while the glaciers contribution represents 25% (see Table 4.1). This results indicates a slightly smaller contribution from glaciers than reported by Church et al. (2013). If we add the Greenland ice sheet contribution and the Antarctic surface mass balance then the sum of the contributors to sea level is in agreement with the low end observed sea level rise estimates over 1971–2015 (Frederikse et al., 2018). This result suggests that the contribution of Antarctica ice sheet dynamics to sea level rise has been small, if any, before the 1990s.

Since AR5, extended simulations along with recent findings in observations and improved model estimates allow for a new more robust and more consistent and more comprehensive comparison between sea level estimates with from observations and climate models. Compared to AR5, the glacier contribution is updated with a new glacier inventory and improvements to the glacier mass balance model, which have caused a decrease in the model estimate of the 20th century glacier contribution (Marzeion et al., 2015). The Greenland SMB is estimated with a new regional SMB-component downscaling technique, which accounts for the regional variations in Greenland SMB (Noël et al., 2015). In addition, updated groundwater extraction estimates (e.g., Doell et al., 2014) were used for the land water storage contribution. They tend to be lower than the values included in AR5. This is in agreement with recent publication, showing that only 80% of the extracted groundwater reaches the ocean (Wada et al., 2016). When all the new estimated contributions are combined together, there is a gap between observations (mean of the five tide gauge reconstructions, see Section 4.2.2.2.1) and climate models before 1990. Only 50 ± 30% of the observations can be explained by climate models for the period 1901–1920 to 1970–1990 (Slangen et al., 2017b). The gap is essentially explained by a bias in modelled Greenland SMB and glacier ice loss around Greenland in the early 20th century (see Sections 4.2.2.3.3 and 4.2.2.3.4). This bias is potentially due to the internal variability of the climate system which is not expected to be in phase in climate models. When this bias is corrected, 75 ± 38% of the observed rise in sea level can be explained by climate model simulations (Slangen et al., 2017b). Compared to the individual reconstructions, the bias-corrected simulations agree best with the Dangendorf et al. (2017) and Hay et al. (2015) reconstructions, explaining 92% of the observed change in these cases.

For the more recent satellite altimetry period (from 1993–2015; Watson et al., 2015; Dieng et al., 2017), 102 ± 33% (105 ± 35% when bias corrections are included) of the observed rise in sea level is explained by the simulations (Slangen et al., 2017b). In this later period, the uncertainties in the observations are smaller as the data coverage is almost global and the resolution is higher, both spatially and temporally. Compared to AR5, the ability of climate models to reproduce the 20th century sea level changes due to thermal expansion, glacier mass loss and ice sheet surface mass balance is improved at global scale and regional scale. There is good agreement between climate models and observations at both global and regional scale since 1960 which gives confidence in climate models to project future changes of these contributions to sea level. However, before 1960, significant discrepancies between climate models and observations arise from the unability of climate models to reproduce some observed regional changes in glacier and Greenland ice sheet SMB around the southern tip of Greenland. It is not elucidated wether this bias in climate models is due to the internal variability of the climate system or if it is due to some deficiencies in climate models. Overall, the good agreement between climate models and observations of the thermal expansion, the Glacier and the ice sheet SMB contributions over the last 55 years gives *high confidence* in the ability of climate model to project the future changes in these contributions to sea level rise at multidecadal time scales.But because of a bias in climate models identified in the first part of the 20th century the confidence is *medium* for longer time scales from centennial to multicentennial time scales. Concerning the ice sheet dynamics contribution to sea level rise, observations show that it has increased compared to the AR5 estimate, but it remains relatively small up to present. This contribution remains too small and too recent to test the reliability of ice-sheet models in projecting future rapid dynamical change.

Table 4.1: Global mean sea level budget over different periods from observations and from climate model based contributions. Uncertainties are 5–95%. The climate model historical simulations end in 2005; projections for RCP8.5 are used for 2006–2015. The modelled thermal expansion, glacier and ice sheet SMB contributions are computed from the CMIP5 models as in Slangen et al. (2017b).

Source	1901–1990	1970–2015	1993–2015	2005–2015
Observed GMSL from tide gauges and Altimetry	1.53 (0.96 to 2.11)	2.06 (1.76 to 2.36)	3.07 (2.70 to 3.44)	3.5 (3.3 to 3.7)
Observed contribution to GMSL				
Thermal expansion	--	0.89 ± 0.05 [a]	1.36 ± 0.4 [a]	1.34 ± 0.4 [a]
Glaciers except in Greenland and Antarctica	0.49 ± 0.15 [b]	0.46 ± 0.55	0.63 ± 0.54	0.72 ± 0.53
Glaciers in Greenland and Antarctica	0.20 ± 0.15 [b,c]	0.06 ± 0.11 [d]	0.14 ± 0.14 [d]	0.18 ± 0.21 [d]
Greenland SMB +Ice sheet discharge	0.20 ± 0.08 [e]	--	0.52 ± 0.15 [f]	0.83 ± 0.03 [f]
Antarctica SMB +Ice sheet discharge	--	--	0.26 ± 0.26 [g]	0.49 ± 0.23 [g]
Land water storage	-0.12[h]	-0.07[h]	0.09[h]	-0.26 ± 0.1[i]
Ocean mass	--	--	--	2.3 (2.11 to 2.49)[j]
Total contributions	--	--	3.0 ± 0.75	3.3 ± 0.74
Modeled contributions to GMSL rise				
Thermal expansion	0.32 (0.04 to 0.60)	0.97 (0.45 to 1.48)	1.48 (0.86 to 2.11)	1.52 (0.96 to 2.09)
Glaciers	0.53 (0.38 to 0.68)	0.73 (0.50 to 0.95)	0.99 (0.60 to 1.38)	1.10 (0.64 to 1.56)
Greenland SMB	-0.02 (-0.05 to 0.02)	0.03 (-0.01 to 0.07)	0.08 (-0.01 to 0.16)	0.12 (-0.02 to 0.26)

Antarctic SMB	-0.02 (-0.07 to 0.03)	-0.10 (-0.23 to 0.03)	-0.14 (-0.35 to 0.06)	-0.16 (-0.40 to 0.08)
Total including land water storage and ice discharge [k]	0.69 (0.18 to 1.20)	1.78 (0.72 to 2.69)	2.99 (1.69 to 4.30)	3.38 (1.98 to 4.78)
Residual wrt to observed GMSL	0.84 (0.48 to 1.93)	0.28 (-0.93 to 1.64)	0.08 (-1.6 to 1.75)	0.12 (-1.48 to 1.72)

Notes:
(a) The number is built from the Cazenave et al. (2018) estimate of the 0–700m depth thermal expansion, assuming no trend below 2000m depth before 1992 and the mean value from Purkey and Johnson (2010), and Desbruyères et al. (2017) aftewards.
(b) The number is calculated as the mean between the estimate from a reconstruction of glacier mass balance based on glacier length (update of Leclercq et al. (2014) and the estimate from a mass balance model forced with atmospheric reanalyses (Marzeion et al., 2015). The uncertainty is assumed to be a gaussian with a standard deviation of half the difference between the two estimates.
(c) Glaciers contribution from Greenland peripheral glaciers only.
(d) The uncertainty include the temporal correlation in geodetic error.
(e) Numbers from Bamber et al. (2018).
(f) Number from Kjeldsen et al. (2015).
(g) Numbers from The Imbie team (2018).
(h) Only direct anthropogenic contribution from Wada et al. (2016).
(i) Land water storage estimated from GRACE excluding glaciers. The number is taken from Cazenave et al. (2018).
(j) Direct estimate of ocean mass from GRACE.
(k) Land water storage is estimated from Wada et al. (2016) and ice discharge is deduced from Shepherd et al. (2012).

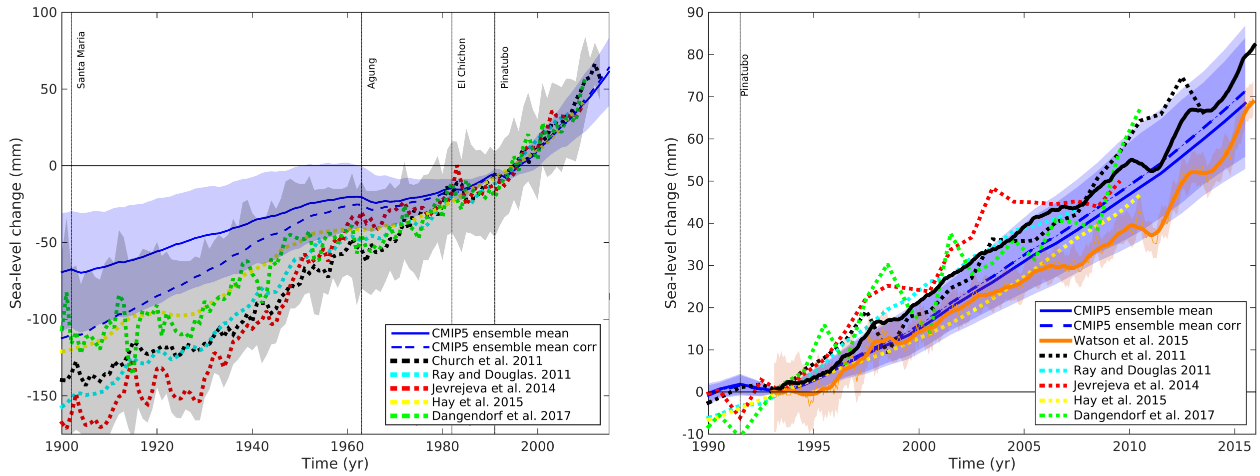


Figure 4.3: Comparison of modelled (as in Section 4.4.2.6) and observed global mean sea level change since 1900 (a) and since 1993 (b). The average estimate of 12 CMIP5 climate model simulations is shown in blue with the 5%–95% *very likely* range shaded in blue and calculated according to the procedures in Church et al. (2013). The average of the 12 model estimates corrected for the bias in glaciers mass loss and Greenland surface mass balance in the 1930s (see Section 4.2.2.3.6) is shown in dashed blue. The estimates from tide gauge reconstructions is shown in other colours in panel a), with the 5%–95% *very likely* range shaded in grey. The satellite altimetry observations corrected for the TOPEX drift (by comparison with tide gauge records, Watson et al., 2015) is shown in orange in panel b), with the 5%–95% *very likely* range shaded in orange and computed from Ablain et al. (2017). All curves in (a) represent anomalies in sea level with respect to the period 1986–2005 (i.e., with zero time-mean over the period 1986–2005) in order to be consistent with sea level projections in Section 4.2.3. All curves in (b) are anomalies with respect to the yearly mean sea level in 1993 at the start of satellite altimetry. Updated from Slangen et al. (2017b).

4.2.2.4 Regional Sea Level Changes During the Instrumental Period

The sea level does not rise uniformly. Observations from tide gauges and satellite altimetry (Figure 4.4) indicate that the sea level shows substantial regional variability at decadal to multi-decadal time scales (Carson et al., 2017; Hamlington et al., 2018). These regional changes are essentially due to changing winds, air-sea heat and freshwater fluxes and the addition of melting ice into the ocean which alter the ocean circulation (Stammer et al., 2013; Forget and Ponte, 2015; Meyssignac et al., 2017b). Ocean models, ocean reanalysis and sea level reconstructions agree in showing that the sea level patterns over the second half of the 20th century change in space and time in response to variability modes of the coupled ocean-atmosphere system such as PDO, ENSO, NAO and SAM (Frankcombe et al., 2013; Nidheesh et al., 2013; Palanisamy et al., 2015a; Carson et al., 2017; Han et al., 2017; Nidheesh et al., 2017)

In the open ocean, the spatial variability and trends in sea surface heights (SSH) observed during the recent altimetry era or reconstructed over the past decades are essentially caused by the steric sea level. In shallow shelf seas and at high latitudes (>60°N and <55°S) the effect of mass redistribution dominates over the steric effect. At regional scale the steric sea level signal is essentially due to temperature changes. The effect of salinity changes is sizeable only locally in several regions like in the Southern Ocean, in the Arctic and in North Atlantic (Forget and Ponte, 2015; Meyssignac et al., 2017b). The variability in steric sea level is mostly generated by anomalies in surface wind stress in particular in the tropics where the sea level variability and trends are the most intense over the last 25 years. The heat and freshwater fluxes from the atmosphere play also a role but of smaller amplitude and more uniformly distributed with latitudes. On global average, the heat and freshwater fluxes from the atmosphere into the ocean are responsible for the total heat that enters the ocean and for the associated global mean sea level rise. At regional scale and local scale, it is both the ocean transport divergences caused by wind stress anomalies and the spatial variability in atmospheric heat fluxes that are responsible for the spatial variability in steric sea level and thus for the regional sea level departures around the GMSL rise (Stammer et al., 2013; Forget and Ponte, 2015).

Over the Pacific, the surface wind anomalies responsible for the sea level spatio-temporal variability are associated with the ENSO, Pacific Decadal Oscillation (PDO) and North Pacific Gire Oscillation (NPGO) modes (Hamlington et al., 2013; Moon et al., 2013; Palanisamy et al., 2015b; Han et al., 2017). In the Indian ocean they are associated with the ENSO and IOD modes (Nidheesh et al., 2013; Han et al., 2014; Thompson et al., 2016; Han et al., 2017). In particular, the PDO has been shown to be responsible for most of the intensified sea level rise that has been observed in the western tropical Pacific Ocean since the 1990s (Han et al., 2014; Thompson and Merrifield, 2014; Moon et al., 2015). Several studies suggested that in addition to the PDO signal, warming of the tropical Indian and Atlantic Oceans enhanced surface easterly trade winds and thus contributes also to the intensified sea level rise in the western tropical Pacific ocean (England et al., 2014; Hamlington et al., 2014; McGregor et al., 2014).

Over the Atlantic, the regional sea level variability at interannual to multi-decadal time scales, is generated by surface wind anomalies and heat fluxes associated to the NAO (Han et al., 2017) and also by ocean heat transport due to changes in the Atlantic meridional overturning circulation (McCarthy et al., 2015). Both mecanisms are not independent as heat fluxes and wind stress anomalies associated to NAO can induced changes in the AMOC (Schloesser et al., 2014; Yeager and Danabasoglu, 2014). Along the coast, on the eastern boundary of the North Atlantic ocean, the main causes for sea level changes are longshore winds and coastal Kelvin waves (Calafat et al., 2012). In the North sea, the decadal variability in sea level is explained by the wind-driven coastally trapped waves generated in the Bay of Biscay and propagating to the North (Dangendorf et al., 2014; Frederikse et al., 2016) while the interannual variability is dominated by the local winds and the inverse barometer effect (Dangendorf et al., 2014). On the western boundary of the North Atlantic Ocean, different studies suggest different drivers of the local sea level. Some studies argue that the wind stress curl in the interior of the basin, the local wind over the shelf and the inverse barometer effect drive the coastal sea level variability (Andres et al., 2013; Thompson and Mitchum, 2014; Woodworth et al., 2014; Piecuch and Ponte, 2015; Piecuch et al., 2016), while others suggest that the AMOC and the Gulf Stream variations are the dominant drivers (Ezer, 2013; Ezer et al., 2013; Yin and Goddard, 2013). Over the Arctic, North atlantic winds and to a smaller extent inverse barometer effects drive the sea level variability (Volkov, 2014; Fukumori et al., 2015). In the Norwegian Sea coastal signals propagating from the eastern boundary of the North Atlantic also contribute (Calafat et al., 2013). In the Southern Ocean, the sea level variability is dominated by the SAM influence in particular in the Indian and Pacific sectors. The SAM influence becomes weaker equatorwards in these sections while the influence of PDO, ENSO and IOD increases (Frankcombe et al., 2015). In the southern ocean, the zonal asymmetry in westerly winds associated to the SAM, generates convergent and divergent transport in the Antarctic Circumpolar Current (ACC) which may have contributed to the regional asymmetry of decadal sea level variations during most of the twentieth century (Thompson and Merrifield, 2014).

As for GMSL, net regional sea level changes can be estimated from a combination of the various contributions to sea level change. The contributions from dynamic sea level, atmospheric loading, glacier mass changes and ice sheet SMB can be derived from CMIP5 climate model outputs either directly or through downscaling techniques (Perrette et al., 2013; Kopp et al., 2014; Slangen et al., 2014a; Bilbao et al., 2015; Carson et al., 2016; Meyssignac et al., 2017a; Meyssignac et al., 2017c). The contribution from groundwater depletion, reservoir storage and dynamic ice sheet mass changes are not simulated by climate models over the 20th century and has to be estimated from observations. The sum of all contributions including the GIA contribution, provides a modelled estimate of the 20th century net regional sea level changes which can be compared with observations from satellite altimetry and tide-gauge records (see Figure 4.4).

In terms of inter-annual to multi-decadal variability, there is a general agreement between the model regional sea level and tide gauge records, over the period 1900–2015 (see inset figures in Figure 4.4). The relatively large, short-term oscillations in observed sea level -black lines- which are due to the natural internal climate variability are comprised in general within the modeled internal variability of the climate system represented by the blue shaded area -90% CL-). But, as for GMSL, climate models tend to systematically underestimate the observed sea level trends from tide gauge records, particularly in the first half of the 20th century. This underestimation can essentially be explained by the bias in modelled Greenland SMB, and glacier ice loss around Greenland in the early 20th century (see Sections 4.2.2.3, 4.2.2.3.4 and 4.2.2.3.6). The correction of this bias improves the agreement between the spatial variability in sea level trends from observations and from climate models (see Figure 4.4.). Climate models indicate that the spatial variability in sea level trends observed by tide-gauge records over the 20th century is dominated by the GIA contribution and the steric contribution over 1900–2015. Locally all contributions to sea level changes are important as any contribution can cause significant local deviations; Around India for example, the groundwater depletion is responsible for the low 20th century sea level rise (because of the associated local decrease in geoid).

These results show the ability of models to reproduce the major 20th century regional sea level changes due to GIA, thermal expansion, glacier mass loss and ice sheet surface mass balance. This is a tangible progress since AR5. But some doubts remain on the ability of climate models to reproduce local variations like for the glaciers and the Greenland SMB contribution to sea level in the region around the southern tip of Greenland or the thermal expansion at the coast on the shelves. Because of these elements there is still *medium confidence* in climate models to project future regional sea level changes associated with thermal expansion, glacier mass loss and ice sheet surface mass balance. The other contributions to 20th century sea level, including the growing ice sheet dynamics contribution and land water storage changes, have not been simulated so far by climate models. Thus, the ability of models to reproduce associated observed past changes has not been fully tested so far.

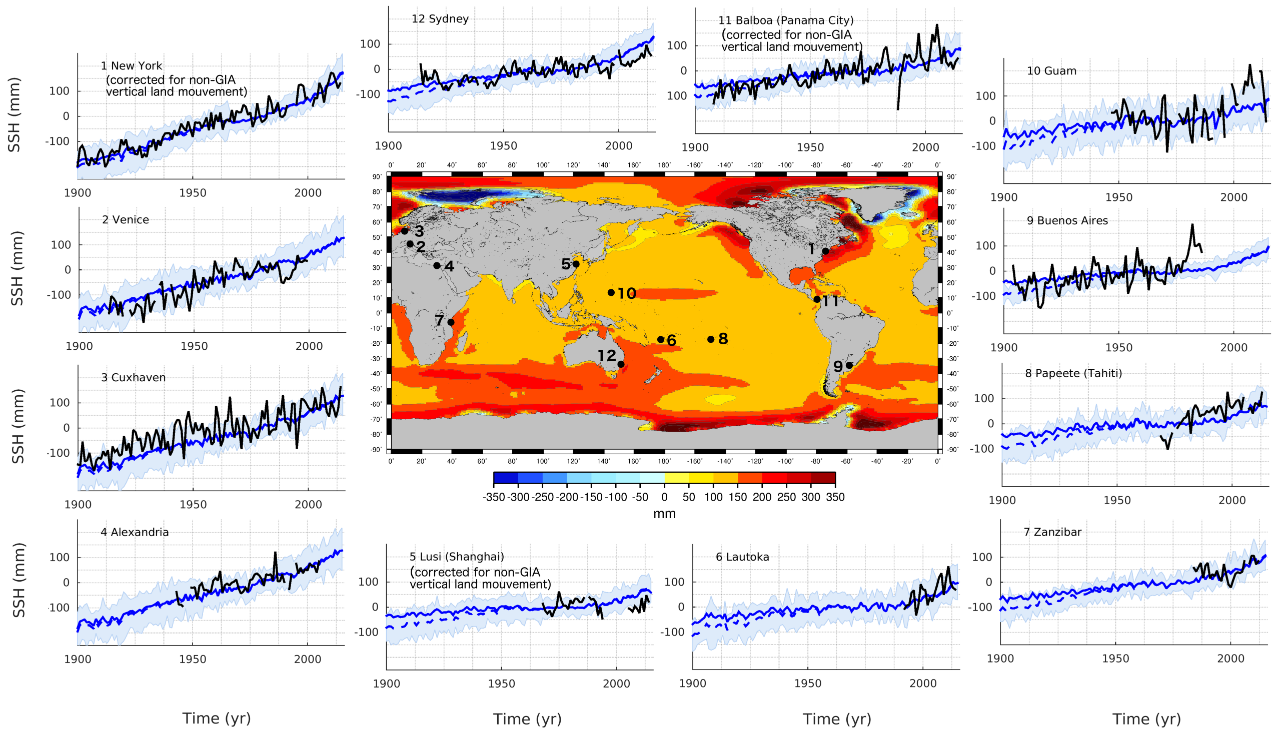


Figure 4.4: Map of rates of change in modelled relative sea level for the period 1901–1920 to 1996–2015 from climate model inputs. Also shown are relative sea level changes (black lines) from selected tide gauge stations for the period 1900–2015. For comparison, the estimate of the modelled relative sea level change at the tide gauge station from climate models is also shown (blue plain line for the model estimates and blue dashed line for the bias corrected model estimates, see Section 4.2.2.3.6) with each tide gauge time series. The relatively large, short-term oscillations in local sea level (black lines) are due to the natural internal climate variability. Tide gauge records have been corrected for vertical land motion not associated with GIA where available: i.e., for New York, Balboa and Lusi (Meyssignac et al., 2017a; Meyssignac et al., 2017c).

4.2.2.5 Local Coastal Sea Level

Since the local coastal sea level is affected by global, regional and coastal scale features and processes, it may differ substantially from the global average. At the coast, the sea level change is additionally affected by wave run up, tidal level, wind forcing, sea level pressure (SLP), the dominant modes of climate variability (Section 4.2.3.5), seasonal climatic periodicities, mesoscale eddies, changes in river flow, tectonics and subsidence. These local contributions, combined with extreme events that generate storm surges, primarily due to tropical and extratropical storms, result in anomalous conditions termed extreme sea level (ESL). Flood risk due to ESL is exacerbated due to its interaction with relative sea level (RSL) changes, and hence vulnerability assessments may combine uncertainties around ESL and RSL, both in terms of contemporary assessments and future projections EG (Little et al., 2015b; Vousdoukas, 2016; Vousdoukas et al., 2016; Wahl et al., 2017). Changes in mean sea level have been dealt with in previous sections (e.g., Section 4.2.2.3.6). Here we focus on some of the components of ESL that have been assessed in combination with changes in RSL. Church et al. (2013) concluded that change in sea level extremes is *very likely* to be caused by a RSL increase, and that storminess and surges will contribute towards these extremes; however, it was noted that there was *low confidence* in region-specific projections.

Recent advances in statistical and dynamical modelling of wave effects at the coast (wave run up), storm surges, and inundation risk have reduced the uncertainties around the inundation risks at the coast Vousdoukas et al. (2016) and assessments of the resulting highly resolved coastal sea levels are now emerging (Cid et al., 2017; Muis et al., 2017; Wahl et al., 2017). This progress was facilitated due to the availability of, for example, the Global Extreme Sea Level Analysis (GELSA-2; Woodworth et al., 2016) high-frequency dataset, advances in Coordinated Ocean Wave Climate Project (COWCLIP; Hemer et al., 2013), coastal altimetry datasets (Cipollini et al., 2017), and the Global Tide and Surge Reanalysis (GTSR) (Muis et al., 2016), while new analyses of datasets have been available since before the publication of AR5 have continued (e.g., PSML; Holgate et al., 2012)

A general approach to reanalysis and projection entails coupling statistically-generated spectra of the local contributions to the components of ESL with dynamically downscaled high-resolution general circulation models (GCMs; Hemer and Trenham, 2016). Hemer and Trenham (2016) noted that wave models forced by GCMs need to be assessed for their skill in simulating historical conditions in order to determine the sources of variation between the various approaches.

Although ESL is experienced episodically by definition, Marcos et al. (2015) examined the long-term behavior of storm surge using state space models and detected decadal and multidecadal variations in storm surge that are not related to changes in RSL. They found that, although 82% of their observed time series showed synchronous patterns at regional scales, the pattern tended to be non-linear, implying that it would be difficult to infer future behaviour unless the physical basis for the responses is understood. An analysis of the relative contributions of SLR and ESL due to storminess showed that in the US Pacific North West, increases in wave height and period have had a larger effect on coastal flooding and erosion than RSL (Ruggiero, 2012) since the early 1980s. This is also true in other regions distributed over the entire globe (Melet et al., 2016; Melet et al., 2018). Changes in the sea level harmonics and seasonal phases and amplitudes of the wave period and significant wave height were found for the Gulf of Mexico coast since 1990 (Wahl et al., 2014; Wahl and Plant, 2015). They found that lower winter and higher summer sea levels have led to almost a doubling in high water levels caused by SLR, and that the trends in the wave parameters have contributed towards an approximately 30% increase in risk of flooding. Such effects are *likely* to be highly dependent on the local conditions. For example, using WAVEWATCH III, TOPEX/Poseidon altimetry tide model data and atmospheric forcing physically downscaled using Delft3D-WAVE and Delft3D-FLOW in what they call the Coastal Storm Modeling System (CoSMoS), Vitousek et al. (2017) was able to detect local hazards (at a scale of hundreds of meters) across regions along the Californian coast. Hoeke et al. (2015) showed using statistical approaches that ESL may vary by up to 1 m, over distances of less than 1 km, due to the storm track of tropical cyclones interacting with local coastal morphological properties. The addition of a 1 m RSL caused ESL to 'modestly' decrease, whilst resulting in the increase of wave energy impacting the coast. The finding of Hoeke et al. (2015) is typical for high oceanic islands with a narrow littoral zone that are common in the tropics and subtropics in the Indian, Atlantic and Pacific Oceans; the failure to include wave setup when modeling inundation risk faced by such islands may lead to a significant underestimation of ESL (Hoeke et al., 2013). A study for the Maldives shows that the contribution of wave set-up is essential to estimate flood risks (Wadey et al., 2017).

A general pattern that emerges from ESL estimates at global and regional scales is that the direction of the trend in wave projections can be reasonably well modelled, but that projections of the magnitude of change are less reliable EG (Grabemann et al., 2015; Cid et al., 2017; Muis et al., 2017). Wahl et al. (2017) showed that for long return period events, the average combined global uncertainties around present-day ESL estimates are larger than the GMSL projection uncertainties, and at least as large as the GSML projections.

In deltas, the local sea level can be dominated by subsidence more than by above processes. Whereby subsidence in this context includes both a long-term isostatic adjustment from the weight of overlying sediments and more recent compaction (both natural and anthropogenically forced). It is often a primary driver of elevated local sea level rise and increased flood hazards in those regions. This is particularly true for deltaic systems, where fertile soils, low-relief topography, freshwater access, and strategic ports have encouraged the development of many of the world's most densely populated coastlines and urban centers. It is estimated, for example, that globally one in fourteen humans resides in mid-to-low latitude deltas (Day et al., 2016). Although in these areas RSL is dominated by subsidence, climate effects need to be included for estimating risks (Syvitski et al., 2009).

Deltas are formed by the accumulation of unconsolidated river born sediments and porous organic material, both of which are particularly prone to compaction. It is the compaction which causes a drop in land elevation (i.e., subsidence) that increases the rate of local sea level rise above what would be observed along a static coastline or one where only climatological forced processes control the relative sea level. Under stable deltaic conditions, the accumulation of fluvially-sourced surficial sediment and organic matter offsets this subsidence (Syvitski and Saito, 2007); however, in many cases this natural process of delta construction has been disturbed by reductions in fluvial sediment supply via upstream dams and fluvial channelization (Vörösmarty et al., 2003; Syvitski and Saito, 2007; Syvitski et al., 2009; Luo et al., 2017). Further, the extraction of groundwater, oil, and gas that fill the pore space of deltaic sediments and provide support for overlying material has significantly increased the rate of compaction and resultant subsidence along many populated deltas (Higgins, 2016). In addition, Nicholls (2011) pointed to subsidence by the weight of buildings in megacities in South-East Asia.

Average subsidence rates of 6–9 mm yr^{-1} are reported for the highly populated areas of Ganges-Brahmaputra-Meghna delta in the urban centers of Kolkata and Dhaka (Brown and Nicholls, 2015). A fraction of this might be caused by long-term processes of increased sediment loading during the Holocene resulting from changes in the monsoon system (Karpytchev et al., 2018). These rates will *likely* decrease in the Ganges-Brahmaputra-Meghna delta in the near future due to planned dam projects and an estimated 21% drop in resulting sediment supply (Tessler et al., 2018). Observations of enhanced subsidence on the Ganges-Brahmaputra-Meghna are common to most heavily populated deltaic systems. Coastal Mega-cities that have been particularly prone to human-enhanced subsidence include Bangkok, Ho Chi Minh city (Vachaud et al., 2018), Jakarta, Manila, New Orleans, West Netherlands and Shanghai (Yin et al., 2013; Cheng et al., 2018). On a global scale, observed average rates of modern deltaic subsidence range from 6–100 mm yr^{-1} (Bucx et al., 2015; Higgins, 2016). Rates of recent deltaic subsidence over the last few decades have been at least twice the 3 mm yr^{-1} rate of global mean sea level rise observed over this same interval (Higgins, 2016; Tessler et al., 2018). Numerical models that have reproduced these observed rates of deltaic subsidence by considering human-induced compaction and reduced sediment supply, support anthropogenic causes for elevated rates of subsidence (Tessler et al., 2018).

In summary, ESL and subsidence interacts with RSL change in various ways in many vulnerable areas. Therefore, we conclude with *high confidence* that the inclusion of the local processes (wave run up, storm surges, tides, erosion, sedimentation and compaction) is essential to estimate local, relative and extreme sea level changes, as in some cases they dominate the large-scale sea level rise patterns. Although erosion, sedimentation and compaction may be very large locally, they are not accounted for in the projection sections of this chapter as no global data sets are available which are consistent with RCP scenarios and the scale is often smaller than those applied in climate models.

4.2.2.6 Detection and Attribution

Here, we define detection and attribution following the terminology of Hegerl et al. (2010). A change in an observed variable (e.g., sea level rise) is detected, if it is demonstrated that the likelihood of such a change occurring by chance, due to internal variability, is small. Attribution is the process of quantifying the evidence for a causal link between a specific external forcing—such as solar variability, volcanic eruptions, or anthropogenic changes to the atmospheric composition—and an observed change in the climate system (Hegerl et al., 2010). Attribution studies can only succeed if there is understanding of the physical processes involved in translating an externalforcing into observable changes in the climate system, if an adequate representation of these processes and resulting forced change and natural variability is possible in numerical models, and if adequate observations of the investigated change of the climate system are available.

Bindoff et al. (2013) concluded that it is *very likely* that there has been a substantial contribution to ocean heat content from anthropogenic forcing since the 1970s, that it is *likely* that loss of land ice is partly caused by anthropogenic forcing, and that subsequently, it is *very likely* that there is an anthropogenic contribution to the observed trend in global mean sea level rise since 1970. However, these conclusions were based on the understanding of the responsible physical processes, instead of attribution studies dedicated to quantifying the effect of individual external forcings. Since AR5, such formal studies have attributed changes in individual contributions of sea level change (i.e., thermosteric sea level change and glacier mass loss), and in the total global mean sea level, to anthropogenic forcing.

4.2.2.6.1 Attribution of individual contributions of sea level change to anthropogenic forcing

Marcos and Amores (2014) compared observed thermosteric sea level rise in the upper 700 m of the ocean during the period 1950–2005 with CMIP5 model reconstructions, using 'natural-only' forcing (i.e., solar and volcanic variability) and 'historical' forcing (i.e., additionally including anthropogenic greenhouse gases, aerosols, and land-use change). They found that during the period 1970–2005, 87% (95% confidence interval: 72%–100%) of the observed thermosteric sea level rise is anthropogenic. Slangen et al. (2014c) included the full ocean depth in their analysis and quantified the effect of individual external forcings, by considering ‘anthropogenic-only’, ‘greenhouse gas-only’ and ‘anthropogenic aerosol-only’ CMIP5 reconstructions additionally to the ‘natural-only’ and ‘historical’ forcing CMIP5 reconstructions. They concluded that a combination of anthropogenic and natural forcing is necessary to explain the temporal evolution of observed global mean thermosteric sea level change during the period 1957 to 2005. Anthropogenic forcing was found to be responsible for the amplitude of observed thermosteric sea level change, while natural forcing was found to cause the forced variability of observations. Observations could best be reproduced by scaling the patterns from ‘natural-only’ forcing experiments by using a factor of 0.70 ± 0.30 (2 standard deviations of the CMIP5 ensemble subset used), indicating a potential overestimation of forced variability in the CMIP5 ensemble. Patterns from the anthropogenic-only’ forcing experiments needed to be scaled by a factor of 1.08 ± 0.13 (2 standard deviations of the CMIP5 ensemble subset used), indicating a realistic response of the CMIP5 ensemble to anthropogenic forcing.

Taking an approach similar to that of Marcos and Amores (2014), Marzeion et al. (2014) compared globally observed glacier mass change to results from a global glacier model forced by ‘natural-only’ and ‘historical’ reconstruction from the CMIP5 ensemble. They concluded that while natural climate forcing and long-term adjustment of the glaciers from the preceding Little Ice Age leads to continuous glacier mass loss throughout the simulation period of 1851–2010, the observed rates of glacier mass loss since 1990 can only be explained by including anthropogenic forcing. During the period 1851 to 2010, only 25 ± 35% of global glacier mass loss can be attributed to anthropogenic forcing, but since the anthropogenic fraction of mass loss is found to increase throughout the considered period, 69 ± 24% of the mass loss is attributed to anthropogenic forcing during the period 1991–2010. Uncertainties are large as glaciers are relatively small and therefore their climate conditions are poorly resolved in climate models (see Section 2.2.3.2 for a more detailed discussion of attribution of glacier mass change on regional scales).

For ice sheet mass loss, no attempts have been made to attribute changes as time series are short with respect to the time scale of ice sheets, and our physical understanding of ice dynamics is still too limited. However, Fyke et al. (2014) suggest that the anthropogenic signal will emerge in the surface mass balance of Greenland within the first half of the 21st century (increased melt in the periphery, and increased accumulation in the center).

The effects of groundwater depletion and reservoir impoundment on sea level change are anthropogenic by definition (e.g., Wada et al., 2012).

4.2.2.6.2 Detection and attribution of global mean sea level change

By estimating a probabilistic upper range of long-term persistent natural sea level variability, Dangendorf et al. (2015) detected a fraction of observed sea level change that is unexplained by natural variability and concluded by inference that it is *virtually certain* that at least 45% of the observed increase in global mean sea level since 1900 is attributable to anthropogenic forcing. Similarly, Becker et al. (2014) provided statistical evidence that the observed sea level trend, both in the global mean and at selected tide gauge locations, is not consistent with unforced, internal variability. They inferred that more than half of the observed global mean sea level trend during the 20th century is attributable to anthropogenic forcing.

Using a semi-empirical model relating rates of sea level change to global mean temperature anomalies, Kopp et al. (2016) concluded that it is *extremely likely* that at least 41% of the observed global mean sea level rise during the 20th century is attributable to 20th century warming, and that it is extremely likely that global mean sea level exceeded natural variability by 1970.

Slangen et al. (2016) reconstructed global mean sea level from 1900 to 2005 based on CMIP5 model simulations separating individual components of radiative climate forcing and combining the contributions of thermosteric sea level change with glacier and ice sheet mass loss. They found that the naturally caused sea level change, including the long-term adjustment of sea level to climate change preceding 1900, caused 67 ± 23% of observed change from 1900 to 1950, but only 9 ± 18% between 1970 and 2005. Anthropogenic forcing was found to have caused 15 ± 55% of observed sea level change during 1900–1950, but 69 ± 31% during 1970 to 2005. The sum of all contributions explains only 74 ± 22% of observed global mean sea level change during the period 1900–2005 considering the mean of the reconstructions of Church and White (2011), Ray and Douglas (2011), Jevrejeva et al. (2014) and Hay et al. (2015). However, the budget could be closed taking into contribution of glaciers that are missing from the global glacier inventory or have already melted (Parkes and Marzeion, in press).

Based on these multiple lines of evidence, we conclude with *high confidence* that anthropogenic forcing *very likely* is the dominant cause of observed global mean sea level rise since 1970.

4.2.2.6.3 Regional detection, local emergence of an anthropogenic signal

Since sea level variability is larger at the regional scale than at the global scale, attribution of observed regional sea level change to specific climate forcings is more challenging. For example, Palanisamy et al. (2015a) show explicitly that the anthropogenic fingerprint of sea level rise predicted by CMIP5 models for the Pacific Ocean is too small compared to the level of internal variability to be detected in altimetric observations in the considered region, which is mostly affected by the Pacific Decadal Oscillation. In several regions climate models are not able to reproduce the unforced and forced signal in sea level. Sérazin et al. (2016) show limitations for western boundary currents and Bilbao et al. (2015) discuss shortcomings in the Pacific Ocean.

In a related approach, a number of studies have addressed the observation period necessary to locally detect an anthropogenic signal in sea level rise. Lyu et al. (2014) concluded that relative to the reference period 1986 to 2005, the anthropogenic signal in sea level change will be detectable in 50% of the ocean area by 2020. Similarly, Richter and Marzeion (2014) concluded that relative to 1990, the forced signal will become detectable by 2020 locally in ocean areas with low internal variability of sea level, such as the tropical Atlantic Ocean. In this region, also Bilbao et al. (2015) predict the earliest detectability of an anthropogenic trend. Jordà (2014) showed that the time needed for local detection of a centennial linear trend of 2 mm yr^{-1} is on average 40 years. Richter et al. (2017) showed that the glacier contribution increases the detectability of sea level change away from the locations of ice mass loss, and that spatial smoothing on a scale of 2000 km leads to detectability of an anthropogenic signal in 93% of the ocean area when considering the period 1970–2015.

We conclude with *medium confidence* that an attribution of observed regional and local mean sea level change to anthropogenic forcing cannot yet be achieved for most of the ocean.

4.2.2.6.4 Attribution of sea level extremes to anthropogenic forcing

While there is a strong relation between the frequency of occurrence of sea level extremes and the local mean sea level (see Section 4.2.3.4), the conventional approach of attribution to external climate forcing is not applicable to individual extreme events, which are unique by definition and whose occurrence is strongly influenced by chance (e.g., Trenberth et al., 2015; see Section 4.2.3.4 on a discussion of extreme events). However, it is possible to quantify the evidence that anthropogenic climate change has altered the probability of a type of event occurring (e.g., Trenberth et al., 2015; Otto et al., 2016; Stott, 2016). For example, Takayabu et al. (2015) find evidence that the storm surge of Typhoon Hayan was intensified through anthropogenic influence. They find that removing the anthropogenic warming signal of the sea surface and the atmosphere would lead to a decrease in simulated wind speeds and an increase in simulated core pressure in 15 out of 16 ensemble members, increasing the differences between simulated and observed values. Removing the anthropogenic signal further leads to a mean decrease of the storm surge height of around 20%.

4.2.3 Projections of Sea Level Change

As a consequence of climate change, the global and regional mean sea level will change. AOGCM are used to make projections of the climate changes and the associated sea level rise. AOGCMs can be applied on century time scales, to provide estimates of the steric (temperature and salinity effects on sea water density) and ocean dynamical (ocean circulation) components of sea level change, both globally and regionally. However, the glacier and ice sheet component are calculated off-line based on AOGCM climatologies. GCMs also resolve climate variability related to changes in precipitation and evaporation, which is relevant for changes in the hydrological cycle which play a role in shorter duration sea level changes (Cazenave and Cozannet, 2014; Hamlington et al., 2017). With various degrees of success those models capture El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO) and other modes of variability which affect sea level through redistributions of energy and salt in the ocean. Results from the CMIP5 AOGCM archive produced for AR5 are used to provide information on expected changes in the oceans and on the evolution of climate glaciers and ice sheets. New estimates from CMIP6 are not yet available and will be discussed in AR6. These models do not (yet) explicitly calculate changes in ice mass, partly because of the small scales necessary to resolve ice sheet processes properly, and partly because the relevant physical processes are poorly understood. Typically, ice sheet and glacier changes are calculated based on the relevant variables of ocean and atmospheric temperature and precipitation. These off-line climatologies can be dynamically or statistically downscaled to match the high spatial resolution required for ice sheets and glaciers, but serious limitations remain. Notably lacking is the interactive coupling between the land ice, ocean, and atmospheric components in most models. This deficiency limits adequate representation of potentially important feedbacks between changes in ice sheet geometry and climate, for example through fresh water and iceberg production impacting on ocean circulation and sea ice, which can have global consequences (Lenaerts et al., 2016; Donat-Magnin et al., 2017). Dynamics of the interaction of ice streams with bedrock and till at the ice base remains difficult to model due to lack of direct observations Nevertheless, several new ice sheet models have been generated over the last few years, particularly for Antarctica (Section 4.2.3.1) focusing on the dynamic contribution of the ice sheet to sea level change, which remains the key uncertainty in future projections (Church et al., 2013), particularly beyond 2050 (Kopp et al., 2014; Nauels et al., 2017b; Slangen et al., 2017b; Horton et al., In Press).

Information beyond that provided by climate models is needed to describe local and relative sea level changes. Geodynamic models are used to calculate relative sea level changes due to mass changes in past and future. This includes both short-term Earth gravitational and rotational changes, as ice and water are redistributed around the globe, and long-term glacial isostatic adjustment (GIA). Input for those models are provided by the mass changes following from the off-line ice models, time series of terrestrial water mass changes which typically require climate input, and reconstruction of past ice sheet changes over the last glacial cycle. Combining different models leads to projections of RSL (Section 4.2.3.2).

At the local spatial scales of specific cities, islands, and stretches of coastlines, hydrodynamical models (Section 4.2.3.3) and knowledge on sedimentation and erosion are necessary to analyse the impacts of highly variable processes leading to ESL, such as tropical cyclone-driven storm surges. These hydrodynamical models are capable of providing statistics on the variability or the change in variability of the water level required for flood risk calculations at specific locations and at spatial scales of less than 1 km. The models also rely on input from climate models, like temperature, precipitation, wind regime, and storm tracks (Colbert et al., 2013; Garner et al., 2017).

In summary, climate models play an important role at the various stages of projections in providing, togetherwith emission scearios, geodynamic, ice-dynamic, and hydrodynamic models, the required information for hazard estimation for coasts and low-lying islands. In this report we rely on results of the CMIP5 model runs.

Besides this sequence of sections leading to projections of ESL, we address the uncertainties and decadal predictability of sea level (Section 4.2.3.4) and the long-term scenarios, beyond 2100 (Section 4.2.3.5).

4.2.3.1 Dynamic Contribution of Ice Sheets

4.2.3.1.1 Greenland

The Greenland Ice Sheet (GIS) is currently losing mass at roughly twice the pace of the Antarctic Ice Sheet (see Chapter 3 and Table 4.1). About 60% of the mass loss between 1991 and 2015 has been attributed to increasingly negative surface mass balance (SMB) from surface melt and runoff on the lower elevations of the ice-sheet margin. Ice dynamical changes account for the remaining 40% of mass loss (Csatho et al., 2014; Enderlin, 2014; van den Broeke et al., 2016). The ability of firn on Greenland to retain meltwater until it refreezes has diminished markedly since the late 1990s. These changes in firn have increased rates of runoff more than rates of meltwater production, especially in lower elevations (Noël et al., 2015). Recent reductions in ice velocity in western Greenland have been linked with increases in meltwater and changes in the basal hydrologic regime, but on decadal time scales the relationship between meltwater and ice dynamics seems not important (van de Wal et al., 2015), which is confirmed by ice sheet model experiments (Shannon et al., 2013). The future evolution of meltwater-buffering by firn, coarse ice-sheet model spatial resolution, and complex processes linking surface, englacial, and basal hydrology with ice dynamics provide ongoing challenges for ice sheet models and their predictions (Goelzer et al., 2013; Stevens et al., 2016; Noël et al., 2017). However, recent ice sheet modelling since AR5 (Edwards et al., 2014; Fürst et al., 2015; Vizcaino et al., 2015) indicates that increasing surface melt will continue to dominate Greenland's contribution to GMSL throughout the 21st century, regardless of which emissions scenario is followed (*medium confidence*).

Fürst et al. (2015) used ten different CMIP5 AOGCM simulations to provide offline SMB and ocean forcing for a Greenland-wide ice sheet model, accounting for influences of warming subsurface ocean temperatures and basal lubrication on ice dynamics. In their RCP8.5 ensemble, they found a GIS contribution to GMSL in 2100 of 10.15 cm ± 3.24 cm. This wide range of RCP8.5 results highlights substantial climate-driven uncertainty in 21st century GIS projections, as found in other studies (Edwards et al., 2014). The median estimates of Fürst et al. (2015) are in good agreement with previous multi-model results (Bindschadler et al., 2013) and the assessment of AR5 (Church et al., 2013), which reported a *likely* RCP8.5 range of Greenland's contribution to GMSL between 7 cm and 21 cm by 2100.

Nick et al. (2013) used detailed flowline models of four Greenland outlet glaciers (Petermann, Kangerdlugssuaq, Jakobshavn Isbræ, and Helheim) to estimate a dynamical contribution to sea level in an RCP8.5 scenario of 11.3–17.5 mm by 2100, and 29–49 mm, by 2200. However, their study did not include the Northeast Greenland Ice Stream (NEGIS), which has recently been reported to be a potentially important contributor to future sea level (Khan et al., 2014). In their Greenland-wide model, Fürst et al. (2015) found an overall reduction in the rate of dynamic ice discharge to the ocean. This response, caused by ongoing thinning of the ice sheet margin and landward retreat of outlet glaciers away from the coast suggests Greenland's potential for a rapid, dynamic contribution to sea level may be limited, as found in other ice-modelling studies (Goelzer et al., 2013; Lipscomb et al., 2013; Vizcaino et al., 2015). One reason for this is the limited direct access of the interior ice sheet to the ocean. Figure 4.5 illustrates a fundamental geometrical difference between Greenland and Antarctica. In Greenland, most of the bedrock at the ice-sheet margin is above sea level. The opposite condition exists in Antarctica and in places where the subglacial bedrock slopes downward, away from the coast (reverse-sloped), the glacial ice is susceptible to dynamical instabilities that can contribute rapid ice loss to the ocean (see Cross-Chapter Box 3 in Chapter 1).

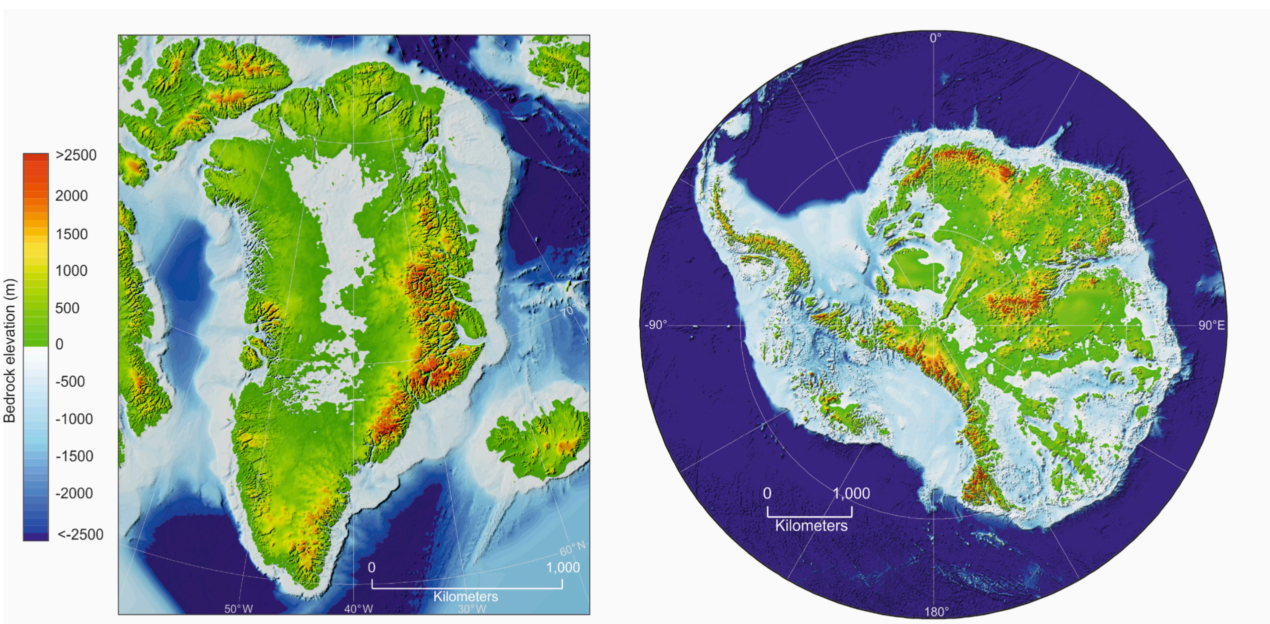


Figure 4.5: Bedrock topography below the existing ice sheets in Greenland (left) and Antarctica (right; Fretwell et al., 2013; Morlighem et al., 2017). Horizontal scales are not the same in both panels. Note the deep subglacial basins in West Antarctica and the East Antarctic margin. The ice above floatation in these areas is equivalent to >20m of GMSL.

Recent subglacial mapping since AR5 has uncovered extensive, deep valley networks extending into the GIS interior (Morlighem et al., 2014; Morlighem et al., 2017). These new data show that the termini of many marine-terminating outlet glaciers are deeper than previously known and may be more exposed to warm subsurface Atlantic Water than previously considered. While detailed and accurate subglacial topography has been shown to be important in the modeling of individual Greenland outlet glaciers (Aschwanden et al., 2016), the potential for these newly revised bedrock boundary conditions to substantially change the outcome of Greenland-wide model simulations is not yet known.

In summary, new modelling since AR5 (Fürst et al., 2015; Vizcaino et al., 2015) builds on previous studies suggesting future Greenland ice loss will be dominated by surface processes, rather than dynamic ice discharge to the ocean (*medium confidence*). Based on these modeling studies, GIS is not expected to contribute more than 20 cm of GMSL rise by 2100 in a RCP8.5 scenario, similar to the upper end of the *likely* range reported by AR5 (Church et al., 2013). Confidence in the projections will remain low until the dynamical implications of newly discovered subglacial topographic features and bathymetric details at the ice margin (Morlighem et al., 2017) are more thoroughly tested. Greenland ice-sheet simulations are sensitive to uncertainties in the applied climate forcing (Edwards et al., 2014), but updated climate projections since AR5 are not yet available. Because of the consistency of recent modeling studies with the assessment of Church et al. (2013), we use Greenland's contribution to future sea level reported in AR5 in our projections of GMSL.

4.2.3.1.2 Antarctica

The Antarctic Ice Sheet (AIS) contains almost eight times more glacial ice above flotation (grounded ice above sea level that causes sea-level rise if lost to the ocean) than Greenland. One third of the ice sheet sits on bedrock hundreds of meters (or more) below sea level (Fretwell et al., 2013) and most of its margin is in direct contact with the ocean (Figure 4.5). These geographic features make the overlying ice sheet vulnerable to dynamical instabilities that can cause rapid ice loss (Weertman, 1974; Schoof, 2007; Pollard et al., 2015). Changes in the surrounding ocean affecting sub-ice oceanic melt rates, and changes in the overlying atmosphere affecting surface mass balance and surface meltwater production can trigger these instabilities, but the timing, magnitude, and potential pace of future retreat remains deeply uncertain.

In contrast to Greenland, Antarctica's recent contribution to sea-level rise (Nerem et al., 2018; The Imbie team, 2018) has been dominated by ice-dynamical processes rather than changes in surface mass balance (Helm et al., 2014; Mouginot et al., 2014; Rignot et al., 2014; Velicogna et al., 2014; Williams et al., 2014; Li et al., 2015; Khazendar et al., 2016; Martín-Español et al., 2016; Scheuchl et al., 2016; Martin-Español et al., 2017; Seroussi et al., 2017). Since AR5, it has become increasingly evident that ice loss in this region is being driven by sub-ice oceanic melt (thinning) of ice shelves (Paolo et al., 2015; Wouters et al., 2015; Khazendar et al., 2016) and the resulting loss of back stress (buttressing) that impedes the seaward flow of grounded ice upstream. Whether observed increases in sub-ice ocean melt is anthropogenically influenced or part of the natural regional variability in ocean circulation is unclear (Jenkins et al., 2018).

Where grounding lines are poised on reverse-sloped (retrograde) bedrock, the initial thinning of a marine terminating ice margin (possibly initiated by the thinning or loss of buttressing ice shelves) can trigger a so called 'Marine Ice Sheet Instability' (MISI) caused by the non-linear relationship between sea ward ice flux and ice thickness at the grounding line (Weertman, 1974). MISI was described extensively in AR5 (see Cross-Chapter Box 2 in Chapter 1).

A number of ice-sheet modeling studies since AR5 have focused on the potential response of WAIS to increasing sub-ice shelf and grounding zone melt rates (Cornford et al., 2015; Feldmann and Levermann, 2015; Arthern and Williams, 2017). The WAIS interior rests on bedrock hundreds to thousands of meters below sea level (Figure 4.5) and several of its major outlet glaciers, including the 120-km wide Thwaites Glacier in the Amundsen Sea (Rignot et al., 2014), have grounding lines currently retreating on retrograde bedrock, making them potentially vulnerable to the onset of MISI (Figure 4.6). Sub-ice melt rates are highly sensitive to ocean temperature, water depth, boundary layer and turbulent processes at the ice-ocean interface, as well as the small scale details of the ice-ocean interface and ice shelf cavity geometry (Jenkins, 1991; Holland et al., 2008; Dinniman et al., 2016). Previous continental-scale ice sheet modelling studies (e.g., DeConto and Pollard, 2016) have used relatively simple parameterizations of sub-ice melt, based on time-evolving temperatures from atmosphere-ocean GCM simulations to calculate melt rates under ice shelves. This approach lacks two-way interactions between the ocean and ice sheet. Seroussi et al. (2017) found that parameterizations of oceanic sub-ice melt lacking two-way interaction between a retreating ice margin and the surrounding ocean can overestimate melt rates in time-evolving simulations of marine based glacier retreat. Since AR5, progress has been made to interactively couple dynamical ice and ocean models

(Schodlok et al., 2016; Asay-Davis et al., 2017; Goldberg et al., 2018). However, explicit representation of the relevant processes requires high spatial resolution that remains computationally infeasible at the continental scale. More efficient methods have recently been developed to link standard-resolution ocean models to realistic ice-shelf cavities, using parameterizations of buoyancy plume processes and convection (Lazeroms et al., 2018; Reese et al., 2018). These methods are promising, but have yet to be applied to long-term future simulations.

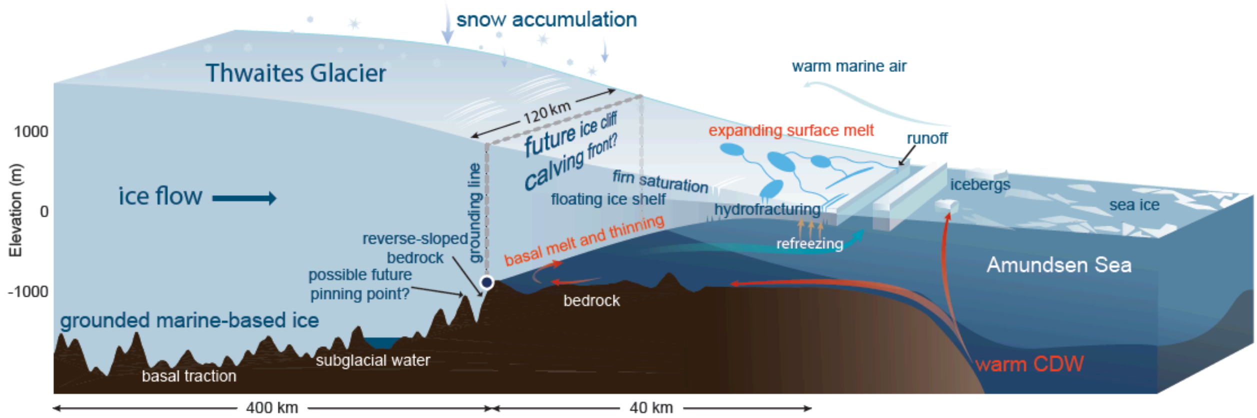


Figure 4.6: Processes affecting the Thwaites Glacier in the Amundsen Sea sector of Antarctica. The grounding line is currently retreating on reverse-sloped bedrock at a water depth of ~600 m (Joughin et al., 2014; Mouginot et al., 2014). The glacier is 120 km wide, widens upstream, and is minimally buttressed by a laterally discontinuous ~40 km long ice shelf. The remaining shelf is thinning in response to warm, sub-shelf incursions of circumpolar deep water (CDW), with melt rates up 60 m yr^{-1} near the groundling line (Rignot et al., 2014; Schodlok et al., 2016; Seroussi et al., 2017). The bathymetry upstream of the grounding zone is complex, but it generally slopes downward into a deep basin, up to 2,000 m below sea level under the center of the WAIS (far left). By itself, Thwaites contains enough ice to raise GMSL by ~0.4 m (Holt et al., 2006; Millan et al., 2017), but it could have a destabilizing impact on the broader WAIS (Feldmann and Levermann, 2015), which contains the equivalent of > 3.3 m of sea level rise. Atmospheric processes and surface meltwater may soon begin to play an increasingly important role in addition to the ocean-driven retreat already underway (Scambos et al., 2017).

Studies using highly resolved (a few km or less) ice models have mostly been limited to the study of single outlet glaciers (Favier et al., 2014; Joughin et al., 2014; Seroussi et al., 2017), or to WAIS only (Cornford et al., 2015; Nias et al., 2016). While limited to 50-yr simulations, Seroussi et al. (2017) provide the first, interactively coupled ice-ocean model simulations of Thwaites Glacier at a high spatial resolution. Like Joughin et al. (2014), their model demonstrates MISI-like grounding line retreat at a rate of ~1 km yr^{-1}, comparable to observations between 1992 and 2011 (Rignot et al., 2014). However, the retreat is interrupted when the main trunk of the glacier stabilizes on a bathymetric ridge, ~20 km upstream of the present-day grounding line (Figure 4.6). Due to the short duration of the simulation, the long-term potential for retreat into the interior of the ice sheet is not captured. Cornford et al. (2015) used a dynamical ice sheet model with an adaptive mesh that maintains very high spatial resolution at the grounding zone. This represents a significant modeling advance relative to most studies before AR5. In an idealized, extreme ocean warming scenario, they demonstrate that rapid ice-shelf thinning can produce up to 20 cm of GMSL rise from WAIS alone by 2100. However, using more realistic climate and ocean forcing representing an A1B emissions scenario from the IPCC Special Report on Emissions Scenarios (SRES) (IPCC, 2000), they find only 5 cm of GMSL rise by 2100, some of which is compensated by increased precipitation over the ice sheet. Similarly to Seroussi et al. (2017), they find strong dependency of Thwaites Glacier retreat on model resolution, initial conditions, and surface mass balance forcing. Arthern and Williams (2017) also use adaptive mesh techniques, but with a different (vertically integrated) formulation to simulate the response of the Amundsen Sea sector of West Antarctica to increasing sub-ice shelf melt rates. They also demonstrate that without increased melting, retreat of the Amundsen Sea outlet glaciers will be sustained, in agreement with Joughin et al. (2014). Arthern and Williams (2017) also use two alternative parameterizations of sub-ice shelf melting, one applying melt only to the bottom of fully floating grid cells, and an alternative formulation that applies some melt to partially grounded grid cells. The later treatment substantially increases the response of the ice sheet to subsurface ocean temperatures, as also found by Golledge et al. (2015) and a more recent study by Yu et al. (2018). This points to the need for additional analysis of marine melt-rate parameterizations near the grounding line and their potential to introduce model-dependent behaviour. In an ensemble of simulations using a range of model physical parameters, Nias et al. (2016) demonstrated substantial model sensitivity to poorly resolved basal boundary conditions (topography and basal traction), also contributing to model uncertainty. Uncertainty in future Thwaites retreat is critical, because the 120 km wide glacier is poised on a mostly reverse sloped bed (Millan et al., 2017), that reaches more than 300 km upstream into the heart of the WAIS where the ice is up to 2 km thick (Figure 4.6) (Scambos et al., 2017). The WAIS contains enough ice above floatation to cause > 3.3 m of GMSL rise (Bamber et al., 2009) if lost to the ocean.

Yu et al. (2018) simulate future Thwaites retreat using a regional grid domain and a range of model formulations with varying approximations of ice stress balance, different ocean melt schemes, and different basal friction laws. Like Arthern and Williams (2017) they find increased model sensitivity when ocean melt is applied to partially grounded grid cells, along with other model-specific dependencies. However, all of their simulations demonstrated sustained retreat, and a bathymetrically controlled future acceleration.

In summary, these regional-scale modelling studies demonstrate the potential for warming ocean temperatures to initiate grounding line retreat and thinning of upstream ice through reduced buttressing. This lends support to the notion that the observed retreat of some Amundsen Sea outlet glaciers (Mouginot et al., 2014; Rignot et al., 2014) will be sustained and might accelerate in the future, in line with MISI theory. However, the irreversibility of retreat and the long-term implications for the wider WAIS remain uncertain.

Since AR5, atmospheric forcing has become increasingly recognized to be an important factor for the future of the AIS, as it is on Greenland today. A sustained (15 days) melt event over the Ross Sea sector of the WAIS in 2016 illustrated both the connectivity of Antarctica to the tropics and El Niño, and the possibility that future meltwater production on ice shelf surfaces could fundamentally change in the near future (Nicolas et al., 2017). This was highlighted by Trusel et al. (2015), who use the snow component in the RACMO2 regional atmospheric model (Kuipers Munneke et al., 2012), to evaluate the future expansion of surface meltwater based on output from CMIP5 GCMs. Under RCP8.5 forcing, they find a substantial expansion of surface meltwater production on ice shelf surfaces after 2050 that exceed melt rates observed before the 2002 collapse of the Larsen B Ice Shelf. Surface meltwater is important for both ice sheet dynamics and surface mass balance due to its potential to lower albedo, saturate the firn layer, deepen surface crevasses, and to cause flexural stresses that can contribute to ice shelf break up (hydrofracturing) (Banwell et al., 2013; Kuipers Munneke et al., 2014). When and if melt rates will be sufficiently high in future warming scenarios to trigger widespread hydrofracturing is still under debate. This is a key question, because ice shelf loss is associated with the onset of both the marine ice sheet and ice cliff instabilities (see Cross-Chapter Box 2 in Chapter 1).

Continental-scale ice sheet simulations are ultimately required to provide projections of future GMSL rise from Antarctica. However, due to the large spatial scale of the region, processes involving interactions between the atmosphere, ocean, sea ice, ice shelves and ice sheets, have yet to be simulated collectively. Continental-scale ice sheet models still rely on simplifying approximations of the equations representing three-dimensional ice flow, and in some cases, they parameterize ice flow at the grounding line (Schoof, 2007) to improve computational efficiency. Such simplifications are necessary to allow long simulations that can be validated against geological information, in addition to modern observations (Briggs et al., 2013; Pollard et al., 2015). Processes related to MISI are best represented at high spatial resolution and without simplifications of the underlying physics (Favier et al., 2014; Cornford et al., 2015; Yu et al., 2018). However recent model intercomparisons have shown that simplified, continental-scale models can perform reasonably well relative to models with higher resolution and more explicit physical treatments, and can capture grounding line dynamics and the essence of MISI (Pattyn et al., 2012; Pattyn and Durand, 2013). Accurate atmospheric forcing (SMB) and sub-ice melt (Golledge et al., 2015; Yu et al., 2018) are also prerequisite to resolving the time-evolving dynamics of the system.

Since AR5, several Antarctic continental-scale models have been applied to future greenhouse gas scenarios on century and longer timescales (Levermann et al., 2014; Golledge et al., 2015; Ritz et al., 2015; Winkelmann et al., 2015; Clark et al., 2016; DeConto and Pollard, 2016; DeConto et al., in review). Ritz et al. (2015) used a hybrid physical-statistical modelling approach, whereby the timing of MISI onset is determined statistically rather than physically. They estimated probabilities of MISI onset in eleven different sectors around the ice-sheet margin based on observations of continent-wide retreat over the last few decades, and expected future climate change following an IPCC SRES A1B emission scenario only. In places where MISI is projected to begin, the persistence and rate of grounding-line retreat is parameterized as a function of the local bedrock topography (slope), ice thickness at grounding lines following Schoof (2007), and a formulation of basal friction. The advantage of this approach is that the relative simplicity of the ice model allows thousands of iterations, allowing a probabilistic assessment of the results and the calibration with present-day retreat rates. While their future climate scenario following the SRES A1B scenario is not directly comparable to the RCPs used in other recent studies, they concluded that Antarctica could contribute up to 30 cm GMSL by 2100 (95% quantile). This study represents a statistically rigorous approach in which model parameters are based on a synthesis of observations and projected surface and sub-shelf forcing, rather than coming directly from climate and ocean models. However, the model calibrations rely on recent observations, which may not provide adequate future guidance under warmer climate and ocean conditions. In addition, their model considers only processes associated with MISI, and does not consider possible contributions from other physical processes which may emerge, for which no recent analogue exists.

Golledge et al. (2015) used PISM (Parallel Ice Sheet Model; Winkelmann et al. (2011)), to simulate the future response of the AIS to RCP emission scenarios. They did not attempt to calibrate their model to the current observations as in Ritz et al. (2015). The PISM model links grounded, streaming, and shelf flow, has freely evolving grounding lines, and captures MISI dynamics. PISM's parameterized treatment of sub-ice melt applies melt under partially grounded grid cells (Feldmann and Levermann, 2015) makes the model more sensitive to subsurface ocean warming, although the validity of this approach is contested (Arthern and Williams, 2017; Yu et al., 2018). In their future ice sheet simulations, subsurface ocean temperatures are extrapolated from surface ocean temperatures simulated by a simple slab ocean model. They simulated a 39 cm contribution to GMSL by 2100 in RCP8.5, mainly through MISI, but using a more conservative oceanic melt-rate parameterization, the GMSL contribution is reduced from 39 to 10 cm. This difference highlights the ongoing uncertainty in heavily parameterized continental-scale ice sheet models, including their sensitivity to ocean forcing. While providing alternative outcomes with the two basal melt rate parameterizations, the authors do not provide a probability distribution for their results.

Levermann et al. (2014) used simplified emulations of temperature increase in order to estimate both sub-ice melt and SMB in order to calculate the dynamic response for five ice-sheet models calibrated against recent rates of retreat and including a parameterized delay for ocean warming. For scenarios including a delay in ocean warming they find 0.0–0.23 m GMSL for RCP2.6 (90% range) and 0.01–0.37 m for RCP8.5 in 2100. Substantial uncertainty arises from the different model treatments of grounding line dynamics and ice shelves. However, they conclude that the single greatest source of uncertainty stems from the external forcing.

DeConto and Pollard (2016) used an ice sheet model with a formulation similar to that used by Golledge et al. (2015), but they include two fundamental glaciological processes not accounted for in other continental scale models: 1) surface melt and rain water influence on crevasse penetration in divergent flow regimes (hydrofracturing); and 2) structural failure of marine-terminating ice fronts that have lost their ice shelves due to ocean melt and hydrofracturing, and are tall enough (~800 m) to generate stresses that exceed the strength of the ice (Bassis and Walker, 2012). These hydrofracturing and marine ice cliff instability (MICI) processes (Cross-Chapter Box 2 in Chapter 1) are represented with simplistic parameterizations, but their inclusion improves model performance relative to geological records of Pliocene and Last Interglacial sea level (Dutton et al., 2015; Pollard et al., 2015; DeConto et al., in review) and emerging geological records of ice retreat in East Antarctic subglacial basins (Cook et al., 2013; Reinardy et al., 2015). Mechanisms other than ice cliff collapse have been hypothesized that could drive substantial East Antarctic ice loss in the absence or reduction of buttressing ice shelves. This includes a model basal sliding scheme based on Coulomb friction near the grounding line (Tsai et al., 2015; Pattyn, 2017). As such, the MICI solution to the Pliocene sea level problem (Pollard et al., 2015) may not be unique (Aitken et al., 2016). However, justification for including hydrofracturing and ice-cliff calving parameterizations in models used for future simulations is provided by the observed break up of ice shelves in response to surface meltwater (Scambos et al., 2004; Scambos et al., 2009) and direct observations of ice-cliff failure in the few places where thick ice (>800 m) at marine-terminating grounding lines have lost their buttressing ice shelves (e.g., Jakobshavn, Helheim, and Crane glaciers). Further support for ice-cliff failure contributing to rapid ice loss is provided by a modelling study by Parizek et al. (Submitted), who use a 'Full Stokes' ice model to demonstrate that tall ice fronts are inherently unstable, and who argue that retrogressive slumping caused by the stress differences near the cliffs are the key instability mechanism.

Accounting for hydrofracturing and MICI processes in a continental ice sheet model, driven by offline atmosphere and ocean model climatologies, substantially increases projected Antarctic contributions to GMSL in RCP4.5 and RCP8.5 ensembles (DeConto and Pollard, 2016). DeConto and Pollard (2016) provide four alternative ensembles for each RCP scenario, representing two alternative ocean model treatments (with and without an ocean temperature bias correction), and two alternative Pliocene sea level targets used to tune their model physical parameters. The model ensembles use a range of uncertain parameters associated with hydrofracturing and MICI, validated relative to Last Interglacial and Pliocene sea level targets, however; their simulations do not explore the full range of model parameter space, and their simple statistical treatment of ensemble results don't provide a probabilistic assessment of Antarctica's future (Kopp et al., 2017; Edwards et al., 2018). Their four ensemble means for the Antarctic SLR contribution range between 0.26–0.58 m and 0.64–1.14 m GMSL by 2100, for RCP4.5 and RCP8.5, respectively. RCP8.5 is shown to produce as much as 15 m of GMSL sea level rise by 2500, mainly from the retreat of ice in deep East Antarctic basins in addition to West Antarctica. Golledge et al. (2015) and DeConto and Pollard (2016) find very little GMSL rise from Antarctica in their RCP2.6 scenario (0.02–0.16 m), implying a much reduced probability of extreme sea level rise from Antarctica under strong mitigation. The DeConto and Pollard (2016) study lacks quantitative calibration with present-day mass loss rates and there is large uncertainty in their SMB model and the timing of increased surface meltwater production and sub-ice melt, but it demonstrates the potential for physical processes not considered by AR5 to exert a strong influence on future rates of GMSL rise.

DeConto et al. (in review) use revised model physics, improved ice-driving climatologies in line with other independent atmospheric modelling studies (Trusel et al., 2015), and a combination of geological data and modern satellite observations of mass loss (The Imbie team, 2018) to calibrate their model physical parameters. Like DeConto and Pollard (2016) they account for hydrofracturing MICI processes, but allow faster Antarctic ice-cliff calving rates, up to those observed in Greenland today. The improved atmospheric forcing delays the onset of hydrofracturing and thereby the collapse of ice shelves by several decades. Their updated RCP8.5 ensemble using 196 combinations of model parameter values produces 0.35 ± 0.24 m of GMSL in 2100; considerably less than reported in DeConto and Pollard (2016). However, their simulated rates of ice loss accelerate early in the 22nd century and reach 4 cm yr^{-1} by 2140 (ensemble median), mainly due to the onset of widespread hydrofracturing and ensuing ice-cliff calving (Cross-Chapter Box 2 in Chapter 1). The RCP2.6 and 4.5 ensembles predict 7 ± 1 cm and 8 ± 2 cm GMSL rise by 2100 respectively. While their RCP2.6 and RCP4.5 results are similar over the 21st century, the scenarios diverge substantially in the 22nd century (36 ± 19 cm GMSL versus 25 ± 16 cm GMSL in 2200). A few (~3%) individual RCP2.6 ensemble members simulate up to 0.8 m of sea level rise by 2200, mainly through the rapid retreat of Thwaites Glacier, reinforcing the ongoing uncertain sensitivity of this major outlet glacier to warming reported in other studies (Cornford et al., 2015; Nias et al., 2016; Seroussi et al., 2017; Yu et al., 2018). Edwards et al. (2018) demonstrate the need for more robust statistical treatment of model ensemble results like those reported by DeConto and Pollard (2016) and DeConto et al. (in review).

These simulations including hydrofracturing and ice-cliff calving point to the potential for a far greater contribution to sea level under high emissions than than other studies, particularly on longer time scales (Edwards et al., 2018), but deep uncertainty remains. Accounting for the influence of surface meltwater on ice shelf breakup (hydrofracturing) makes the timing of retreat particularly sensitive to the emergence of daily summer temperatures above 0 ºC. However only a few studies (e.g., Trusel et al., 2015) have explored this timing in any detail. Realistically capturing the meltwater-buffering capacity of the firn layer is also important, because saturated, meltwater has the potential to flow into underlying crevasses to cause hydrofracturing (Kuipers Munneke et al., 2014). Supraglacial and englacial hydrology are highly complex, but crudely represented in ice sheet models. The presence of surface meltwater does not necessarily lead to immediate ice shelf collapse (Bell et al., 2017; Kingslake et al., 2017), but surface meltwater was a precursor on ice shelves which have collapsed (Scambos et al., 2004; Banwell et al., 2013). Edwards et al. (2018) use statistical methods to exclude hydrofracturing and cliff instability from DeConto and Pollard's (2016) results, and found that without these processes their model performs in line with previous studies. However, a comparable statistical analysis of DeConto et al. (in review) has not been done.

Another fundamental limitation of these continental-scale studies is the lack of explicit interaction between the retreating ice sheet and the surrounding ocean, at spatial resolutions capable of capturing explicit feedbacks between local winds, sea ice, circulation in ice shelf cavities, and sub-ice melt rates (Asay-Davis et al., 2016; Donat-Magnin et al., 2017; Hellmer et al., 2017; Seroussi et al., 2017). Freshwater input during future ice-sheet retreat could significantly alter sea ice, water column stratification, and ocean circulation surrounding the ice sheet, with plausible, albeit largely untested impacts on the amount of warm water penetrating ice shelf cavities to drive basal melt. Accounting for ocean-ice interactions at a continental scale, while capturing the relevant processes continues to be a major modelling challenge, requiring higher resolution ocean models than presently used. Feedbacks involving the overlying atmosphere and the time-evolving trajectory of Antarctic surface climate are also important, but these atmospheric linkages also continue to be inadequately represented in long-term future simulations. In light of uncertainties in both atmospheric and ocean forcing, and glacial hydrology related to hydrofracturing, there is *low confidence* in the projected timing of when widespread collapse of major buttressing ice-shelves might begin, but this outcome remains a possibility in the second half of the 21st century and on longer timescales.

The MICI mechanism was not considered in quantitative ice loss estimates by AR5, and it adds substantially to the dynamical component of ice loss, previously assumed to be limited to deformation, basal sliding, and non ice-cliff calving. We stress that hydrofracturing and ice-cliff processes have only been included in one continental ice sheet model. In reality, mechanical ice failure is controlled by many interacting processes, including the stress regime at the ice front, water depth, ice thickness, flow speed, conditions at the bed of the ice, pre-existing crevasses, lateral shear, undercutting of the calving face, and tides among others. The presence of mélange (a mix of previously calved, broken icebergs and sea ice) could also provide some buttressing support to a retreating cliff face providing a negative feedback (Amundson et al., 2010). Including the back-stress provided by mélange is shown to have little impact on the rate of large scale ice sheet retreat (Pollard et al., 2018), but these processes have not been directly accounted for in enough models to draw any conclusions at this time.

DeConto et al. (in review) report that the potential for Antarctic ice-cliff calving rates to exceed rates observed in narrow Greenland fjords, provides an important source of uncertainty at the high end of their projections. Antarctic outlet glaciers like Thwaites Glacier (Figure 4.6) are thicker and much wider than their Greenland counterparts like Jakobshavn, and as they retreat into interior basins they have the potential to form taller and much wider calving faces, with higher stresses and possibly much higher rates of brittle failure. However, due to the general lack of observations and mechanistic, process-based modelling to date, the potential pace of sustained ice loss by this process at the spatial scale of an Antarctic outlet glaciers like Thwaites remains fundamentally unknown, and could be much faster than calving rates observed in Greenland.

In addition to the model including MICI from DeConto and Pollard (2016) and substantially revised in DeConto et al. (in review), only the studies by Ritz et al. (2015) and Golledge et al. (2015) provide continental-scale estimates of future Antarctic ice loss, under a range of greenhouse gas emissions scenarios. These vary considerably, both in their approaches and their projections of Antarctica's future contribution to GMSL, allowing the first quantitative assessment of the full dynamical contribution of Antarctica, which could not be made by Church et al. (2013) in AR5. Their assessment reported median values (and *likely* ranges) of 0.05 m (-0.04–0.13) and 0.04 m (-0.06–0.12), for RCP4.5 and RCP8.5, respectively, for the Antarctic contribution in 2081-2100 relative to 1986-2005, while adding the following: 'Based on current understanding, only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause global mean sea level to rise substantially above the *likely* range during the 21st century. This potential additional contribution cannot be precisely quantified but there is *medium confidence* that it would not exceed several tenths of a meter of sea level rise during the 21st century'(Church et al., 2013). Given the publications after AR5 we reassess Antarctica's contribution to sea level change and now include the possibility of marine ice sheet instability allowing for a more complete assessment of the *likely* range of the projection. Based on the new studies, we now conclude that considerable divergence in the forcing among the different scenarios means that projecting the dynamic contribution independent of the RCP scenario, as done by Church et al. (2013) due to a lack of literature on the topic, is no longer needed. The recent studies indicate a very limited contribution of Antarctica to sea level for the RCP2.6 scenario (*medium confidence*) during the 21st century. For the higher RCP8.5 scenario, the contribution is higher and the difference among the studies is larger, leading to a large uncertainty than for the lower emission scenarios (see Table 4.2).

In a quantitative assessment of Antarctica's future contribution to GMSL the study by Ritz et al. (2015) is difficult to use as they only provided results for the A1B scenario and not for the RCP scenarios, though the limited contribution for A1B up to 2100 is in line with the study by Golledge et al. (2015) and DeConto et al. (in review) and as such supports the assessment for RCP4.5. The results by DeConto and Pollard (2016) are significantly higher even for RCP4.5, likely related to their high surface melt rates on the ice shelves. For this reason, only the results by Golledge et al. (2015) and DeConto et al. (in review) are used to assess the Antarctic contribution for the different RCP scenarios as independent estimates, as physical processes and calibration procedures are different. Both studies are given equal weight as there is no obvious criterion to give more weight to one or the other. The estimates from Golledge et al. (2015) are based on model results using two alternative subgrid parameterizations for sub-ice basal melt, where the higher estimate allows melt at partially grounded grid cells. For this assessment, the average of Golledge et al. (2015) high and low estimate are used, and we assess the difference between those two as the *likely* range of their results. The DeConto et al. (in review) results have an uncertainty estimate based on a large ensemble of model simulations, trained to paleo evidence and current rates of ice sheet mass loss. The Golledge et al. (2015) and the DeConto et al. (in review) results are combined as two independent Gaussian distributions to assess the Antarctic contribution. The *likely* range is the 17–83 percentile of this combined distribution.

The DeConto et al. (in review) ensemble distributions do not provide compelling evidence for a non-Gaussian distribution, unlike some studies based on expert elicitation, particularly beyond 2100 (Bamber et al., 2018). The study by Ritz et al. (2015) with a modest A1B forcing scenario also indicates a skewed probability distribution in 2100. Given the limited number of model studies for RCP8.5 we cannot quantify the skewness in the probability distribution function and we judge the distribution to be Gaussian for all RCP scenarios.

In addition, the ocean-only forcing experiments presented by Levermann et al. (2014) provide a lower limit of 10 cm for the Antarctic contribution under RCP8.5 in 2100, which is in qualitative agreement with the results based on Golledge et al. (2015) and DeConto et al. (in review). The expert elicitation approach (Bamber et al., 2018) suggests considerably higher values for all RCP scenarios than provided in Table 4.3 for RCP2.6, RCP4.5 and RCP8.5, if the contribution of the Greenland ice sheet is assumed to be equal to the estimates by Church et al. (2013).

As the importance of MISI is difficult to assess on longer time scales, there remains deep uncertainty for the Antarctic contribution to GMSL after 2100 (Cross-Chapter Box 4 in Chapter 1). Results on these long-time scales are discussed in 4.2.3.5.

Table 4.2: An overview of different studies estimating the future Antarctic contribution to sea level rise. GMSL estimates listed here are median values. The estimates from DeConto et al. (in review) are based on a model calibration using IMBIE2 data (The Imbie team, 2018), rather than alternative calibrations using shorter GRACE satellite time series which result in higher values. Estimates from Golledge et al. (2015) are based on the average contribution to GMSL over the 21st century, based on two alternative ensembles using different sub-ice melt schemes. This average is not explicitly reported in the original paper where the individual values of 0.1 and 0.39 m are reported. SMB is the surface mass balance, BMB the basal melt balance. Data from Ritz et al. (2015) refer to the ice dynamical contribution and should be adjusted downward by approximately 0.02 m for RCP4.5 in 2100, in order to allow direct comparison with the other studies.

	Ritz et al. (2015)	Golledge et al. (2015)	DeConto and Pollard (2016)	DeConto et al. (in review)
	RCP2.6/RCP4.5/ A1B/RCP8.5	*RCP2.6/RCP4.5/ A1B/RCP8.5*	*RCP2.6/RCP4.5/ A1B/RCP8.5*	*RCP2.6/RCP4.5/ A1B/RCP8.5*
GMSL 2050 (m)	-/-/0.03/-	0.00/0.01/-/0.03	0.02/0.03/-/0.04	0.03/0.03/-/0.02
GMSL 2100 (m)	-/-/0.12/-	0.02/0.05/-/0.18	0.14/0.41/-/0.79	0.07/0.08/-/0.35
GMSL 2200 (m)	-/-/0.41/-	0.10/0.33/-/1.15	0.35/1.67/-/5.39/	0.25/0.36/-/4.16

Uncertainties	Quantiles	High-average	Ensemble selections	Ensemble selections
Tuning targets	Present-day rates from observations	None	Last Interglacial and Pliocene	Last Interglacial and Pliocene IMBIE2
Grounding Line	Conditional on bed slope and Schoof flux	Sub-grid parameterization	Pollard and DeConto (2012)	Pollard and DeConto (2012)
Dynamics	Several basal friction laws	Hybrid, 10-20 km grid Till friction angle	Hybrid, 10 km grid	Hybrid, 10 km grid
Hydrofracturing	No	No	Yes	Yes
Marine Cliff Instability	No	No	Yes	Yes
Initialization	Observed rates	Focus on long time scales	1950	1950
SMB	parameterized	PDD scheme	Regional Climate Model	Regional Climate Model
BMB	parameterized	Slab Ocean GCM	NCAR CCSM4	NCAR CCSM4
Driving mechanism for retreat	Observations, statistics	Ocean (2/3)	Atmospheric forcing dominates	Atmospheric and ocean forcing

4.2.3.2 Global Projections of Sea Level Rise

There is only limited evidence for major changes since AR5 in the other (Glaciers, Greenland, Thermal expansion and land water storage) components to sea level rise, partly caused by a lack of new CMIP simulations. For the glacier component this is reinforced by the GlacierMIP experiment phase 1 (Hock, in review). Hence, we have constructed new projections by replacing the AR5 estimate for Antarctica by a new assessment as outlined in the previous paragraph and maintaining similar contributions for the other components. Results for the Antarctic component are not based on an ensemble mean, but on just two studies. Results are shown in Table 4.3, so the Total—Antarctica AR5 is a value derived from the data underlying Table 13.5 in Church et al. (2013) by subtracting the Antarctic contribution from the total distribution. Time series for the different RCP scenarios are shown in Figure 4.7 indicating a divergence in both magnitude and uncertainty for RCP8.5 during the second half of the century between this report and the AR5 projections (Church et al., 2013). The estimated values for the Antarctic contribution in 2081–2100 under RCP8.5 is the component with the largest uncertainty. As a consequence, the uncertainty in the GMSL projections are larger than for the results presented by Church et al. (2013).

Table 4.3: Median values and *likely* ranges for projections of global mean sea level (GMSL) in meters in 2081–2100 relative to 1986–2005 for three scenarios. In addition, rates for 2046–2065 are mentioned as well as the GMSL in 2100 and the rate of GMSL in 2100. Values between parentheses reflect the *likely* range. SMB is surface mass balance, DYN the dynamical contribution, LWS land water storage. Total—Antarctica AR5 is the GMSL contribution in Church et al. (2013) without the Antarctic contribution of Church et al. (2013) to this the newly derived Antarctic contribution is added to arrive at the GMSL.

	RCP2.6	RCP4.5	RCP8.5	Comments
Thermal expansion	0.14 (0.10–0 .18)	0.19 (0.14–0.23)	0.27 (0.21–0.33)	AR5
Glaciers	0.10 (0.04–0.16)	0.12 (0.06–0.18)	0.16 (0.09–0.23)	AR5
Greenland SMB	0.03 (0.01–0.07)	0.04 (0.02–0.09)	0.07 (0.03–0.17)	AR5
Greenland DYN	0.04 (0.01–0.06)	0.04 (0.01–0.06)	0.05 (0.02–0.07)	AR5
LWS	0.04 (-0.01–0.09)	0.04 (-0.01–0.09)	0.04 (-0.01–0.09)	AR5
Total - Antarctica AR5*; 2081–2100	0.35 (0.23–0.48)	0.43 (0.30–0.57)	0.60 (0.43–0.78)	SROCC implicit in AR5
Total AR5 - Antarctica AR5; 2046–2065	0.22 (0.15–0.29)	0.24 (0.17–0.31)	0.28 (0.20–0.36)	SROCC implicit in AR5
Antarctica 2046–2065	0.02 (0.01–0.02)	0.02 (0.01–0.03)	0.02 (0.02–0.03)	SROCC

Antarctica 2081–2100	0.04 (0.03–0.05)	0.05 (0.03–0.07)	0.18 (0.05–0.31)	SROCC
Antarctica 2100	0.04 (0.03-0.05)	0.07 (0.04-0.09)	0.27 (0.08-0.45)	SROCC
GMSL 2046–2065	0.24 (0.17–0.31)	0.26 (0.19–0.33)	0.30 (0.22–0.39)	SROCC
GMSL 2081–2100	0.39 (0.26–0.52)	0.48 (0.34–0.63)	0.78 (0.47–1.09)	SROCC
GMSL in 2100	0.42 (0.28-0.57)	0.55 (0.39–0.71)	0.97 (0.55–1.40)	SROCC
Rate (mm yr^{-1})	4	7	19	SROCC

Notes :
*The uncertainty in this value is calculated as in Church et al. (2013).

Results as presented in Table 4.3 are used to calculate the regional RSL projections as shown in Figure 4.8 and used in 4.2.3.4 to calculate extreme sea level projections. The time series show a difference in the second half of the century between the SROCC values and AR5 values both in magnitude and the uncertainty for RCP8.5. Results of SROCC are consistent with Church et al. (2013) if the caveat on the initiation of marine ice sheet instability is accounted for.

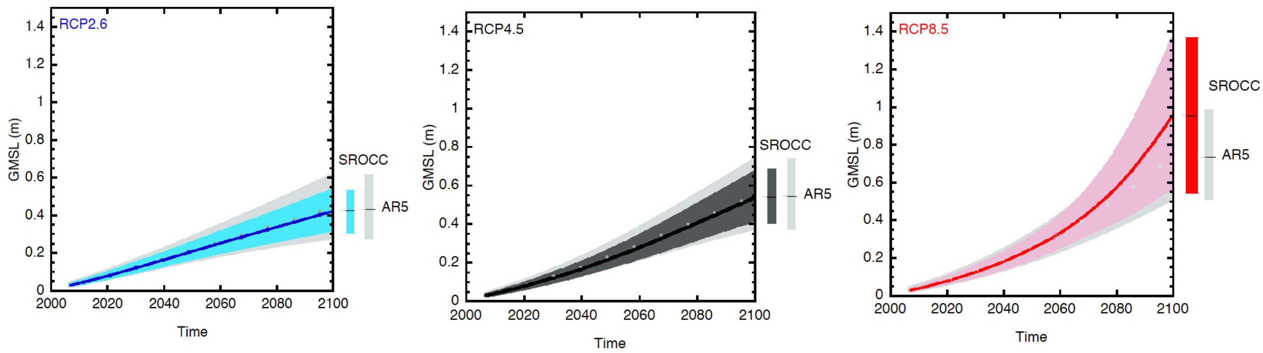


Figure 4.7: Time series of GMSL for RCP2.6, RCP4.5 and RCP8.5 as used in this report and, for reference the AR5 results (Church et al., 2013). Results are based on AR5 results for all components except the Antarctic contribution. Results for the Antarctic contribution in 2081–2100 are provided in Table 4.3. All components are treated independently and the shaded area is the 17–83% confidence interval, which is considered to be the *likely* range.

Including the updated results in terms of magnitude and uncertainty for the Antarctic component also changes the regional patterns in sea level projections. Results of the regional patterns as shown in Figure 4.8 show an increased sea level rise with respect to the results presented in AR5 nearly everywhere for RCP8.5 because of the increased Antarctic contribution. Differences are largest along the diagonal from the Indian Ocean to the North-Atlantic Ocean as a result of gravitational and rotational effects.

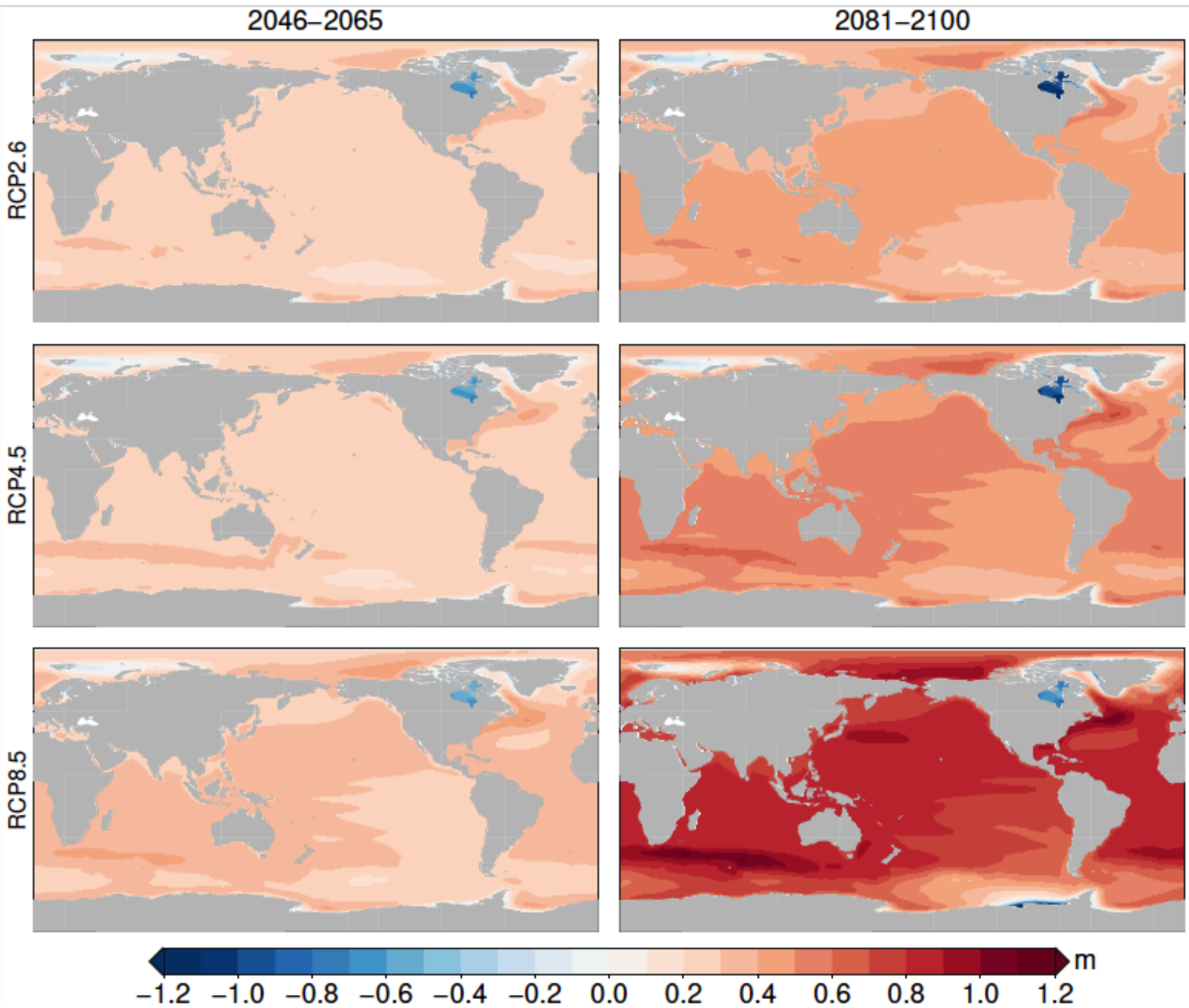


Figure 4.8: Regional relative sea level change for RCP2.6, RCP4.5 and RCP8.5 in meters as used in this report for ESL calculations. Results are median values based on the values in Table 4.3 for Antarctica including the gravitational and rotational effects, and results by Church et al. (2013) for the other components. The left column is for the time slice 2046–2065 and the right column for 2081–2100.

4.2.3.3 Probabilistic Sea Level Projections

Since AR5, several studies have produced sea level rise projections in coherent frameworks that link together global-mean and local relative sea level rise projections. The approaches are generally similar to those adopted by AR5 for its global-mean sea level projections: a bottom-up accounting of different contributing processes (e.g., land-ice mass loss, thermal expansion, dynamic sea level), of which many are 'probabilistic', in that they attempt to describe more comprehensive probability distributions of sea level change than the '*likely*' ranges presented by Church et al. (2013). They achieve this by applying statements for the Antarctic ice sheet contribution based on a single study and or by ignoring that other climate variables are only presented with a limited likely range as well. As such these probabilistic studies present full probability density function, but they make a priori assumptions violating the idea that a probability density function captures the full range.

An example is the study by Le Bars et al. (2017) who expand the projection by Church et al. (2013) in a probabilistic way with the Antarctic projections by DeConto and Pollard (2016) to obtain a full probability density function for sea level rise. Similar approaches are provided by Kopp et al. (2014) and Jackson and Jevrejeva (2016). These estimates are necessary from a quantitative risk management perspective (see Section 4.3.3). An even more general approach has been taken by Cazenave and Cozannet (2014) who frame a possibilistic framework of sea level rise including existing probabilistic estimates and combining them.

This section first briefly reviews key sources of information for probabilistic projections (Section 4.2.3.3.1), with a focus on new results since AR5, then summarizes the different global and regional projections (Section 4.2.3.3.2). Eventually, we distinguish bottom-up projections which explicitly describe the different component to sea level rise (Section 4.2.3.3.3) and semi-empirical projections (Section 4.2.3.3.4).

4.2.3.3.1 Components of probabilistic global mean sea level projections

Thermal expansion: Global mean thermal expansion projections rely on AOGCM projections (Kopp et al., 2014; Slangen et al., 2014a; Jackson and Jevrejeva, 2016) or simple climate model projections (Perrette et al., 2013; Nauels et al., 2017b; Wong et al., 2017), and are substantively unchanged since AR5. For those studies relying on the CMIP5 AOGCM ensemble, interpretations of the model output differ mainly with regard to how the range is understood. For example, Kopp et al. (2014), interprets the 5th–95th percentile of CMIP5 values as a *likely* range of thermal expansion. The differences among the studies yield discrepancies smaller than 10 cm, e.g., Slangen et al. (2014a) use 20–36 cm in 2081–2100 vs. 1986–2005, while (Kopp et al., 2014) project a *likely* range of 28–46 cm in 2081–2099 vs 1991–2009. Little et al. (2015b) note that the ‘crossover time’, at which scenario-driven uncertainty in global mean thermal expansion becomes larger than internal variability, occurs in about 2035.

Glaciers: Projections of glacier and ice cap mass change rely either on models of glacier surface mass balance and geometry, forced by temperature and precipitation fields (Slangen and Van de Wal, 2011; Marzeion et al., 2012; Hirabayashi et al., 2013; Radić et al., 2014; Huss and Hock, 2015), or simple scaling relationships with global mean temperature (Perrette et al., 2013; Bakker et al., 2017a; Nauels et al., 2017a). Glacier mass change projections published since AR5, based on newly developed glacier models, confirm the overall assessment of AR5 (see also Section 4.2.3.2).

Land water storage: Projections of the GMSL rise contributions due to dam impoundment and groundwater withdrawal are generally either calibrated to hydrological models EG (Wada et al., 2012) or neglected. Recent coupled climate-hydrological modelling suggests that a significant minority of pumped groundwater remains on land, which may reduce total GMSL rise relative to studies assuming full drainage to the ocean (Wada et al., 2016). However, there are no substantive updates to projections of the future land-water storage contribution to GMSL rise since AR5.

Ice sheets: Existing GMSL projections rely upon some combination of (1) past expert assessments by the IPCC based on physical models of varying degree of complexity (Meehl et al., 2007; Church et al., 2013). Alternatively, structured expert elicitation has been used for the GMSL contribution of ice sheets. Approach (1) is partly based on the CMIP5 ensemble of which the uncertainty range was assessed to be larger than the direct uncertainty range from the models yielding that the 5%–95% range from the models was interpreted as the *likely* range from 17%–83%, and partly based on statistical-physical modelling of the ice dynamic contribution (Little et al., 2013). Approach (2) was based on a more formal expert elicitation protocol (Cooke, 1991; Bamber and Aspinall, 2013) instead of physical based models. It led to a significant higher estimate of the contribution of the ice sheets to sea level rise. However, results were criticized by post-processing the expert data of individual ice sheets to a total sea level contribution from the ice sheets (de Vries and van de Wal, 2015; Bamber et al., 2016; de Vries and van de Wal, 2016). Alternatively, Horton et al. (2014) used a simpler elicitation protocol focusing on the total sea level rise rather than the ice sheet contribution alone. Finally, several studies (e.g., Bakker et al., 2017a; Kopp et al., 2017; Le Bars et al., 2017) used the results of a single ice sheet model study from DeConto and Pollard (2016) as the GMSL contribution of ice sheets.

Beside the total contribution of ice sheets several studies address the contribution of either Greenland or Antarctica (see Section 4.2.3.1.1 and 4.2.3.1.2). Critical for GMSL projections is the *low confidence* in the dynamic contribution of the Antarctic ice sheet beyond 2050 in previous assessments, as discussed in Section 4.3.2.1.2.

4.2.3.3.2 From probabilistic global mean sea level projections to regional relative sea level change

Differences between GMSL and relative sea level change are driven by three main factors: (1) dynamic sea level (DSL), for instance, the thermal expansion component and the circulation driven changes, (2) GIA effects (often separated into instantaneous gravitational and rotational effects) caused by redistribution of mass within cryosphere and hydrosphere, leading to fingerprint patterns, and (3) long term processes caused by GIA that lead to vertical land motion. Finally, the inverse barometer effect caused by changes in the atmospheric pressure, sometimes neglected in projections, can also make a small contribution, particular on shorter time scales. For the 21st century as a whole estimates are smaller than 5 cm at local scales (Church et al., 2013; Carson et al., 2016).

Dynamic sea level (DSL): Projections of dynamic sea level change are necessarily derived through interpretations of AOGCM projections. As with thermal expansion projections, interpretations of the CMIP5 ensemble differ with regard to how the model range is understood and the manner of drift correction, if any (Jackson and Jevrejeva, 2016). However, relative to tide-gauge observations, AOGCMs tend to overestimate the memory in dynamic sea level; thus, they may underestimate the emergence of the externally forced signal of DSL change above scenario uncertainty (Becker et al., 2016). DSL from AOGCM does not include the changes resulting from ice melt because ice melt is calculated off-line.

Gravitational-rotational effects: All projections of relative sea level change include fingerprints for cryospheric changes, which however may differ in the details with which these are represented. Some studies also include a fingerprint for land-water storage change (Slangen et al., 2014a). Recent work indicates that, for some regions with low mantle viscosity, fingerprints cannot be treated as fixed on multi-century timescales (Hay et al., 2017). This effect has not yet been incorporated into comprehensive RSL projections, but is probably only of relevance near ice sheets. For adaptation purpose Larour et al. (2017) developed a method to map indicating which areas of ice mass loss are important for which major port city. We have *high confidence* in the patterns caused by gravitational and rotational effect, as in AR5.

Long term solid Earth processes: These processes can be an important driver of relative sea level change, particularly in the near- to intermediate-field of the large ice-sheets of the Last Glacial Maximum (e.g., North America and northern Europe). This process is incorporated either by physical modelling (e.g., Slangen et al., 2014b) or by estimation of a long-term trend from tide-gauge data (e.g., Kopp et al., 2014), which is then spatially extrapolated. In the former case, projections may exclude other important local factors contributing to vertical land motion (e.g., tectonic uplift/subsidence and groundwater/hydrocarbon withdrawal); in the latter, projections may assume that these other processes proceed at a steady rate and thus do not allow for management changes that affect groundwater extraction.

4.2.3.3.3 Semi-empirical projections

Semi-empirical models provide an alternative approach for process-based models aiming to close the budget between the observed sea level rise and the sum of the different components contributing to sea level rise. In general, motivated by a mechanistic understanding, semi-empirical models use statistical correlations from time series analysis of observations to generate projections. They implicitly assume that the processes driving the observations and feedback mechanisms remain similar over past and future. In the past differences between semi-empirical projections and process-based models was significant but for more recent studies the differences are vanishing. Less and less value is given to semi-empirical models given the ongoing advances in closing the sea level budget and in the process understanding of the dynamics of ice. It is now realized that they poorly capture or miss altogether the recent observed changes in Antarctica. MISI may have a very different character in the near future than in the recent past and hydrofracturing is impossible to quantify on observational records only. Moreover, the results from semi-empirical models (Kopp et al., 2016; Mengel et al., 2016; Mengel et al., 2018) are in general agreement with Church et al. (2013). Total sea level projections by semi-empirical models (Nauels et al., 2017a) deviate only from process-based models if they include specific estimates of the dynamic contribution of Antarctica which strongly deviate from the values adopted by Church et al. (2013), such as the combined hydrofracturing and ice cliff instability mechanism as presented by DeConto and Pollard (2016).

4.2.3.3.4 Recent probabilistic and semi-empirical projections

A wide range of probabilistic sea level projections exist, ranging from simple scaling relations to partly process-based components combined with scaling relations. Table 4.4 illustrates the overlap between many of the studies. Many rely for an important part of their components on CMIP simulations. The largest difference can be found in the treatment of the ice dynamics, particularly for Antarctica, which are usually not CMIP5 based. Instead, each derives from one of several estimates of the Antarctic contribution. These results are extremely useful for the purposes of elucidating sensitivities and bounds. In this report, we rely on the Antarctic component from Section 4.2.3.2 for calculating the *likely* range of RSL. Hence the values in Table 4.4 are not used for the final assessment of RSL including the SROCC specific Antarctic contribution presented in Section 4.2.3.2. Comparing the probabilistic projections is difficult because of the subtle differences between their assumptions. Nevertheless, values of sea level rise are presented in Table 4.5. Typically, values range much more for 2100 than for 2050.

Table 4.4: Sources of Information Underlying Bottom-up Projections of Sea level Rise Projections. (CMIP5=Climate Modelling Intercomparison Experiment, GIA+VLM=Glacial Isostatic Adjustment and Vertical Land Motion).

Study	Thermal expansion	Glaciers	Land water storage	Ice Sheets	Dynamic sea level	Fingerprint	GIA+VLM
Perrette et al. (2013)	CMIP5	Global surface mass balance sensitivity and exponent from AR4; total glacier volume from Radić and Hock (2010)	Not included	Greenland's surface mass balance from AR4; semi-empirical model using historical observations.	CMIP5	Bamber et al. (2009)	Not included
Grinsted et al. (2015)	CMIP5	Church et al. (2013)	Wada et al. (2012)	Church et al. (2013); Expert elicitation from Bamber and Aspinall (2013)	CMIP5	Bamber et al. (2009)	GIA projections from Hill et al. (2010) using observations
Slangen et al. (2014b)	CMIP5	CMIP5; glacier area inventory Radić and Hock (2010) in a glacier mass loss model	Wada et al. (2012)	SMB Meehl et al. (2007), ice dynamics Meehl et al. (2007) and Katsman et al. (2011)	CMIP5	Mitrovica et al. (2001)	GIA resulting of ice sheet melt from glacier mass loss model
Kopp et al. (2014)	CMIP5	CMIP5; Marzeion et al. (2012)	Chambers et al. (2017); Konikow (2011)	Church et al. (2013); Expert elicitation from Bamber and Aspinall (2013)	CMIP5	Mitrovica et al. (2011)	GIA, tectonics, and subsidence from Kopp et al. (2013)
Kopp et al. (2017)	CMIP5	CMIP5; Marzeion et al. (2012)	Chambers et al. (2017); Konikow (2011)	DeConto and Pollard (2016)	CMIP5	Mitrovica et al. (2011)	GIA, tectonics, and subsidence from Kopp et al. (2013)
Le Bars et al. (2017)	CMIP5	Four glacier models Giesen and Oerlemans (2013) Marzeion et al. (2012), Radić and Hock (2010), Slangen and Van de Wal (2011)	Wada et al. (2012)	DeConto and Pollard (2016); Fettweis et al. (2013) Church et al. (2013)	CMIP5	-	-
Jackson and Jevrejeva (2016)	CMIP5	Marzeion et al. (2012)	Wada et al. (2012)	Church et al. (2013); Expert elicitation from Bamber and Aspinall (2013)	CMIP5	Bamber et al. (2009)	GIA resulting of ice sheet melt from glacier mass loss model Peltier et al. (2015)

De Winter et al. (2017)	CMIP5	CMIP5; glacier area inventory Radić and Hock (2010) in a glacier mass loss model	Wada et al. (2012)	Church et al. (2013); Expert elicitation de Vries and van de Wal (2015); Ritz et al. (2015)	CMIP5	Mitrovica et al. (2001)	GIA resulting of ice sheet melt from glacier mass loss model

Table 4.5: Median and *likely* GMSL rise projections (m). Values between brackets are *likely* range, if no values are given the *likely* range is not available. The upper half of the Table shows the result from the probabilistic approaches mentioned in Table 4.4 and the lower half of the Table shows semi-empirical results which are not built up from the different components as distinguished in Table 4.4.

	2050			2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Probabilistic studies						
Perrette et al. (2013)	---	0.28 (0.23–0.32)	0.28 (0.23–0.34)	---	0.86 (0.66–1.11)	1.06 (0.78–1.43)
Grinsted et al. (2015)	---	---	---	---	---	0.8 (0.58–1.20)
Slangen et al. (2014a)	---	---	---	---	0.57 (0.37–0.77)	0.74 (0.45–1.04)
Kopp et al. (2014)	0.24 (0.20–0.29)	0.26 (0.21–0.31)	0.29 (0.24–0.34)	0.49 (0.36–0.66)	0.59 (0.44–0.77)	0.79 (0.62–1.01)
(Kopp et al., 2017)	0.23 (0.16–0.33)	0.26 (0.18–0.36)	0.31 (0.22–0.40)	0.56 (0.37–0.78)	0.91 (0.66–1.25)	1.46 (1.09–2.09)
De Winter et al. (2017)	---	---	---	---	---	0.68/0.86
Jackson and Jevrejeva (2016)	---	---	---	---	0.52 (0.34–0.69)	0.72 (0.52–0.94)
Le Bars et al. (2017)	---	---	---	---	1.06 (0.65-1.47)	1.84 (1.24-2.46)
Semi-empirical studies						
Nauels et al. (2017b)	0.22 (0.17–0.27)	0.23 (0.19–0.28)	0.25 (0.20–0.30)	0.43 (0.34–0.54)	0.52 (0.43–0.63)	0.71 (0.58–0.87)
Nauels et al. (2017a)	0.20 (0.14–0.29)	---	0.25 (0.18–0.33)	0.49 (0.33–0.71)	0.67 (0.43–0.99)	0.88 (0.59–1.27)
Bakker et al. (2017a)	0.18	0.21	0.23	0.51	0.68	1.11
Wong et al. (2017)	0.26	0.28	0.30	0.55	0.77	1.50
Jevrejeva et al. (2012)	---	0.29	0.33	---	0.67	1.00
Schaeffer et al. (2012)	---	---	---	---	0.90	1.02
Mengel et al. (2016)	0.17	0.17	0.19	0.38	0.51	0.81

4.2.3.4 Extreme Sea Level Projections

Extreme sea levels (ESL) events, are water level heights that consist of contributions from mean sea level, storm surges, tides, and waves. Compound effects of surges, tides and waves are drivers of the Extreme sea level events. Paragraph 4.2.3.4.1 discusses the combination of mean sea level change with a characterization of the extreme sea level events derived from tide gauges over the historical period and the paragraphs 4.2.3.4.2 and 4.2.3.4.3 evaluate possibly changes in these characteristics caused by cyclones and waves.

Even a small increase in mean sea level can significantly augment the frequency and intensity of flooding. This is because SLR elevates the platform for storm surges, tides, and waves, and because there is a log-linear relationship between a flood's height and its occurrence interval. For example, tidal changes are non-linearly related to mean high water so that, for fixed coast lines in 10% of the coastal cities, changes in projected mean high water are larger than the SLR itself by 10% (Pickering et al., 2017). Changes are most pronounced in shelf seas. Over 300 million people reside in areas that are exposed to ESL, experiencing tens of billions of dollars in damages per year (Wahl et al., 2017). Roughly 1.3% of the global population is exposed to a 1/100-year flood (Muis et al., 2016). This exposure to ESL and its damage could increase significantly with SLR, potentially amounting to 10% of the global gross domestic product by the end of the century in the absence of adaptation (Wahl et al., 2017).

The frequencies of ESL events can be estimated with hydrodynamic or statistical models. Hydrodynamic models simulate a series of ESL over time, which can then be fitted by extreme value distributions to estimate the frequency and intensity (that is, the height of the 1/100-year flood) of ESLs. Often they still must be combined with a tide model to estimate the total extreme sea level. Statistical models fit tide gauge observations to extreme value distributions to directly estimate storm tide distributions or combine probabilistic sea-level rise scenarios with storm surge modelling. This can be done on global scale or local scale, for example, Lin et al. (2016) and Garner et al. (2017) estimating the increase flood frequency along the US East coast). Both of these modelling approaches can account for projections of SLR. The statistical models implicitly assume that the extreme values distribution is not changing over time. Rasmussen et al. (2018) used a combination of a global network of tide gauges and a probabilistic localized SLR to estimate expected ESL events showing inundation reductions for different temperature stabilization targets.

An advantage of the use of hydrodynamic models is that they can quantify interactions between the different components of ESL. Hydrodynamical models can be executed over the entire ocean with flexible grids at a high resolution (up to 1/20° or ~5 km) where necessary, appropriate for local estimates (Kernkamp et al., 2011). Input for those models are wind speed and direction, and atmospheric pressure. Results of those models show that the Root Mean Squared Error between modelled and observed sea level is less than 0.2 m for 80% of a data set of 472 stations covering the global coastline (Muis et al., 2016) at 10-minute temporal resolution over a reference period from 1980–2011. This implies that for most locations it can be used to describe the variability in ESL. Problematic are the areas where ESL is dominated by tropical storms. Models exist, which perform well for present-day conditions (Stammer et al., 2014).

Statistical models have shown that the estimation of ESL is highly sensitive to the characterization of SLR and flood frequency distributions (Buchanan et al., 2017). This is confirmed by Wahl et al. (2017) who estimate that the 5–95 percentile uncertainty range, attained through the application of different statistical extreme value methods and record lengths, of the current 1/100-year flood event is on average 40 cm, whereas the corresponding range in projected GMSL of AR5 under RCP8.5 is 37 cm. For ESL events with a higher return period, differences will be larger. Capturing changes in the ESL return periods in the future is even more complicated because both the changing variability over time and the uncertainty in the mean projection must be combined. A statistical framework to combine RSL and ESL, based on historical tide gauge data was applied to the U.S. coastlines (Buchanan et al., 2016). Hunter (2012) and the AR5 (Church et al., 2013) projected changes in flood frequency worldwide; however, these analyses used the Gumbel distribution for high water return periods, which implies that the frequency of all ESLs (e.g., whether the 1/10-year or 1/500-year) will change by the same magnitude for a given sea level rise, and thus can underestimate or overestimate ESL (Buchanan et al., 2017). Hence, the amplification factors of future storm return frequency in AR5 WGI Figure 13.25 may underestimate flood hazards in some areas, while overestimating them in others. By using the Gumbel distribution, Muis et al. (2016) may also inadequately estimate flood frequencies.

4.2.3.4.1 Relative sea level and extreme sea level projections based on tide gauge records

Here we present results in ESL based on the global projections as presented in 4.2.3.2 for the tide gauges in the GESLA2 database (Woodworth et al., 2016). Return periods are calculated as a combination of regional relative sea level changes and a characterization of the variability in sea level as derived from the GESLA2 data set which contains tide gauges from all over the world. By doing so, it is assumed that the variability as characterized by the tide gauges is not changing over time. To accommodate the non-exponential character of the relation between return height and return period in the tide gauges the relation is characterized by a Generalized Pareto Distribution (GPD) fit on declustered (72 hours between the peaks) tide gauge observations, with a threshold value of 99.7%, basically following the approach by Arns et al. (2013). Uncertainties are estimated by a Monte Carlo simulation with perturbed GPD parameters and GMSL changes to estimate the confidence intervals (Frederikse et al., in review). To estimate future return heights and periods the fits from the tide gauges are combined with the RSL as presented in 4.3.2.1 for RCP2.6, RCP4.5 and RCP8.5 for two periods: 2046–2065 and 2081–2100. Results are shown for 12 selected tide gauges in Figure 4.9. Depending on the curvature of the relation between return height and return period, future extreme level conditions are determined by the regional relative sea level increase or by the current variability in sea level arising from the tide gauge record, see inset Figure 4.9. If the difference between mean sea level and typical extremes is large (e.g., Cuxhaven) the regional relative sea level rise is less important and vice versa (e.g., Kerguelen Island). For Balboa, Sydney and Kerguelen Island, the projected relative-sea level rise is so large that the return heights are above the return heights as measured by the tide gauges (black crosses in Figure 4.9). A discrepancy exists between locations that experience rare and very high ESLs (such as Papeete and New York), and those that have a statistical upper bound to ESLs (such as Kerguelen Island and Sydney). The rare, very high historical ESLs are often found in regions where cyclones and hurricanes occur. At these locations, the present-day return period and amplification factor (see Figure 4.9 and caption) are largest for relatively common events, but these values are limited for rare events. The statistical upper bound to ESLs are often found in regions where tidal variability is large with respect to storm surges. In these locations, sea level rise will particularly increase the occurrence frequency of rare events.

More importantly, most of the locations show that a return height with a historical return period of 1/100, are projected to occur more than once a year under future conditions. This is expressed in Figure 4.10 for three climate scenarios, in the middle of the 21st century and at the end of the 21st century. From the curves of return height versus return period as shown in Figure 4.9, we can derive several quantities relevant for decision making: the $PDRP_1$ which is the present-day return period that corresponds to the return height associated with a return period of 1 after a change in relative sea level, see inset in Figure 4.9; the $SSLR_{100}$, which is the mean sea level change scaled by the present-day 100-yr return height. It is used in Cross-Chapter Box 4 in Chapter 1; and the AF_{100} is the amplification factor during changed conditions for events, which have under present-day conditions a return period of 100 years. Both PDRP and AF depend on the curvature of the relation between return height and return period and change as a function of the return period. Results for each tide gauge station are provided in the Supplementary Information (SI4.1). Figure 4.10 shows the very large changes in extreme sea level over time as a function of three different RCP scenarios. The figure shows that, in many locations, events which currently have an estimated return period of a hundred years or more become annual events by the end of the century, particularly under the higher RCP8.5 scenario.

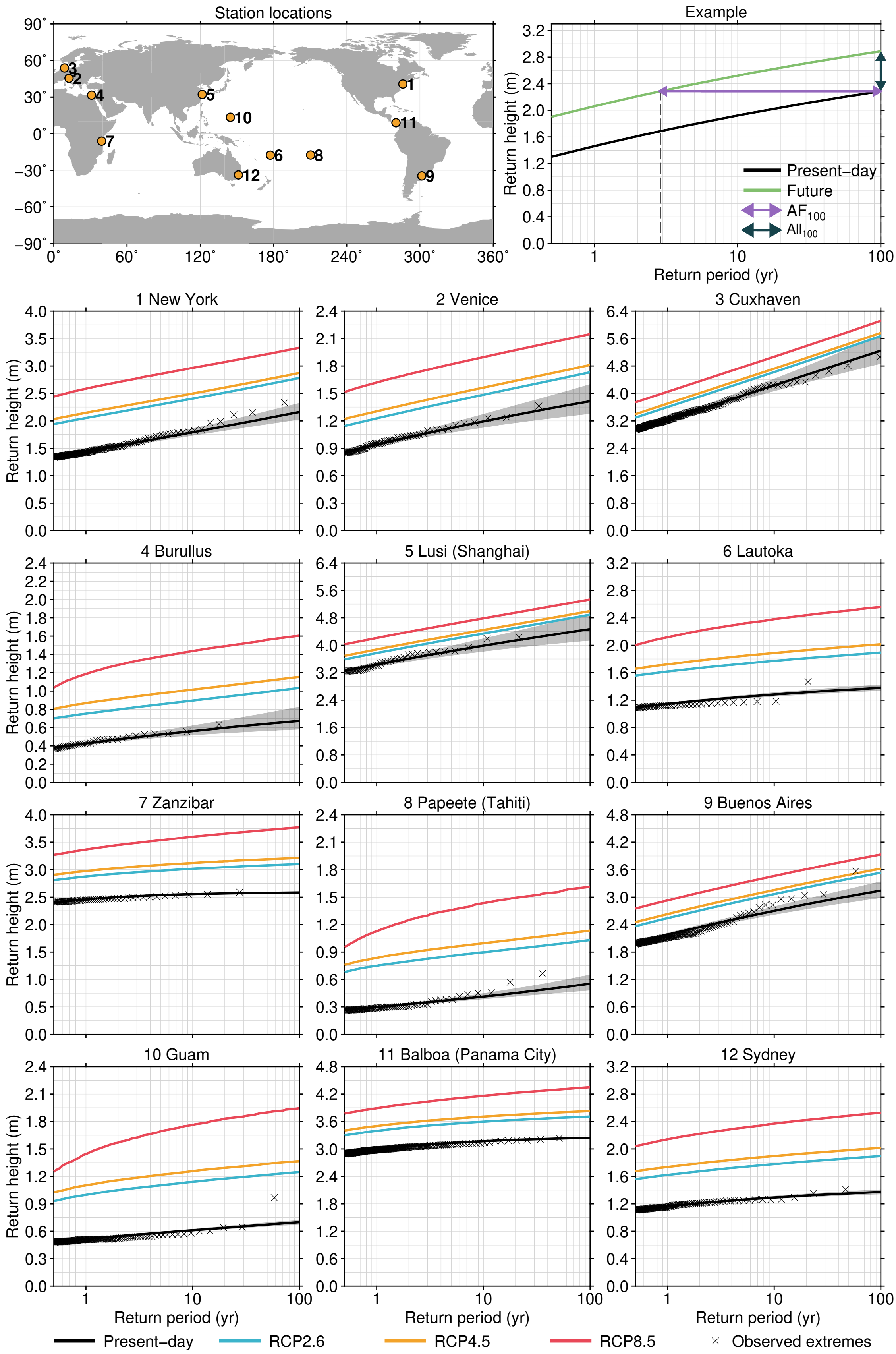


Figure 4.9: The relation between return height and return period at a set of characteristic tide gauge locations (see upper left for their location) for present-day condition (black lines) and 2081–2100 conditions for three different RCP scenarios. The upper right hand panel provides an example illustrating the relationship between return height and return period for current and future conditions; the green line in this panel shows the ensemble mean of the expected return height above the 1986–2005 reference for a location's mean sea level. The coloured lines for the different locations show this expected return height for different

RCP scenarios. The AF_{100} expresses the increase in frequency of events which currently have a return period of 100 years. The AII_{100} expresses the increase in the ensemble mean of the expected return height for events which currtenly have a return period of 100 years.

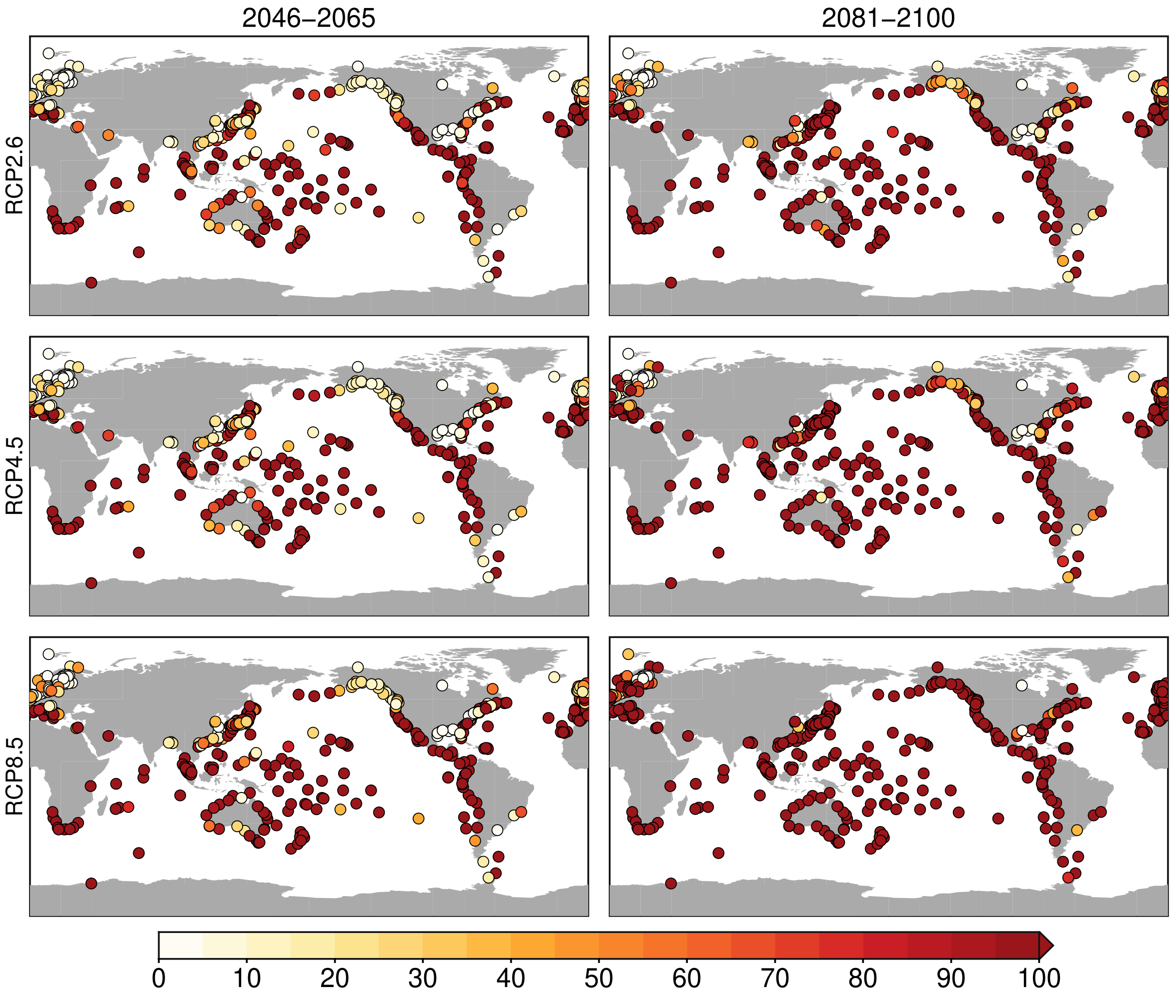


Figure 4.10: The colors of the dots express the factor by which the frequency of extreme sea level events increase in the future for events which currently have a return period of 100 years. Results are shown for three RCP scenarios and two future time slices as median values. Results are shown for tide gauges in the GESLA2 database. The accompanying confidence interval can be found in SI4.1.

In summary, extreme sea level estimates as presented in this subsection, clearly show that as a consequence of sea level rise, events which are currently rare (e.g., with an expected return period of 100 years), will occur yearly or more frequently at many locations for RCP8.5 by the end of the century (*high confidence*). For some locations, this change will occur as soon as mid-century for RCP8.5 and by 2100 for all emission scenarios. The affected locations are particularly located in low-latitude regions, away from the tropical cyclone tracks. In these locations, historical sea level variability due to tides and storm surges is small compared to projected sea level rise. Therefore, even limited changes in mean sea level will have a noticeable effect on ESLs, and for some locations, even RCP2.6 will lead to the annual occurrence of historically rare events by mid-century.

4.2.3.4.2 Waves

A warming climate is expected to affect wind patterns and storm characteristics, which in turn will impact wind waves that contribute to high coastal water levels. Wind-wave projections commonly are based on dynamical and statistical wave models forced by projected surface winds from General Circulation Models (GCMs), notably those participating in the Coupled Model Intercomparison Project (CMIP). In the framework of the Coordinated Ocean Wave Climate Project (COWCLIP), an ensemble of CMIP3-based global wave projections (Hemer et al., 2013) was produced and the results were summarized in the AR5

(WGI Chapter 13). Casas-Prat et al. (2018) expanded the geographic domain to include the Arctic Ocean, highlighting the vulnerability of high-latitude coastlines to wave action as ice retreats. A review and consensus-based analysis of regional and global scale wave projections, including CMIP5-based projections, has been provided by Morim et al. (2018) as part of COWCLIP. Consistent patterns of wind-wave climate changes in response to global warming have been established. Projections of annual and seasonal mean significant wave height changes agree on an increase in the Southern Ocean, tropical eastern Pacific and Baltic Sea; and on a decrease over the North Atlantic and Mediterranean Sea. Projections of mean significant wave height lack consensus over the eastern north Pacific and southern Indian and Atlantic Oceans. Projections of future extreme significant wave height are consistent over the Southern Ocean (agreed increase) and Northeastern Atlantic and Mediterranean Sea (agreed decrease). Knowledge on projected changes in wave period and direction are currently more limited than for significant wave height, in spite of their important role in coastal hazards. Although regional projections of wind-waves exist, they have been largely applied to Europe while highly vulnerable regions (high risk and lower adaptive capacity) have been largely overlooked.

A number of studies have included waves, in addition to tides and sea level anomalies, to assess coastal vulnerability to sea-level rise using dynamical and statistical approaches. The Coastal Storm Modeling System (CoSMoS; Barnard et al., 2014) includes a series of embedded wave models to estimate high resolution projections of total water levels along the Southern California coast for different extreme scenarios (O'Neill et al., 2018). Arns et al. (2017) find that an increase in sea level may reduce the depth-limitation of waves, thereby resulting in waves with greater energy approaching the coast. Including wave effects is crucial for coastal adaptation and planning. For example Arns et al. (2017) report that coastal protection design heights need to be increased by 48%–56% in the German bight region relative to a design height based on sea level rise only. Combining sea level rise with extreme sea theory applied to past observations of tides, storm surges and waves, Vitousek et al. (2017) found that a 10-to-20 cm sea level rise could result in a doubling of coastal flooding frequency in the Tropics. For the Southern North Sea region, Weisse et al. (2012) argue that an increasing storm activity also increases hazards from extreme sea levels. In the North Sea region, under RCP8.5, Vousdoukas et al. (2017) quantify the extreme sea level including a wave model to be nearly 1 m. This is the highest in Europe and corresponds to a 40% increase of the RSL trends caused by increased storm surge and waves. As a consequence, flood risk will increase from once every 100-year to once every year for about 5 million Europeans.

A stationarity of the wave climate is often assumed for projections of extreme sea levels (Vitousek et al., 2017). Yet, wave contributions to coastal sea level changes (setup and swash) depend on several factors that can vary in response to internal climate variability and climate change, including deep-water wave field, water-depth, and geomorphology. Melet et al. (in review) reported that over the last decades, wave setup and swash interannual-to-decadal changes induced by deep-water wave height and period changes alone were sizeable compared to steric and land-ice mass loss coastal sea level changes. Projected 20-yr mean wind-driven changes in wave setup could also represent a non-trivial fraction (±10%–20%) of the projected coastal sterodynamic sea level changes over the mid and end of the 21st century under RCP8.5 (Melet et al., in review).

Comprehensive broad-scale projections of extreme sea levels including regional sea level changes, tides, waves, storm surges, interactions between these processes and accounting for the non-stationarity of waves and storm surges are yet to be performed.

4.2.3.4.3 Effects of cyclones

Tropical (TCs) and extratropical cyclones (ETCs) tend to determine extremes in sea level such as coastal storm surges, high water events, coastal floods, and their associated impacts on coastal communities around the world. The projected potential future changes in TCs and ETCs frequency, track and intensity is therefore of great importance. AR5 (WGI Chapter 14) concluded that it is *likely* that the frequency of TCs globally will either decrease or remain unchanged, but category 4/5 tropical cyclones are *likely* to increases, and maximum wind speed and rainfall rates will increase (Christensen et al., 2013). More recently, it was realized that the modelled global frequency of TCs is underestimated and that the geographical pattern is poorly resolved in case of TC tracks, very intense TCs (i.e., category 4/5) and TC formation by using low resolution climate models (Camargo, 2013). Therefore, after AR5, multiple methods including downscaling CMIP5 climate models (Knutson et al., 2015; Yamada et al., 2017), high-resolution simulations (Camargo, 2013; Yamada et al., 2017), TC–ocean interaction (Knutson et al., 2015; Yamada et al., 2017), statistical models (Ellingwood and Lee, 2016) and statistical-deterministic models (Emanuel et al., 2008) have been developed, and the simulation capability of tropical cyclones (TCs) has been substantially improved. Although through downscaling CMIP5 climate models (Emanuel, 2013), an increase in global TC frequency is projected during the 21st century in most locations, especially in the western North Pacific region, North Atlantic and South Indian Oceans (Emanuel, 2013), most models still project a decrease or constant global frequency of TCs. Additionally, it is noting that a robust increase in ratio of intense TCs at the same time. This is similar to IPCC AR5 and many studies (Emanuel et al., 2008; Holland et al., 2008; Knutson et al., 2015; Kanada et al., 2017; Nakamura et al., 2017; Scoccimarro et al., 2017; Zheng et al., 2017).

In addition to an increase in the frequency there are also robust projected increases in the lifetimes, precipitation, and landfalls of TCs under global warming. Moreover, confidence in these projections continues to increase with improved simulation (Walsh et al., 2016). It is *likely* that these projected increases are intensified by favourable marine environmental conditions, expansion of the tropical belt, or ocean warming in the northwest Pacific, and increasing water vapour in the atmosphere (Kossin et al., 2014; Moon et al., 2015; Cai et al., 2016; Mei and Xie, 2016; Cai et al., 2017; Scoccimarro et al., 2017; Kossin, 2018).

Previous extensive studies also indicated the important role of warming oceans in the TC activity (Emanuel, 2005; Mann and Emanuel, 2006; Trenberth and Fasullo, 2007; Trenberth and Fasullo, 2008; Villarini and Vecchi, 2011; Trenberth et al., 2018), since the ocean is the major "fuel" of the TCs. Besides, TCs stir the ocean and mix the subsurface cold water to the surface, leaving a cold wake after a storm passage (Shay et al., 1992; Lin et al., 2009). Hence, ocean subsurface structure affects TC intensity. The increased thermal stratification of the upper ocean under global warming will reduce the projected intensification of TCs (Huang et al., 2015). The effect is estimated to be not more than about 15% (Emanuel, 2015; Tuleya et al., 2016). At the same time studies suggest a strengthening effect of ocean freshening in TC intensification, opposing the thermal effect (Balaguru et al., 2016). A complicating factor is that there is no physical theory to predict the number of global TCs. Currently TC frequency is broadly diagnosed using semi-empirical genesis indices, which may be problematic in predicting future global TC number (Sobel et al., 2016). We conclude that it is *likely* that the intensity of severe TCs will increase in a warmer climate, but there is still *low confidence* on the frequency change of TCs in the future.

For ETCs, AR5 concluded that the global number of ETCs is not expected to decrease by more than a few percent due to anthropogenic change. The Southern Hemisphere (SH) storm track is projected to have a small poleward shift, but the magnitude is model dependent (Christensen et al., 2013). AR5 also found a *low confidence* in the magnitude of regional storm track changes and the impact of such changes on regional surface climate (Christensen et al., 2013). Recent projection studies indicate that trends in regional ETCs vary from region to region. Modelling studies project a significant increase in the frequency of extreme ETCs, extending from the South Atlantic across the South Indian Ocean into the Pacific (Chang, 2017). The number of storms throughout the North Atlantic basin is expected to decrease (Michaelis et al., 2017). However, an increase in the number of ETCs has been projected across the northeast North Atlantic (Colle et al., 2013; Zappa et al., 2013; Michaelis et al., 2017). The number of Mediterranean cyclones is also expected to decrease (Zappa et al., 2013). Note that the projected frequency in ETCs still remains uncertain due to different definitions of cyclone, model biases or climate variability (Chang, 2014; Chang et al., 2016). Considering these processes imply that changes in TC and ETC characteristics will vary locally and therefore we have *low confidence* in the regional storm changes, which is in agreement with the AR5 WGI Chapter 14 (Christensen et al., 2013).

TCs and ETCs can cause storm surge, high water events, heavy precipitation, and coastal flooding. The probabilities of sea level extremes induced by TC storm surge are *very likely* to increase significantly over the 21st century due to the effect of sea level rise alone. Risk from TC storm surge increases in the highly vulnerable coastal regions, e.g., at coasts of China (Feng and Tsimplis, 2014), west Florida coast, north of Queensland, Persian Gulf, and even in well protected area such as the Greater Tokyo area (Tebaldi et al., 2012; Lin and Emanuel, 2015; Ellingwood and Lee, 2016; Hoshino et al., 2016; Dinan, 2017; Lin and Shullman, 2017). The flood return period has greatly decreased over the past decades and is also expected to decrease greatly in the near future (by 2030–2045; Reed et al., 2015; Garner et al., 2017). For example, in New York City, the return period of a 2.25-m flood has decreased from ~500-yr before 1800 to ~25-yr during 1970–2005 and further decreases to ~5-yr by 2030–2045 (Garner et al., 2017). The annual probability of 500 mm of area-integrated rainfall induced by TC, like Harvey in 2017 in Texas, will increase from 1% in the in the late 20th century to 18% by the end of this century (Emanuel, 2017b). It is *very likely* that the flood return period in low-lying areas such as coastal megacities has decreased over the past 20th century and the high water events is expected to increase in frequency in the future. In addition, the compound effects of sea level rise, storm surge and waves on extreme sea levels and the associated flood hazard are assessed in Chapter 6 (Section 6.3.3.3 and 6.3.4).

Observed damages from ETCs/TCs to coastal regions have already increased over the past 30 years and will continue in the future (*high confidence*): under 2.5°C global surface air temperature scenario, TCs damages are expected to increase TCs damages by 63% in the North Atlantic, and 28% in the Western North Pacific (Ranson et al., 2014). Additionally, the global population exposed to ETCs/TCs hazards has increased almost threefold between 1970 and 2010, and this trend is expected to continue for at least a few decades (Peduzzi et al., 2012). This projected increase in coastal population will expose more people to ETCs/TCs hazards and risk in coastal regions, making preparations and evacuations more difficult and costly due to an increase of poorly anticipated ETCs/TCs that rapidly intensify before landfall in a warming climate (Emanuel, 2017a).

Besides, heavier precipitation and stronger low-level winds under future climate conditions are also expected for ETCs storms (Michaelis et al., 2017), and will result in increasing risk of the related damages or hazards over the North Atlantic (Michaelis et al., 2017). Onshore winds caused by ETCs can accentuate tides and enhance storm surge, resulting in severe risks at costs, e.g., battering shorelines and damaging structures (Vose et al., 2014). For example, future heavy precipitation partially induced by extreme ETCs are expected to have an impact on the timing of European floods (Blöschl et al., 2017).

4.2.3.5 Uncertainties and Decadal Predictability of Sea Level

Recent studies have explored the predictability of sea level anomalies (SLAs) at decadal and shorter time scales, based on similar efforts to predict sea surface temperatures and other physical variables (Meehl et al., 2009; Kirtman et al., 2013). On these time scales, SLAs typically fall well below 10 cm amplitude and are associated with changes in the ocean circulation driven by surface wind stress (e.g., Moon et al., 2013; Trenary and Han, 2013; Thompson et al., 2016), and buoyancy fluxes (Piecuch and Ponte, 2012). At high latitudes and on continental shelves, wind-driven variations in mass also contribute to SLAs (Roberts et al., 2016).

The dynamical prediction of SLA variability on seasonal to decadal time scales relies on high resolution coupled global circulation models (GCMs), initialized with the current state of the ocean-atmosphere (Kirtman et al., 2013). Miles et al. (2014) demonstrated skillful (i.e., exceeding persistence) dynamical predictions of hindcast SLA conditions up to 7 months in advance, with particularly high skill in the equatorial Pacific region. McIntosh et al. (2015) used a similar approach to examine coastal SLA predictability. Polkova et al. (2014) examined decadal hindcasts initialized every 5 years and found high predictive skill of annual-mean regional steric sea level owing to isopycnal motions (subtropics), thermosteric mixed layer changes (subtropical Atlantic), and halosteric contributions due to water mass formation (subpolar North Atlantic). Widlansky et al. (2017) combined dynamical and statistical (Chowdhury et al., 2014; Chowdhury and Chu, 2015) SLA forecasts into an operational prediction tool for Pacific sites.

The greatest uncertainty in SLA prediction is the specification of future wind conditions. Due to the complexity of the wind-forced circulation, Piecuch and Ponte (2011) contend that SLAs cannot be predicted other than variability associated with remotely forced dynamics. Likewise, SLA changes associated with the inverse barometer effect have low predictability. Examples where remotely-forced dynamics play a role, include the equatorial Pacific region associated with El Nino-Southern Oscillation (ENSO) events (Miles et al., 2014) and at mid-latitude regions, owing to westward propagating Rossby waves that cause forecast skill with a lead time of 2 to 5 years (Polkova et al., 2015). Other uncertainties involved in dynamical predictions include observational initialization and incomplete model physics (Kirtman et al., 2013; Hu et al., 2017), such as the uncertainty in the spatial distribution of tidally-driven mixing (Melet et al., 2016).

A number of studies have linked SLA variability with climate modes (recently, Hamlington et al., 2016; Hamlington et al., 2017; Lyu et al., 2017; Moon and Song, 2017). Hence the ability to predict climate modes, e.g., decadal variability in the Pacific (Newman et al., 2016), may lead to useful predictions of related SLA patterns. As an example of the potential of this approach, Meehl et al. (2016) demonstrated that ENSO events together with long-term heat buildup or deficit in the western tropical Pacific can trigger an Interdecadal Pacific Oscillation (IPO) phase shift. Decadal predictability of the IPO also may be linked to trans-basin variability and shifts in the Walker Circulation (Chikamoto et al., 2015).

As there is no clear evidence that climate models are changing over time, we conclude with *medium confidence* that SLA magnitudes on decadal time scales will remain similar over the next century. Moreover, given the limited skills involved in predicting future wind states, we have *low confidence* in projections of SLA decadal variability.

4.2.3.6 Long-Term Scenarios, Beyond 2100

Sea level rise at the end of the century will be higher in all cases even if follow the Paris Agreement (Nicholls et al., 2018a). The reasons for this are mainly related to glacier melt, thermal expansion and ice sheet mass loss. These processes operate on long time scales, implying that even if the rise in global temperature slows or the trend reverses, sea level will continue to rise. A study by Levermann et al. (2013) based on paleo-evidence and physical models formed the basis of the assessment by Church et al. (2013) indicating that committed sea level rise is approximately 2.3 m per degree warming for the next 2000 years. This rate is based on a relation between ocean warming and basal melt, without accounting for surface melt followed by hydrofracturing and ice cliff failure after collapse of ice shelves as suggested to be the dominant mechanism for ice mass loss by DeConto and Pollard (2016).

If we consider the long-term contribution of the various components of SLR we observe considerable differences. For glaciers, the long-term is of limited importance, because the sea level equivalent of all glaciers is restricted to ~0.4 m and there is *high confidence* that the contribution of glaciers to sea level rise expressed as a rate will decrease over the 22nd century (Marzeion et al., 2012). For thermal expansion the gradual rate of heat absorption in the ocean will lead to a further sea level rise for several centuries (Zickfeld et al., 2017). By far, the most important uncertainty on long timescales arises from the contribution of the major ice sheets. The time scale of response of ice sheets is thousands of years. Hence if ice sheets contribute significantly to sea level in 2100, they will necessarily also contribute to sea level in the centuries to follow. Only for low emission scenarios, like RCP2.6, can a substantial ice loss be prevented according to ice-dynamical models (Golledge et al., 2015; DeConto and Pollard, 2016).

For Greenland, surface warming may lead to the condition that ablation becomes larger than accumulation, and that the associated surface lowering increases ablation further (positive feedback). As a consequence, the ice sheet will significantly retreat. Church et al. (2013) concluded that the threshold for perpetual negative mass balance is based on modelling studies between 1ºC (*low confidence*) and 4ºC (*medium confidence*) above preindustrial temperatures. Passing such thresholds commits the world to a long term and large contribution to sea level rise from the Greenland Ice Sheet. At the same time the geological evidence suggested that the Greenland ice sheet largely survived the Last Interglacial where temperatures were estimated to be 0.5˚C –1˚C above pre industrial level suggesting the lower threshold to be higher than 1˚C.

The mechanisms for decay of the Antarctic ice sheet are related to ice shelf melt by the ocean, followed by accelerated loss of grounded ice and marine ice sheet instability, possibly exacerbated by hydrofracturing of the ice shelves and ice cliff failure (Cross-Chapter Box 2 in Chapter 1). The latter processes have the potential to drive faster rates of ice mass loss than the surface mass balance processes that are *likely* to dominate the future loss of ice on Greenland. Furthermore, the loss of marine-based Antarctic ice represents a long-term (millennial) commitment to elevated sea level rise, due to the long thermal memory of the ocean. Once marine based Antarctic ice is lost, local ocean temperatures will have to cool sufficiently for buttressing ice shelves to reform, allowing retreated grounding lines to readvance (DeConto and Pollard, 2016). A minimum time scale, whereby the majority of West-Antarctica decays, was derived from a schematic experiment with an ice flow model by Golledge et al. (2017), where ice shelves were removed instantaneously and prohibited from regrowing. Results of this experiment show a sea level rise from West-Antarctica of approximately 4.5 m in a century. Gradual melt of ice shelves, and partial retreat of East-Antarctic ice will lengthen this time scale to millennial or longer (Cross-Chapter Box 2 in Chapter 1). Prescribing a uniform warming of 2°C–3°C in the Southern Ocean triggers an accelerated decay of West

Antarctica in a coarse resolution model with a temperature-driven basal melt formulation yielding 1 to 2 m sea level rise by the year 3000 and up to 4 m by the year 5000 (Sutter et al., 2016). Forcing an ice sheet model with Coulomb friction in the grounding line zone yields to a sea level rise of 2 m after 500 year for a sub-ice shelf melt of 20 m a^{-1} (Pattyn, 2017). On these longer time scales the interaction between ice and the solid Earth may also lead to the possibility of a negative feedback slowing retreat by elastic uplift and gravitational effects that reduce the water depth at the grounding line (Gomez et al., 2010; de Boer et al., 2014; Barletta et al., 2018).

A blended statistical and physical model, calibrated by observed recent ice loss in a few basins (Ritz et al., 2015) projects an Antarctic contribution to sea level of 30 cm by 2100 and 72 cm by 2200, following a SRES A1B scenario roughly comparable to RCP6.0. The key uncertainty in these calculations was found to come from the dependency on the relation between the sliding velocity and the friction at the ice-bedrock interface. Several parameterizations are used to describe this process. Golledge et al. (2015) present values between 0.6 m and 3 m by 2300 for the higher emission scenarios. In contrast to the previous studies, Cornford et al. (2015) used an adaptive grid model, which can describe more accurately grounding line migration (Cross-Chapter Box 2 in Chapter 1). Due to the computational complexity of their model, simulations are limited to West Antarctica. Starting from present-day observations, they find that the results are critically dependent on initial conditions, sub ice-shelf melt rates, and grid resolution. The glacier for which the vulnerability is most uncertain is the 120 km-wide Thwaites Glacier, in the Amundsen Sea sector of West Antarctica. Thwaites Glacier is currently retreating in a reverse-sloped trough up extending into the central West Antarctic Ice Sheet (Figure 4.6), where the bed is up to 2 km below sea level. The projected contributions of WAIS are found to be limited to 48 cm in 2200 following an A1B scenario. In addition to Thwaites, several smaller outlet glaciers and ice streams may contribute to sea level on long time scales, but in this study a full West-Antarctic retreat does not occur due to limited oceanic heating under the two major ice shelves (Filchner-Ronne and Ross) keeping ice streams flowing into the Ross and Weddell Seas in place. A study by DeConto and Pollard (2016) based on an ice flow model calibrated to reproduce geological sea level high-stands, shows a maximum contribution of more than 15 m sea level from the Antarctic ice sheet reached after approximately 500 years. They find the potential for considerably more sea level rise on long timescales than other studies, because they include model physics representing the influence of surface meltwater and rain on crevasse penetration (hydrofracturing of ice shelves), and the mechanical failure of ice at thick, marine terminating ice margins (marine ice cliff instability). However, the representation of these processes remains simplistic at the continental ice sheet scale (Cross-Chapter Box 2 in Chapter 1).

Nonetheless, recent studies using independently developed Antarctic ice-dynamical models (Golledge et al., 2015; DeConto and Pollard, 2016; DeConto et al., in review) agree that low emission scenarios, like RCP2.6, are required to prevent substantial future ice loss. However, observations (Rignot et al., 2014) and modelling of the Thwaites Glacier in West Antarctica (Joughin et al., 2014), suggest grounding line retreat on the glacier's reverse sloped bedrock is already underway and possibly capable of driving major WAIS retreat on century timescales. Whether the retreat is driven by ocean changes or variability (Jenkins et al., 2018) is still under debate. Hence it is not possible to conclude on a lower emission scenario, which prevents substantial future ice loss.

A study by Clark et al. (2016) addresses the evolution of the ice sheets over the next 10,000 years and concludes that given a climate model with an equilibrium climate sensitivity of 3.5°C, the estimated combined loss of Greenland and Antarctica ranges from 25 to 52 m of equivalent sea level, depending on the emission scenario considered, with rates of GMSL as high as 2–4 m per century. A worst-case scenario was explored with an intermediate complexity climate model coupled to a dynamical ice model (Winkelmann et al., 2015), in which all readily available fossil fuels are combusted at present-day rates until they are exhausted. The associated climate warming leads to the disappearance of the entire Antarctic Ice Sheet with rates of sea level rise up to around 3 m per century.

In summary, there is *high confidence* in continued thermal expansion and the loss of ice from both the Greenland and Antarctic ice sheets beyond 2100. A complete loss of Greenland ice contributing about 7 m to sea level over a millennium or more would occur for sustained GMST between 1°C (*low confidence*) and 4°C (*medium confidence*) above preindustrial levels. Due to deep uncertainties regarding the dominant processes that could trigger a major retreat, there is *low confidence* in more specific estimates of the contribution of the Antarctic ice sheet beyond 2100 (from 1 m in 1000 years to up to 15 m in 500 years).

High-emission scenarios or exhaustion of fossil fuels over a multi-century period lead to rates of sea level rise as high as several meters/century in the long term (*low confidence*). Low-emission scenarios lead to a limited contribution over multi-century time scales (*high confidence*).

4.2.4 Synthesis of the Physics of Sea Level for Low-lying Islands and Coasts

This section aims to synthesize the key messages of our (geo-)physical understanding of sea level changes through time from the past to the present and future, which is important for determining exposure, vulnerability, impacts and risk related to sea level rise.

Past changes in sea level are informative as they show us the broad range of sea level in space and time over a wide range of climate conditions. These show that during past warm periods the sea level was considerably higher than today. During the Last Interglacial 130–115 Kyr BP, global temperatures are estimated to be 0.5°C–1.0°C higher than during the pre-industrial period, CO_2 around 280 ppm and sea level 6–9 m higher, but the forcing is different. The sea level estimates for the Mid-Pliocene are highly uncertain but possibly up to 20 m above the current level, with temperatures 1.9 to 3.6 degrees higher and CO_2 probably somewhat lower than today. Such results are a reason for concern and show that ice sheets are highly sensitive to modest warming (*high confidence*). These key finding suggest that with a few degrees of warming, substantial parts of the Antarctic and Greenland ice sheets may disappear on time scales of thousands of years or less.

However, we lack a firm understanding of the mechanisms which may lead to such an outcome and to the resulting rates of ice loss. Most modelling studies point to an insufficient contribution from Greenland during the Eemian period to explain the observed sea level rise. In addition, the temperature changes expected in the first half of the 21st century will not lead to a strong negative surface mass balance in Antarctica. For this reason, much research focuses on mechanisms which could contribute to mass loss for the ice sheets in the possible absence of a strong further warming. Mechanisms put forward are hydrofracturing of ice shelves, Marine Ice Sheet Instability, and Marine Ice Cliff Instability (see Cross-Chapter Box 2 in Chapter 1). Once ice shelves are broken up more regions maybe exposed to ice cliff instability implying a more sensitive dynamical response of the ice sheets than observed over the last century. Timing of ice shelf collapse by surface melt followed by hydrofracturing is currently poorly constraint. Geological observations also provide little constraint on these processes and records of on-going changes since the start of satellite observations are too short to allow strong conclusions on possible retreat mechanisms for the ice sheet under present-day climate conditions. However, there is a growing consensus that the ice-ocean interaction may be more important than hitherto assumed (*medium confidence*).

Church et al. (2013) were able to close the budget of observed sea level and the sum of the individual components. More recent insight indicate that the observed smaller sea level rise over the 20th century is a bit smaller, implying a stronger acceleration towards the end (*medium confidence*). This does not imply that our understanding is complete: particularly at smaller local scales, which matter for society, we have difficulties explaining the observations. This is even more true where short duration events determining the frequency of extreme sea level are concerned. At the same time, we note an increase in the rate of sea level rise as the mass of the ice sheets decreased, hence there is further awareness of the need to understand the detailed mechanism of retreat of ice sheets.

In the context of improved evidence of the present-day rates of change, but a limited understanding of drivers of ice sheet mass changes, we evaluated projections of models of future sea level rise. Where an increase in the understanding of the processes and improved observational evidence of retreat of the Antarctic ice sheet allows us now to include processes like MISI in the likely range of the projections (Section 4.2.3). An improved comprehension on century time scales also implies that, especially for projection later in the 21st century, process-based models are more informative than empirical models that are based on statistical correlations over the recent past. The latter models do not implicitly capture MISI. Hence, we can rely on process-based models for the 21st century when projections within the *likely* range are sufficient for the purposes of the user community. For 2050, there is a limited scenario dependency, but for the second half of the 21st century scenarios model simulation (Golledge et al., 2015; Ritz et al., 2015; DeConto and Pollard, 2016) diverge particularly on centennial time scales as illustrated in Figure 4.11. On a millennial time-scale, the difference in GMSL between RCP2.6 and RCP8.5 is about 10 meters in some model simulations, whereas it is only decimeters at the end of 21st century and a few centimeters around 2050. Clearly, we cannot rely on process-based models to provide reliable information useful for responses to coastal risk for time scales larger than a century. Alternatively, Clark et al. (2016) assessed the very long time-scale ~10^4 years without rapid ice dynamics and constrained by paleo-data only. This study provides limited constraints on mass loss rates at centennial time scales, but present results which are roughly similar to the magnitudes presented in Figure 4.11.

Deep uncertainty remains for these time scales and probabilistic approaches are not sufficient either. This is because they are typically developed including the MICI based on the DeConto and Pollard (2016) estimates for Antarctica, which are considered to be deeply uncertain. Hence, probabilistic scenarios (Le Cozannet et al., 2017) can only be defined, depending on a priori assumptions for the long term processes driving the dynamics of the Antarctic ice sheet.

The strong divergence between the scenarios makes it impossible to predict the future evolution on the basis of the existing literature. The specific trajectories that will be followed may depend critically on if and when certain tipping points are reached. Most critical in that respect are presumably the tipping points corresponding (1) to the threshold where the ablation in Greenland becomes larger than the accumulation, causing an irreversible and nearly full retreat of the ice sheet; and (2) to the thresholds for ice shelf stability in West Antarctica, which depend on surface melt and sub-ice melt. However, our ability to predict which trajectory of GMSL in Figure 4.11 will be followed might well take place only after the tipping point is passed in time. Improved insights to this problem may arise from physical modelling, together with results from dedicated monitoring systems. We conclude that the sea level rise on millennial time scales is strongly dependent on the emission scenario indicating, in combination with the lack in predictability of the tipping points, the importance of emissions mitigation for minimizing the risk to low-lying coastlines and islands (*high confidence*).

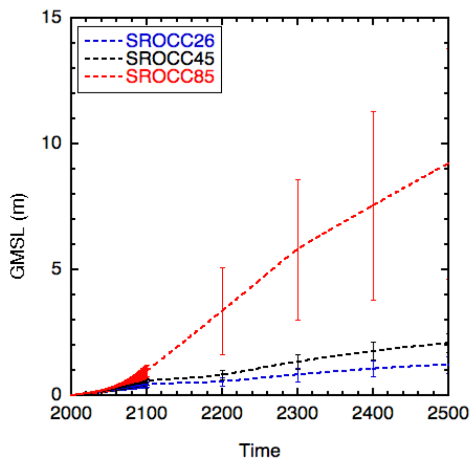


Figure 4.11: Schematic illustration of the evolution of GMSL over time, based on the *likely* range of projections for the (solid lines) as presented in section 4.2.3, Table 4.3. The dotted lines are indicative of possible futures on long time scales order 500 years, based on the studies by Golledge et al. (2015) and DeConto et al. (in review) on top of the projections for 2100. Uncertainties increase as time evolves and should be considered as indicative as they are based on two studies only. Extending RCP8.5 in time leads to a much higher Antarctic contribution than for the lower emission scenarios.

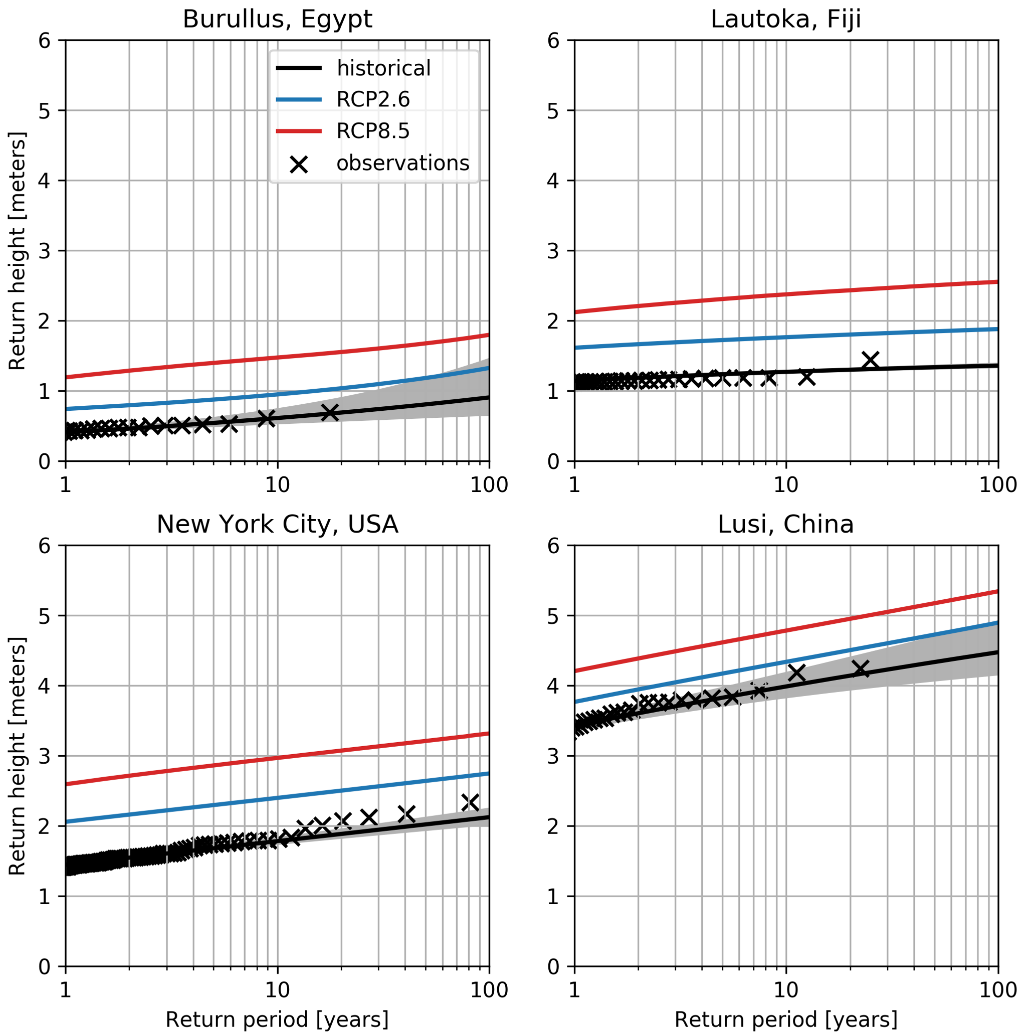
Many of the impacts of sea level rise do not depend on the gradual change of sea level rise over time but rather on the combination of the trend and the many processes which are important at local scales over short periods of time as shown in Figure 4.9 and 4.10. For this reason, the frequency of ESL is considered as well (Section 4.2.3). Results of the combined effect of RSL and ESL show that events which are rare (return period of 100 years or larger) in the historical context (probability < 0.01 yr^{-1}) will take place every year at some locations under each emission scenario (*high confidence*). This implies that adaptation is needed irrespective of the uncertainties in the Antarctic contribution. Particularly for small islands in the Pacific that are exposed to limited variability due to storm surges, the frequency of rare events will increase dramatically.

Under RCP8.5 this is already the case in 2050 for most locations, whereas for lower emission scenarios this will only be the case at the end of the century (*medium confidence*). From a purely physical perspective, the type and magnitude of adaptation needed depends on the Antarctic contribution as this dominates the uncertainty on century time scales.

[START BOX 4.1 HERE]

Box 4.1: Case Studies of Coastal Hazard and Response

This box presents case studies that demonstrate how information from all sections of this chapter are relevant when identifying and managing risks related to recent and projected (Box 4.1, Figure 1) sea-level rise at particular locations.

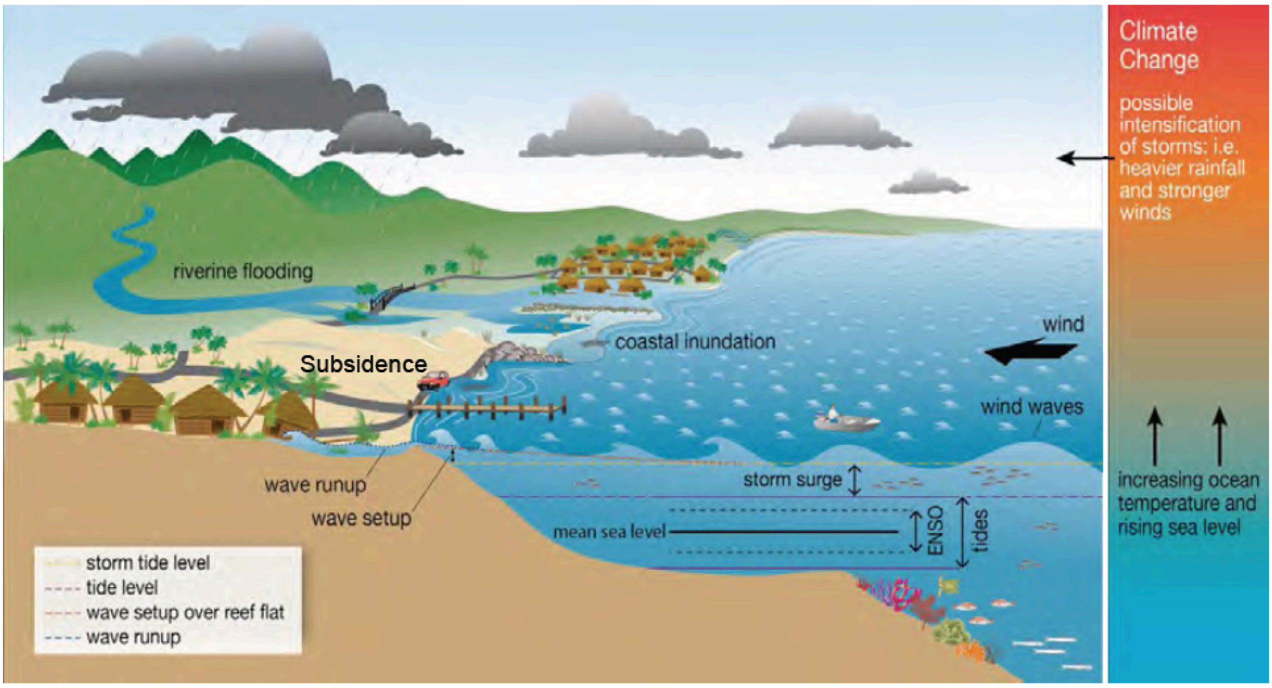


Box 4.1, Figure 1: Historical and projected extreme sea levels at four stations discussed in this Box. The return height of extreme sea level events is shown as a function of its average expected return period. Observations (crosses) are derived from tide-gauge records. The historical return height (black) is the best fit through these observations, and the 5%–95% confidence intervals (grey band) are shown. Note that the confidence interval for Lautoka is too narrow to be visible. Future return heights represent the effect of regional sea level change for the period 2081–2100 for scenarios RCP2.6 (blue) and RCP8.5 (red). The increased height of the 100-year event for scenario RCP2.6 (RCP8.5) is 0.42 (0.89) m for Burullus; 0.52 (1.2) m for Lautoka; 0.62 (1.19) m for New York; and 0.42 (0.87) m for Lusi. The increased frequency of

the historical 100-year event for scenario RCP2.6 (RCP8.5) is a factor of 14 (>1000) for Burullus; >1000 (>1000) for Lautoka; 63 (830) for New York; and 6 (35) for Lusi. The notation >1000 indicates that uncertainties allow estimation of a lower bound only.

Coastal Flooding and Inundation, Nadi, Fiji

The Nadi River basin and Nadi Town, the third-largest conurbation in Fiji, are located on the western side of the main island of Viti Levu. Box 4.1, Figure 2 illustrates the main hazards that contribute to riverine flooding and coastal inundation for the Nadi Basin, namely heavy rainfall, elevated sea levels and subsidence of the delta. Tropical cyclones are particularly hazardous because entail storm surges and high waves that result in extreme sea levels. In addition to causing flooding of low-lying coastal terrain, ESLs during a storm surge can slow the drainage of floodwater from coastal river systems to the ocean. This in turn may worsen the severity and extent of coastal and upstream flooding, through the 'backwater' effect.



Box 4.1, Figure 2: Natural hazards that contribute to flooding and inundation. Adapted from McInnes and Hoeke (2014). Storm surge, waves, ENSO, and tides combine to create sea level extremes.

People and built assets in the Nadi River flood plain are already being affected by climate change. Observed sea level shows a long-term increase of 4 mm/year. But this increase is nearly obscured by interannual and other variability associated with tropical cyclone and El Niño events. Over the past 75 years, extreme rainfall events have become more likely. This is reflected in the fact that, of the 84 floods which have occurred in the Nadi River Basin since 1870, 54 occurred post 1980. There have been 26 major floods since 1991 (Hay, 2017).

But the increased frequency of flooding is not all attributable to increases in sea level and extreme rainfall events. River channels have become filled with sediment, largely owing to deforestation of the hinterland. Much of the mangrove fringe has been sacrificed for development of various kinds. Like many river deltas, the one on which Nadi is located is subsiding (Chandra and Gaganis, 2016).

The flood that occurred in March, 2012, is considered the largest historical flood on record, with a 50-year return period. It affected more than 150,000 people, including four fatalities. In January, 2009 large areas of Fiji were inundated by devastating floods which claimed over 11 lives, left 12,000 people temporarily homeless and caused FJ$ 113 million (USD $54 million) of damage. Worst hit was the Nadi area, with total damage estimated at FJ$ 81.2 million (USD $39 million; Hay, 2017).

Exceptionally high sea levels are associated with coastal inundation, accelerated coastal erosion and salt-water intrusion into groundwater. There is a high level of exposure to inundation for most of the Nadi flood plain, with the potential for a serious disaster if a 1-in-100 year design flood were to occur. Projected changes in the ESL at the Lautoka tide gauge near Nadi for mid-to-late-21st century result in large increases in the frequency of extreme sea levels (keeping storm characteristic constant) compared to current ESLs. The water level for the 0.01 annual probability event (the "100-year" event) during 2081–2100 is shown in Box 4.1, Figure 1 under RCP2.6 and RCP8.5 respectively. The return frequency for the current 0.01 probability water level decreases to many times per year for both RCPs. Overall, projected changes in sea level were found to make the largest contribution to increased extreme sea-level risk (McInnes and Hoeke, 2014). Levels of uncertainty are indicated in Figure 4.9.

Various initiatives to help alleviate flooding and inundation in the Nadi basin have been proposed. These include both structural (e.g., ring dikes, river widening, bridge rebuilding, retarding basins, shortcutting tributaries, dams and diversion channels) and non-structural (e.g., early flood warnings, improved land management practices in upper basin) interventions.

Box 4.1, Table 1 shows recent improvements in understanding summarized in Section 4.2, suggesting that significant changes in the basis for the design and planning of the structural and related interventions could be made. The baseline assessment is the understanding that existed prior to SROCC.

Box 4.1, Table 1: Changes in the Basis for Design and Planning of Structural and Related Interventions (see Hay (2017) and Box 4.1, Figure 2)

	Baseline Assessment	Consistent with SROCC Assessment
Hazards	Design storm tide: 1.3 m Two-day design rainfall: 436 mm Subsidence: Not considered	Design storm tide: 2.6 m (100-year extreme sea level late 21st century) Two-day design rainfall: 670 mm Subsidence: 0.4 mm yr^{-1}
Exposure and Vulnerability	Exposure and vulnerability assessed for present day only—thus static, with no reference to drivers.	Exposure and vulnerability assessed for the present day and future time periods, with the projections taking into account both bio-physical and human drivers.
Levels of Risk	Reflect current levels of risk, with no allowance for climate, biophysical or socio-economic changes.	Risks reflect the full suite of biophysical and socio-economic changes over the life of the planned investment project, including their interactions.
Response Options	Interventions based entirely on reducing current levels of risk, with the primary focus being on structural measures to reduce flood hazard, and thereby flood risk. Non-structural measures not prioritised.	Rational mix of structural and non-structural interventions to reduced risks likely to occur over and beyond the life of the planned investment project.
Planning and Decision-Making	Takes a narrow 'flood control' approach aimed at 'controlling' single hazards, rather than managing the multiple and interacting risks in their broader contexts.	Takes a risk-based, flexible design approach that addresses the tension between the constancy of a given design standard on the one hand and, on the other hand, increasing flood risk over time due to further floodplain development, climate change leading to higher peak flows and inundation, and river channel bed aggradation.
Governance and Institutional Dimensions	The Natural Disaster Management Act (1988) focuses on coping with emergency situations and relief and rehabilitation, and less on risk reduction and disaster prevention. The Drainage Act (1985) establishes Drainage Boards that maintain, improve and inspect existing drainage channels and constructs new ones in relevant areas. Both the Town Planning Act and the Subdivision of Land Act regulate all land and building developments, land subdivision, on-site operations and activities defined as development under the Act. The Nadi Town Drainage Plan was completed in August 2000, in order to address	A holistic catchment management approach integrates flooding from all sources, as well as changes in catchment land use. Flood management aims to achieve a particular level of flood hazard protection that is desired and accepted by stakeholders, with residual risks fully understood, proactively planned for and their consequences managed. A comprehensive "Flood Management Strategy and Plan" for the Nadi River Basin would help achieve the desired complementarity between flood control structures and non-structural measures. Strengthening of policies on water and land management, as well as

drainage problems and reduce flood damage in Nadi town. However, the Plan was developed without distinction between inland water and river water, without hydraulic analysis and verification, and without a scientific basis. While retention dams were constructed, the other initiatives in the Plan have not seen substantive implementation.

addressing related legal and institutional issues, could be undertaken at the national, basin and local government levels as part of preparing a flood management strategy and plan.
Such an approach within the Nadi municipality would proactively reduce exposure of individuals, communities and assets to existing flood hazards, and thus complement the investment in flood protection works to protect existing flood-prone areas.

A Comparison of Coastal Flood Hazard, Vulnerability and Adaptation Measures between New York City and Shanghai

New York City (NYC) is the financial center of the US and lies at the junction of the Hudson River and Atlantic Ocean. Shanghai is the economic center of China, located at the mouth of the Yangtze River where it enters the East China Sea. Both cities play critical roles in the global economy and trade, with dense population, infrastructure, and concentrated assets in the floodplain (e.g., Lower Manhattan in NYC) and a long history of extreme flooding events.

Hurricane Sandy (2012) and Typhoon Winnie (1997) are considered to be the largest recorded historical flood events for NYC and Shanghai, respectively. Hurricane Sandy killed 55 people in NYC and neighboring states and caused over USD $32 billion losses to the US. New Jersey and New York areas witnessed the most substantial damage along the coastlines (Xian et al., 2015). Typhoon Winnie killed more than 310 people and caused damage exceeding USD $3.2 billion to China. Many dikes and flood walls along coastal Shanghai and Zhejiang were breached by surge flood waters. Storm surge and heavy rainfall inundated many parts of the towns and cities as the typhoon moved inland. The estimated return period of a flood reaching the levels attained during Hurricane Sandy is from 100 to 1200 years at the Battery tide gauge (Sweet et al., 2013; Zervas, 2013; Lopeman et al., 2015; Lin et al., 2016; Xian et al., 2018). The return period of the flood level attained during Typhoon Winnie is about 100 years at the Wusong tide gauge station (Yin et al., 2013; Xian et al., 2018).

The two cities face an increasing flood risks in the future due to sea level rise and local land subsidence. NYC's sea level at the Battery station rose at an average rate of 1.3 mm yr^{-1} (excluding land subsidence) over the last 100 years (Xian et al., 2018). Sea level at the Wusong station in Shanghai rose at a faster average rate 2.6 mm yr^{-1} (excluding land subsidence) through the period of 1910–2000 (Yin et al., 2011). Land subsidence rate in Shanghai, estimated at 5mm/year, is also much higher than in NYC. The Shanghai rate is dominated by tectonic subsidence (TS) and compaction of sediments (Gong and Yang, 2008; Shanghai Municipal Bureau of Planning and Land Resources, 2008; Yin et al., 2013). Therefore, the mean rate of sea level rise in Shanghai is considerably higher than NYC. Both rates far exceed the global mean rate of rise over 20th century.

The exposed assets of both cities to flood risks is also high. Hanson et al. (2011) estimated that for 2005 the value of exposed coastal assets in the New York-Newark area (USD $320 billion) was over four times that of Shanghai (USD $73 billion). By 2070, the magnitude of the exposed assets of Shanghai (USD $1.7 trillion) is expected to be close to that of the New York-Newark metropolitan area ($2.1 trillion; Hanson et al., 2011). Limited construction and development activities have occurred in NYC (especially in Manhattan, Brooklyn, and the Bronx) since 1979, compared with the rapid development in Shanghai, whose urban area increased by 1064% from 1979 to 2010 owing to the rapid economic transition and development in China (Xian et al., 2018). Most of Shanghai's growth in exposed value has occurred near the low elevation urban center. Future development along the coast is *likely* to be greater for Shanghai than NYC. In terms of future urban development for both of the two cities, a full risk assessment would take into account historical observation and the dynamic, increasing nature of flood risk. Response options include a wide range of structural and non-structural measures.

Individual past extreme flood events have influenced the immediate reaction of policy makers and can be the driving force for protection measures (Pelling and Dill, 2010; Albright, 2011). Comparing past updates of the flood defense heights with past annual maximum water levels at the Wusong station in Shanghai shows that each update is associated with an extreme flood event induced by a severe typhoon (i.e., typhoons in 1962, 1974, and 1981). In contrast, the peak water tide of Hurricane Sandy stands out in the record at the Battery tidal gauge station. Unlike the frequent episodes of severe flood inundation experienced by Shanghai, NYC suffered relatively moderate consequences from individual events before Hurricane Sandy. This and others factors led to higher-standard flood protection measures in Shanghai, such as sea walls with a 200-year coastal flood return level design that protect its coastlines and critical infrastructure in developed areas, and flood walls with 1000-year riverine flood return level along the Huangpu River to protect the city from riverine flooding. New York City, on the other hand, has relatively low protection, consisting of sandy dunes (e.g., on Staten Island), vegetation (e.g., in Queens) and low-rise sea walls in lower (Manhattan). Since Hurricane Sandy in 2012, discussions about possible flood protection strategies for concentrated assets and infrastructure engaged a range of stakeholder groups. For example, implementation of the 'Big U' project, a proposed coastal protection system for lower Manhattan, has begun and new public and private hospitals are required to be out of the flood zones. Moreover, the Metropolitan Transit Authority introduced new equipment that includes custom doors and curtains that can be deployed to protect underground subway stations and can withstand 4.3 m of water above street level from future flooding. Construction and siting guidelines for publicly-financed projects in the current and future flood zones have been tightened (NYC, 2018). The degree to which these protection projects will be completed and the guidelines enforced remains uncertain.

In spite of higher-standard of flood protection measures, the current protections in Shanghai may also not be sufficient to prevent future flooding (see Lusi tide gauge; Box 4.1, Figure 1). Previous studies show that around half of the length of current sea walls in Shanghai may be overtopped by storms in 2100 (Wang et al., 2012). For any coastal megacities like Shanghai and NYC, delaying investment in coastal protection until disaster strikes can result in additional costs later, e.g., demolishing and then reconstruction of sea walls, as evidenced by past experience in Shanghai (Xian et al., 2018). Alternatively, the time-varying nature of the hazard can be systematically incorporated into the design process (Lickley et al., 2014), making allowance for periodic updating with new information on the changing climate and development setting, in order to increase the probability that the protection height remains consistent with the level of acceptable risk (Section 4.4.4.1).

Governance and funding structure are also important to consider when interpreting effectiveness of adaptation by megacities. For example, Shanghai has a high level of autonomy in decision making, and objectives of the central and local governments are aligned, limiting governance conflicts in implementing extensive efforts needed to protect the city (Wei and Leung, 2005; Yin et al., 2011). In addition, rapid economic growth in Shanghai and China during the past 30 years provided adequate funding for large-scale infrastructure (Zhang, 2003). In contrast, for NYC, the multiple jurisdictions of the city, state, and federal governments present a challenge to financing and implementing measures to mitigate climate-related risks (Rosenzweig and Solecki, 2014). More effective implementation experience than NYC's comes from megacities in other highly developed countries including London with planning, construction, and potential upgrading of the Thames Barrier and Rotterdam with dike-rings, a surge barrier, and other structural and non-structural measures (Ranger et al., 2013).

Box 4.1, Table 2: Changes in the Basis for Design and Planning of Structural and Related Interventions

	Baseline Assessment	Consistent with SROCC Assessment
Hazards Assessment	100-yr storm tide: 4.5m Shanghai vs 2.1m NYC Subsidence: 5 mm yr^{-1} Shanghai vs 1-2 mm yr^{-1} NYC	Design storm tide: 5.3 m Shanghai vs 3.3 m NYC (100-year ESL late 21st century) Subsidence in Shanghai can be higher
Multiple Drivers of Exposure and Vulnerability	Current exposure & vulnerability considers topographic elevation, social vulnerability .	Exposure and vulnerability for the current and future time periods should take into account projections that consider both physical and human drivers.
Levels of Risk	Reflect current hazard plus some freeboard: 0.3–1m for NYC; 0.5+ m for Shanghai, with no consideration for storm characteristics and socio-economic changes.	Risks reflect the full suite of climate change and socio-economic changes and their interdependency for the planned coastal projects; use freeboard that accounts for ESL uncertainty, such as ESL with probability >5% during planning horizon.

Response Options	Structural measures: fixed-height sea wall, building retrofit; Non-structural: insurance, building codes.	Optimal mix of structural and non-structural measures to minimizee combined total costs; more flexible design that reflects the dynamic risk.
Planning and Decision Making	Funding and governance can slow down the long-term planning and implementation process.	Flexible adaptation responses to uncertain long-term risk facilitate protection planning and impementation.
Governance and Institutional Dimensions	Shanghai has higher autonomy and alignment of central and local. governments; NYC's decision making in context of multilayer governance.	More effective coordination and transparency among local and central government agencies are needed in response to increasing risks.

Climate Change Adaptation in Nile Delta Regions of Egypt

The Nile Delta makes up only 2% of Egypt's total area but holds 41% of its total population (Hereher, 2010) estimated at 95 million in 2016 (World Bank, 2017). The area of the Nile Delta is about 20,000 km2 (Van der Most et al., 2009). It includes many of Egypt's highly populated cities and the majority of its industries (Dahshan et al., 2016). It is also Egypt's food basket, containing more than 63% of its cultivated lands and the majority of its fish farms (Hereher, 2009; El-Sayed, 2016) and ranks among the world's most fertile farming areas (Stanley and Warne, 1993).

Its relevance for the national economy can hardly be underestimated (Bucx et al., 2014). Moreover, the Nile Delta's coastal lagoons are among the most productive natural systems in Egypt, they are internationally renowned for their abundant bird life, while the wetlands of the Nile delta constitutes about 25% of the total wetlands area in the Mediterranean region, and produce 60% of fish catch of Egypt (Government of Egypt, 2016).

The Nile Delta is considered to be one of the world's three "extreme" vulnerability hotspots (Parry et al., 2007). Coastal flooding and/or permanent inundation of these areas will lead to a decline in water quality in the coastal freshwater lagoons, with consequential adverse impacts on fisheries and biodiversity (GCF, 2017). Moreover, Gebremichael et al. (2018) inferred that an estimated 2660 km2 in northern delta will be inundated by year 2100 using eustatic sea level rise of 0.44 m.

Subsidence of the delta heightens vulnerability to coastal flooding, particularly when combined with sea-level rise (Box 4.1, Table 3). This results from both natural (e.g., compaction of river sediments over time) and anthropogenic drivers (e.g., construction of dams that restrict the flow of sediment that would otherwise reach the river mouth and build up delta lands; groundwater extraction, and onshore gas fields, Gebremichael et al. (2018)).

Box 4.1, Table 3: Sea level rise and subsidence rates in the Nile Delta (Elshinnawy et al., 2010)

Region	Alexandria (West Delta)	Al-Burullus (Mid Delta)	Port Said (East Delta)
(1) Subsidence (mm yr^{-1})	0.4	1.1	3.35
(2) SLR (mm yr^{-1})	1.2	1.2	1.95
Tidal Trend (mm yr^{-1}) (sum of 1+2)	1.6	2.3	5.3

Among present critical challenges are marked reduction of Nile water and sediment below the High Aswan Dam that can reach the delta coast. It is expected that problems of fresh water and energy poverty in the lower Nile Basin are likely to be seriously exacerbated in years ahead by construction of Ethiopia's Grand Renaissance Dam (GERD) (Stanley and Clemente, 2017).

The Nile Delta region, which is less than 0.5 m above sea level, is clearly extremely vulnerable to SLR (Shaltout et al., 2015). Comparing projected twenty - first century SLR and digital elevation data indicates that, with the median sea level rise under RCP8.5, the Nile delta region will experience markedly increased flooding during the current 1% annual probability event without effective adaptation measures, such as shore protection and integrated coastal-zone management. The water level attained at the Burullus tide gauge in the current 1% annual probability event, about 0.9m, is expected to recur many times per year late in the 21st century under RCP2.6 and RCP8.5. The future 1% probability event attains a height of about 1.3 m and 1.9m for RCP2.6 and RCP8.5, respectively (Box 4.1, Figure 1).

As a result, the low-lying northern coast and Nile Delta region are a high priority for adaptation to climate change (Government of Egypt, 2016). The Sustainable Development Strategy (SDS) 2030 also includes coastal adaptation to climate change (SDS 2015), with increasing the climate resilience of infrastructure being a high priority. The Government has already committing $200 million to start addressing the urgent needs for Alexandria by constructing hard coastal protection structures. It is also taking an integrated coastal zone management approach to long-term planning for the entire North Coast in the face of climate change. Recent activities include development of a framework for decision making to address coastal adaptation planning, integrating sea-level rise risks within an adaptive capacity approach for human/natural systems, identification of the main challenges associated with the protection of people living in coastal cities, strengthening decision-making capacity for predicting and mitigating climate change impacts on agriculture and the environment along the Nile Delta coast and identifying migration and human security dimensions in the development of policies and plans to address climate change (GCF, 2017).

Box 4.1, Table 4: Changes in the Basis for Design and Planning of Structural and Related Interventions

	Baseline Assessment	**Consistent with SROCC Assessment**
Hazards	Tidal trend: +1.6 – 5.3 mm yr^{-1} Subsidence: +0.4 – 3.4 mm yr^{-1}	100-year ESL 1.3m and 1.9m RCP2.6 and RCP8.5, respectively Subsidence: 0.4–3 mm yr^{-1}
Exposure and Vulnerability	Coastal flooding has adverse effects on Egypt's economy and society, given the concentration of population, industry, agriculture, aquaculture, tourism and transport infrastructure in the Nile Delta.	The northern part of the coastal delta zone is the site of Egypt's second largest city, Alexandria, with a population of 2.9 million in 1986, 3.3 million in 1996, and more than 4.1 million in 2006 (CAPMAS, 2006). This region accounts for more than 50% of Egypt's economic activity through agriculture, industry and fisheries. The Nile Delta covers only about 2% of Egypt's area but hosts about 41% of the country's population and comprises nearly 63% of its agricultural land (Hereher, 2010; Mabrouk et al., 2013). It is among the most densely populated agricultural areas in the world, with 1,360 inhabitants per km² (Masria et al., 2014), and in terms of economic activities, fisheries productivity is about 185,000 tons yr^{-1} from the northern lakes (Oczkowski and Nixon, 2008). About 40% of all Egyptian industries are located in Nile Delta (Negm et al., 2016). As Egypt does not produce enough food to feed its current population, any loss of prime agricultural land due to coastal flooding from sea level rise (SLR) will have a direct adverse impact on the livelihoods of millions of people and lead to hardship throughout the entire economy (UNDP, 2017).
Levels of Risk	An increase in frequency and severity of storm surges is already evident; and the continuation of rising seas, sinking lands, and more frequent and intense storms is inferred from the review of recent trends and future climate change forecasts (GCF, 2017).	These threats are projected to intensify, driven in part by the increasing frequency and intensity of extreme coastal storms and associated storm surges, as well as acceleration of sea-level rise and, possibly, subsidence (GCF, 2017).

Response Options	Unconnected and small incremental steps toward increasing management capability in Egypt to confront coastal flood risks associated with sea-level rise, including enhancing planning paradigms and interventions that account for climate change threats, including enhancing community preparedness, building capacity, and improving resilience to coastal flooding impacts.	A new coastal planning paradigm is needed to enable better management of the future range of climatic risks to the natural and built environment, covering both structural and non-structural interventions. These would be sequenced to account for urgently needed coastal protection. A systematic observation network would be developed, to monitor changing marine conditions and evaluate the effectiveness of coastal protection measures.
Planning and Decision Making	One of the most prominent obstacles to ICZM in Egypt is the complex and sometimes unclear institutional framework for addressing development activities; the limited and often ad hoc approach between different agencies. There is an absence of a systematic approach to coordinate the different tasks of the involved ministries and institutions, to set agreed priorities and to clarify overlapping mandates.	Transformational change to sustain long-term coastal resilience along its North Coast, including a comprehensive approach to coastal protection that addresses urgent near-term risks while putting in place a framework for a systematic and integrated planning of coastal zone development in the North Coast that addresses mid- to long-term risks under climate change.
Governance and Institutional Dimensions	Some recent projects and proposals aim to integrate the management of SLR risks into the development of Egypt's Low Elevation Coastal Zone (LECZ) in the Nile Delta (GCF, 2017).	Strengthening the regulatory framework and institutional capacity to improve resilience of coastal settlements and development infrastructure, implement innovative and environmentally friendly measures that facilitate/promote adaptation in the Nile Delta and establish a monitoring and assessment framework and knowledge management systems on adaptation (Masria et al., 2014).

[END BOX 4.1 HERE]

4.3 Exposure, Vulnerability, Impacts and Risk Related to Sea Level Rise

4.3.1 Introduction

Section 4.2 demonstrates that sea level is rising and accelerating and that it will continue to rise throughout the 21st century and beyond. It also shows that extreme sea level events that are historically rare, will become common by 2100 under all emission scenarios, leading to severe flooding in the absence of strong adaptation (*high confidence*). In the RCP8.5 emission scenario, many small islands and megacities in the three oceans and at all latitudes will experience such events annually by 2050. In such a context, Section 4.3 takes stock of the most recent scientific literature since IPCC AR5 on the dimensions of exposure and vulnerability (Section 4.3.2), on observed and projected impacts (Section 4.3.3), and on recent methodological advances in exposure and vulnerability assessments (Box 4.2). It concludes by discussing compound events and IPCC Reasons for Concern related to SLR (Section 4.3.4), and includes a synthesis figure on the future risks of impact to illustrative geographies and with/without successful adaptation. To allow for a global picture, this section encompasses a wide range of low-lying coastal areas, such as small islands (including Small Island Developing States), coastal cities, deltas and other continental coasts.

[START BOX 4.2 HERE]

Box 4.2: Methodological Advances in Exposure and Vulnerability Assessments

The methods for exposure and vulnerability assessments are well established and evolved further since AR5. This box showcases recent advances in methodologies in assessing exposure and vulnerability to sea level rise and its physical impacts, such as coastal flooding. Since the emphasis is on methodological advances, not all references cover a coastal context. Exposure refers to the presence of people; livelihoods;

environmental services and resources; infrastructure; or economic, social, or cultural assets in places that could be adversely affected (SREX Annex II: Glossary) by sea level rise among other things. Vulnerability is the propensity or predisposition to be adversely affected (SREX Annex II: Glossary).

Advances in exposure assessment

Many studies deal with exposure assessment, most of them considering exposure as one manifestation of risk, with a smaller number of studies interpreting exposure as a geographical location (Jurgilevich et al., 2017). Since AR5, major advances have taken place in two main areas: i) spatial-temporal assessment of exposure and ii) projected future exposure.

Improved spatial-temporal exposure assessments

The assessment of exposed elements is frequently based on census data, which is usually available at coarse resolutions. The disaggregation of census data to a higher resolution grid has often been based on proxies such as population distribution. However, technological advances (e.g., drones, mobile data, big data) and the free and ready availability of satellite data have brought, and will continue to bring, advances in exposure analysis. Exposure assessment is increasingly based on the combination of high resolution satellite imagery and spatio-temporal population modelling to understand diurnal differences in flood risk exposure (Smith et al., 2016a), dynamic gridded population information for daily and seasonal differences in exposure (Renner et al., 2017), a combination of remotely-sensed and geospatial data with modelling for a gridded prediction of population density at ~100 m spatial resolution (Stevens et al., 2015), or open building data using building locations, footprint areas and heights (Figueiredo and Martina, 2016). In addition, methods based on mobile phone data (Deville et al., 2014; Ahas et al., 2015), and social media-based participation are increasingly available for population distribution mapping (Steiger et al., 2015). Some of these methodologies have been already applied in coastal assessments (Smith et al., 2016a). The level of spatial resolution is shown to impact the accuracy and precision of the risk assessment (Figueiredo and Martina, 2016) especially in case of localized hazards such as hailstorms or floods. Integrating daily and seasonal changes with the distribution of population in turn improves population exposure information for risk assessments especially in areas with highly dynamic population distributions, such as in highly touristic areas (e.g., Renner et al., 2017).

Projections of future exposure

Many climate risk and vulnerability assessments used and continue to use present-day data for population, land use and ecosystem exposure against projected future hazards (e.g., Shepherd and Binita, 2015). As coastal communities may change (e.g., grow or shrink due in- and outmigration trends), the potentially exposed population and assets will change. Recent studies assess exposure considering not only projected sea levels but also expected changes in population size (Jongman et al., 2012; Hauer et al., 2016), involving different socio-economic scenarios together with changing growth rates for coastal areas and the hinterland (Neumann et al., 2015) and using spatially explicit simulation models for urban, residential, and rural areas (Sleeter et al., 2017). Also migration-based changes in population distribution (Merkens et al., 2016; Hauer, 2017) are considered as well as simulated future land use (specifically urban growth) to investigate future exposure to sea level rise (Song et al., 2017). Other studies have started to assess future exposure trends by accounting for the role of varying patterns of topography and development projections leading to different rates of anticipated future exposure (Kulp and Strauss, 2017), which may influence how effectively coastal communities might adapt (*limited evidence, medium agreement*). As coastal communities may change (e.g., expand over time), the potentially exposed assets and population will change. Additionally to population size and spatial distribution, recent studies aim to account for the socio-demographic characteristics of these potentially exposed future populations (Shepherd and Binita, 2015), and anticipate future risk by projecting the evolution of the exposure of socially vulnerable sub-populations (Hardy and Hauer, 2018). Using social heterogeneity modelling (Rao et al., 2017) when developing future exposure scenarios enhances the quality of risk assessments in coastal areas (Hardy and Hauer, 2018). Subnational population dynamics combined with an extended coastal narrative-based version of the five Shared Socioeconomic Pathways (SSP) for global coastal population distribution was used for assessing global climate impacts at the coast, highlighting regions where high coastal population growth is expected and which therefore face increased exposure to coastal flooding (Merkens et al., 2016).

Advances in vulnerability assessment

Since the IPCC SREX report, vulnerability has been more consistently considered in climate risk assessments (*medium evidence, medium agreement*). It is recognised that climate risk is not just hazard-driven, but also a socio-economic phenomenon that evolves with changing societal and institutional conditions (*high evidence, high agreement*). Many studies related to climate risk and adaptation include vulnerability assessments, most of them considering vulnerability as a pre-existing condition while some interpret vulnerability as an outcome (Jurgilevich et al., 2017). Since AR5 major advances in the assessment of vulnerability took place in the following areas: (i) understanding the importance of dynamic assessments, (ii) assessing the vulnerability of social-ecological systems, (iii) assessing vulnerabilities to multiple hazards simultaneously, (iv) using vulnerability functions and/or thresholds instead of linear functions for more realistic outcomes, and (v) using new, better data in vulnerability assessments.

Increasing importance of dynamic assessments

The dynamic nature of vulnerability, and the need to align climate forecasts with socio-economic scenarios, was a key message of IPCC SREX. Due to challenges in methodology and data availability, particularly of future socio-economic data, it is only now that an increasing number of studies include socio-economic and spatial dynamics into assessments of future vulnerability. Lack of data is overcome by extrapolating empirical information of past trends in flood vulnerability (Jongman et al., 2015; Mechler and Bouwer, 2015; Kreibich et al., 2017), downscaling global scenarios, for example, the shared socioeconomic pathways (SSPs) (Van Ruijven et al., 2014; Viguié et al., 2014; Absar and Preston, 2015), or by using participatory methods, surveys and interviews to develop future scenarios (Ordóñez and Duinker, 2015; Tellman et al., 2016). The uncertainty of the downscaled projections is an issue that needs to be considered in the interpretation along with the limitation that, even if population data projections are available, the future level of education, poverty etc. is exceedingly hard to predict (Jurgilevich et al., 2017). Suggestions to overcome these shortcomings entail the use of a combination of different data sources for triangulation and inclusion of uncertainties (Hewitson et al., 2014), or the meaningful involvement of stakeholders to project plausible future socioeconomic conditions through co-production (Jurgilevich et al., 2017). Recent innovations in (flood) risk assessment include the integration of behavioural adaptation dynamics into risk assessments, which may lead to an improvement in risk-management strategies and related investments (Aerts et al., 2018).

Social-ecological vulnerability assessments

The majority of existing coastal vulnerability and risk assessments focus largely on the social and/or economic dimension (Mondal, 2013; Tessler et al., 2015; Mansur et al., 2016). In many cases, especially in rural, natural resource-dependent settings, where the population directly rely on the services provided by ecosystems, the vulnerability of the ecosystems (e.g., fragmented, degraded ecosystems with low biodiversity) directly influence the that of the population. Social-ecological vulnerability assessments provide a valuable framework for identifying and understanding important social-ecological linkages, and the implications of dependencies and other feedback loops in the system. Since AR5 several methods have been developed and piloted to assess and map social-ecological vulnerability using, for example, the sustainable livelihood approach and resource dependence metrics for Australian coastal communities (Metcalf et al., 2015), integration with local climate forecasts for coral reef fisheries in Papua New Guinea (Maina et al., 2016), an ecosystem, supply-demand model for an integrated vulnerability assessment in a Rostock, Germany (Beichler, 2015) indicators developed in a participatory way for multiple hazards in river deltas (Hagenlocher et al., 2018), and human-nature dependencies and ecosystem services for small-scale fisheries in French Polynesia (Thiault et al., 2018). Hotspots of social vulnerability may be, but are not necessarily associated with hotspots of ecosystem vulnerability, highlighting the need to specifically adapt management interventions to local social-ecological settings and to adaptation goals (Hagenlocher et al., 2018; Thiault et al., 2018). The number of social-ecological assessment studies is increasing but socio-economic factors still tend to dominate these assessments (Sebesvari et al., 2016).

Assessment of vulnerability to multiple hazards simultaneously

The same social-ecological system is often exposed to more than one hazard. Increasingly, multi-hazard risk assessments are undertaken at the coast (e.g., flooding and inundation of coastal lands in India; Kunte et al., 2014), to understand the inter-relationships between hazards (e.g., Gill and Malamud, 2014), and by focusing on hazard interactions where one hazard triggers another or increases the probability of others occurring. Liu et al. (2016a) provide a systematic hazard interaction classification based on the geophysical environment that allows for the consideration of all possible interactions (independent, mutex, parallel, series) between different hazards, and for the calculation of the probability and magnitude of multiple interacting natural hazards occurring together. The hazard interaction classification was then piloted in China's Yangtze River

Delta (Liu et al., 2016a). Also, vulnerability indicators might have to be different, depending on the hazard(s) considered. For example, the existence of shelters will lower vulnerability in the context of cyclones while it is irrelevant in case of drought. Some advances have been achieved since AR5 by using, for example, modular sets of vulnerability indicators flexibly adapting to the hazard situation (Hagenlocher et al., 2018).

Using vulnerability functions, thresholds, innovative ways of aggregation in indicator-based assessment, improved data sources

Vulnerability functions account for the fact that vulnerability and impact may not be linearly related to hazard intensity or exposure (*medium evidence, high agreement*). The use of vulnerability functions has been shown to be helpful in assessing the damage response of buildings to tsunamis (Tarbotton et al., 2015), and accounting for non-linear relationships between mortality and temperature above a 'comfort temperature' (El-Zein and Tonmoy, 2017). Several publications have shown that additive or multiplicative methodologies have weaknesses when using indicator-based vulnerability assessments (e.g., Fernandez et al., 2017). Outranking procedures and the concepts of preference, indifference and dominance thresholds have been applied as a form of data aggregation to reflect the non-compensatory nature of different vulnerability indicators (e.g., proximity to the sea cannot always be fully compensated by being wealthy; Tonmoy and El-Zein, 2018). Similarly to advances in exposure assessments, freely available data and mobile technologies hold promise for enabling better input data for vulnerability assessments, for example, through a combination of mobile phone and satellite data to determine and monitor vulnerability indicators such as poverty (Steele et al., 2017), or to use data on subnational dependency ratios and high resolution gridded age/sex group datasets (Pezzulo et al., 2017).

Summary

Since AR5, advances have been made in exposure and vulnerability assessments to better characterize sea level rise-related coastal hazard risk and enable the identification and localization of appropriate adaptation and risk reduction strategies. Main areas of post-AR5 progress include providing better projections for cascading and multiple hazards and physical impacts, such as sea level rise coastal flooding and salinization, and more realistic information on exposure and vulnerability. Nevertheless, coastal assessments that take a social-ecological perspective to multiple hazards in a dynamic and forward looking way are still rare.

[END BOX 4.2 HERE]

4.3.2 Dimensions Exposure and Vulnerability to Sea Level Rise

4.3.2.1 Key Insights from the IPCC's SREX and AR5 Publications

4.3.2.1.1 Recent knowledge on the environmental dimension of exposure and vulnerability

Exposure of coastal ecosystems to sea level rise and related coastal hazards change by two means: alterations in the spatial coverage and distribution of ecosystems within the potentially exposed area and changes in the size of the exposed area caused by relative sea level rise. The vulnerability of coastal ecosystems to sea level rise and related coastal hazards differs strongly across ecosystem types and depends on human interventions (e.g., land use change and fragmentation, coastal squeeze, anthropogenic subsidence) and impacts (e.g., pollution), as well as climate change related impacts other than sea-level rise such as changes in temperature and precipitation patterns. On the other hand, sea level rise and its physical impacts, such as flooding or salinization, also increase ecosystems´ vulnerability and decrease the ecosystems´ ability to support livelihoods and provide coastal protection. There is a *high evidence* that healthy, diverse, connected coastal ecosystems support local adaptation at the coast to sea level rise and its consequences. This section explores new knowledge since AR5 regarding changes in ecosystem´s exposure and vulnerability as well as processes affecting the ability of ecosystems to adapt to SLR, and associated impacts such as flooding or salinization on coastal social-ecological systems and coast-dependent livelihoods.

Changes in the exposure of coastal ecosystems

The effects of coastal habitat loss on ecosystem exposure are well documented (Lavery et al., 2013; Serrano et al., 2014; Short et al., 2014; Yaakub et al., 2014; Cullen-Unsworth and Unsworth, 2016; Breininger et al., 2017), and depend on the type of ecosystem, its conservation status, and interactions with SLR (Kirwan and

Megonigal, 2013). For instance, coastal habitat loss due to human growth and encroachment due to development, and human structures that restrict tides and, thus, interrupt mass flow processes (water, nutrients, sediments) impact tidal ecosystems depending on the type of restriction, its severity and the geomorphology of the system (Burdick and Roman, 2012). In addition, seagrass and other benthic ecosystems, for example, are declining across their range at unprecedented rates (Telesca et al., 2015; Unsworth et al., 2015; Samper-Villarreal et al., 2016; Balestri et al., 2017), due to degrading water quality (i.e., increased nutrient and sediment or DOC loads) from upland-based activities, which include deforestation, agriculture, aquaculture, fishing, and urbanization, port development, channel deepening, dredging and anchoring of boats (Saunders et al., 2013; Ray et al., 2014; Deudero et al., 2015; Abrams et al., 2016; Benham et al., 2016; Mayer-Pinto et al., 2016; Thorhaug et al., 2017). However, the exact magnitude of area loss is still uncertain especially at smaller scales (Yaakub et al., 2014; Telesca et al., 2015). Also, human-induced impacts have facilitated the replacement of seagrasses by alternative vegetation, but the implications of habitat shifts for ecosystem attributes and processes and the services they deliver remain poorly known (Ray et al., 2014; Tuya et al., 2014). On the other hand, although threatened, coastal dunes may remain stable because their distribution is adequately covered by protected areas (Prisco et al., 2013). However, their distribution, like that of marshes and other coastal ecosystems, is limited by 'coastal squeeze', which prevents inland migration of current wetland ecosystems (Schile et al., 2014; Hopper and Meixler, 2016).

Changes in the vulnerability of coastal ecosystems

Large and small-scale processes influence the stability of coastal ecosystems and can interact to restrict ecosystem responses to SLR and thus increase vulnerability. At the large-scale, global changes in precipitation and air temperature represent a potentially significant risk to ecosystems, which increases the vulnerability of ecosystems to sea-level rise and related hazards (Garner et al., 2015; Osland et al., 2017). Maximum temperature and mean precipitation change over the last 100 years are main drivers of ecosystem stability (Mantyka-Pringle et al., 2013). In addition, seawater warming may affect marine communities and ecosystems but research remains sparse and results are contradictory (Crespo et al., 2017; Hernán et al., 2017). Also, the synergistic effects between climate change and habitat loss due to human impact and urban development are increasingly well-documented but the effects are still not well-known at larger spatial and temporal scales (Kaniewski et al., 2014; Sherwood and Greening, 2014). In addition, and although evidence is limited, recurrent disturbances may lead to losses in ecosystem adaptive capacity (Villnäs et al., 2013).

At smaller scales, conversion of coastal areas to urban, agricultural, and industrial uses exacerbates pressure on ecosystems, increases their vulnerability to natural hazards including sea-level rise and decreases their ability to support coastal livelihoods and to deliver ecosystem services such as storm protection, fisheries production, wildlife habitat, recreational use, tourism, and global biodiversity (Foster et al., 2017). The vulnerability of exposed ecosystems is highly variable, as shown in intertidal rocky reef habitats in Australia (*high confidence*) (Thorner et al., 2014). Even without SLR, the transition zone between two coastal ecosystems and adjacent uplands responds dynamically and rapidly to inter-annual changes in inundation, with local factors, such as management of water control structures, outweighing regional ones (Wasson et al., 2013). The resulting interaction of these variables and dynamics with fragmentation, land use planning and management (Richards and Friess, 2017) has only recently started to be investigated.

Research to date has focused on identifying synergisms among stressors (Campbell and Fourqurean, 2014; Lefcheck et al., 2017; Moftakhari et al., 2017; Noto and Shurin, 2017), but antagonisms and other feedbacks may be just as common (Brown et al., 2013; Conlisk et al., 2013; Maxwell et al., 2015; Crotty et al., 2017) and are seldom investigated, as is also true for thresholds and tipping points in coastal ecosystem stability and vulnerability (Connell et al., 2017; O'Meara et al., 2017; Wu et al., 2017). This precludes complete understanding of their complex responses, which may be greater than additive responses alone (Crotty et al., 2017), their adequate management, or restoration regimes (Maxwell et al., 2015; Unsworth et al., 2015). Furthermore, although local management cannot entirely avoid severe climate change impacts on ecosystems, it can slow them down and allow for evolutionary adaptation, developing alternate local management or allowing enough time to achieve the reduction of global GHG emissions necessary to slow degradation of ecosystems (Brown et al., 2013).

In contrast, ecosystems with strong physical influences controlling elevation (sediment accretion and subsidence), even where mangrove replacement of salt marsh is expected, do not show changes in their vulnerability to SLR (McKee and Vervaeke, 2018), suggesting strong resilience of some natural ecosystems. In areas such as South Florida and the wider Caribbean, however, mangroves cannot outpace current SLR rates and are at risk of disappearing. These regional and local effects are highly variable (even contradictory between studies; e.g., Smoak et al., 2013; Koch et al., 2015) and are related to local conditions shaping vulnerability such as topography and controls over salinity from freshwater and inputs (Flower et al., 2017), but further research on the mass and surface energy balance is needed (Barr et al., 2013). In addition, the responses and behavior of private landowners who may impede landward migration of ecosystems is incipient (Field et al., 2017) and, thus, highly uncertain. Overall, the long-term resilience of coastal communities and their ability to respond to rapid changes in sea level is largely unknown (Foster et al., 2017).

In summary, coastal areas and ecosystem´s responses to sea level rise around the globe is complex, with many specific responses at the ecosystem level or from keystone (foundation) species remaining poorly understood (Thompson et al., 2015). Likewise, responses are studied independently when holistic approaches may be required to understand how multiple threats affect ecosystem components, structure and functions (Giakoumi et al., 2015). Increasing exposure and vulnerability of coastal ecosystems contributes to both increasing human exposure and vulnerability to sea level rise (Arkema et al., 2013).

4.3.2.1.2 Recent knowledge on the human dimensions

It is widely recognized at least since the 2012 SREX report that patterns of human development create and compound exposure and vulnerability to climate-related hazards, including SLR (*high confidence*). Studies have progressively moved from the analysis of various parameters' influence taken individually (education, poverty, etc.,) to a more systemic approach that describes combinations of parameters, e.g., coastal urbanization and settlement patterns (see Section 4.3.2.2) resulting from urban-rural discrepancies and trends in socioeconomic inequalities. The AR5 thus started differentiating between direct and indirect drivers of exposure and vulnerability (Wong et al., 2014), and between contemporary and historically-rooted drivers (e.g., trends in social systems over recent decades; Marino, 2012; Duvat et al., 2017; Fawcett et al., 2017). It also reported some progress in the development of context-specific studies, especially on coastal megacities, major deltas and small islands (Cross-Chapter Box 7).

The IPCC AR5 also concluded with *very high confidence* that both relative SLR and related impacts are influenced by a variety of local social and/or environmental processes unrelated to climate (e.g., subsidence, glacial isostatic adjustment, sediment supply, coastal squeeze). Some of these processes are partly attributable as anthropogenic drivers, and although they may or may not be directly related to relative SLR, they do cause changes in coastal ecosystem habitat connectivity and ecosystem health conditions, for instance, and consequently influence the ability of coastal social-ecological systems as a whole to cope with and adapt to SLR and its impacts.

However, the scientific literature still barely deals specifically with the exposure and vulnerability of social-ecological systems to SLR. Rather, papers predominantly analyse the immediate and delayed consequences of extreme events such as tropical cyclones, storms and distant swells (see Chapter 6), for instance, and the resulting exposure and vulnerability 'in the context of SLR' (Woodruff et al., 2013). One reason for this focus touches on the difficulty, for society to fully comprehend and science to fully analyse long-term gradual changes like SLR (Fincher et al., 2014; Oppenheimer and Alley, 2016; Elrick-Barr et al., 2017) and ocean warming and acidification (Section 5.4.2.1). Consequently, Sections 4.3.2.2 to 4.3.2.6 concentrate on highlighting the anthropogenic or systemic drivers that have the potential to influence exposure and vulnerability to slow-onset sea level-related hazards, and pay relatively less attention to drivers only influential in the context of extreme events.

4.3.2.2 Settlement Trends

Major changes in coastal settlement patterns have occurred in the course of the 20th century due to various socio-economic processes including population growth and demographic changes (Smith, 2011; Neumann et al., 2015), urbanization and an rural exodus, tourism development, displacement and/or (re)settlement of some indigenous communities (Ford et al., 2015), changes in education levels and socio-economic disparities, etc. This global megatrend has resulted in a growing number of people living in the Low Elevation Coastal Zone (~9% of the world's population; Neumann et al., 2015; Jones and O'Neill, 2016;

Merkens et al., 2016) and in significant infrastructure and assets being located in risk-prone areas (*high confidence*). High density coastal urban development is commonplace in both developed and developing countries, as documented in extensive recent case studies, including, just to mention few, in Canada (Fawcett et al., 2017), China (Yin et al., 2015; Lilai et al., 2016; Yan et al., 2016), Fiji (Hay, 2017), France (Genovese and Przyluski, 2013; Chadenas et al., 2014; Magnan and Duvat, 2018), Israël (Felsenstein and Lichter, 2014), Kiribati (Storey and Hunter, 2010; Duvat et al., 2013), New Zealand (Hart, 2011) and the USA (Heberger, 2012; Grifman et al., 2013; Liu et al., 2016b).

This translates at the regional and local scales (*medium evidence, high agreement*). In Latin America and the Caribbean, for example, it is estimated that 6% to 8% of the population live in areas that are at high or very high risk of being affected by coastal hazards (Reguero et al., 2015; Calil et al., 2017; Villamizar et al., 2017). In the Pacific, ~57% of Pacific Island countries' built infrastructure are located in risk-prone coastal areas (Kumar and Taylor, 2015). In Kiribati, due to the flow of outer, rural populations to limited, low-elevated capital islands, together with constrains inherent in the socio-cultural land tenure system, the built area located <20 m from the shoreline quadrupled between 1969 and 2007–2008 (Duvat et al., 2013). Other examples of rural exodus are reported in the recent literature, for example in the Maldives (Speelman et al., 2017). As a sign of a megatrend, population densification also affects rural areas' exposure and vulnerability. Still in atoll contexts, for example, the growing pressure on freshwater lenses together with a loss in local knowledge (e.g., how to collect water from palm trees), resulted in the increased exposure of communities to brackish, polluted groundwater, inducing water security and health problems (Storey and Hunter, 2010; Lazrus, 2015). Noteworthy are other factors shaping settlement patterns, such as the fact that 'indigenous peoples in multiple geographical contexts have been pushed into marginalized territories that are more sensitive to climate impacts, in turn limiting their access to food, cultural resources, traditional livelihoods and place-based knowledge…aspects of social-cultural resilience' (Ford et al., 2016a, p. 350). Also, 'while traditional settlements on high islands in the Pacific were often located inland, the move to coastal locations was encouraged by colonial and religious authorities and more recently through the development of tourism' (Ballu et al., 2011; Nurse et al., 2014, p. 1623; Duvat et al., 2017). Although these population movements are orders of magnitude smaller than the megatrends described above, they play a critical role at the very local scale in explaining the emergence of, or changes in exposure and vulnerability features.

4.3.2.3 Interaction of Sea-Born and Terrestrial Processes Shaping Coastal Exposure and Vulnerability

While the previous sections concentrate on exposure and vulnerability at the coast, this section provides post-AR5 knowledge on drivers of exposure and vulnerability related to the interplay of coastal and hinterland processes such as changes in catchment connectivity, mass flows (water, sediment, nutrients) as well as coastal squeeze.

Coastal areas, including deltas, are highly dynamic as they are affected by natural and/or human-induced processes locally or originating from both the land and the sea. Changes within the catchment can therefore have severe consequences for coastal areas in terms of sediment supply, pollution, and/or land subsidence. Sediment supply reaching the coast is a critical factor for delta sustainability (Tessler et al., 2018) and has declined drasticly in the last few decades resulting from dam construction, land use changes and sand mining (Ouillon, 2018; high confidence, high agreement). For instance, Anthony et al. (2015) reported largescale erosion affecting over 50% of the delta shoreline in the Mekong delta between 2003 and 2012, which was attributed in part to a reduction in surface-suspended sediments in the Mekong river potentially linked to dam construction within the river basin, sand mining in the river channels, and land subsidence linked to groundwater over-abstraction locally. Schmitt et al. (2017) demonstrated that these and other drivers in sediment budget changes can have severe effects on the very physical existence of the Mekong delta by the end of this century, with the most important single driver leading to inundation of large portions of the delta being ground-water pumping induced land subsidence. Thi Ha et al. (2018) estimated the decline in sediment supply to the Mekong delta to be around 75% between the 1970s and the period 2009–2016. In the Red River, the construction of the Hoa Binh Dam in the 1980s lead to a 65% drop in sediment supply to the sea (Vinh et al., 2014). Based on projections of historical and 21st century sediment delivery to the Ganges-Brahmaputra-Meghna, Mahanadi, and Volta deltas Dunn et al. 2018 showed that these deltas fall short in sediment and may be unable to maintain their current elevation relative to sea level, suggesting increasing salinization, erosion, flood hazards, and adaptation demands.

Another, rarely considered factor is the shift in tropical cyclone climatology which also plays a critical role in explaining changes in fluvial suspended sediment loads to deltas as demonstrated by Darby et al. (2016), again for the Mekong delta. More generally, most conventional engineering strategies that are commonly employed to reduce flood risk (including levees, sea-walls, and dams) disrupt a delta's natural mechanism for building land. These approaches are rather short-term solutions which overall reduce the long-term resilience of deltas (Tessler et al., 2015; Welch et al., 2017). Systems particularly prone to flood risk due to anthropogenic activities include North America's Mississippi River delta, Europe's Rhine River delta, and deltas in East Asia (Renaud et al., 2013; Day et al., 2016). In regions where suspended sediments are still available in relatively large quantities, rates of sedimentation can vary depending on multiple factors, including the type of infrastructure present locally, as was shown by Rogers and Overeem (2017) for the Ganges-Brahmaputra-Meghna (Bengal) Delta in Bangladesh as well as seasonal differences in sediment supply and place of deposition. For example, in meso-tidal and macro-tidal estuaries, during floods most of the sediments is depositing in the coastal zones and that a large part of these sediments are brought back to the estuary during the low flow season by tidal pumping. This can lead to significantly higher deposition rates in the dry season as it was shown by Lefebvre et al. (2012) in the lower Red River estuary and by Gugliotta et al. (2018) in the Mekong delta. Enhanced sedimentation further upstream in estuaries and a silting-up of estuarine navigation channels can have high economic consequences for cities with a large estuarine harbour will be. In Haiphong city in North Vietnam the authorities decided to build a new harbour further downstream, for a cost estimated at USD $2 billion (Duy Vinh et al., 2018).

Overall, reduced freshwater and sediment inputs from the river basins are critical factors determining delta sustainability (Renaud et al., 2013; Day et al., 2016). In some contexts, this can be addressed through basin-scale management which allow more natural flows of water and sediments through the system, including methods for long-term flood mitigation such as improved river-floodplain connectivity, the controlled redirection of a river (i.e., avulsions) during times of elevated sediment loads, the removal of levees, and the redirection of future development to lands less prone to extreme flooding (Renaud et al., 2013; Day et al., 2016; Brakenridge et al., 2017). These actions could potentially increase the persistence of coastal landforms in the context of sea level rise. Next to decreasing sediment inputs to the coast, river bed and beach sand mining has been shown to contribute to shoreline erosion, for example, for shorlines of Crete (Foteinis and Synolakis, 2015), several sub-Saharan countries such Kenya, Madagascar, Mosambique, South Africa, Tanzania (UNEP, 2015). At the global scale, 24% of the world's sandy beaches are eroding at rates exceeding 0.5 m yr^{-1}, while 28% are accreting. The largest and longest eroding sandy coastal streatches are in North-America (Texas; Luijendijk et al., 2018).

Shorline erosion leads to coastal squeeze if the eroding coastline approaches fixed and hard built or natural structures as noted in AR5 (Pontee, 2013; Wong et al., 2014), a process to which sea level rise also contributes (Doody, 2013; Pontee, 2013). The AR5 further noted that coastal squeeze is expected to accelerate due to rising sea levels (Wong et al., 2014). Doody (2013) characterized coastal squeeze as coastal habitats being pushed landward through the effects of sea level rise and other coastal processes on the one hand and, and on the other hand, the presence of static natural or artificial barriers effectively blocking this migration, thereby squeezing habitats in an increasingly narrower space. There are distinctions being made between coastal squeeze being limited to (1) the consequences of sea level rise vs. other environmental changes on the coastline and (2) the presence of only coastal defence structures vs. natural sloping land or other artificial infrastructure (Pontee, 2013). Recent publications have emphasised coastal squeeze related to sea level rise, although inland infrastructure blocking habitat migration was not necessarily limited to defence structures (Torio and Chmura, 2015; McDougall, 2017). Coastal ecosystem degradation by human activities leading to coastal erosion was also considered (McDougall, 2017). As long as SLR impacts remain moderate, the dominant impact will be linked to land-based development. With increased impacts of SLR, the latter will be become predominant assuming no further development on the coast.

Preserved coastal habitats can play important roles in terms of reducing risks related to some coastal hazards and initiatives are put in place to reduce coastal squeeze, such as managed realignment which includes the removal of fixed barriers inland (Doody, 2013). Coastal squeeze can lead to degradation of coastal ecosystems and species (Martínez et al., 2014), but if inland migration is unencumbered, observation data and modelling have shown that net area of coastal ecosystems could increase under various scenarios of sea level rise, depending on ecosystems considered (Torio and Chmura, 2015; Kirwan et al., 2016; Mills et al., 2016). However, recent modelling research has shown that rapid sea level rise in a context of coastal squeeze could be detrimental to the areal extent and functionality of coastal ecosystems (Mills et al., 2016) and, for marshes, could lead to a reduction of habitat complexity and loss of connectivity, thus affecting both aquatic and terrestrial organisms (Torio and Chmura, 2015). Contraction of marsh extent is also identified by Kirwan et al. (2016) when artificial barriers to landward migration are in place. Adaptation to sea level rise therefore needs to account for both development and conservation objectives so that trade-offs between protection and realignment that satisfy both objectives may be identified (Mills et al., 2016).

In summary, catchment-scale changes have very direct impacts on the coastline, particularly in terms of water and sediment budgets (*high confidence*). The changes can be rapid and modify coastlines over short periods of time, outpacing the effects of SLR leading to increased exposure and vulnerability of social-ecological systems (*high confidence*). Beyond 2050, SLR is expected to generate greater impacts, especially in high-emission scenarios (*high confidence*). Without losing sight of this fact, it is however imperative that catchment-level processes be understood and managed to limit rapid increases in exposure and vulnerability. Further to hinterland influences, coastal squeeze increases coastal exposure as well as vulnerability by the loss of a buffer zone between the sea and infrastructure behind the habitat being squeezed. The clear implication is that coastal ecosystems progressively lose their ability to provide regulating services with respect to coastal hazards, including with respect to the risk posed by sea level rise in terms of inundation and salinization. The vulnerability of communities is increased through the loss of other ecosystem services that these ecosystems could provide, for example in terms of direct income linked to tourism or when livelihoods are directly dependent on these ecosystems. Vulnerability is also increased when freshwater resources become salinized, particularly in the case when these resources are already scarce.

4.3.2.4 Other Human Dimensions

Important progress has also been made on capturing the role of anthropogenic drivers of exposure and vulnerability that were reported only as emerging issues at the time of the AR5. This is partly due to the progressive geographical extension of social science studies dealing with climate issues, for example, on the Arctic (Ford et al., 2012; Ford et al., 2014) and small islands (Petzold, 2016; Duvat et al., 2017), and to their downscaling at the local level, for instance, within cities (Rosenzweig and Solecki, 2014; Paterson et al., 2017; Texier-Teixeira and Edelblutte, 2017) or at the household level (Koerth et al., 2014). Four examples of such emerging issues are discussed below. The two firsts are gender inequality and the loss of indigenous knowledge and local knowledge, both more broadly reflecting growing scientific and non-scientific concern about the influence of socio-economic inequalities and the decline in human-nature ties, respectively, on exposure and vulnerability to coastal hazards, including SLR. The two others, social capital and risk perception, illustrate recent advances in understanding the complexity of anthropogenic drivers of exposure and vulnerability, with a growing attention paid to multi-parameter, dynamic and context-specific analyses (Bennett et al., 2016; Duvat et al., 2017) showing both the intertwining of a society's basic characteristics, and the variable direction of drivers' influence (Hesed and Paolisso, 2015; McCubbin et al., 2015).

4.3.2.4.1 Gender inequality

Gender inequality, which cannot be isolated from other socio-economic dynamics, came to prominence recently in climate change studies (~15 years ago; see Pearse, 2017). In light of sea-related hazards and SLR specifically, the issue is still mainly investigated in the context of developing countries, although growing attention is paid to the situation in developed countries (e.g., Lee et al., 2015; Pearse, 2017). Recent studies in southern coastal Bangladesh, for example, show that women get less access than men to climate- and disaster-related information (both emergency information and training programmes), to decision-making processes at the household and community levels, to economic resources including financial means such as micro-credit, to land ownership, and to mobility within and outside the villages (Rahman, 2013; Alam and Rahman, 2014; Garai, 2016). Gender inequity may be inherent in unfavourable background conditions (higher illiteracy rates, deficiencies in food and calories intake, and poorer health conditions) as a result of, among other things, traditions, social norms and patriarchy. Together, these barriers disadvantage women more than men in developing effective responses to anticipate gradual environmental changes such as persistent coastal erosion, flooding and soils salinization (*medium evidence, high agreement*). Such conclusions are in line with the literature on gender inequality and climate change at large (Alston, 2013; Pearse, 2017), thus suggesting no major SLR-inherent specificities.

4.3.2.4.2 Loss of indigenous and local knowledge

Despite the identification of this issue in AR4, its treatment in AR5 was very limited, partial and ambiguous, as, for example, contradictory reference was made to indigenous people as both powerless victims in the face of climate change, and ultimate holders of valuable knowledge to address climate change. Recent literature partly focussing on SLR reaffirms that indigenous knowledge (IK) and local knowledge (LK; Cross-Chapter Box 3 in Chapter 1; see SROCC Annex I: Glossary) are key to determining how people recognize and respond to environmental risk (Bridges and McClatchey, 2009; Lefale, 2010; Leonard et al., 2013; Lazrus, 2015), and therefore to increasing adaptive capacity and reduce long-term vulnerability (Ignatowski and Rosales, 2013; McMillen et al., 2014; Hesed and Paolisso, 2015; Janif et al., 2016; Morrison, 2017). Using examples of small islands in southeast Asia, Hiwasaki et al. (2015) describe IK and LK as being fully part of social-ecological processes structuring cultural traditions and activities. IK and LK contribute both as a foundation and an outcome to customary resource management systems aiming at regulating resources use and securing critical ecosystems protection (examples in Indonesia; Hiwasaki et al., 2015), at structuring the relationships between people and authorities, and at framing and maintaining a sense of the environment in the community (examples in Timor Leste; Hiwasaki et al., 2015). In turn, this allows local communities to predict and prepare for both sudden shock events that have historical precedent and, when IK and LK are embedded in day-to-day rituals, festivals, legends or decision-making processes, to also anticipate the consequences of gradual changes, like in sea level (examples in Indonesia; Hiwasaki et al., 2015). Customary resource management systems based on IK and elders' leadership—for instance, Rahui in French Polynesia (Gharasian, 2016), or Mo in the Marshall Islands (Bridges and McClatchey, 2009)— also allow communities to diversify access to marine and terrestrial resources using seasonal calendars, to ensure collective food and water security, and to maintain ecological integrity (McMillen et al., 2014). In rural Pacific atolls, traditional food preservation and storage (e.g., storing germinated coconuts or drying fish) still play a role in anticipating disruptions in natural resources availability (Campbell, 2015; Lazrus, 2015). Such practices have enabled the survival of isolated communities from the Arctic to tropical islands in constraining sea environments for centuries to millennia (McMillen et al., 2014; Nunn et al., 2017a). Morrison (2017) argues that IK and LK can also play a role in supporting sustainable internal migration in response to SLR, by avoiding social and cultural uprooting. It is also important to spotlight that in some specific contexts, climate change will also imply no-analogue changes, such as rapid ice-melt and changing conditions in the Arctic that have no precedent in the modern era, and could thus limit the relevance of IK and LK in efforts to address significantly different circumstances. Except in these specific situations, the literature suggests that the loss of IK and LK and related social norms and mechanisms will increase populations' exposure and vulnerability to the impacts of SLR (Nakashima et al., 2012). The literature notably points out that modern, externally-driven socio-economic dynamics, such as the introduction of imported food (noodles, rice, canned meat and fish, etc.), diminish the cultural importance of IK-based practices and diets locally, together with introducing dependency to monetization and external markets (Hay, 2013; Campbell, 2015). Such trends may increase long-term vulnerability to SLR (*medium evidence, high agreement*). For example, in the rural Nanumea Atoll, Tuvalu, IK supports the traditional search of 'unity or balance between the social sphere and the environmental conditions, [with the] Pre-Christian cosmology [linking] the behavior of Nanumean chiefs with the well-being of the environment' (Lazrus, 2015, p. 56). In such a context, the loss of cultural ties with in situ environmental features and dynamics increases the community's exposure and vulnerability to environmental disruptions and gradual changes, notably through unsustainable livelihood practices and poor consideration of natural hazards. Finally, given that IK and LK are largely based on observing and 'making sense' of the surrounding environment (moon, waves, winds, animal behaviors, topography, etc.), the loss of IK and LK reflects a more general concern about the loss of environmental connectedness in contemporary societies, which is not limited to remote, rural and developing communities (*medium evidence, medium agreement*). In developed contexts too, the loss of LK has played a critical role in recent coastal disasters (e.g., Katrina in 2005 in the USA, Kates et al., 2006) and increasing vulnerability to SLR (e.g., Newton and Weichselgartner, 2014; Wong et al., 2014).

4.3.2.4.3 Social capital

Recent studies confirm that besides weaknesses in the face of climate change impacts, small communities also have social structures that can increase adaptive capacity to coastal hazards (Petzold, 2018). The concept of social capital can be used in this context (Aldrich and Meyer, 2015; Petzold and Ratter, 2015). Influenced by underlying social processes, such as socioeconomic (in)equalities, gender issues, health, social networks, among others, social capital indicates the level of societal cohesion between individuals, between groups of individuals, and between people and institutions. It applies to both developing and economically advanced contexts, for example in densely populated deltas (Jordan, 2015), European coasts (Jones and Clark, 2014; Petzold, 2016), Asian urban or semi-urban coastal areas (Lo et al., 2015; Triyanti et al., 2017) and Pacific islands (Neef et al., 2018). It is noteworthy that social capital framed as a driver of resilience (i.e., decreasing vulnerability) is mostly studied in the context of extreme events (risk prevention mechanisms, emergency responses, post-crisis actions) and collective management of environmental features (e.g., mangroves replanting, beach cleaning, etc.), and little applied to the anticipation of slow onset changes such as SLR. Some scholars, however, have started to explore the possible contribution of social capital to the public acceptability of long-term adaptation policies (Jones and Clark, 2014; Jones et al., 2015), as well as its limitations, as collective beliefs, social networks, and social and institutional trust can also negatively influence long-term vulnerability to coastal hazards (Young et al., 2014; Jordan, 2015). This suggests that while social capital can help address SLR, it can also be indirectly undermined by SLR (see Section 4.3.3.6.4), for example in the case of the migration away from coastal communities (e.g., Nunn, 2013).

4.3.2.4.4 Risk perception

Risk perception, which is in essence subjective, varying from one individual to another, may influence communities' exposure and vulnerability as it shapes authorities' and people's attitudes towards slow-onset and/or slow onset hazards—as shown by Terpstra (2011), Lazrus (2015), Elrick-Barr et al. (2017) and O'Neill et al. (2016) in case studies of the Netherlands, Tuvalu, Australia and Ireland, respectively. For example, the deaths caused by Storm Xynthia in 2010 in France resulted from demographic features (especially ageing; Vinet et al., 2012), but also from the combination of the construction of one-storey residential buildings in low-lying, flood-prone areas in recent decades; the weak maintenance of coastal dykes; and a proportional increase in newcomers' to the region (Genovese and Przyluski, 2013; Chadenas et al., 2014). Yet, such a combination of drivers is partly rooted in progressive discounting of coastal hazard risks and subsequent loss of risk memory, as illustrated in coastal disasters such as Hurricane Katrina in 2005 (Burby, 2006; Kates et al., 2006). Risk perception is acknowledged to be a complex anthropogenic driver of exposure and vulnerability due both to its multi-factorial nature and to its context-specific influence on policy, decision-making and action in the face of climate change (Terpstra, 2011; van der Linden, 2015). Risk perceptions stem from intertwined predictors such as 'gender, political party identification, cause-knowledge, impact-knowledge, response-knowledge, holistic affect, personal experience with extreme weather events, [social norms] and biospheric value orientations' (Kellens et al., 2011; Carlton and Jacobson, 2013; Lujala et al., 2015; van der Linden, 2015, p. 112; Weber, 2016; Elrick-Barr et al., 2017). Other predictors can also come into play such as, e.g., the distance to the sea (Milfont et al., 2014; Lujala et al., 2015; O'Neill et al., 2016).

The importance of various risk perception drivers is contested. For example, knowledge about the causes and possible impacts of climate change is usually consdiered a key determinant of risk perception worldwide, whether it is based on local/indigenous traditions or education levels depending on the context (Lee et al., 2015). Refining the analysis by disaggregating "knowledge" for six high-income countries, Shi et al. (2016, p. 756) show that 'general scientific knowledge [is not] a robust predictor of perceived climate change risks [and that] instead, risk perceptions [are] more heavily influenced by cultural worldviews.' This emphasizes that the way that "potential drivers" are measured—e.g., physical vs. perceived distance to the hazard source (O'Neill et al., 2016)—is critical to determine the nature and direction of the influence of these drivers on risk perception, and therefore of risk perception on exposure and vulnerability (Shi et al., 2016). There are however few studies on how the variability of risk perception influences exposure and vulnerability in different geographical and human contexts (e.g., Terpstra, 2011; van der Linden, 2015). There is also a critical lack of studies specifically addressing SLR. Some very recent works conducted in coastal Australia suggest that while people are confident about their ability to cope with an already experienced event, when it comes to SLR, the dominant narrative is articulated around the barriers related to the 'uncertainty in the nature and scale of the impacts as well as the response options available' (Elrick-Barr et al., 2017, p. 1147). SLR is rarely addressed separately from sea-related extreme events, which masks a crucial difference between already-observed and delayed impacts. Climate change is considered as a "distant psychological risk" (Spence et al., 2012), making it and SLR per se 'markedly different from the way that our ancestors have traditionally perceived threats in their local environment' (Milfont et al., 2014; Lujala et al., 2015; van der Linden, 2015, p. 112; O'Neill et al., 2016).

4.3.2.5 Towards a Synthetic Understanding of the Drivers of Exposure and Vulnerability

Recent literature irrevocably confirms that anthropogenic drivers played the major role, over the last century, in the increase of exposure and vulnerability worldwide and they will continue to do so in the absence of adaptation (*medium evidence, high agreement*). Some scholars argue that '(…) even with pervasive and extensive environmental change associated with ~2°C warming, it is non-climatic factors that primarily determine impacts, response options and barriers to adapting' (Ford et al., 2015, p. 1046). Although it is the interaction of climate and non-climate factors that eventually determine the level of impacts, acknowledging the role of a ragne of purely anthropogenic drivers has important implications for action, especially by showing that major action can be already undertaken in favour of long-term adaptation despite uncertainty of local climate change impacts (Magnan et al., 2016). Noteworthy, acting on the human-driven root causes of vulnerability could also have co-benefits, for example on improving the state and condition of coastal ecosystems—and hence on the capacity to cope with or adapt to SLR and it impacts—or, in deltaic regions, on lowering the rates of subsidence. In turn, this can help mitigate the hazards itself, especially relative SLR.

We now better understand the diversity and interactions of the climate and non-climate drivers of exposure and vulnerability. As a result, we realize how much context-specificities (geography, social inequity, risk perceptions, etc.) play a critical role in shaping the direction of influence of individual drivers and of their possible combinations on the ground (*medium evidence, high agreement*).

Recent studies (e.g., cited in this section) also confirm AR5 conclusions that both developing and developed countries are exposed and vulnerable to SLR (*high confidence*).

The ability of coastal ecosystems to serve as a buffer zone between the sea and human assets (settlements and infrastructure), and to provide regulating services with respect to SLR-related coastal hazards (including inundation and salinization), is progressively being lost due to coastal squeeze, pollution, habitat degradation and degradation due to land use conversion, etc. In addition, other climate-related drivers play a growing detrimental role on coastal and marine ecosystems, such as ocean warming and acidification for example (Section 5.2.2). Overall, ecosystem degradation is acknowledged as a major driver of exposure and vulnerability in the coastal zone (*high evidence, high agreement*).

4.3.3 Observed Impacts, and Current and Future Risk of Sea Level Rise

Climate change induces modifications to the ocean's and the cryosphere's physical and chemical parameters (ice density, permafrost thaw rates, river water flows, ocean pH, sea-surface temperature, etc.) that, together with extreme events (e.g., storms, marine heat waves, etc.), explain the extent and rates of changes in mean and extreme sea levels (Section 4.2). This generates six main coastal hazards for low-lying coasts (Figure 4.12): (i) permanent submergence of land by mean sea-levels or mean high tides; (ii) more frequent or intense coastal flooding; (iii) enhanced coastal erosion; (iv) loss and change of coastal ecosystems; (v) salinization of soils, ground and surface water; and (vi) impeded drainage (Seneviratne et al., 2012; Nurse et al., 2014; Wong et al., 2014). Other processes unrelated to sea-level rise induce changes such as starvation of sediments provided by rivers (Kondolf et al., 2014); permafrost thaw and ice retreat (Cramer et al., 2014); or the disruption of natural dynamics by coastal development and activities such as land reclamation or sediment mining, which interfere with the impacts caused by sea-level rise. As shown in Figure 4.12, these hazards affect ecosystems (marshes and mangroves, lagoons, coral reefs, seagrass), natural resources (e.g., groundwater) and ecosystem services (e.g., coastal protection by mangroves or coral reefs). Together with the influence of anthropogenic drivers, these impacts on ecosystems and natural resources directly and indirectly impact society, such as people, assets, infrastructures, agriculture, tourism, fisheries and aquaculture, socioeconomic inequity and well-being, etc. The sections below describe some of the above-mentioned impacts, both observed and projected, but assuming business-as-usual adaptation efforts (i.e., no major additional efforts compared to what is—or not—currently done). This reflects a relative gap in the scientific literature on the consideration of the benefits of enhanced adaptation to reduce future risks; some advances on this aspect are discussed in Section 4.3.4.2.

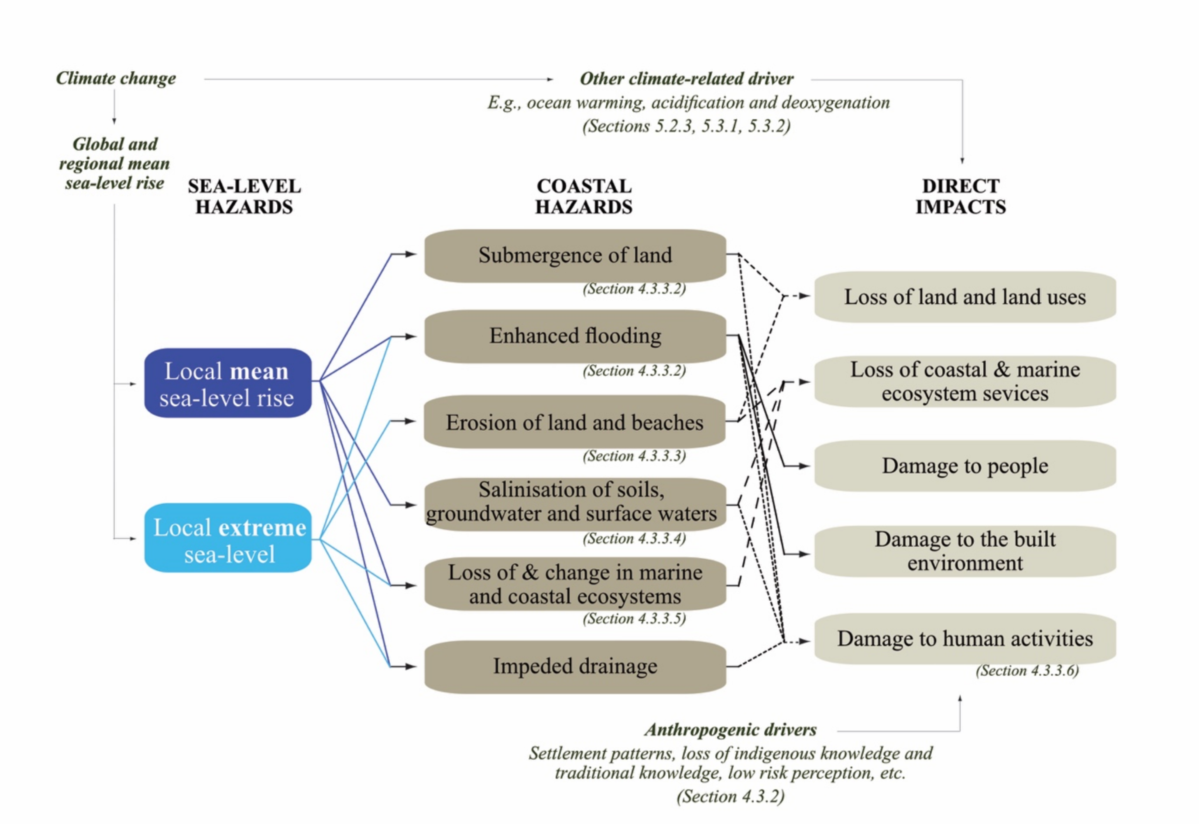


Figure 4.12: Overview of the main cascading effects of sea-level rise. Colours and styles of lines (dotted/non dotted) and boxes are used only for the readability of the figure.

4.3.3.1 Attribution of Observed Physical Changes to Sea Level Rise

The AR5 concludes on the major difficulty to attribute changes observed at the coast to SLR per se because 'the coastal sea level change signal is often small when compared to other processes' (Wong et al., 2014, p. 375). On coastal morphological changes, e.g., contemporary SLR currently acts as a "background driver", with extreme events, changes in wave patterns, tides and human intervention often described as the prevailing drivers of observed changes (Grady et al., 2013; Albert et al., 2016). Despite the complexity of the attribution issue (Romine et al., 2013; Le Cozannet et al., 2014), recent works suggest possibly emerging signs of the direct influence of recent SLR on shoreline dynamics, for example on low-lying, sensitive coasts in New Caledonia (Garcin et al., 2016), the Federal States of Micronesia (Nunn et al., 2017b) and the Solomon Islands (Albert et al., 2016). Early signs of the direct influence of SLR on estuaries' water salinity are also emerging, for example, in the Delaware, USA, where Ross et al. (2015) estimate a rate of salinity increase by as much as 4.4 psu (= g Na+Cl- per Liter) per meter of SLR since the 1950s. Overall, while the literature suggests that it is still too early to attribute coastal impacts to SLR in most of the world's coastal areas, there is agreement that as sea level continues to rise, the frequency, severity and duration of hazards and related impacts, will increase (Woodruff et al., 2013; Lilai et al., 2016; Vitousek et al., 2017). Perceivable impacts—and hence attributable impacts—on shoreline dynamics are expected as soon as the second half of the 21st century (Nicholls and Cazenave, 2010; Storlazzi et al., 2018).

As a result, the following sections involve both studies directly attributing observed changes to SLR, and others attributing changes to coastal hazards such as salinization, which is driven by various processes—among others by SLR.

4.3.3.2 Submergence and Flooding of Coastal Areas

Rising mean sea-levels permanently submerge coastal low-lying areas if these are not protected. Before land is permanently submerged coastal areas are threatened by more frequent and intense extreme sea-level events resulting from the non-linear superimposition of rising mean sea levels, tides, atmospheric surge, waves and possibly contributions of rain and rivers flows (Section 4.2.3.4). Global and regional assessments of current and future coastal flood exposure and risk have explored a much wider range of uncertainties than considered in AR5.

4.3.3.2.1 Exposure

A first set of post AR5 exposure studies has focused on human mobility and socioeconomic development, assessing exposure in terms of the number of people living in the LECZ, which is the coastal area below 10 m that is hydrologicaly connected to the ocean. Two new global exposure studies thereby accounted for sub-national human dynamics such as coast-ward migration or coastal urbanization, which increases estimates of the population living in the LECZ in 2100 by 85 to 239 million people as compared to only considering national dynamics (Merkens et al., 2016). Under the five Shared Socioeconomic Pathways (SSP) and without SLR, the population living in the LECZ increases from 640–700 million in 2000 to over one billion in 2050 under all SSPs, and then declines to 500–900 million in 2100 under all SSPs, except for SSP3 (i.e., world in which countries will increasingly focus on domestic issues, or at best regional ones), for which coastal population reaches 1.1–1.2 billion (Jones and O'Neill, 2016; Merkens et al., 2016).

A second set of exposure studies has focused on combining information on future mean and extreme sea-level hazards with information on exposure. For example, under 21cm of global mean SLR, Neumann et al. (2015) find that the population exposed to the hundred-year flood event increases from about 189 million in 2000 to 316–411 million in 2060 under different socio-economic scenarios accounting for urbanisation and urban growth, with the largest absolute changes in South and South-east Asia (up to 173 million additional people in 2060) and the largest relative changes in Africa. Vitousek et al. (2017, p. 6) estimate that 'only 5–10 cm of SLR, expected under most projections to occur between 2030 and 2050, doubles the flooding frequency in many regions, particularly in the Tropics. A larger rise in sea-level of 1.2 m at the end of the century is estimated to multiply by ~2 to 5 the flooded areas for coastal communities along the east coast of the US (Dahl et al., 2017). Taking into account population growth, Hauer et al. (2016) estimate that 4.2 and 13.1 million people in the US would be exposed to 0.9 and 1.8 m SLR by 2100. Under 1.2 m SLR by the end of the century, Lilai et al. (2016) estimate that about 460,000 (13%) people of the Xiamen city area, China, will be living below the 100-year return period storm tide. In Latin America and the Caribbean Reguero et al. (2015) estimate that the number of people living below the 100-yr storm tide level will increase from 7.5 million in 2011 to 9 million by the end of the century and assuming RCPs 4.5 or 8.5. Studies that have looked at differential exposure to mean SLR between 1.5 and 2.0 °C GMST stabilization scenario have found small differences (Rasmussen et al., 2018). It is important to note that exposure studies ignore vulnerability and adaptation and hence their results should not be interpreted as risk. Often studies give the impression that areas exposed to a given mean SLR will automatically be submerged, which is misleading as it ignores that coasts can be, and frequently are, protected against mean and extreme sea-levels (Section 4.4.3.1.1).

4.3.3.2.2 Flood risk

Flood risk studies go beyond exposure studies in that they combine information on exposure, vulnerability, flood hazard and adaptation. Since AR5, a number of new studies have assessed current and future flood risk in terms of the expected number of people affected and monetary average annual losses (AAL) at global levels (Hinkel et al., 2014; Diaz, 2016; Lincke and Hinkel, 2017; Brown et al., 2018; Nicholls, 2018), and at the level of major cities around the world (Abadie et al., 2016; Hunter et al., 2017; Abadie, 2018). All of these studies take into account a SLR scenarios range wider than the *likely* range of AR5, which is consistent with the range of projections assessed in this report (Section 4.2.3.2).

Without considering enhanced adaptation, there is *high confidence* that sea-level rise will have disastrous consequences. For example, considering 21st century sea-level rise scenarios of 25–123 cm and uncertainties in elevation data, population data and socio-economic scenarios, Hinkel et al. (2014) find that 0.2%–4.6% of global population is expected to be flooded annually in 2100, with AAL amounting to 0.3%–9.3% of global GDP. Using the probabilistic city-level scenarios of RCP8.5 from Kopp et al. (2014), Abadie et al. (2016) estimate AAL for 19 European and Turkish Asian cities, with the biggest losses in 2100 occurring in Istanbul and Odessa (USD 5–10 billion; not discounted). Extending this analysis to 120 cities globally, Slangen et al. (2016) find that New Orleans and Guangzhou Guangdong rank highest with AAL above USD1 trillion (not discounted) in each city. For Europe and without further investment in adaptation, AAL are expected to rise from € 1.25 billion today to 93 and € 961 billion by the end of the century (Vousdoukas et al., 2018).

All of these numbers must be taken with caution, because SLR impacts assessed without adaptation cannot provide an adequate characterization of future coastal flood risks. Hard coastal protection is widely used in North Western Europe, South-East Asia and most major coastal cities around the world and there is also *high agreement* that this trend will continue specifically for urban and densely populated areas even under high-end SLR (Section 4.4.3.1). Furthermore, there is *medium confidence* that hard coastal protection is generally very effective in reducing flood risks during the 21st century, and also *medium confidence* that this is economically efficient for densely populated areas (Hinkel et al., 2014; Diaz, 2016; Lincke and Hinkel, 2017; Brown et al., 2018; Hinkel et al., 2018; see also Section 4.4.4.2) even under high-end sea-level rise. For example, Hinkel et al. (2014) find that coastal protection reduces people flooded and AAL by 2 to 3 orders of magnitude, with global annual investment and maintenance costs of USD 12–71 billion in 2100 (Section 4.4.3.1.6). During the 21st century, technical limits to protection are small (Section 4.4.3.1.4), but adaptation entails major social challenges (Section 4.4.3.1.7) and is economically less favourable for rural and less densely populated areas (Section 4.4.3.1.6). Hence, a probable impact of SLR will be a diverging world, with richer and densely populated areas well protected behind dikes and poorer less densely populated areas struggling with SLR impacts, and eventually retreating from the coast (Hinkel et al., 2018).

Since AR5, the literature has also started to explore a range of other critical dimensions of uncertainty relevant for assessing current and future coastal flood risk. At global scales, uncertainty in socio-economic development, digital elevation data, emission scenarios, and sea-level rise within a given emission scenario, are roughly at equal footing with respect to determining the magnitude of flood risks in the 21st century (Hinkel et al., 2014). At a European level, the number of people living in the 100-year coastal floodplain can vary between 20% and 70% based on the use of different inundation models and the inclusion or exclusion of wave set up (Vousdoukas, 2016). Using elevation data from local sources instead of global elevation data can result in differences of about 50% in flood damages (Wolff et al., 2016). Comparing damage functions attained in different studies for European cities, Prahl et al. (2018) find up to four-fold differences for floods above 3 m. Another major sources of uncertainty relates to uncertainties in present-day extreme sea levels due to the application of different extreme value methods (Wahl et al., 2017; Section 4.2.3.4). In line with AR5 we find that other types of responses beyond hard protection such as accommodation (e.g., early warning, building codes), advance and retreat (Sections 4.4.2 and 4.4.3), have hardly been considered in global and regional scale coastal flood risk assessments and that a comprehensive assessment of uncertainty across all uncertainty dimensions is missing.

4.3.3.3 Coastal Erosion and Projected Global Impacts of Enhanced Erosion on Human Systems

Coastal erosion is a well-known problem, but it is only now that scientifically-based quantified assessments of its worldwide significance are emerging (Cazenave and Cozannet, 2014; Luijendijk et al., 2018). For example, Luijendijk et al. (2018) estimate that over the 1984-2016 period, about a quarter of the world's sandy beaches eroded at rates exceeding 0.5 m/yr. While such global results can be challenged due to the relatively large detection threshold (+/-0.5m/yr), there is growing literature showing that the phenomenon is expanding in many regions, such as Brazil (Amaro et al., 2015), China (Yang et al., 2017), Colombia (Rangel-Buitrago et al., 2015), the Arctic (Mars and Houseknecht, 2007; Jones et al., 2009; Barnhart et al., 2014), and the western Pacific (Barnhart et al., 2014; Albert et al., 2016; Garcin et al., 2016), and along a large number of deltaic system worldwide (e.g., Section 4.2.2.5).

Since the AR5, however, there is growing appreciation and understanding of the ability of coastal systems to respond dynamically to SLR (Passeri et al., 2015; Lentz et al., 2016; Deng et al., 2017). Most low-lying coastal systems exhibit important feedbacks between biological and physical processes (e.g., Wright and Nichols, 2018), that have allowed them to maintain a relatively stable morphology under moderate rates of SLR (< 0.3 cm yr^{-1}) over the past few millennia (Woodruff et al., 2013; Cross Chapter Box 7). In a global review on multi-decadal changes in the surface area of 709 atoll reef islands, Duvat (Submitted) shows that in a context of more rapid SLR than the global mean (Becker et al., 2012), 73.1% of islands were stable in area, while respectively 15.5 % and 11.4 % increased and decreased in size. While anthropogenic drivers played a role especially in urban islands (i.e., stabilisation when coastal defences, increase in size when reclamation works), this study and others suggest that when enough sediment supply, some low-lying coastal systems have had the capacity to naturally adjust to SLR until now (*robust evidence, high agreement*). However, it has been argued that this capacity could be reduced in the coming decades, due to the combination of higher rates of SLR, increased wave energy (Albert et al., 2016), changes in run-up (Shope et al., 2017) and storm wave direction (Harley et al., 2017), ocean warming and acidification, and a continued increase in anthropogenic pressure.

From a global scale perspective, and without considering the potential benefits of adaptation, (Hinkel et al., 2013b) estimates that about 6,000 to 17,000 km^2 of land is expected to be lost during the 21st century due to enhanced coastal erosion associated with SLR, in combination with other drivers. This could lead to a displacement of 1.6 to 5.3 million people and associated cumulative costs of 300 to 1000 billion USD. Beach and shore nourishment following annual cost-benefit optimisation including the tourism added value had been estimated to cost about $65 to $220 billion USD and to have the potential to limit 21st century cumulative land losses sufficiently to at least halve forced migration and reduce its costs by 80% approximately. Importantly, these global figures mask the wide diversity of local situations; and some literature is emerging on the non-physical and non-quantifiable impacts of coastal erosion, e.g. on the loss of recreational grounds and the induced risks to the associated social dimensions (e.g., individuals' relationships; Karlsson et al., 2015).

4.3.3.4 Salinization

Salinization describes the consequences of saline or brackish water intrusion both by submergence of the surface and by ground penetration in the case of porous soils. It results in increasing salinity levels of groundwater, surface water and soils, with associated consequences on freshwater resources, ecosystems and livelihoods.

4.3.3.4.1 Coastal groundwater lenses

Groundwater volumes will primarily be affected by variations in precipitation patterns (Taylor et al., 2013; Jiménez Cisneros et al., 2014), which are expected to increase water stress in small islands (Holding et al., 2016). While SLR will mostly impact groundwater quality (Bailey et al., 2016) and in turn exacerbate salinization induced by marine flooding events (Gingerich et al., 2017), it will also affect the water-table height (Rotzoll and Fletcher, 2013; Jiménez Cisneros et al., 2014; Masterson et al., 2014; Werner et al., 2017) and barrier islands (Masterson et al., 2014). This will have consequences on both freshwater availability (for people and agriculture) and vegetation dynamics. At many locations, direct anthropogenic influences such as groundwater pumping for agricultural or urban uses, impact salinization of coastal aquifers more strongly than SLR in the 21st century (Ferguson and Gleeson, 2012; Jiménez Cisneros et al., 2014; Uddameri et al., 2014), with trade-offs in terms of groundwater depletion that may contribute to land subsidence and thus increase marine flooding risk. The natural migration of groundwater lenses inland in response to SLR can also be severely constrained by urbanization, e.g., in semi-arid South Texas, USA (Uddameri et al., 2014). Yet, the influence of land-surface inundation on seawater intrusion and resulting groundwater lenses salinization has been underestimated until now (Ataie-Ashtiani et al., 2013; Ketabchi et al., 2014). Such impacts will potentially also combine with a projected drying of most of the tropical-to-temperate islands by mid-century (Karnauskas et al., 2016).

4.3.3.4.2 Surface waters

The quality of surface water resources (in estuaries, rivers, reservoirs, etc.) can be affected by the intrusion of saline and/or brackish water, both in a direct (increased salinity) and indirect way (altered environmental conditions which change the behavior of pollutants and microbes). In terms of direct impacts, statistical models and long-term (1950-present) records of salinity show significant upward trends in salinity and a positive correlation between rising sea levels and increasing residual salinity, for example in the Delaware Estuary, USA (Ross et al., 2015). Higher salinity levels, further inland, have also been reported in the Gorai river basin, Southwestern Bangladesh (Bhuiyan and Dutta, 2012), and in the Mekong Delta, Vietnam. Importantly, salinity intrusion in these deltas is caused by a variety of factors such as changes in discharge and water abstraction along with relative sea-level rise. Salinity intrusion is prevalent in these geographies. In the Mekong Delta for instance, salinity intrusion extends around 15 km inland during the rainy season and typically around 50 km during dry season (Gugliotta et al., 2017). Brackish water species such as mangroves, molluscs, and diatoms, have been reported even more inland, demonstrating that in the Mekong Delta, low salinity brackish water may reach up to 160 km inland during the dry season. More broadly, the impact of salinity intrusion can be significant in river deltas or low-lying wetlands, especially during low-flow periods such as in the dry season (Dessu et al., 2018). In Bangladesh, e.g., some freshwater fish species are expected to lose their habitat with increasing salinity, with profound consequences on fish-dependent communities

(Dasgupta et al., 2017). In the Florida Coastal Everglades, sea level increasingly exceeds ground surface elevation at the most downstream freshwater sites, affecting marine-to-freshwater hydrologic connectivity and transport of salinity and phosphorous upstream from the Gulf of Mexico. In the Everglades, the impact of SLR is higher in the dry season when there is practically no freshwater inflow (Dessu et al., 2018), and salinity intrusion was shown to also cause shifts in the diatom assemblages, with expected cascading effects through the ecosystem and the food web (Mazzei and Gaiser, 2018). Salinization of surface water may lead to limitations in drinking water supply (Wilbers et al., 2014), as well as to future fresh water shortage in reservoirs, e.g., for Shanghai (Li et al., 2015). Salinity changes the partitioning and mobility of some metals, and hence their concentration or speciation in the water bodies (Noh et al., 2013; Wong et al., 2015; de Souza Machado et al., 2018). Varying levels of salinity also influence the abundance and toxicity of Vibrio cholerae in the Ganges Delta (Batabyal et al., 2016).

4.3.3.4.3 Soils

Soil salinization is one of the major soil degradation threats, with sea water intrusion being one of the common causes (Daliakopoulos et al., 2016). In a study in the Ebro Delta, Spain, for instance, soil salinity was shown to be directly related to distances to the river, to the delta inner border, and to the river old mouth (Genua-Olmedo et al., 2016). Land elevation was the most important variable in explaining soil salinity. Sea water intrusion is partially driven by sea-level rise but attribution varies among geographies with other drivers such as tidal influences, changes in river discharge in coastal deltas and estuaries, water extraction, drought etc. being important factors. Independent from clear attribution to sea-level rise, sea water intrusion leads to a salinization of exposed soils with changes in carbon dynamics (Ruiz-Fernández et al., 2018) and microbial communities (Sánchez-Rodríguez et al., 2017), soil enzyme activity (Zheng et al., 2017), and metal toxicity (Zheng et al., 2017). Sea-level rise was shown to decrease organic carbon (C_{org}) concentrations and stocks in sediments of salt marshes as reworked marine particles contribute with a lower amount of C_{org} than terrigenous sediments. C_{org} accumulation in tropical salt marshes can be as high as in mangroves and the reduction of C_{org} stocks by ongoing sea-level rise might cause high CO_2 releases (Ruiz-Fernández et al., 2018). Pore water salinity levels in coastal marsh soils can become significantly elevated in just one week of flooding by sea water, which can potentially negatively impact macrophytes and associated microbial communities for significantly longer time periods (McKee et al., 2016). These changes affect agriculture directly with impacts on plant germination (Sánchez-García et al., 2017), plant biomass (rice and cotton) production (Yao et al., 2015), and yield (Genua-Olmedo et al., 2016). Sea-level rise will also alter the frequency and magnitude of wet/dry periods and salinity levels in coastal ecosystems, with consequences on the formation of climate-relevant greenhouse gases, such as CH_4, CO_2, and N_2O (Liu et al., 2017) and therefore feedbacks to the climate.

4.3.3.5 Ecosystems and Ecosystem Services

Ecosystems provide natural resources and various services, e.g., provisioning services (food, water, etc.), cultural (e.g., recreation and ecotourism, or aesthetic values) and regulating services such as protection against sea-born hazards (e.g., waves). This section only discusses sea-level rise related impacts on some examples of critical marine ecosystems (marshes, mangroves, lagoons, coral reefs and seagrasses) and ecosystem services (coastal protection), although it is recognized that terrestrial ecosystems (e.g., forests abutting tidal wetlands) also play an important role.

4.3.3.5.1 Tidal wetlands

Potentially one of the most important of the eco-morphodynamic feedbacks allowing for relatively stable morphology under SLR is the ability of marsh and mangrove systems to enhance the trapping of sediment, which in turn allows tidal wetlands to grow and increase the production and accumulation of organic material (Kirwan and Megonigal, 2013). When ecosystem health is maintained and sufficient sediment exists to support accretion, this particular feedback has generally allowed marshes and mangrove systems to build vertically at rates equal to or greater than SLR up to present day (Kirwan et al., 2016; Woodroffe et al., 2016). While recent reviews suggest that mangroves' surface accretion rate will only keep pace with high SLR scenario (RCP8.5) up to years 2055 and 2070 in fringe and basin mangrove settings, respectively (Sasmito et al., 2016), process-based models of vertical marsh growth that incorporate biological and physical feedbacks rather support survival under rates of SLR as high as 1-to-5 cm/yr before drowning (Kirwan et al., 2016). These rates are substantially higher than what could be supported without vegetation and highlight the importance of eco-morphodynamic feedbacks for maintaining and building new land at the coast. Threshold rates of SLR before marsh drowning however vary significantly from site-to-site and can be substantially lower than 1 cm yr^{-1} in micro-tidal regions where the tidal trapping of sediment is reduced and/or in areas with low sediment availability (Lovelock et al., 2015; Ganju et al., 2017; Watson et al., 2017). In the extreme case of no sediment supply, it has been estimated that salt marshes cannot accrete faster than 3 mm yr^{-1} , and clastic sediment supply may limit many wetlands along the Gulf and East Coast of the US to a threshold SLR of less than 0.5 cm yr^{-1} (Morris et al., 2016). Global environmental change may also to lead to changes in growth rates and productivity of different mangrove species, including the replacement of environmentally sensitive species by those possessing greater climatic tolerance (Krauss et al., 2014; Reef and Lovelock, 2014). Processes impacting lateral erosion are just as important, if not more, than vertical accretion rates in determining coastal wetland survival (e.g., Mariotti and Carr, 2014). In general, most marsh and mangrove systems established themselves at their current locations over the last few thousand years and under relatively slow rates of sea-level change (Newman and Rusnak, 1965; Redfield, 1972; Ellison and Stoddart, 1991; Parkinson et al., 1994). Preserved marsh peat that dates prior to this interval, when rates of SLR were similar or greater than Present, are predominantly found along open-beach faces and off-shore, indicating that these systems were not stationary, but instead migrated landward or transgressing under higher rates of SLR (Kirwan and Megonigal, 2013). However, these off-shore records are incomplete due to the erosive nature of this landward migration, making it difficult to assess how prominent marsh and mangrove environments were along the coast during earlier epochs of rapid shore-line retreat (Parkinson et al., 1994). For most low-lying coastlines, a seaward loss of wetland area due to marsh retreat could be offset by a similar landward migration of coastal wetlands (Kirwan and Megonigal, 2013; Schile et al., 2014), this landward migration having the potential to maintain and even increase the extent of coastal wetlands globally (Morris et al., 2012; Kirwan et al., 2016; Schuerch et al., 2018). This natural process will however be constrained in areas with steep topography or equipped with hard engineering structures (i.e., coastal squeeze, Section 4.3.2.4). Seawalls, levees and dams can also prevent the fluvial and marine transport of sediment to wetland areas and reduce their resilience further (Giosan, 2014; Tessler et al., 2015; Day et al., 2016; Spencer et al., 2016).

4.3.3.5.2 Coral reefs

Coral reefs are considered to be the marine ecosystem most threatened by climate-related ocean change, especially ocean warming and acidification, even under an RCP2.6 scenario (Gattuso et al., 2015; Albright et al., 2018; Hoegh-Guldberg et al., in press). Most of the attention has been paid to tropical coral reefs and very limited literature on the impacts of climate change on cold or deep-water coral communities (Hoegh-Guldberg et al., in press). For example, the 2016 coral bleaching event caused extensive coral mortality especially in the Pacific and Indian Oceans (Hughes et al., 2017; Perry and Morgan, 2017), and >50% of the world's reefs are under medium or high risk of degradation' (Burke, 2011; Gattuso et al., 2014, p. 97). In sharp contrast to the susceptibility of coral reefs to ocean warming and acidification, some studies suggest that SLR may have negligible impacts on coral reefs' vertical growth because the projected rate and magnitude of SLR by 2100 are within the potential accretion rates of most coral reefs (van Woesik et al., 2015). Other scholars, however, stress that the overall net vertical accretion of reefs may decrease after the first 30 years of rise in a 1.2 m SLR-scenario (Hamylton et al., 2014), and that most of the reefs will not be able to track SLR under RCP4.5 and beyond (Perry et al., 2018). The AR5 concludes that 'a number of coral reefs could (...) keep up with the maximum rate of sea-level rise of 15.1 mm yr^{-1} projected for the end of the century (*medium confidence*) but a lower net accretion than during the Holocene (Perry et al., 2013) and increased turbidity (Storlazzi et al., 2011) will weaken this capability (*very high confidence*)' (Wong et al., 2014, p. 379). A key point is that SLR will indeed not act alone. The cumulative impacts of other drivers, including anthropogenic ones, are estimated to reduce the ability of coral reefs to keep pace with future SLR (Hughes et al., 2017; Yates et al., 2017) and thereby reduce the capacity of reefs to provide sediments and protection to coastal areas. For example, the combination of erosion, human amendment, and acidification is altering seafloor topography, increasing risks from SLR in carbonate-sediment-dominated regions (Yates et al., 2017). Both ocean acidification (Albright et al., 2018; Eyre et al., 2018) and ocean warming (Perry and Morgan, 2017) have been estimated to slow growth rates and reef accretion. Recent literature also shows that alterations of coral reef 3D structure from changes in growth, breakage, disease, or acidification can profoundly affect their ability to buffer waves impacts (through wave-breaking and wave-energy-damping), and therefore face SLR (Yates et al., 2017; Harris et al., 2018). Another concern is that locally, even small SLR can increase turbidity on fringing reefs which can reduce light, and therefore, reduce photosynthesis. SLR-induced turbidity can be caused by increased coastal erosion and the transfer of sediment to nearby reefs and enhanced sediment resuspension (Field et al., 2011). Such impacts also can adversely affect photosynthesis, feeding, and recruitment patterns (Field et al., 2011; Siegle and Costa, 2017).

4.3.3.5.3 Seagrasses

Due to their natural capacity to enhance accretion and in the absence of mechanical or chemical destruction by human activities, seagrasses are not expected to be severely affected by SLR *per se*, except indirectly through the increase of the impacts of extreme weather events and waves on coastal morphology (i.e., erosion); as well as through changes in light levels and sometimes through effects on adjacent ecosystems (Saunders et al., 2013). Extreme flooding events have also been shown to cause large-scale losses of seagrass habitats (Bandeira and Gell, 2003), and seagrasses in Queensland, Australia, were lost in a disastrous flooding event (Campbell and McKenzie, 2004). Changes in ocean currents can have either positive or negative effects on seagrasses—creating new space for seagrasses to grow or eroding seagrass beds (Bjork et al., 2008). But overall, seagrass will primarily be negatively affected by the direct effects of increased sea temperature on growth rates and the occurrence of disease (Marba and Duarte, 2010; Burge et al., 2013; Koch et al., 2013; Thompson et al., 2015; Gattuso et al., 2018; Section 5.2.2.3.4), and by heavy rains that may dilute the seawater to a lower salinity. Noteworthy is that some positive impacts are expected, as ocean acidification is *likely* to benefit photosynthesis and growth rates of seagrass (Repolho et al., 2017).

4.3.3.5.4 Coastal protection by marine ecosystems

Major 'protection' benefits derived from the above-mentioned coastal ecosystems include wave attenuation and shoreline stabilization, for example, by coral reefs (Elliff and Silva, 2017; Siegle and Costa, 2017) or salt marshes (Möller et al., 2014). Recently, a global meta-analysis of 69 studies demonstrated that, on average, these ecosystems together reduced wave heights between 35%–71% at the limited locations considered (Narayan et al., 2016), with coral reefs, salt-marshes, mangroves and seagrass/kelp beds reducing wave heights by 54%–81%, 62%–79%, 25%–37% and 25%–45%, respectively. Additional studies suggest greater wave attenuation in mangrove systems (Horstman et al., 2014), and highlight broader complexities in wave attenuation related to total tidal wetland extent, water depth, and species. Global analyses show that natural and artificial seagrasses can attenuate wave height and energy by as much as 40% and 50%, respectively (Fonseca and Cahalan, 1992; John et al., 2015), while coral reefs have been observed to reduce total wave energy by 94%–98% (n = 13) (Ferrario et al., 2014) and wave-driven flooding volume by 72% (Beetham et al., 2017). However, even for the limited number of studies available on particular ecosystems, the range for total wave attenuation is significant due both to variability in the coastal setting and individual storm characteristics. In addition, it is noteworthy that the effectiveness of tidal wetlands and reefs in attenuating waves and storm surge are different. For example, specific to marshes, storm surge attenuation based on a recent literature review by Castagno et al. (In review) range from -2 to 25 cm km^{-1} length of marsh, where the negative value denotes actual amplification. Other ecosystems provide coastal protection, including macroalgae, oyster and mussel beds, and also beaches, dunes and barrier islands, but there is less understanding of the level of protection conferred by these other organisms and habitats (Spalding et al., 2014). Additionally, human-driven pressure on these ecosystems is inherently difficult to forecast due to the possible implementation of new policies and the effectiveness of management and climate mitigation efforts.

While there is little literature on the extent to which SLR specifically will affect coastal protection by marine ecosystems, it is estimated that SLR may reduce this ecosystem service (*limited evidence*, *high agreement*) through the above-described impacts on the ecosystems themselves, and in combination with the impacts of other climate-related changes to the ocean (e.g., ocean warming and acidification; Sections 5.3.1.1.1, 5.3.1.2.1). Wave attenuation by coral reefs, for example, is estimated to be negatively affected in the near future by changes in coral reefs' structural complexity more than by SLR (Harris et al., 2018), this later (changes in mean and extreme levels) adding a layer of stress. Beck et al. (2018) estimate that under RCP8.5 by 2100, a 1 m loss in coral reefs' height will increase the global area flooded under a 100-year storm event by 116% compared to today, against +66% with no reef loss. Similarly, intact coral reefs limit wave run-up during tsunami events (Kunkel et al., 2006) and while we find no studies specific to changes in reefs' effects on the tsunami hazard with sea level rise, the latter has recently been shown to significantly increase tsunami run-up on coastal terrain of varying structure in Macao (Li et al., 2018) [PLACEHOLDER for FINAL DRAFT: add more literature on the effects of SLR on the future of coastal protection from marine ecosystems].

4.3.3.6 Human Activities

4.3.3.6.1 Coastal agriculture

SLR will affect agriculture mainly through land submergence, soil salinization, salinization and reduction of fresh groundwater resources, and land loss due to permanent coastal erosion. This affects on production and food security, especially in heavily coastal agriculture-dependent countries such as Bangladesh (Khanom, 2016). Recent literature confirms that salinization is already a major problem for traditional agriculture in deltas (Wong et al., 2014; Khai et al., 2018) and low-lying island nations where, for example, taro patches are threatened (Nunn et al., 2017b). Taking the case of rice cultivation, recent works emphasize the prevailing role of combined surface elevation and soil salinity, such as in the Mekong delta (Vietnam; Smajgl et al., 2015) and in the Ebro delta (Spain; Genua-Olmedo et al., 2016), estimating for the latter a decrease in the rice production index from 61.2% in 2010 to 33.8% by 2100 in a 1.8 m SLR scenario. For seven wetland species occurring in coastal freshwater marshes in central Veracruz of the Gulf of Mexico, an increase in salinity was shown to affect the germination process under wetland salt intrusion (Sánchez-García et al., 2017). In coastal Bangladesh, oilseed, sugarcane and jute cultivation was reported to be already discontinued due to challenges to cope with current salinity levels (Khanom, 2016), and salinity is projected to have an unambiguously negative influence on all dry-season crops over the next 15–45 years (especially in the southwest; Clarke et al., 2018; Kabir et al., 2018). Salinity intrusion and salinization can trigger land use changes towards brackish or saline aquaculture such as shrimp or rice-shrimp systems with impacts on environment, livelihoods and income stability (Renaud et al., 2015). However, increasing salinity is only one of the land use change drivers along with, for example, policy changes, and market prices at the household level (Renaud et al., 2015).

4.3.3.6.2 Coastal tourism

SLR may significantly affect coastal tourism destinations' landscapes (e.g., beaches) and cultural features (e.g., Marzeion and Levermann, 2014; Fang et al., 2016), as well as critical transportation modes (e.g., harbour facilities and airports; Monioudi et al., 2018). Future attractiveness will however also depend on changes in air temperature, seasonality and sea surface temperature (including induced effects such as invasive species, e.g., jellyfishes, and disease spreading; Burge et al., 2014; Section 5.3.2.2.3; Weatherdon et al., 2016; Hoegh-Guldberg et al., in press). Future changes in climatic conditions in tourists' areas of origin will also play a role in reshaping tourism flows (Bujosa and Rosselló, 2013; Amelung and Nicholls, 2014), in addition to mitigation policies on air transportation and to non-climatic components such as, e.g., accommodation and travel prices, resort's facilities, and tourists' and tourism developers' perceptions of climate-related changes (Shakeela and Becken, 2015). Since AR5, forecasting the consequences of climate change effects on global-to-local tourism flows remains challenging (Rosselló-Nadal, 2014; Wong et al., 2014; Hoegh-Guldberg et al., in press). There are also concerns about the effect of SLR on tourism facilities, for example hotels in Ghana (Sagoe-Addy and Addo, 2013), in a context where tourism infrastructures themselves often contribute to the degradation of natural buffering environments through, for example, coastal squeeze (e.g., Section 4.3.2.4) and human-driven coastal erosion. Again, forecasting is constrained by the lack of scientific studies on tourism stakeholders' long-term strategies and adaptive capacity (Hoogendoorn and Fitchett, 2018).

4.3.3.6.3 Coastal fisheries and aquaculture

Recent studies support the AR5 conclusion that ocean warming and acidification are considered more influential drivers of changes in fisheries and aquaculture than SLR (Larsen et al., 2014; Nurse et al., 2014; Wong et al., 2014). The negative effects of SLR on fisheries and aquaculture are indirect, through adverse impacts on habitats (e.g., coral reef degradation, reduced water quality in deltas and estuarine environments, and soil salinization, etc.), as well as on facilities (e.g., damage to harbours). This makes future projections on SLR implications for coastal and marine fisheries and aquaculture an understudied field of research. Conclusions only state that future impacts will be highly context-specific due to local manifestations of SLR and local fishery-dependent communities' ability to adapt to alterations in fish and aquaculture conditions and productivity (Hollowed et al., 2013; Weatherdon et al., 2016). Salinity intrusion also contributed to conversion of land or freshwater ponds to brackish or saline aquaculture at many low-lying coastal areas of South-East Asia such as in the Mekong delta in Vietnam (Renaud et al., 2015).

4.3.3.6.4 Social values

Social values refer to what people consider as being of critical importance about the places in which they live, and that range across a broad diversity of material to immaterial things (assets, beliefs, etc.; Graham et al., 2014). Social values thus offer an opportunity to address a wider perspective on impacts on human systems, e.g., complementary to quantitative assessments of health impacts (e.g., loss of source of calories, food insecurity; Keim, 2010). They also offer an opportunity to better consider immaterial dimensions, such as loss of cultural heritage (Marzeion and Levermann, 2014) or of socializing activities (Karlsson et al., 2015), or some cultural ecosystem services (Fish et al., 2016). They also provide an opportunity to better capture context-specificities in valuing the physical/ecological/human impacts' importance for and distribution within a given society. This is an emerging field of research (no detailed mention in AR5) due to the transdisciplinary and qualitative nature of the topic. Graham et al. (2013) advance a 5-category framing of social values specifically at risk from SLR: health (i.e., the social determinants of survival such as environmental and housing quality and healthy lifestyles), feeling of safety (e.g., financial and job security), belongingness (i.e., attachment to places and people), self-esteem (e.g., social status or pride that can be affected by coastal retreat), and self-actualisation (i.e., people's efforts to define their own identity). Another growing issue relates to social values at risk due to the loss of territorial sovereignty in low-lying island nations (Yamamoto and Esteban, 2016) and parts of countries and individual properties (Marino, 2012; Maldonado et al., 2013; Aerts, 2017; Allgood and McNamara, 2017). Emerging studies also highlight the potential additional risks to social values in areas where displaced people locate (Davis et al., 2018).

4.3.4 Conclusion on Coastal Risk

The sections above demonstrate that despite areas of uncertainty on the extent and rate of sea level change (Sections 4.2.2, 4.3.3), expected SLR represents a major vehicle for increased risk on a multidecade to century scale (*medium evidence, high agreement*). The vast majority of low-lying coasts around the globe, whether in the Northern or Southern hemisphere, urban or rural, continental or island, at any latitude, are affected (Cross-Chapter Box 7). This chapter also shows that risk will not only result from SLR, but also from SLR interactions with other climate- and ocean-related changes (e.g., extreme events), from the sensitivity of natural coastal systems (e.g., Sections 4.3.2.3, 4.3.3.5, 4.3.3.5) and from anthropogenic processes such as coastal urbanization, population growth, and changes in lifestyles and types of economic activities (e.g., Sections 4.3.2.2, 4.3.2.6, 4.3.3.6). This section adds to this the role of compound events, and provides a synthesis of risk induced by SLR at the global scale and for specific geographies (megacities, urban atoll reef islands, populated deltas, Arctic regions).

4.3.4.1 Compound Events

A compound event occurs when impacts of a climate event or trend interact with or precondition the impacts of a simultaneous or subsequent event (SREX Sections 1.2.3.2 and 3.1.3). One statistical definition is 'an extreme impact that depends on multiple statistically dependent variables or events' (Leonard et al., 2013, p. 115). More broadly, compound events are a 'combination of multiple drivers and/or hazards that contributes to societal or environmental risk' (Zscheischler et al., 2018). Extreme impacts from compounding can occur even when one or more of the individual events is not extreme or if the events are of distinct types, such as simultaneous coastal and riverine flooding (SREX Section 3.1.3). Impacts of events that are nonsynchronous can also interact to increase losses, for example due to memory in a hydrological system (Hillier et al., 2015). An initial event, even occurring at a great distance from subsequent events, may lead indirectly to compound effects by reducing societal and individual capacity to respond to subsequent events. For example, emergency response to Hurricane Harvey's impact on Texas in 2017 drew down financial and human resources that would otherwise have been available for disaster response to Hurricane Maria (FEMA, 2018), worsening the impact of the latter on Puerto Rico. See Section 6.8 of this report for a general discussion of compound events occurring in a multi-risk context.

Other identified hazards relevant to the coastal environment whose impacts interact are storm tides arising from the combination of sea level rise and tropical cyclones (Little et al., 2015a) and extreme storm surge in combination with extreme precipitation in the US (Wahl and Plant, 2015; Moftakhari et al., 2017) exacerbating flooding. More generally, coastal cities and other settlements are exposed to the compound effects of surge from tropical and extratropical cyclones in the context of sea level rise and pluvial flooding associated with climate change.

AR5 discussed compound risk (potential compound events) and pointed to geographic areas where compound risk is particularly relevant to SROCC. The report stated that 'examples include the Arctic (where thawing and sea ice loss disrupt land transportation, buildings, other infrastructure, and are projected to disrupt indigenous culture); and the environs of Micronesia, Mariana Island, and Papua New Guinea (where coral reefs are highly threatened due to exposure to concomitant sea surface temperature rise and ocean acidification)' (Oppenheimer et al., 2014, p. 1042). We have *high confidence* that the frequency of compound events related to sea level rise as well as those related to marine heat waves (Frölicher et al., 2018), and the associated risk to Arctic and coral reef systems will increase over the 21st century.

4.3.4.2 Reasons for Concern and Future Risks of Impact to Local Geographies

The sections above provide compelling evidence that low-lying coastal areas are vulnerable to SLR not only because of the acceleration of SLR over the last decades, but also because of anthropogenic drivers such as settlement patterns (*high confidence*). SLR projections for the 21st century, together with other ocean-related changes (e.g., ocean warming and acidification) and the possible increase in human-driven pressures at the coast, make low-lying islands, coasts and communities relevant illustrations of some of the five Reasons for Concern (RFCs) developed by the IPCC since the Third Assessment Report (McCarthy, 2001; Smith et al., 2001) to assess risks from a global perspective. The RFCs describe "the relationship between global mean temperature increase and five categories of impacts (…) in order to facilitate interpretation of Article 2 [of the UNFCCC]" (Oppenheimer et al., 2014, p. 1042). Risks to unique and threatened systems (RFC1) such as coral reefs and the Arctic, risks associated with extreme weather events (RFC2) such as tropical cyclones, risks associated with the uneven distribution of impacts (RFC3) such as between communities in the LECZ and those at higher elevation, and risks associated with large-scale singular events (RFC5), such as rapid loss of a significant part of the Greenland or Anarctic ice sheet are all discussed in sections 4.2 and 4.3.

The AR5 Synthesis Report (IPCC, 2014b) refined the RFC approach by developing two additional RFCs referring to risks to marine species arising from ocean acidification, and risks to human and natural systems from SLR; and recent scientific advances lead to a re-evaluation of all RFCs (O'Neill et al., 2017). Despite the difficulty in attributing observed impacts to SLR *per se* (Section 4.3.3.1; O'Neill et al., 2017) estimate that at the global scale, risks related to SLR are already detectable and would increase rapidly, so that 'high risk may occur before the 1 m level is reached' (p. 34)—1 m above the 1986–2005 level is used as a benchmark for the SLR RFC. O'Neill et al. (2017) also suggest that limits to coastal protection and ecosystem-based adaptation exist above 1 m rise by 2100. Integrating new knowledge on Antarctica's possible contribution to SLR, Section 4.2.3.2 in this report estimates that the 1 m benchmark lies well within the *likely* range before 2100 under a RCP8.5 scenario (see Fig. 4.7). In addition, previous assessments of the RFCs left gaps including the potential benefits from adaptation in terms of risk reduction and sustainable development. Accordingly, in what follows, we revisit the AR5 and O'Neill et al. (2017) assessments here from the particular perspective of risks related to sea level rise. RFC5 should be reevaluated in light of the new projections of sea level rise in Section 4.2.3.2 but we defer that assessment to AR6 since this RFC and the other four original ones address a range of non-coastal risks as well.

Building on the RFC rationale, this chapter explores a new, complementary way to address risks of SLR-related impacts by the end of the century on generic categories of low-lying coastal areas. This approach reports several areas of progress compared to previous exercises:

- Scale of analysis and geographical scope: To date, the RFCs and associated burning embers have been developed at a global scale (Oppenheimer et al., 2014; Gattuso et al., 2015; O'Neill et al., 2017), and consequently do not address the spatial variability of risk, a point especially emphasized in sections 4.3.2.7, 4.3 and 5.3, as well as in the Cross-Chapter Box 7. In addition, assessments usually identify risks either for global human dimensions (e.g., to people, livelihood, breakdown of infrastructures, biodiversity, global economy, etc.; IPCC, 2014b; Oppenheimer et al., 2014; O'Neill et al., 2017) or for ecosystems and ecosystem services (Gattuso et al., 2015; Section 5.3.4; Hoegh-Guldberg et al., in press). Our assessment moves the focus from the global to more local scales by considering four generic categories of low-lying coastal areas that are considered at the frontline of SLR impacts: coastal megacities, urban atoll reef islands, populated deltas and Arctic settled areas (Figure 4.13, Panel B). This assessment considers various case studies for each of these geographies, in order to represent a broad range of situations around the world.

- Sea-level rise scenarios: Due to the better understanding of the contribution of glaciers and polar ice sheets to global mean SLR, Section 4.2 of this chapter provides updates for ranges and mean values for RCPs (see Table 4.3), allowing for advances in SLR-related risk assessment compared to AR5 (IPCC, 2014b). Building on this, we consider here the end-century SLR (2081–2100) relative to 1986–2005 levels for two contrasting scenarios, RCP2.6 and RCP8.5, and mean values are used to assess risk transitions (Figure 4.13, Panel A). For the sake of readability and also to reflect the approximate nature of risk transitions, we use round numbers for these means: +40 cm for the RCP2.6, +100 cm for the RCP8.5, and +140 cm as the upper *likely* range for RCP8.5 (and instead of real estimates of +0.42, +0.96 and +1.36, respectively; Table 4.3).
- Risks considered: In line with the AR5 (IPCC, 2014b), current and future risks result from the interaction of SLR-related hazards with the vulnerability of exposed ecosystems and societies. The assessment especially addresses more or less direct risks to coastal populations, assets, infrastructures and livelihoods, as they can be considered, according to the findings of this chapter, relevant to capturing manifestation of dangerous anthropogenic interference with the climate system in low-lying coastal areas and at a local scale. They refer to damages to people, the built environment and land due to coastal flooding and erosion (Sections 4.3.3.2, 4.3.3.3); impacts of salinization to water resources (Section 4.3.3.4); and threats to ecosystems and ecosystem services (Section 4.3.3.5) and to human activities (4.3.3.6). Specific metrics have been developed (see SI4.2 for details) and their contribution to risk of impact for the Present-day and the end of the century have been assessed based on the authors' expert judgment.
- Risk also varies across time and future risks will especially depend on both changes in sea level (mean, extremes, rates) and the effectiveness of coastal societies' responses to both extreme events and slow onset changes. To capture the response dimension (Section 4.4), three adaptation scenarios have been considered. The first one is called "No-to-moderate adaptation" (see (A) bars in Panel B, Fig. 4.13) and represents a business-as-usual scenario where only incremental adaptation is implemented; e.g., moderate protection added to highest density areas, or sporadic epidosdes of coastal retreat or beach nourishment. The second one, called "High adaptation" (bars (B) in Fig. 4.13), refers to an ambitious combination of both incremental and transformational adaptation; for example relocation of entire districts in a megacity, and/or creation/restoration of beach-dune systems at a significant scale. The third adaptation scenario touches upon the "limits to adaptation" (bars (C) in Fig. 4.13), i.e. extreme situations where it is hard to distinguish whether the measure is an impact of SLR (and ocean change more broadly), or an adaptation solution. This is typically the case for the relocation of the full population of urban atoll islands either elsewhere in the country (i.e. on an inland area or another island) or abroad (i.e., international migration) (Section 4.4.3.5). Our assessment does not consider this scenario for megacities and deltas.
- [PLACEHOLDER FOR FINAL DRAFT: various aspects will be improved/developed in the Final Draft of Chapter 4: Megacities from non-developed countries will be integrated to the "megacities" analysis; Assessment for deltas and for Arctic regions will be developed; Depending on results from other chapters, the contribution of possibility abrupt changes, the crossing of environmental and/or anthropogenic tipping points or changes in extreme sea levels, to risk will be considered for the various geographies]

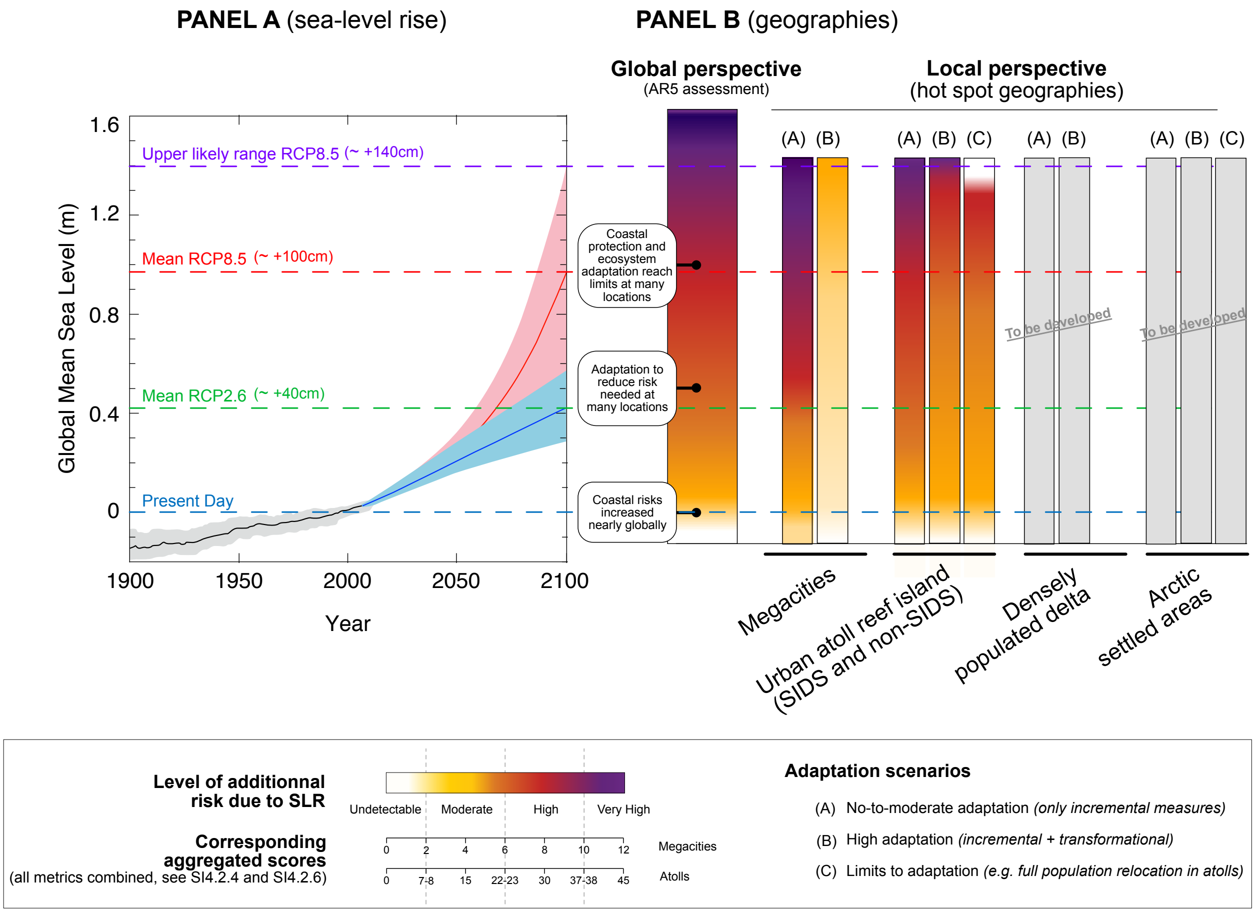


Figure 4.13: Synthetises from the findings of a first round of assessment, and details on the assessment methodology and results are described in SI4.2 to this chapter [PLACEHOLDER FOR FINAL DRAFT: the assessment will be refined, as well an in-depth discussion of the results]. It shows that risks from SLR are already detectable for all the geographies considered (bars (A) in Panel B), and that in the absence of ambitious adaptation, these risks are expected to significantly increase (bars (A) in Panel B) even in a RCP2.6 scenario. Under a ~+40 cm rise in sea level by the end of this century, risk will be close to high for megacities and urban atolls, and close to very high in higher SLR scenarios. This demonstrates some similarities in the challenges that urban low-lying coastal areas are facing, whatever their context-specificities or nature (island/continental, developed/developing county) (CCB-5). The assessment also shows that in the case of ambitious adaptation efforts (bars (B) in Figure 4.13), adequate coastal defences can play a decisive role in decreasing risks in coastal megacities. This conclusion must however be nuanced by the fact that our assessment does not consider either financial (e.g., long-term investments) nor social aspects that can act as limiting factors to the development of hard engineering coastal defences (Graham et al., 2014; Jones et al., 2014; Elrick-Barr et al., 2017; Hinkel et al., 2018). In urban atolls, compared to megacities, ambitious adaptation efforts mixing adequate coastal defences and the restoration/enhancement of buffering ecosystems (e.g., coral reefs) are expected to have more modest benefits in terms of risk reduction. These benefits can still be considered as relatively substantial in a ~+100 cm SLR scenario compared to a ~+40 cm scenario, as they allow risk to decrease from high-to-very-high to moderate-to-high (in (A) and (B) bars, respectively). These benefits however become negligible when approaching the upper range of RCP8.5, and risk comes back to a very high level once the ~+140 cm rise in sea level is reached. This context raises the issue of the limits to adaptation in urban atoll reef islands, i.e., the actual effectiveness of removing all the people from the island. This would result in the annihilation of *in situ* vulnerability, as shown with the white colour at the upper end of (C) bar in Panel B; although through the displacement of vulnerability (i.e., to destinations areas) rather than its eradication. This highlights the risk of generating maladaptation elsewhere (i.e., transboundary risks) and, therefore, the limits to adaptation.

4.4 Responses to Sea Level Rise

4.4.1 Introduction

This section assesses the literature on responses to GMSLR and the observed and anticipated changes in sea level taking place in coastal localities around the world. SLR responses refers to provisions, plans and actions undertaken to reduce risk and build resilience in the face of SLR (see Cross-Chapter Box 3 in

Chapter 1). These responses range from 'ignoring' SLR to endeavours that can be incremental or transformational, and involve anticipatory, autonomous, planned, private, public and reactive adaptation (AR5). We use the term 'SLR responses' to encompass these different types of adaptation and recognise the reactive and proactive dimensions of this governance challenge (see Cross-Chapter Box 2 in Chapter 1). The section starts by outlining post-AR5 literature on the types of SLR response measures that have been used, including protection, accommodation, advancement and retreat (Section 4.4.2). Attention focuses on observed responses, their costs, benefits, co-benefits, negative consequences and associated governance challenges (Section 4.4.3). The setting, and the approaches and tools used in making social choices about SLR, are then examined (Section 4.4.4). Limits, barriers and lessons learned from efforts to implement SLR responses at the local level are then examined (Section 4.4.5) before the section concludes with an introduction to developments in the emerging literature on climate resilient development pathways (Section 4.4.6).

4.4.2 Types of Responses

This subsection gives a brief overview of the types of human responses to SLR and its impacts (Table 4.7), hence establishing a common vocabulary for the remainder of this section. A detailed assessment of the literature on each type of response follows in the next section (Section 4.4.3). The broader term response is used here instead of adaptation, because some responses such as retreat may or may not be meaningfully considered to be adaptation (Hinkel et al., 2018). Responses that address climate change itself, such as mitigating greenhouses gases or geoengineering temperature and sea-level responses to emissions (Moore et al., 2018) fall beyond the scope of this chapter.

Following earlier IPCC Reports we distinguished between Protection, Retreat and Accommodation responses to sea-level rise and its impacts (Nicholls et al., 2007b; Wong et al., 2014), but add Advance as a forth type of response that had not received much attention in the climate change literature but plays an important role in coastal development throughout the world. Note that all responses are generally not responses to SLR only, but also to current coastal risks as well as many socio-economic factors and related hazards. A noteworthy exception are responses to nuisance flooding in the US. Furthermore, in practise, many responses are hybrid, applying responses that combine these different types (Section 4.4.2.6).

Protection reduces the chances of coastal impacts from occurring and include three sub-categories of measures. First, there are hard engineering structures such as dikes, seawalls, breakwaters and surge barriers to protect against flooding and erosion, or barriers and barrages to also protect against salt water intrusion (Nicholls et al., 2018a). Second there are sediment-based measures such as beach and shore nourishment, dunes (also referred to as soft structures) and land raising. Third, there are ecosystem-based adaptation (EbA) measures that use ecological features such as reefs and coastal vegetation to provide adaptation benefits. While beaches and dunes could also be considered ecosystems-based measures, here we treat them under sediment-based measures, because they have long been considered jointly with hard protection measures in coastal engineering and the sediment volume and dynamics plays a greater role in providing protection effect than the ecosystem aspect (Hinkel et al., 2013a; Hanley et al., 2014; Pontee et al., 2016).

Advance creates new land by building seaward and upwards. This includes land reclamation above sea levels by land filling with pumped sand or other fill material, planting vegetation with the specific intention to support natural accretion of land and surrounding low areas with dikes, termed polderisation, which also involves a drainage and possibly pumping system. While historically advance was mainly a response to land scarcity, which remains the case, they are increasingly considered in the context of adaptation to sea-level rise (e.g., RIBA and ICE, 2010).

Accommodation does not prevent coastal impacts from occurring, but reduces coastal residents', assets' and infrastructure's vulnerability to these. Accommodation includes both biophysical measures such as raising building´s floor level, improving drainage systems and shifting to cultivation of saline-tolerant crops, as well as institutional measures such as emergency planning, community participation in local government decision-making, establishment of marine parks and protected areas, integrated coastal management plans and insurance systems (Nurse et al., 2014; Wong et al., 2014).

Retreat reduces exposure to coastal impacts by moving people, infrastructures and activities out of the exposed coastal area. Retreat includes i) migration, which is the permanent or semi-permanent move by a person, at least for one year (Adger et al., 2014), ii) forced displacement and iii) planned relocation (also called planned retreat or managed realignment), which is typically initiated, supervised and implemented by governments (Wong et al., 2014; Hino et al., 2017). Measures such as managed realignment or managed relocation, can also involve an aspect of habitat creation by providing space for new habitat. Sometimes, this new habitat can be designed and managed to provide protection to inland assets, among other ecosystem services (French, 2006; MacDonald et al., 2017).

Table 4.7: Overview of exemplary responses to coastal risks and SLR and the impacts they address.

Categories		Responses (examples)		Impact Addressed						
				Flooding	Submergence	Erosion	Impeded Drainage	Salinity Rivers	Salinity Aquifers	Habitat change and loss
Protect	Hard	Sea wall		X	X					
		Sea dike		X	X					
		Breakwater		X		X				
		Groynes				X				
		Fixed barrage/closure dam		X	X			X		
		Storm surge barrier		X						
		Saltwater intrusion barriers						X	X	
	Sediment-based	Land raising	Through artificial filling	X	X	X	X		X	
			Through controlled natural sedimentation (e.g., tidal river management)	X		X			X	
		Shore and beach nourishment	Emergency nourishment	X		X				
			Periodic nourishment	X		X				
			Mega-nourishment (e.g., Sand engine)	X		X				
		Dunes	Conservation	X		X				
			Restoration	X		X				
	Ecosystem-based	Vegetation	Conservation	X		X				X
			Restoration	X	X	X				X
		Reefs	Conservation	X		X				X
			Restoration	X		X				X
Advance	Land reclamation	Through land filling with pumped sand or other fill material		X	X	X	X			
		Through sediment accretion by vegetation and natural processes		X	X	X	X			X
		Through polders (Enclosed areas with dikes and improved drainage)		X	X	X	X			
Accommodation	Physical	Floor raising		X	X					

		Flood-proofing of buildings	X						
		Drainage systems				X	X	X	
		Land-use change (salt tolerant crops, aquaculture, etc.)	X	X					
	Institutional	Early warning system	X						
		Insurance systems	X		X				
		Emergency planning	X						
		Setback zones	X	X	X	X	X	X	X
Retreat	Individual	Migration	X	X	X	X	X	X	X
		Displacement	X	X	X	X	X	X	X
	Societal	Relocation	X	X	X	X	X	X	X

4.4.3 Observed and Projected Responses, their Costs, Benefits, Co-benefits, Negative Consequences, Efficiency and Governance

Since AR5, the literature on responses has grown significantly. It is assessed in the following subsections for the four above-described broad types of responses (Section 4.4.2). Each type of response is assessed consecutively in terms of the following seven categories:

1. Observed responses across geographies, describing where the different types of responses have been implemented.
2. Projected responses, that is the nature and potential extent of responses in the future, as assessed in the literature through modelling or in a more qualitative way.
3. Economic cost of responses, which refers to the economic costs of implementing and maintaining responses. Other costs that arise due to negative side-effects of implementing a response are captured under the category 5 "co-benefits and negative consequences".
4. Effectiveness in terms of reducing SLR risks and impacts. This includes biophysical and technical limits beyond which responses cease to be effective (Hinkel et al., 2018).
5. Co-benefits and negative consequences that occur next to the intended benefits of reducing SLR risks and impacts.
6. Economic efficiency which refers to the overall monetized balance of costs, benefits, co-benefits and negative consequences (e.g., benefit-cost ratio or net benefit). Economic barriers arise if the overall costs are higher than the overall benefits.
7. Governance, which refers to governance structures such as organisations and formal and informal institutions (e.g., laws, policies, conventions, practises, social norms and discourse, etc.) that have developed alongside the observed responses and have been found to hinder or foster the effective, efficient and equitable implementation of responses (Cross-Chapter Box 2 in Chapter 1). Factors that hinder the governance of implementing responses will be referred to as governance barriers.

4.4.3.1 Hard and Sediment-Based Protection

4.4.3.1.1 Observed hard and sediment-based protection across geographies

Coastal protection through hard measures is widespread around the world, although it is difficult to provide estimates on how many people are protected by them. Currently, at least 20 million people living below normal high tides are protected by hard structures (and drainage) in countries such as Belgium, Canada, China, Germany, Italy, Japan, the Netherlands, Poland, Thailand, the UK, and the USA (Nicholls, 2010). Many more people living above high tides but in the flood plain are also protected by hard structures in major cities around the world. There is a concentration of these measures in North West Europe and East Asia, although extensive defences are also found in and around many coastal cities and deltas. For example, large scale coastal protection exists in Vancouver (Canada), Alexandria (Egypt) and Keta (Ghana; Nairn et al., 1999) and 6,000 km of polder dikes in coastal Bangladesh. Gittman et al. (2015) estimate that 14% of the total US coastline has been armoured, with New Orleans being an example of an area below sea level dependent on extensive engineered protection (Kates et al., 2006; Rosenzweig and Solecki, 2014; Cooper et al., 2016). Defences build and raised for tsunami protection, such as post 2011 in Japan (Raby et al., 2015) or post 2004 in the Maldives (Wadey et al., 2017) also provides protection against SLR.

The application of sediment-based measures also has a long history offering multiple benefits in terms of enhancing safety, recreation and nature (JSCE, 2000; Dean, 2002; Hanson et al., 2002; Cooke et al., 2012). About 24% of the world's sandy beaches are currently eroding by rates faster than 0.5 m yr^{-1} (Luijendijk et al., 2018). In the USA, Europe and Australia responses are often driven by the recreational value of beaches and the high economic benefits associated to beach tourism. More recently, sediment-based measures are seen and implemented as effective and yet flexible measures to address SLR (Kabat et al., 2009) and experiments are being conducted with innovative decadal scale application of sediments such as the sand engine in The Netherlands (Stive et al., 2013).

There is *high confidence* that most major upgrades in defences happened after coastal disasters. Dikes were raised and re-enforced after the devastating coastal flood of 1953 in the Netherlands and the UK and in 1962 in Germany. In New Orleans, investments in the order of USD $15 billion including a major storm surge barrier followed Hurricane Katrina in 2005 (Fischetti, 2015) and in New York the Federal Government made available USD $16 billion for disaster recovery and adaptation (NYC, 2015). Examples in which SLR has been considered proactively in the planning process include sea-level rise safety margins in e.g. Germany and France, upgrading defences according to cost-benefit analysis in the Netherlands and SLR guidances in the United States (USACE, 2011). In few places, proactive responses predate concerns about climate change. For example, the Thames Barrier protecting London commissioned 1982 includes a linear allowance for relative rise in extreme sea levels based on extrapolating historic trends (Gilbert et al., 1984).

4.4.3.1.2 Projected hard and sediment-based protection

There is high agreement that hard and sediment-based coastal protection will continue to be a widespread response to SLR, but low agreement on how to project future coastal protection. A descriptive model assuming that coastal societies continue to raise hard protection with increasing affluence, as observed in North West European countries with a long tradition in coastal protection, suggest that about half of the global coastline will be protected during 21st century SLR (Hinkel et al., 2014). Prescriptive models assuming that coastal societies upgrade hard protection following scenario-based cost-benefit analysis find that 22% of the globe will be protected under various SSPs and 1 m of 21st century global mean SLR (Nicholls et al., 2018b). Another prescriptive model applying robust decision making using the criterion of benefit-cost ratios one finds that this would lead to protecting 13% of the global coastline (Lincke and Hinkel, 2017) under SLR scenarios up to 2 m, all SSPs and discount rates up to 6% (Figure 4.14).

4.4.3.1.3 Economic cost of hard and sediment-based protection

There is *high evidence* and *medium agreement* on the costs of hard protection. The cost of protection through hard measures can be expressed as cost per unit length protected and increase in height of the structure (Table 4.8). This was recognised by Dronkers et al. (1990) who calculated unit costs of defences, which were used in a first estimate of the global cost of adapting to a 1 m rise in sea level in the IPCC First Assessment Report. These unit costs have been subsequently refined as reviewed by Jonkman et al. (2013) and continued to feed into global adaptation cost estimates (Hinkel et al., 2014; Nicholls et al., 2018a). The variance in costs has been examined by a few authors such as Jonkman et al. (2013) but in general there has been limited systematic data collection across sites, although useful national guidance does exist in some cases (Environment Agency, 2015). Defences depend on good maintenance to remain effective. An annual maintenance cost of 1% to 2% of capital costs can be expected for this purpose (Jonkman et al., 2013). While this seems small, maintenance costs accumulate with the accumulating defence stock, and if protection is widely practised through the 21st century, the bulk of the costs are maintenance rather than capital cost (Nicholls et al., 2018a). For some types of infrastructure such as surge barriers, maintenance costs could be higher, but they are poorly described and hence more uncertain (Nicholls et al., 2007a). Protection-based adaptation to saltwater intrusion is more complex and bespoke than adaptation to flooding and erosion, and there is less experience to draw upon.

Table 4.8: Capital and maintenance costs of hard protection measures.

Measure	Capital Cost (in million USD per km of coastline and 10 cm SLR/height unless stated otherwise)	Annual Maintenance Cost (% of capital cost)
Sea Wall	0.04–2.75 (Linham et al., 2010)	1 to 2% per annum (Jonkman et al., 2013)
Sea Dike	0.09–2.92 (Jonkman et al., 2013)	1 to 2% per annum (Jonkman et al., 2013)
Breakwater	0.25–1.0 (Narayan et al., 2016)	1% per annum (Jonkman et al., 2013)
Storm Surge Barrier	0.5–27 (Jonkman et al., 2013) or 2.2 (Mooyaart and Jonkman, 2017) million Euro per meter width	1% per annum (Mooyaart and Jonkman, 2017) or 5 to 10% per annum (Nicholls et al., 2007a)
Saltwater Intrusion Barriers	Limited knowledge	Limited knowledge

Sediment-based measures are generally costed as the unit cost of sand (or gravel) delivery times the volumetric demand. Unit costs range from USD 3–15 m^{-3} sand (Linham et al., 2010), with some high outlier costs in the UK and New Zealand. Costs are small where sources of sand are plentiful and close to the sites of demand and where shoreface nourishment delivers the sand to the beach. This situation is found in the Netherlands where the entire open coast is maintained with large-scale shore nourishment (Mulder et al., 2011) and the innovative sand engine has been implemented as a full-scale decadal experiment (Stive et al., 2013).

The difference between hard and sediment-based measures is that the later are sacrificial and require regular re-nourishment to maintain the design standard (Linham and Nicholls, 2010). Hence the costs of nourishment need to consider a whole-life basis (with appropriate discounting) to reflect the repeated re-nourishment volumes, but the maintenance costs are generally lower compared to hard engineering. One essential maintenance cost component is regular beach/shoreface monitoring to assess the beach volume. The capital costs for dunes are like those for beach nourishment, although placement and planting vegetation may raise costs. Maintenance costs vary from almost nothing to several million dollars km^{-1}, although costs are usually at the lower end of this range (Environment Agency, 2015).

4.4.3.1.4 Effectiveness of hard and sediment-based protection

There is high confidence that well designed and maintained hard and sediment-based protection is very effective in reducing risk to the impacts of SLR and ESL by providing predictable levels of safety (Horikawa, 1978; USACE, 2002; CIRIA, 2007). This includes situations in which coastal mega-cities in river deltas have experienced, and adapted to, relative SLR of several meters caused by land subsidence during the 20th century (Kaneko and Toyota, 2011). In principle, there are no technological limits to protect the coast during the 21st century even under high-end SLR of 2 m (Hinkel et al., 2018). Technologically challenges arise in some places, such as in South-east Florida because protected areas can be flooded from below due to the underlying porous limestone (Bloetscher et al., 2011), but generally these do not make hard protection technologically unfeasible but rather make it too expensive for some areas (Hinkel et al., 2018). See Section 4.4.3.1.6.

Maintaining this effectiveness over time requires regular monitoring and maintenance, and accounting for changing conditions such as sea level rise and widespread erosional trends in front of the defences. In any case, there will always be residual risks that should never be forgotten or taken for granted. These risks can be reduced, but never eliminated, by engineering protection infrastructure to very high standards, such as, so-called “unbreakable dikes” (De Bruijn et al., 2013).

4.4.3.1.5 Co-benefits and negative consequences of hard and sediment-based protection

When space is limited (e.g., in urban setting), co-benefits can be generated through multi-functional hard flood defences, which combine flood protection with other urban functions such as car parks, buildings, roads or recreational spaces into one multifunctional structure (Stalenberg, 2013; van Loon-Steensma and Vellinga, 2014).

Negative consequence of hard protection include the alteration of hydrodynamic and morphodynamic patterns, which in turn may export flooding and erosion problems downdrift (Dickson et al., 2007; Dawson et al., 2009). Furthermore, hard protection hinders or prohibits the onshore migration of geomorphic features and ecosystems causing coastal squeeze (Pontee, 2013; Gittman et al., 2016), leading to both a loss of habitat as well as of the protection function of ecosystems (See Sections 4.3.2.4 and 4.4.3.2). Another possibly adverse consequence of protecting the coast by hard structures, also emphasised in AR5, is the risk of locking into a development pathway in which growing urban areas are situated behind higher and higher defences, with increasing risks of catastrophic consequence in the case of protection failure, because protection attracts further economic development in the flood zone behind, which again leads to further raising defences with sea-level rise and growing affluence (Wong et al., 2014; Welch et al., 2017).

An important co-benefit of sediment-based protection such as beach nourishment and dune management is that it preserves beach and associated environments, as well as tourism (Everard et al., 2010; Hinkel et al., 2013a; Stive et al., 2013). Seabed dredging of sand and gravel can have negative impacts on marine ecosystems such as sea-grass meadows and corals (Erftemeijer and Lewis III, 2006; Erftemeijer et al., 2012). Nourishment practices on sandy beaches have also been shown to have negative consequences to local ecosystems if local habitat factors are not taken into considerations when planning and implementing nourishment and maintenance (Speybroeck et al., 2006). A further emerging issue is beach material scarcity mainly driven by demand of sand and gravel for construction, but also for beach and shore nourishment (Peduzzi, 2014; Torres et al., 2017), which challenges sourcing the increasing volumes of sand (and gravel) required to sustain beach volumes that are adequate to provide a sufficient level of protection in the face of sea level rise (Roelvink, 2015).

4.4.3.1.6 Economic efficiency of hard and sediment-based protection

At global scales there is medium evidence but high agreement that during the 21st century the benefits of reducing coastal flood risk through hard protection exceed the capital and maintenance costs for protection infrastructure for cities and densely populated areas, even under high-end sea level rise (Diaz, 2016; Lincke and Hinkel, 2017). Two new global studies confirm the findings of AR5 that protection against increased coastal flooding is economically efficient for urban areas during the 21st century (Wong et al., 2014). For example, Diaz (2016) find that under 21st century SLR of 0.3 to 1.3 m and SSP2, adaptation in terms of protection and retreat reduces global net present costs of SLR by a factor of seven as compared to no adaptation (applying a discount rate of 4%). Lincke and Hinkel (2017) find that during the 21st century it is always economically efficient to protect 13% of the global coastline, which corresponds to 90% of global floodplain population, under SLR scenarios from 0.3 to 2.0 m, five Shared Socio-economic Pathways (SSPs) and discount rates up to 6% (Figure 4.14).

These findings suggest that it generally makes economic sense to continue to protect existing urban areas by hard defences, following current practice (Section 4.4.2). High-end sea level rise above 2 m beyond 2100 could change this picture, but given the deep uncertainty involved, the point in time when it would be economically meaningful for cities to switch from a protection to a retreat strategy is still far away (Hinkel et al., 2018), although studies addressing specifically this question are currently not available. For less densely populated and currently not protected areas, the situation is more complex. For example, across the wide range of scenarios considered, Lincke and Hinkel (2017) find that for about 65% of the world's coast it is economically efficient not to protect and for 21% of the coasts no robust solution emerges (Figure 4.14). There is, however, no study available that has looked at robustness and economic efficiencies across all four types of response measures.

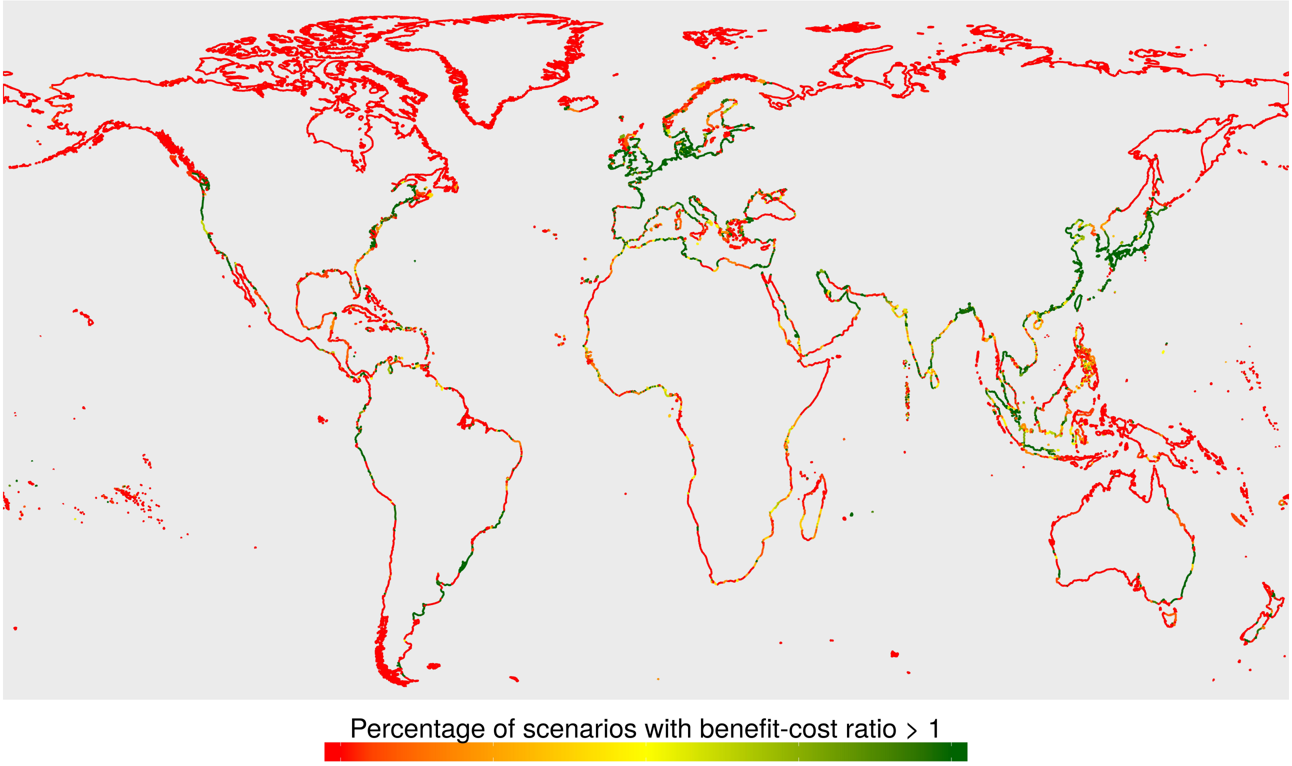


Figure 4.14: Economic robustness of coastal protection under SLR scenarios from 0.3 m to 2.0 m, the five SSPs and discount rates of up to 6%. Coastlines are coloured according to the percentage of scenarios under which benefit-cost ratio are above 1. Source: Lincke and Hinkel (2017).

4.4.3.1.7 Governance of hard and sediment-based protection

Reviews and comparative case studies confirm findings of AR5 that governance challenges (also called barriers) are amongst the most frequent hindrances to implementing coastal adaptation (Ekstrom and Moser, 2014; Hinkel et al., 2018). One main issue thereby is conflicting interests of stakeholders. This includes conflicts between those favouring protection and those being negatively affected by adaptation measures. In Catalonia, for example, the tourism sector welcomes beach nourishment since it directly benefits, while those living from natural resources (e.g., fishermen) show a growing opposition (González-Correa et al., 2008). This also includes conflict related to the distribution of public money between coastal actors receiving public support for adaptation and non-coastal actors paying for this through taxes (Elrick-Barr et al., 2015). Generally, access to financial resources for coastal adaptation, including from public sources, development and climate finance or capital markets (Ekstrom and Moser, 2014; Hinkel et al., 2018). In many parts of the world, coastal adaptation governance is further complicated by existing conflicts over resources. For example, illegal coastal sand mining is currently a major driver of coastal erosion in many parts of the developing world (Peduzzi, 2014).

An associated governance challenge is ensuring the effective maintenance of coastal protection. Ineffective maintenance has caused many coastal disasters in the past such as in New Orleans, just to mention one prominent example (Andersen, 2007). AR5 highlighted that effective maintenance is challenging in a small island context due to a lack of adequate funds (and mechanisms guaranteeing their sustainability), policies (especially maintenance programs) and technical skills (Nurse et al., 2014). In some countries in which coastal defence systems have a long history, effective governance arrangements for maintenance, such as the Water Boards in the Netherlands, have emerged. In Bangladesh, where Dutch-like polders have been introduced in the 1960s, maintenance has been a challenge due to shifts in multi-level governance associated with independence, national policy priorities and donor involvement (Dewan et al., 2015).

A further governance challenge is to implement governance systems and decision making procedures that are adaptive in order to account for unfolding climate change as more knowledge and experience about climate change and its impacts becomes available. While there is a lot of normative literature putting forward adaptative or transformative governance designs (Folke et al., 2005; Chaffin et al., 2016; Glavovic, 2016), there is limited empirical literature analysing their performance (Cross-Chapter Box 2 in Chapter 1). There is also a substantial normative literature on how to make flexible and adaptive decisions. Both the normative governance a normative decision making literature will be assessed in Section 4.4.4.

4.4.3.2 *Ecosystem-Based Protection*

Ecosystem-based Adaptation (EbA) measures refer to a wide spectrum of measures that involve the sustainable management, conservation, and restoration of ecosystems to enable adaptation to the impacts of climate change. For example, these could include large areas of conserved or restored natural coastal wetland or coral reefs, or smaller 'greenbelts' of coastal vegetation that are periodically managed to provide some wave reduction to inland flood protection structures. These measures are also referred to by various other names, including Natural and Nature-based Features, Nature-based Solutions, Ecological Engineering, Ecosysytem-based Disaster Risk Reduction or Green Infrastructure (Bridges, 2015; Pontee et al., 2016). It is also mostly in this context that the term 'hybrid' measures is used, in referring to measures that combine specific aspects of EbA design with aspects of traditional engineering design, such as a measure that includes a marsh green-belt in front of a seawall, or a seawall especially designed to include niches for habitat formation (Coombes et al., 2015). EbA measures protect the coastline in three ways: by attenuating the energy, and hence height, of incoming waves and in the case of salt marsh and mangroves also storm surge levels as they provide space for flood retention (Krauss et al., 2009; Zhang et al., 2012; Vuik et al., 2015; Rupprecht et al., 2017); by trapping and stabilizing coastal sediments, and through this, raising elevation and reducing rates of erosion (Shepard et al., 2011); and by raising shoreline elevations through the build-up of organic matter and detritus (Shepard et al., 2011; McIvor et al., 2012a; McIvor et al., 2012b; Cheong et al., 2013; McIvor et al., 2013; Spalding et al., 2014).

4.4.3.2.1 *Observed ecosystem-based protection across geographies*

Relative to hard adaptation measures whose global distribution is not known in detail (Scussolini et al., 2015), the current global distribution of coastal ecosystems is well-studied (e.g., for saltmarshes and mangroves, respectively; Giri et al., 2011; Mcowen et al., 2017). Meanwhile potential restoration extents are not as well-understood. Ecosystem-based adaptation, by definition, can only exist and function where the the enviromental conditions are appopiate for a given ecosystem. Habitats like mangroves, salt marshes and reefs cover about ~40% to 50% of the world's coastlines (Wessel and Smith, 1996; Burke, 2011; Giri et al., 2011; Mcowen et al., 2017). However, there is no clear estimate on the global length of coastline covered by all habitats relevant in the context of SLR partially because a mismatch between the spatial resolutions of different estimates available. Mangroves occur on tropical and subtropical coasts, an cover around 13,776,000 ha across 118 countries (Giri et al., 2011). At least 150,000 km of coastline in over 100 countries benefit from the presence of coral reefs (Burke, 2011). The extent of other coastal habitats are less known: salt marshes are estimated to occur in 99 countries, with nearly 5,500,000 ha mapped across 43 countries (Mcowen et al., 2017). Such estimates can be used to assess the economic or societal value of each ecosystem at multiple spatial scales. For example, coral reefs are estimated to protect over 100 million people from wave-induced flooding globally (Ferrario et al., 2014).

A key motivation for ecosystem-based adaptation (EbA) is that they can help shift coastal protection practice towards more sustainable options (Cheong et al., 2013; Temmerman et al., 2013; Cohen-Shacham et al., 2016; Wamsler et al., 2016). Main challenges identified in the IPCC AR 5 were the low number of implemented ecosystem-based solutions to assess either the risks or the benefits comprehensively (AR5 Cross-Chapter Box on EbA).

Since AR5 there is growing number of implemented ecosystem-based measures worldwide. Specifically in coastal areas, several countries and communities are implementing EbA measures for coastal protection (Narayan et al., 2016). There is also a push to include the evaluation of the benefits of these measures into systems of national accounts (Beck and Lange, 2016). In parallel, EbA measures are increasingly being incorporated and required within national plans, strategies and targets (Lo, 2016), and also within international adaptation funding mechanisms such as the Adaptation Fund (AF; e.g., Sri Lanka, India; Epple et al., 2016). Given their relative novelty as an adaptation measure, there is wide-spread interest in building and collecting knowledge of EbA implementation case-studies and examples. Table 4.8 provides a non-exhaustive selection of databases that compile several examples of EbA consideration and implementation worldwide including those implemented at the coast.

EbA adaption can also be used within retreat, advance responses and accomodation. For example, coastlines have been retreated by relocating high-risk properties inland, while making space for ecosystem restoration (French, 2006; Coastal Protection Authority, 2017). Similarly, there are examples of coastal restoration being used to advance coastlines and build land elevation (Chung, 2006). EbA can also be an element of accomodation responses by, for example, restoring or creating marshes to provide space for flood water (Temmerman et al., 2013).

Table 4.8: Examples of databases of EbA measures including coastal applications.

Scope and spatial extent	Description
Database on ecosystem-based approaches to Adaptation (UNFCCC) Global / global	An initiative under the Nairobi work programme to provide examples of ecosystem-based approaches to adaptation, supplementing information to FCCC/SBSTA/ 2011/INF.8, mandated by the SBSTA at its thirty-fourth session under the Nairobi work programme. Link: http://www4.unfccc.int/sites/NWP/Pages/soe.aspx
Coastal Resilience (The Nature Conservancy) / global	Coastal Resilience is a global network of practitioners who are applying an approach and web-based mapping tool designed to help communities understand their vulnerability from coastal hazards, reduce their risk and determine the value of nature-based solutions. Link: http://coastalresilience.org/
SAGE (Sytem approach to geomorphic engineering) / U.S.A.	SAGE is a Community of Practice of U.S federal, state, and local agencies, non-governmental organizations, academic institutions, engineers, and private businesses working together to use and promote green-gray approaches to ensure coastal community and shoreline resilience. SAGE provides a searchable project database: Link: http://sagecoast.org/info/sagesearch.html#
Climate Change Adaptation Database - Integrating Biodiversity into Climate Change Adaptation Planning (CBD) / global	The database provides web-based guidance on the integration of biodiversity within adaptation planning. It gathers information tools and case studies from a number of relevant partners. It provides links to scientific studies and other resources on biodiversity-related climate change adaptation. These examples can assist managers and governments to find adaptation options that will not have a negative impact on biodiversity. Link: https://adaptation.cbd.int/options.shtml#sec1
PANORAMA – Solutions for a healthy planet (GIZ, IUCN, UN Environment, GRID Arendal, Rare) / global	An interactive platform and database of specific, applied examples of successful NBS, EbA and Eco-DRR processes or approaches structured according to regions, ecosystems, specific thematic areas, governance and hazards addressed. Useful for identifying different targets (Aichi, Sendai Framework, SDGs, NDC) and outlining challenges. Link: http://panorama.solutions/en/explorer/grid/1042
Natural Water Retention Measures catalogue (EU) / Europe	NWRM cover a wide range of actions and land use types. Many different measures can act as NWRM, by encouraging the retention of water within a catchment and, through that, enhancing the natural functioning of the catchment. The catalogue of measures hereunder is sorted by sector. It has been developed in the NWRM project, represents a comprehensive but non prescriptive wide range of measures. Link: http://nwrm.eu/measures-catalogue
Naturally resilient communities (US National Planning Association) / U.S.A.	This database allows to explore over 50 solutions and case studies on nature-based solutions and included case studies of successful projects from across the US to help communities learn more and identify which nature-based solutions might work for them. The explorer allows to filter by cost, region, hazards, and more. Link: http://nrcsolutions.org/ http://nrcsolutions.org/
Equator Initiative, Solutions Database / global	The Solutions Database helps to learn how local communities and indigenous peoples around the world are making possible the achievement of the UN Sustainable Development Goals through nature-based actions.

	Link: https://www.equatorinitiative.org/knowledge-center/nature-based-solutions-database/

In addition to these larger-scale efforts there is a multitude of local ecosystem-based adaptation measures being implemented by coastal communities around the globe, that aim to enhance coastal resources while providing coastal protection and other co-benefits and are often under-reported, such as community-based mangrove planting and rehabilitation actions. Many of these ecosystem-based adaptation measures involve community participation and ownership, and thus create synergies with Community-based adaptation (Reid, 2016)—a process that is led by communities based on their priorities, needs and capacities (See Section 4.4.4.4).

In summary, uptake of EbA was very strong since AR5 with a growing number of case studies, implementations and experiences. Adopting and implementing EbA still remains a challenge. The main challanges include that EbA implementation demands socio-ecological research and undertanding of the system (Wasson et al., 2015; Scarano, 2017). Solutions are typically site specific; tend to need time to be fully functional and typically need more space than grey measures.

4.4.3.2.2 Projected ecosystem-based protection

While there are projections available of ecosystem responses to climate change and sea-level rise (Section 4.3.3), to date, there are no dedicated projections on the global extend of EbA.

4.4.3.2.3 Economic cost ecosystem-based protection

There is limited evidence and low agreement on the costs of ecosystem-based measures to make generally valid estimations of the unit costs across large spatial scales. The total cost of an ecosystem-based measure includes capital costs, maintenance costs, the cost of land and, in some situations, permitting costs (Bilkovic, 2017). The costs of restoring and maintaining coastal habitats depend on coastal setting, habitat type and project conditions. In general, unit restoration costs are lowest for mangroves, higher for salt marshes and oyster reefs and highest for seagrass beds and coral reefs (Table 4.9). These unit costs are highly variable, even for the same habitat type (Lewis, 2001). Reported unit restoration costs vary from less than USD $10,000 per hectare for mangroves to more than USD $150,000 per hectare for coral reefs (Bayraktarov et al., 2016; Narayan et al., 2016).

The conservation of coral reefs and other coastal habitats may also entail substantial opportunity costs that are often overlooked (Stewart et al., 2003; Balmford et al., 2004; Adams et al., 2011; Hunt, 2013). Globally, coastal ecosystem are amongst the ecosystems that face the highest rates of human destruction, with estimated annual losses of 1%–3% of mangroves area, 2%–5% seagrass area and 4%–9% corals (Duarte et al., 2013). Conserving these areas means reversing these trends, which in itself would be a transformative change, but would also support and enhance coastal adaptation to SLR. An increasing number of targeted public and private financial mechanisms are emerging, that can promote and incentivise the implementation and, where required, maintenance of ecosystem-based measures for adaptation and risk reduction (Colgan et al., 2017; Sutton-Grier et al., 2018).

An advantage of EbA measures is that, under the right conditions and to a certain extent, natural habitats have the capacity to respond and adapt to changes in their coastal environment, making them ‘maintenance-free’. However, maintenance can become important in the immediate aftermath of storms, when wetlands and reefs can be damaged by high winds, waves and surges, and further affected by sediments and debris (Smith III et al., 2009; Puotinen et al., 2016). At present, there is limited evidence for the conditions that will determine when EbA measures can self-adapt and when they will require human intervention to recover.

Table 4.9: Costs of ecosystem-based protection

Type of measure	Capital Costs	Maintenance Costs
Vegetation Conservation	None	Thinning, clearing debris after storms, etc.: Mangrove: USD $5000 ha^{-1} yr^{-1} in Florida (Lewis, 2001).

Vegetation Restoration (Marshes/Mangroves, Maritime Forests)	Mangroves: USD $9000 ha$ (median) (Bayraktarov et al., 2016); USD $2000–$13,000 ha^{-1} in American Samoa (Gilman and Ellison, 2007); Salt Marshes: USD $67,000 ha^{-1} (Bayraktarov et al., 2016)	No data available; similar to maintenance costs for Vegetation Conservation
Reef Conservation (Coral/ Oyster)	None	No data available; low
Reef Restoration (Coral/ Oyster)	USD $165,600 ha^{-1} (median) (Bayraktarov et al., 2016); Oyster Reefs: USD $66,800 ha^{-1} (median) (Bayraktarov et al., 2016)	No data available; low

4.4.3.2.4 Effectiveness of ecosystem-based protection

There is high evidence on the effectiveness of EbA reducing extreme sea-level but low agreement on the size of the effect (Gedan et al., 2011; Doswald et al., 2012; Lo, 2016; Renaud et al., 2016). Dozens of independent field, experimental and numerical studies have observed and measured the wave attenuation and flood reduction benefits provided by natural habitats such as marsh and mangrove wetlands (Barbier and Enchelmeyer, 2014; Möller et al., 2014; Rupprecht et al., 2017), coral reefs (Ferrario et al., 2014), oyster reefs (Scyphers et al., 2011), submerged seagrass beds (Infantes et al., 2012). A synthesis of 69 such studies showed average attenuation rates of 32, 21, 12 and 5 cm per 100 m in salt marshes, coral reefs, mangroves and seagrasses respectively (Narayan et al., 2016), though it is noted here that wave attenuation is generally non-linear across these habitats with the first few 10s of meters responsible for the majority of the total attenuation (Koch et al., 2009).

As a consequence, there is also low agreement regarding the size of economic benefits of EbA. The most common value-estimation methods for ecosystem-based measures for risk reduction are the replacement cost approach (Barbier, 2007) and the avoided damages approach (Beck and Lange, 2016). Using these methods, studies have shown that coastal habitats can save lives during cyclones (Das et al., 2009), avoid several millions of dollars in flood damages from storm surges (Barbier et al., 2013; Narayan et al., 2017; Beck et al., 2018), reduce the required crest heights and maintenance costs for seawalls and dykes (Möller et al., 2001; International Federation of Red Cross and Red Crescent Societies, 2011; Van Slobbe et al., 2013), and be restored to provide protection from waves at costs 2 to 5 times lower than breakwaters (Ferrario et al., 2014; Narayan et al., 2016).

The effectiveness of ecosystem-based measures exhibits high variability in space depending on storm, wetland and landscape parameters (Koch et al., 2009; Loder et al., 2009; Wamsley et al., 2010; Pinsky et al., 2013), which makes it difficult to extrapolate the physical and economic benefits across geographies. Studies based on field observations, experiments and numerical models elucidate some of the parameters that influence this effectiveness, such as structural complexity in coral reefs (Harris et al., 2018), vegetation density, height and structural complexity in salt marshes (Möller, 2006; Möller et al., 2014) and mangrove forests (Maza et al., 2016). Depending on these parameters, rates of surge attenuation can vary between 5 and 70 cm km^{-1} (Krauss et al., 2009; Vuik et al., 2015). Critical gaps remain in our understanding of these parameters that together affect the success of ecosystem-based measures including choice of species and restoration techniques, lead time, natural variability and residual risk, temperature, salinity, wave energy and tidal range (Smith, 2006; Stiles Jr, 2006). For example, common reasons for the failure of mangrove restoration projects include poor choice of mangrove species, planting in the wrong tidal zones and in areas of excessive wave energy (Primavera and Esteban, 2008; Bayraktarov et al., 2016; Kodikara et al., 2017).

The effectiveness of ecosystem-based measures also exhibits high seasonal, annual and longer-term variability. For example, marsh and seagrass wetlands typically have lower densities in winter which reduces their coastal protection capacity (Möller and Spencer, 2002; Paul and Amos, 2011). In the long-term, there is limited evidence and low agreement for how changes in sea level, sediment inputs, ocean temperature and ocean acidity will influence the extent, distribution and health of marsh and mangrove wetlands, coral reefs and oyster reefs (Hoegh-Guldberg et al., 2007; Lovelock et al., 2015; Crosby et al., 2016; Albert et al., 2017). Furthermore, ecosystem-based measures may have differential lead times before they are effective. For example, newly planted mangroves provide less wave attenuation until they mature (~3–5 years; Mazda et al., 1997). In contrast, a reef restoration project that uses submerged concrete structures perform as a breakwater as soon as the sub-structure is in place (Reguero et al., 2018).

4.4.3.2.5 Co-benefits and negative consequences of ecosystem-based protection

There is high confidence that ecosystem-based measures provide multiple co-benefits such as sequestering carbon (Siikamäki et al., 2012; Hamilton and Friess, 2018), facilitating income from tourism (Carr and Mendelsohn, 2003; Spalding et al., 2017), enhancing fishery productivity (Carrasquilla-Henao and Juanes, 2017; Taylor et al., 2018), improving water quality (Coen et al., 2007; Lamb et al., 2017), providing raw material for food, medicine, fuel and construction (Hussain and Badola, 2010; Uddin et al., 2013), and providing a range of intangible and cultural benefits generally difficult to express in monetary terms (Scyphers et al., 2015). The value of mangroves was shown to be dominated by their climate mitigation and coastal protection services (including erosion control and defence against extreme weather events) as opposed to their provisioning services (Emerton et al., 2016). Ecosystem-based measures also have an implicit benefit in that they generally do not harm the coastal environment like hard protection structures do (Section 4.4.3.1.4; Bulleri, 2010; Gittman et al., 2016). Estimating the economic value of these co-benefits is crucial when comparing ecosystem-based measures with other coastal adaptation measures.

One of the biggest drawbacks of EbA is space required (Royal Society, 2014), and competition for space is often why the ecosystems have declined in the first place (see Section 4.4.3.3). On developed coasts this space is often not available. In such cases, hybrid measures that either make limited use of natural features, or build ecological enhancements into man-made structures can provide an effective compromise. Like any other feature that interacts with coastal processes, natural wetlands and reefs can increase flooding in some instances, for example, due to the redistribution or acceleration of flows in channels within a wetland system (Marsooli et al., 2016) or an increase in infragravity wave energy behind a reef (Roeber and Bricker, 2015).

4.4.3.2.6 Economic efficiency of ecosystem-based protection

There is limited evidence regarding the overall economic efficiency of EbA. A study of coastal protection measures on the Gulf of Mexico coastline of the USA estimated EbA measures as having average benefit-cost ratios above 3.5 for future (2030) flood risk conditions, obtained by extrapolating historic sea-level observations and assuming a discount rate of 2% (Reguero; see Section 4.4.3.2.2). This study illustrates how economic exposure on the coastline influences the economic efficiency of EbA measures, with wetland restoration in high-risk areas being nearly 4 times more cost-effective than restoration in conservation-priority areas situated away from developed coastlines.

4.4.3.2.7 Governance of ecosystem-based protection

While the coastal protection benefits of natural ecosystems are increasingly being recognized within international discourse and national coastal adaptation, resilience and sustainable development plans and strategies (Section 4.4.3.2.1), there are few examples of instruments specifically tailored at the protective function of EbA. One example is the Living Shorelines Regulations of the state government of Maryland in the USA (Maryland DEP, 2013), which requires that improvements to coastal protection for private properties must consist of marsh creation or other non-structural shoreline stabilization measures unless a waiver is obtained. Most regulatory and funding mechanisms for natural coastal ecosystems, however, focus on conserving these ecosystems for their biodiversity and habitat and not for coastal adaptation. Another governance challenge is that obtaining permits for EbA could be more difficult compared to established hard measures, like in the USA (Bilkovic, 2017).

There are, however, an increasing number of public and private mechanisms and instruments that seek to encourage the use and implementation of EbA measures (Colgan et al., 2017). For example, a regulation by the Federal Emergency Management Agency (FEMA) of the USA, allows to take into account the co-benefits of EbA in the assessment of the benefit-cost ratio of FEMA-funded coastal recovery projects (FEMA, 2015). There is also an increasing number of guidelines for designing and implementing EbA measures, that illustrate a wide-spread effort to establish a body of practice for these responses (Hardaway Jr and Duhring, 2010; Van Slobbe et al., 2013; Van Wesenbeeck et al., 2017; Bridges et al., 2018).

4.4.3.3 Advance

4.4.3.3.1 Observed advance across geographies

Advance has a long history in most areas where there are dense coastal populations and a shortage of land. This includes land reclamation through polders around the southern North Sea (Germany, the Netherlands, Belgium and England) and China (Wang et al., 2014), which is the same region where there is a lot of hard coastal protection in place (Section 4.4.3.1). Land claim has also taken place in all major coastal cities to some degree, even if just for the creation of the port and harbour areas by raising coastal flat above normal tidal levels through filling with sediments. On some steep coasts where there is little flat such as Hong Kong, higher areas have been lowered to create fill material to build land out into the sea.

Globally, it is estimated that about 33,700 km^2 of land has been gained from the sea during the last 30 years (about 50% more than has been lost), with the biggest gains being due to land reclamation in places like Dubai, Singapore and China (Wang et al., 2014; Donchyts et al., 2016). In Shanghai alone, 590 km^2 land has been reclaimed during the same period (Sengupta et al., 2018). In Lagos, 25 km^2 of new land are currently being reclaimed (https://www.ekoatlantic.com/). Land reclamation is also popular in small islands. The Maldives have recently increased the land area of their capital region by constructing a new island call Hulhumalé, which has been built 60 cm higher than the normal island elevation of 1.5 m, in order to take into account future SLR (Hinkel et al., 2018).

4.4.3.3.2 Projected advance

While in the past, advance was not primarily a response to SLR, but to a range of drivers including land scarcity and population pressure, as well as management of extreme events, future advance measures are expected to become more integrated with coastal adaptation and might even be seen as an opportunity to support and fund adaptation in some cases (Linham and Nicholls, 2010; RIBA and ICE, 2010; Nicholls, 2018). While there is no literature on this, significant further land claim is expected in land scarce situations such as found in China, Japan and Singapore over the coming few decades.

4.4.3.3.3 Costs of advance

Contrary to protection measures, little systematic monetary information is available about costs of advance measures, specifically not in the peer-reviewed literature. The costs of land reclamation are extremely variable and depend on the unit cost of fill versus the volumetric requirement to raise the land. Hence, filling shallow areas is preferred on a cost basis.

4.4.3.3.4 Effectiveness of advance

Similar to hard protection, land reclamation is mature and effective technology and can provide predictable levels of safety. If the entire land is raised above the height of extreme sea-levels, residual risks are much lower as compared to hard protection as there is no risks of defence failure.

4.4.3.3.5 Co-benefits and negative consequences of advance

The major co-benefit of advance is the creation of new land. The major drawbacks include groundwater salinisation, enhanced erosion and loss of coastal ecosystem and habitat, and the growth of the coastal floodplain (Li et al., 2014; Nadzir et al., 2014; Wang et al., 2014; Chee et al., 2017). In China, for example, about 50% of coastal ecosystems have been lost due to land reclamation, leading to a range of impact such as loss of biodiversity, decline of bird species and fisheries resources, reduced water purification and more frequent harmful algal blooms (Wang et al., 2014). Inadvertently historic land claim through polders may have enhanced exposure and risk to coastal flooding by creating new populated flood plains, but this has not been evaluated.

4.4.3.3.6 Economic efficiency of advance

In the scientific literature, there is little evidence about the benefit-cost ratios of advance, but benefit-cost ratios of land reclamation can be very high in urban areas due to high land and real-estate prices (Bisaro and Hinkel, 2018).

4.4.3.3.7 Governance of advance

Land reclamation raises equity issues with regards to access and distribution of the new land created, specifically due to the political economy associated to high land values and the involvement of private capital and interests (Bisaro et al., in review), but this has hardly been explored in the literature.

4.4.3.4 Accommodation

Accommodation includes a diverse set of biophysical and institutional responses aiming at reducing either exposure or vulnerability to climate risks and impacts and thus enabling the habitability of coastal zones despite increasing levels of hazard occurance. In the context of sea-level rise and related coastal hazards following accommodation measures has been considered in the literature: Physical accommodation to reduce exposure and vulnerability to coastal flooding includes building regulation and codes which apply standards for new construction and retrofitting existing properties and individual retrofitting decisions on the household level such as raising house floors, building stilt houses, lifting valuable goods to higher floors or shelfs.

Physical accommodation for salinity intrusion include land use changes and changes in production sytsms such as changing land use froms, such as rice paddies to brackish/salt shrimp aquaculture or the use of salt tolerant crop varieties. There are no physical accommodation measures for erosion. Institutional responses include early warning system, emergency planning, insurance schemes, and setback zones.

4.4.3.4.1 Observed accommodation across geographies

There is a *high agreement* among experts that accommodation is a core element of adaptation and taking place on various scales based on different accommodation measures such as flood-proofing of buildings, implementing drainage systems, land-use changes but also early warning system, emergency planning, setback zones or insurance schemes. However, since acoomodation entails a large number of different responses, no literature is available which would summarize observed accommodation wordwide. There is *low evidence* of accomodation occurring directly as a consequence of sea level rise but *high evidence* of accommodation measures being implemented in response to coastal hazards such as coastal flooding, salinization and other sea-borne hazards such as cyclones.

The primary objective of these measures is to reduce or avoid impacts of coastal flooding upon structures such as houses. Flood-proofing may include the use of building designs and materials which make structures less vulnerably to flood damages and/or prevent floodwaters from entering structures. Examples include raising the floor of houses in the lower Niger delta (Musa et al., 2016), construction of verandas with sandbags and shelves in houses to elevate goods during floods in coastal communities in Cameroon (Munji et al., 2013). In Semarang City, Indonesia, residents adapted to coastal flooding by elevation of their houses by 50 to 400 cm or moving their goods to safer places, without making structural changes (Buchori et al., 2018). Residents of Can Tho (FEMA, 2014) City of the Mekong Delta, Vietnam elevated houses in response to tidal flooding (Garschagen, 2015). In urban areas extensive drainage systems contribute to accommodation such as Hong Kong and Singapore, which relies on urban drainage systems to handle large volumes of surface runoff generated during storm events (Chan et al., 2018). Farming practices have been adapted to frequent flooding in the lower Niger delta: farmers raise crops above flood waters by planting on mounds of soil and apply ridging and terracing of farmlands to form barriers (Musa et al., 2016). In floodplains of Bangladesh flooting gardens help to maintain food production even if the area is submerged (Irfanullah et al., 2011). The traditional way in the floodplain of Bangladesh is to build homesteads on a raised mound, built with earth from the excavation of canals and ponds (ADPC, 2005).

Communities in The Netherlands are experimenting with floating/amphibious houses capable to adapt to different water levels and similar conciderations are discussed also in other geographies such as in Bangkok (Nilubon et al., 2016). Flood-proofing is widely applied in the USA where wet and dry flood-proofing measures are recognised: wet flood-proofing reduces damage from flooding while dry flood-proofing making a building watertight or substantially impermeable to floodwaters up to the expected flood height (FEMA, 2014). In that sense dry flood-proofing could be also interpreted as a protection measure on the level of individual sructures.

Physical accommodation to salinization and saline water intrusion is more poorly documented. It mainly entails agricultural adaptation to soil salinity and saline surface and ground water as described for the land use changes towards alternating rice-shrimp systems and shrimp aquaculture in the Mekong delta (Renaud et al., 2015) or using methods, which descrease soil salinity such as flashing rice fields with fresh water to wash out salinity (Renaud et al., 2015) or applyieng maize straw in wheat fields (Xie et al., 2017). Coastal communities are also experimenting with the use of salt tolerant varieteies as a result of breeding programms, for example, in Indonesia (Rumanti et al., 2018), or saline irrigation water in conjunction with fresh water such as for maize in coastal Bangladesh (Murad et al., 2018).

Early warning systems (EWS) are frequently incorporated into the overall risk reduction strategy. They fall under "accommodation" as they allow for remaining in the potentially hazard-proce area while they provide information on future or ongoing events to reduce loss of life and damages. In contrast to structural protection measures EWS are cost-effective, have shorter installation time and lower impact on the environment (Sättele et al., 2015). EWS have undergone a rapid technical development and are today frequently implemented in an integrated risk management.

Climate risk insurance schemes have been recently developed to address sudden and slow onset hazards at the coast and to increase overall resilience. Index based insurance products are increasingly offered particularly in low-income countries and have been also included in a number of countries in their Nationally Determined Contributions (NDCs) and in some cases in their National Adaptation Plans (NAPs) (Kreft et al., 2017). Counties whith existing climate risk insurance schemes includes for example Haiti, Maldives, Seychelles and Vietnam. The InsuResilience Global Partnership for Climate and Disaster Risk Finance and Insurance Solutions was launched at the 2017 UN Climate Conference (COP 23) in Bonn. InsuResilience aims to enable more timely response after a disaster and helps to better prepare for climate and disaster risk through the use of climate and disaster risk finance and insurance solutions. So far, climate risk insurance was mainly used in the context of agriculture, where it has showed great efficacy in boosting investments for increasing productivity (Fernandez and Schäfer, 2018). However, on the global scale the uptake of index insurance is still low (Yuzva et al., 2018).

4.4.3.4.2 Projected accommodation

While there is no literature on projected accomodation, current trends suggest further uptake of accommodation approaches in the coming few decades, especially where protection approaches are not economically viable. Flood proofing of houses and establishment of new building codes is expected to see further uptake in the coming years. Similarly, accomodation measures to salinity are under further development such as rice breeding programs to improve salt tolerance (Linh et al., 2012; Quan et al., 2018). However, the achievements to improve salinity tolerance in rice are so far rather modest (Hoang et al., 2016) but efforts are expected to continue or even intensify. Given that index based insurance products have been included in NDCs and NAPs in a number of countries (Kreft et al., 2017), uptake is expected to grow.

In summary, due to the large variety of different measures implemented worldwide in patchy patterns, we have *low confidence* in quantitative projections of accomodations in response to sea level rise. However, we have high confidence that accomodation measures will continue to be a widespread adaptation option especially in combination with protection and retreat measures.

4.4.3.4.3 Economic cost of accommodation

The economic cost of accommodation varies widely with the measures taken as well as the expected flood hight. For flood proofing of buildings in New York City for instance Aerts et al. (2014) provided economic rationale for the implemention of improved cost-effective building codes - such as elevating new buildings and protecting critical infrastructure. Flood-proofing can also be undertaken by individuals and even small, inexpensive flood-proofing efforts can result in reductions in flood damage (Zhu et al., 2010). In general, costs for flood-proofing increase as the flood protection elevation increases. Other costs include those formaintenance and if applicable insurance premiums. For example, deciding for a greater elevation of a building in the United States. will increase the project's cost; however, the additional elevation may lead to significant savings on flood insurance premiums (FEMA, 2014).

4.4.3.4.4 Effectiveness of accommodation

Accommodation measures are very effective for current conditions and small amounts of sea-level rise, also buying time for large SLR. Success stories include the case of Bangladesh where improved early warning, the construction of shelters and development of evacuation plans helped to reduce fatalities in case of flooding and cyclones (Haque et al., 2012). Analysis of the sitiation in Uganda shows the need to enhance the scientific and technical basis, to focus more strongly on the people at risk and to set aside sufficient funding to ensure the sustainability of EWS (Lumbroso, 2018). Illiteracy, lack of awareness and poor communication are still hampering effective response to early warning (Haque et al., 2012).

Limits occur much earlier as compared to protect, advance and retreat. While dikes can be raised to 10 m and retreat can be implemented to the 10 m contour or higher, accommodating sea-level rise has limits and ultimately a change to retreat or protection would be required.

4.4.3.4.5 Co-benefits and negative consequences of accommodation

The major co-benefit of accomodation is improved resilience of the communities at the place of their locations without retreat, human mobility or the use of land and resources for the construction of protection measures. Floodproofing for example helps to avoid to demolish or relocate structures and it is often an affordable and cost effective approach to reducing flood risk (Zhu et al., 2010). Specific accommodation measures have different co-benefits such as stilt houses not only protect from floding but also from wild animals (Biswas et al., 2015). Accomodation also maintains the landscape connectivity allowing access to the ocean as well as the landward migration of ecosystems, at least to some degree. It also retains flood dynamics and with that the benefits of flooding such as sediment re-disribution. Stilt houses leave space for the floodwater while wet-floodproofing maintains a low hydrostatic pressure on the buildings so that structurels are less prone to faileour during flooding (FEMA, 2014).

In order to include flooding into urban designe communities need to understand and anticipate flooding, and the ecological process of flooding needs to be included into urban design (Liao et al., 2016). The major drawback of accommodation is that it actually does not prevent flooding or salinization, which might have consequences not addressed by the accommodation measure itself. Examples include inundation of an area where houses are flood proofed but schooling of children and business operations are nevertherless disrupted. Significant clean up may also be needed after flood water entered the buildings including the removal of sediments, debris or chemical residues (FEMA, 2014). Also, flood-proofing measures require the current risk of flooding to be known and communicated to and understood by the public through flood hazard mapping studies and flood warning systems information (Zhu et al., 2010). Particularly small businesses were shown to have more difficulties to recover from flooding due to lack of forward planning (Hoggart et al., 2014).

4.4.3.4.6 Economic efficiency of accommodation

With regards to physical accommodation, cost-benefit estimates have been collected in the USA based on the National Flood Insurance Program, although this only addresses present extremes and ignores sea level rise (Zhu et al., 2010). In this context, it has been estimated that elevating new houses by 60 cm might raise mortgage payments by USD $240 a year, but reduce flood insurance by USD $1000 to USD $2000 a year depending on the flood zone (FEMA, 2018). For Ho Chi Minh City, elevating areas at high risk and retrofitting buildings would have benefit-cost ratios of 15 under SLR of 180 cm and a discount rate of 5% during the 21st century (Scussolini et al., 2017). Similarly, flood warning coupled with precautionary measures has been shown to produce significant economic benefits (Parker, 2017).

4.4.3.4.7 Governance of accommodation

While accommodation measures to coastal hazards are often taking place on smaller scale and fall under the decision of individual homeowners, farmers or communities, from the governance perspective it is important to provide guidance on how and to what extent owners can retrofit their homes to reduce the risk to coastal flooding. In New York City for instance, changes to City codes, notably Appendix G of the Building Code, have significant implications for the construction and retrofitting of buildings in the 100-year floodplain by elevating, or flood-proofing existing and new buildings (NYC, 2014).

Modern coastal risk management relies on good governance as it based on analysing the probability and consequences of flooding and salinization across the full range of severity, and implementing mechanisms to prevent or manage all possible events (EEA, 2013). The effectiveness of accomodation measures based on institutional measures such as early warning schemes or evacuation plans largerly depends on the governance structure there are embedded in.

4.4.3.5 Retreat

Climate change is exacerbating millions of people's vulnerabilities by increasing pressure on resources and land, with people retreating from the coast as an expected consequence. Resulting population movements can be broadly associated with three different forms of spatial mobility. These are migration, displacement and planned relocation. Migration is defined in AR5 as the permanent or semi-permanent move by a person at least for one year and involves crossing an administrative, but not necessarily a national border (Adger et al., 2014). In contrast, displacement refers to the involuntary and unforeseen movement of people from their place of residence due to environment-related impacts on livelihoods, property and infrastructure or political or military unrest forcing individuals from their original locations (Black et al., 2013; Islam and Khan, 2018; McLeman, 2018b; Mortreux et al., 2018). Planned relocation, also termed resettlement, managed retreat or managed realignment, is a third form of human mobility response in the face of sea level rise and related impacts (Wong et al., 2014; Hino et al., 2017; Mortreux et al., 2018). Relocation is typically initiated, supervised and implemented from national to local level and involves small communities and individual assets but may also involve large populations (Hino et al., 2017). However, these categories of retreat are not neatly separable – any one person's or household's decision to retreat may be "voluntary" in theory, but in practice, result from very limited choices. Displacement certainly occurs in response to extreme events but some of those retreating may have other options. Resettlement programs may rely on incentives such as land buyouts that households adopt voluntarily.

4.4.3.5.1 Observed retreat across geographies

There is a *high agreement* among experts that the relationship between climate change impacts including sea level rise and migration is more nuanced than suggested by simplified cause-and-effect models and alarmist projections (Adger et al., 2015). Migration is a multidimensional phenomenon that is interwoven with urbanisation, land use, globalisation processes and environmental change, with additional synergies with development and political practices and discourses (Bettini and Gioli, 2016).

Migration drivers can be broadly classified into six discrete categories. These are individual, social, economic, political, demographic and environmental (Black et al., 2011; Koubi et al., 2016). Asset endowed individuals and households are more able to migrate out from flood-prone areas (Milan and Ruano, 2014; Logan et al., 2016), while the poorest households are significantly suceptible to endure material and human losses following a natural hazard and repeated losses of livelihood make them more vulnerable to future risk (Call et al., 2017). Individual and social drivers include perceptions of environmental change (Koubi et al., 2016), which encompasses both direct experience with slow- and sudden-onset events and indirect information from agents' own social networks as well as mass media and governmental agencies. Environmental factors include both extreme weather events and longer-term impacts of climate variability and change (McLeman, 2018b). The literature also points to migration been triggered by thresholds. For example, failure of in-situ adaptation or land use or livelihoods can leads to fundamental change in migration flows and patterns (McLeman, 2018a).

There is *low evidence* of migration occurring directly as a consequence of impacts associated with environmental change generally and sea-level rise specifically. Research examining the linkages between migration and the environment has been conducted in the Pacific (Connell, 2012; Janif et al., 2016), South Asia (Szabo et al., 2016; Call et al., 2017), Latin America (Nawrotzki and DeWaard, 2016; Nawrotzki et al., 2017) and Africa (Gray and Wise, 2016). These studies emphasise the multifaceted nature of migration and the pervasive effects of environmental change across various drivers of migration. The studies also reiterate that climate change has the potential to drastically alter the size and direction of migration flows. There is *high evidence* of environmental hazards displacing people worldwide. In 2017, 18.8 million people were displaced by disasters, of which 18 million by weather-related events including 8.6 million people displaced by floods and 7.5 million by storms, with hundreds of millions more at risk (IDMC, 2017; Islam and Khan, 2018). The majority of moves tend to occur within the borders of countries (Warner and Afifi, 2014; Hunter et al., 2015; Nawrotzki et al., 2017). The government of Vietnam assists and manages rural populations' mobility from vulnerable areas in the Mekong Delta to large industrial areas such as Ho Chi Minh City and Can Tho City with labour needs as a response to future climate change (Collins et al., 2017). Direct evidence of population movement occurring in response to climate change, however, remains controversial. In the case of small islands for example, the AR5 specifies that 'evidence of human mobility as a response to climate change is scarce [and] there is no evidence of any government policy that allow for climate "refugees" from islands to be accepted into another country' (Nurse et al., 2014, p. 1625).

We find *high evidence* of planned relocation taking place worldwide in low-lying zones exposed to the impacts of coastal hazards with uneven processes of implementation and outcomes (Hino et al., 2017; Mortreux et al., 2018). For example, the loss of lives and structural damage caused by Hurricane Katrina triggered reconsideration of the management of the US Gulf coastline. One outcome was the release of the Louisiana Comprehensive Master Plan for a Sustainable Coast that recommended assisted migration among other initiatives (Barbier, 2015). The most recent version of the plan published in 2017 makes explicit reference to the potential relocation of homes and businesses of several communities in the state in the next 50 years due to flooding and sea level rise (Coastal Protection Authority, 2017). While usually discussed after an extreme event, such as Xynthia storm in France (Genovese and Przyluski, 2013) or Hurricane Sandy in the United States (Bukvic and Owen, 2017), relocation plans generally target the reduction of long-term environmental risks including risk due to sea level rise (McAdam and Ferris, 2015; Morrison, 2017). In the developing world, planned relocation interventions have been associated with environmental hazards that threatened lives, livelihoods and properties (Hino et al., 2017). Most of the retreat projects in the United Kingdom and Germany have been carried out for nature preservation as well as risk management purposes. Among these are relocation of communities exposed to coastal hazards such as Change Pathfinder in the United Kingdom and the Hazard Mitigation Grant Program in the United States of America (Hino et al., 2017).

4.4.3.5.2 Projected retreat

Movement of people from unprotected settlements displaced by the slow and continuous loss of productive land to sea-level rise will persist, punctuated by periodic surges of migrants in the aftermath of extreme storm events (McLeman, 2018b). Projection of changes in such flows can inform policy responses.

The number of modelling studies of migration in response to environmental drivers increased rapidly over the past decade (e.g., Kumari et al. (2018), for model typologies and general references on migration modeling). One objective of modeling is quantification of the influence of climate variability, extreme climate events, and climate change on past migration in contexts where multiple non-environmental drivers are also at work. Another is the projection of the effect of climate change over the course of the 21st century on migration. Only a small portion of model studies address migration in response to sea level rise and sea level extremes. AR5 highlighted a conceptual model of migration in response to sea level rise and flooding (Perch-Nielsen et al., 2008) at a time when models quantifying and projecting responses of coastal populations were not available.

Ideally, models projecting coastal migration responses would account for 1) local changes in exposure to episodic flooding accompanying storms and high tides as well as permanent inundation; 2) protection measures like sea walls already in place and anticipatory adaptation that could result in additional protection; 3) potential migration of nearby populations not directly subject to flooding and inundation; 4) changes in the "pull" effects of all locations, including the coastal zones, in response to losses of habitable and productive land and production capacity in coastal zones; 5) government policies and other political factors (The Government Office for Science, 2011) influencing adaptation investments and migration decisions. Each of these factors is important in determining the extent to which retreat occurs and whether it results in migration, permanent and long distance displacement of populations, or withdrawal to nearby locations. No model currently accounts for all of these factors. Furthermore, as with other impacts and responses to climate change, all of the above would need to be considered in the broader context of ongoing changes in exposure and vulnerability due to non-climate factors.

Exposure mapping (as assessed in Section 4.3.3.2) (Hauer et al., 2016 ; Newman et al., 2016) combined with demographic projections and sea level rise scenarios provides a basis for assessment of potential migration. In order to determine how coastal populations might be redistributed in the future, a model projecting future US county-level populations exposed to permanent inundation with 0.9 and 1.8m sea level rise was combined with an empirical model of potential migration destinations to produce the first sea level/migration analysis of migrant destinations (Hauer, 2017). Such models may be effective at capturing network effects (Curtis and Schneider, 2011) as is also the case for agent-based models (see below).

A gravity model modified to account for both distance to destinations and their attractiveness (deriving from such factors as economic opportunity and environmental amenities) projects a net migration into and out of the East African coastal zone ranging from out-migration of 750,000 people between 2020 and 2050 to a small in-migration (Kumari et al., 2018). However, this range includes migration simulated by fresh water availability as well as sea level rise and episodic flooding. A global dynamic general equilibrium framework (Desmet et al., 2018) provides a more comprehensive approach to accounting for economic factors including changes among trade, innovation, and agglomeration and political factors such as policy barriers to mobility. This model projects 0.1%–6% of the world's population migrating by 2100 due to sea level rise and up to 0.1%–4.4% by 2200 (combined range of 95% credible intervals derived from 3 RCPs) with local effects ranging up to an order of magnitude larger for some coastal cities. The model accounts for permanent inundation only and does not account for changes in coastal protection measures which will be implemented in many cities (*very high confidence*; Section 4.4.3.1.2).

Agent-based models attempt to simulate decisions by individuals in face a variety of socioeconomic and environmental changes. Such models have explored the effects on agents' migration decisions of various environmental stresses (Kniveton et al., 2012) and are being developed for sea level rise (Bell et al., in review) but so far, no results related to this driver have been published. Ultimately, such models are expected to produce local projections, including those that distinguish planned retreat from displacement, for which there is currently no literature. Econometric models, common in climate/migration studies (Millock, 2015), have yet to be applied to the sea level rise context. For example, an interesting distinction between migration responses to long term temperature and precipitation trends in contrast to extreme events like flooding has been noted (Bohra-Mishra et al., 2014; Mueller et al., 2014) but similar econometric studies have yet to be done comparing responses to gradual sea level rise versus extreme sea level events.

In summary, due to the large number of factors that need to be taken into account simultaneously to adequately represent the future coastal situation as well as the newness of attempts to model it, we have *low confidence* in quantitative projections of migration in response to sea level rise and extremes of sea level.

4.4.3.5.3 Economic cost of retreat

The economic cost of retreat includes the costs of redeveloping and relocating people and infrastructure further inland, as well as the permanent loss of land and changes in capital stock (Diaz, 2016; McNamara et al., 2018).

Contrary to protect, advance and accommodation responses, maintenance costs hardly arise because there are no protection structures or accommodation measures that need regular financial input (Suppasri et al., 2015; Hino et al., 2017). General equilibrium models (Section 4.4.3.5.2) provide a framework for projecting aggregate costs and have begun to separately estimate sectoral impacts of both gradual and temporary inundation (Schinko, in review).

Cost estimates in the literature are few and these are based on stylized assumptions as little empirical data is available. Estimates suggest that the monetary cost of managed relocation including land acquisition, building of roads and infrastructure and other subsidies may vary between USD $10,000 in Fiji and in the United Kingdom and USD $100,000 per person in Alaska and in the Isle of Jean Charles in the United States (Hino et al., 2017) to as much as three times per capita income based on individual data on wages of those being relocated (Hinkel et al., 2013a). For people involved in the planned relocation in Shaanxi Province, Northwest China, households receive subsidies ranging from USD $1200 to USD $5100 (Lei et al., 2017). In the state of Louisiana, the Comprehensive Master Plan for a Sustainable Coast released in 2012 was tasked with evaluating, prioritizing and integrating coastal protection and restoration projects including property protection and acquisition, and planned relocation over the next 50 years (Barbier, 2015). The Louisana's National Disaster Resilience Competition, Phase II Application states that areas projected to experience in excess of 14 ft of flood inundation over the next 50 years will be considered resettlement zones (State of Louisiana, 2015). The proposed relocation of 100 households located in Isle de Jean Charles in Louisiana was initially costed at approximately USD $100 million to settle 100 households. However, the implementation has been scaled back to relocate 40 households at the cost of USD $48,379,249. This includes land acquisition, infrastructure and construction of new dwellings (State of Louisiana, 2015).

4.4.3.5.4 Effectiveness of retreat

There is *very high confidence* that retreat is effective in terms of reducing the risks and impacts of SLR as reterat directly reduces exposure of human settlements and other land uses retreated (Gioli et al., 2016; Shayegh et al., 2016; Hauer, 2017; Morrison, 2017).

4.4.3.5.5 Co-benefits and negative consequences of retreat

The other outcomes of migration and displacement responses beyond the one of effectively reducing SLR risks and impacts are complex and affect both origin and destination. Households employ migration to diversify their portfolio of economic activities through access to distant labour markets in order to ensure survival or to improve their standards of living. Positive effects depend on the economic characteristics of destination areas. Voluntary migration can move individuals and households from a position of vulnerability to enhanced resilience in light of future impacts caused by sea level rise and associated climate change hazards. Income inequality may be reduced, but only through migration to areas with growing industries. Remittances can provide flexibility in livelihood options, supply capital for investment and spread risk (Scheffran et al., 2012). Migration and displacement brings about a set of challenges around competition for resources and within labour markets, pressure on frontline services and on social cohesion as a result of heightened cultural or ethnic tension (Werz and Hoffman, 2015). There are cultural, social and psychological losses related to disruptions to sense of place and identity, self-efficacy, and rights to ancestral land and culture (McNamara et al., 2018). Areas not directly affected by sea level rise and coastal flooding may gain economically as populations and capital relocate and provide a new source of labour, capital, and innovation to inland areas (see Section 4.4.3.5.2 on general equilibrium models).

The success of relocation in terms of the balance of co-benefits and negative consequences varies across relocation schemes (Hino et al., 2017). One potential co-benefit of planned relocation in well-designed and carefully implemented programmes is improvement of housing standards for vulnerable people (Suppasri et al., 2015). However, the literature suggests that relocated communities have often become further impoverished as a result of resettlement (Wilmsen and Webber, 2015). This reflects that individuals and communities are being removed from cultural and material resources on which they rely, compounded by poor implementation processes that fail to observe concepts of fairness, social and environmental justice and well-being (Herath et al., 2017; Mortreux et al., 2018; Nygren and Wayessa, 2018). There are impacts on social networks, access to services and economic and social opportunities, and across several subjective wellbeing indicators including life satisfaction, identity, self-efficacy and rights to ancestral land and culture (Jones and Clark, 2014; Adams, 2016; Herath et al., 2017; Kura et al., 2017; McNamara et al., 2018). As a result, planned relocation aroused controversy (Genovese and Przyluski, 2013; Ford et al., 2015; Nordstrom et al., 2015; Bukvic and Owen, 2017; Hino et al., 2017; Jamero et al., 2017).

4.4.3.5.6 Economic efficiency of retreat

There is *very limited evidence* of the overall balance between monetized costs, benefits, co-benefits and drawbacks for retreat responses. Retreat responses tend to be more cost-effective than other alternatives such as engineering measures at timescales greater than 25 years compared to those less than 25 years (Turner et al., 2007; Hino et al., 2017).

4.4.3.5.7 Governance of retreat

Environmentally driven migration and displacement gained major attention over the last decade in the international policy community (Goodwin-Gill and McAdam, 2017). Worldwide programmes such as the Nansen Initiative, signed by 110 countries to address the serious legal gap around the protection of cross-border migrants impacted by natural disasters have been implemented (Gemenne and Brücker, 2015). Governments are further encouraged by civil society to relocate people at risk and displaced populations out of disaster-prone areas to avoid potential casualties (Lei et al., 2017; Mortreux et al., 2018). There have been discussions among members of the Pacific Island countries and territories (PICTs) and other nations in the Pacific Rim around new policy mechanisms that would facilitate adaptive migration in the regionin response to natural hazards including sea level rise (Burson and Bedford, 2015).

Studies suggest that government action and allocation of resources towards responses to climate-related events and other environmental change is explained by a combination of risk aversion within political systems, desire to preserve legitimacy, and perceived socioeconomic and political benefits of investment. Inaction on the other hand is often associated with lack of government accountability, aversion to risk or other institutional challenges (Morrison et al., 2017; Mortreux et al., 2018).

Medium evidence has been collected on how governments can improve outcomes of migration and relocation:

- The majority of the literature suggests that outcomes can be improved by upholding the principle of fairness of process and respect for the autonomy of individuals and their decisions of where and how they live (Warner et al., 2013; Schade et al., 2015; McNamara et al., 2018). However, there are cases where logistical and political stances constrain the application of such approach, such as when the government of Sri Lanka prohibited rebuilding along the coastline of the country after the 2004 tsunami (*high agreement*) (Hino et al., 2017).
- If governments plan for migration, displacement and planned relocation proactively by including participation and consultation of those involved in the process there are, it seems, more pathways to positive outcomes for those affected by environmental change (*medium confidence*) (de Sherbinin et al., 2011 ; Gemenne and Blocher, 2017).
- Governments may assist migrants through policy reforms in the relocation to fast growing economic markets in the country. This is the approach adopted in Vietnam on both National Target Program to Respond to Climate Change and the National Strategy for Natural Disaster Prevention, Response and Mitigation targeted at locations within the Mekong Delta vulnerable to the impacts of sea level rise (Nguyen et al., 2015; Collins et al., 2017). These reforms enable temporary migrants full access to frontline services in places outside of their permanent residence under the Vietnamese Household Registration System (Ho Khau; *medium agreement*).
- Outcomes of retreat for migrants themselves and both community of origin and destination can also be improved by building human capital of migrants (skills, health, and education), reducing cost of migration and remittance transfer, and provision of improved safety nets for migrants at their destinations (*high agreement*) (Gemenne and Blocher, 2017).

4.4.3.6 Synthesis

This section synthesises the assessments of the individual types of responses from the previous sections, as well as the limited literature that has explored trade-offs and synergies across different types of responses.

4.4.3.6.1 Hard versus sediment-based protections responses

In principle, both beach-dune systems and dikes can be designed to deliver similar levels of flood risk reduction at the time of construction, but different upgrade strategies are required under SLR. One core advantage of sediment-based measures is their flexibility to increase efforts as SLR unfolds without the need to decide today on measures that are build for decades to come (see also Section 4.4.4.2.4). In this context, the Netherlands has selected sediment-based protection for its open coast, including move to shoreface nourishment, burying hard defenses where they exist and innovative sand engines (VanKoningsveld et al., 2008; Stive et al., 2011; Stive et al., 2013).

4.4.3.6.2 Hard versus ecosystem-based responses

The effectiveness of hard protection responses is better understood and more predictable than the effectiveness of EbA responses, which exhibit a high natural variability in time and space (Section 4.4.3.2.4) (Thieler et al., 2000; USACE, 2002; De Jong et al., 2014). Furthermore, hard protection measures need much less space to achieve the same level of protection than EbA measures. For both of these reasons, hard protection measures are generally favoured where there is limited space and large human values are at risk such as in and around major coastal settlements. Unlike hard protection measures, which are fixed in position and height and will degrade in their risk reduction capacity without maintenance, EbA measures can improve their risk reduction capacity over time (Van Wesenbeeck et al., 2017), can naturally adapt to rising sea levels (Rodriguez et al., 2014; Kirwan et al., 2016; Woodroffe et al., 2016), and autonomously recover from extreme events (Long et al., 2016). However, these capacities are not well understood quantitatively, and while models suggest, for example that oyster reefs can keep pace with predicted sea level rise through 2100 (Rodriguez et al., 2014), empirical data needs to be collected to validate these models. A primary motivation for, and advantage of, EbA measures is that they can enhance achievement of conservation goals in contrast to hard measures which often act to the detriment of these goals. Furthermore, EbA provide co-benefits making them attractive for local populations (Section 4.4.3.2.4). There is *limited evidence* on how hard and EbA responses differ in terms of their cost-effectiveness.

4.4.3.6.3 Hybrid protection responses

In practise hard, sediment-based and ecosystem-based protection responses are often combined and there is high agreement that such hybrid approaches are a promising way forward (Spalding et al., 2014; Sutton-

Grier et al., 2015; Small-Lorenz et al., 2016). For example, for coastlines exhibiting significant changes in direction or where wave attack is strongly oblique, nourishment may need to be combined with hard structures to control alongshore transport of sediment (e.g., groins) or to reduce wave action to limit the required height and volume of beach material (e.g., breakwaters). Also, because EbA measure have differential lead times before they start providing coastal protection benefits, intermediate hard or sediment-based defence measures may be needed. Sediment-based measures can also incorporate aspects of EbA. Examples are long-term nourishments, such as the sand engine, which evolve over many years through natural processes (Stive et al., 2013) or measures such as the management of natural dune systems (Everard et al., 2010). Careful design of hybrid approaches can provide enhanced coastal protection and safety while still providing a number of ecosystem services such as biodiversity conservation, carbon sequestration or improved water quality (Sutton-Grier et al., 2015; Liquete et al., 2016).

4.4.3.6.4 Systems-based responses

The trend towards establishing systems-based approaches for coastal management also needs to be acknowledged. These aim to address large coastal areas and their problems in a strategic manner. Examples include geomorphic approaches such regional sediment budgets and shoreline management planning (Rosati et al., 2004; Rosati, 2005; Thom et al., 2018) and wider broad-scale and delta management approaches (Stive et al., 2011; Van Alphen, 2016; Seijger et al., 2017; Nicholls et al., 2018a). By definition, these approaches are about more than just adapting to SLR, but at the same time, adapting to SLR is one key consideration, and the responses to SLR must be consistent with the wider goals of coastal management to be successful. EbA measures, and large sediment-based responses such as the sand engine (Stive et al., 2011), tend to function at greater spatial and temporal scales than typical coastal engineering structures; and, thus, provide an opportunity and impetus for more holistic consideration of system-wide coastal processes at these scales.

4.4.3.6.5 Complementarities and synergies across all types of responses

All types of responses have important and complementary roles to play given the deep uncertainty about future sea-levels. Protection responses are needed for densely populated and urban areas. Advance can thereby be a way to finance coastal protection through revenues generated from newly created land. Where space is available, or in less populated areas, ecosystem-based protection can supplement or substitute hard protection. No matter how the coast is protected, there remains a finite probability of failure (i.e., residual risk) that societies have to accept. Accommodation measures such as flood forecast, warning and emergency planning offer one way of managing such residual risk. Only retreat can avoid residual risks if there is sufficiently high ground available to retreat to. Due to the long term commitment to SLR (Section 4.2.4), this response is worth considering if coastal population density is low and risks are already high. But for coastal cities and densely populated coastal areas retreat generally does not need to be considered until we know that long-term SLR will be following high-end scenarios, as most these areas can be protected from low-end SLR. Protection, advance and accommodation can buy time until sufficient information on SLR is available to decide. In any case, steering future development away from coastal floodplains can help to avoid locking into the viscous circle of increasing exposure and protection levels (Section 4.4.3.1.5).

4.4.3.6.6 Governance

Governance challenges associated with coastal responses to SLR are diverse and differ across world regions. On the one end of a wide spectrum there are places such as many Small Islands for which SLR is a new phenomenon and new governance arrangements for addressing this need to be formed. On the other end of the spectrum there are places such as North-Western Europe, China, Japan and various coastal megacities in river deltas that have long been dealing with coastal risk and local sea-level rise and thus have governance arrangements in place that are already tackling the challenge of future SLR. A second noteworthy difference in governance challenges lies between densely populated and urban areas, for which coastal protection is economically very favourable, and rural and poorer regions for which it is not. In the former case, the major governance challenge lies in capturing the value of publicly financed adaptation (through taxes, special purpose levies or sales of valuable land), while in the latter case the major challenge lies in supporting poorer and rural communities through transfer payments or donor finance. In both cases, governance arrangements need to address critical equity issues, because SLR, protection, advance and retreat all influence the distribution of land, land value and coastal risks. For protection and advance, this includes equitable access to newly raised or flood protected land. For retreat this includes compensation and the design of fair and inclusive processes for steering human mobility to destinations offering opportunities for the people being moved. Finally, implementing responses requires making difficult social choices addressing trade-offs between multiple goals and diverse interests of people involved. Governance processes and decision-making approaches for dealing with these are discussed in the next section (Section 4.4.4).

4.4.4 Approaches for Making Social Choices and Appraising and Institutionalizing Adaptation Pathways

A diversity of methods and tools are available and applied to develop, appraise and institutionalize social choices in response to SLR. Relevant literature has developed rapidly since AR5. This section starts by examining the ways in which the governance setting frames and structures SLR responses, including the 'wicked problem' character of SLR, the value-laden nature of governance, the influence of adaptation politics in shaping the trajectory of SLR responses, and emerging perspectives on normative imperatives to guide adaptation planning (Section 4.4.4.1). A variety of societal processes and practices are taking place in response to SLR, as part of wider coastal governance efforts, including land-use planning provisions, legislative and regulatory provisions to formalize SLR responses, initiatives to align formal institutional provisions with informal institutional arrangements, as well as innovations in the applications of simulation games, futures and foresight methods, deliberation and conflict resolution processes (Section 4.4.4.2). Attention is then focused on decision analysis methods (Section 4.4.4.3) and community based approaches (Section 4.4.4.4).

4.4.4.1 The Governance Setting for Sea Level Rise Responses

[PLACEHOLDER FOR FINAL DRAFT]

4.4.4.2 Societal Processes and Practices for Responding to Sea Level Rise

[PLACEHOLDER FOR FINAL DRAFT]

4.4.4.3 Decision Analysis Methods

4.4.4.3.1 Context

A range of formal, decision analysis methods are available and applied for appraising and choosing adaptation alternatives. AR5 presented an overview of available methods for adaptation generally (Chambwera et al., 2014; Jones et al., 2014), as well as for coastal adaptation specifically (Wong et al., 2014). Since AR5 the literature on coastal decision analysis has grown significantly. This section assesses recent advances.

Decision analysis methods identify alternatives (also called options or adaptation pathways) from a predefined set of available alternatives that perform best or well with regards to given objectives. An alternative is a specific combination of SLR responses applied over time (See Section 4.4.2). Each alternative is characterised for each possible future state-of-the world (e.g., levels of SLR or socio-economic development) by one or several attributes, which may measure any relevant social, ecological, or economic value associated with choosing and implementing the alternative (Kleindorfer et al., 1993). Attributes commonly used include cost of adaptation alternatives, monetary and non-monetary benefits of the SLR impacts avoided, or net present value (NPV), which is the difference between discounted monetary benefits over time and discounted costs over time.

The analysis of adaptation alternatives should consider all available knowledge, including all major uncertainties in both climate and non-climate factors, ambiguities in expert opinions, and differences in approaches. A partial consideration of uncertainty and ambiguity may misguide the choice of adaptation alternatives (Renn, 2008; Jones et al., 2014; Hinkel and Bisaro, 2016). In the case of coastal adaptation, it is thus necessary to consider uncertainty in global and regional mean and extreme sea-levels (Sections 4.2.3.2, 4.2.3.5 and 4.2.3.4), waves (Section 4.2.3.4.2), local vertical land movement due to glacial-isostatic adjustment, tectonics and land subsidence (Section 4.2.2.5), as well as uncertainties in coastal impact modelling and socio-economic development (Section 4.3).

There is *high agreement* that any decision analysis method should be applied within an adaptive and iterative policy cycle that includes monitoring and evaluation of alternatives and sea-level variables in order to learn from past decisions and collect information to inform future decisions (Haasnoot et al., 2013; Barnett et al., 2014; Burch et al., 2014; Wise et al., 2014; Kelly, 2015; Lawrence and Haasnoot, 2017). Importantly, a monitoring strategy helps to identify required changes in policy sufficiently early to limit the risk of negative impacts (Hermans et al., 2017).

Decision analysis does not posit that there are purely objective ways of making decisions. The application of formal methods entails a number of normative choices concerning the objectives, the specific methods applied, the set of alternatives considered and the attributes used to characterize alternatives. Furthermore, adaptation decisions and their contexts are diverse and different context require different decision making approaches, with formal decision analysis being but one approach to inform to support social choices (Kleindorfer et al., 1993; Hinkel and Bisaro, 2016). Formal analysis is generally indicated if decisions are complex and involve large investments, as it is frequently the case in coastal context. But formal decision analysis should be embedded in a social process that ensures social needs and objectives are properly accounted for (see also Sections 4.4.4.1, 4.4.4.2, 4.4.5.1 and 4.4.5.2.).

4.4.4.3.2 Maximal expected utility versus robust decision making

In the climate change literature there has been an ongoing debate whether decision making should be based on maximising expected utility or on robust decision making (RDM) approaches (Lempert and Schlesinger, 2001) and some of the growing literature on decision analysis of coastal adaptation has picked up this debate (Hallegatte et al., 2012; Haasnoot et al., 2013; Lempert et al., 2013; Wong et al., 2017). This debate is ofte cast in terms of optimal versus robust decision making, but the term optimal is misleading as optimisation is also be applied in a robust decision making setting (Ben-Tal et al., 2009).

The core difference between the two approaches is that expected utility methods require probabilities attached to the states-of-the-world while RDM methods don't. Expected utility methods aim to identify the alternative which leads to the best expected outcome (i.e., the probability weighted sum of all possible outcomes under a given alternative) (Simpson et al., 2016). The expected outcome computed for each alternative can be used for uniquely ranking alternatives across scenarios and identify the best one. The most prominent representative of this approach is cost-benefit analysis under risk, which assesses expected outcomes in terms NPV (the discounted stream of net benefits).

Conversely, RDM methods aim to identify alternatives that perform reasonably well (i.e., "are robust") under all or a wide range of states-of-the-world and hence don't require probabilities. RDM methods include minimax or minimax regret (Savage, 1951), info gap theory (Ben-Haim, 2006), robust optimisation (Ben-Tal et al., 2009) and exploratory modelling methods that create a large ensemble of plausible future scenarios for each alternative and then use search and visualization techniques to extract robust alternatives (Lempert and Schlesinger, 2000). Robustness (i.e., lack of sensitivity to uncertainness) can be defined in terms of a range of attributes such as a desired level of effectiveness or NPV or the flexibility to switch to other alternatives at later points in time (see Section 4.4.4.2.4).

The core criterion to be considered for choosing between expected utility and RDM approaches is the one of deep uncertainty, which is the situation in which parties can't agree to attach a single probability distribution to states-of-the-world either because there is no unambiguous method for deriving objective probabilities or subjective probability judgements of parties differ (Lempert and Schlesinger, 2001; Weaver et al., 2013; Cross-Chapter Box 4 in Chapter 1). For climate change adaptation decision making, this means that the situation of deep uncertainty can only be avoided if either of the following two conditions can be met:

1. Emission or mitigation scenario uncertainty can be neglected because it is small as compared to other sources of uncertainty and a single objective probability distribution can be constructed.
2. Subjective probabilities can be attributed to emission/mitigation scenarios and used to derive a single probability distribution of future mean sea-levels.

The first condition can only be met for a sufficiently short time horizon for which projected SLR does not significantly differ between low-end (e.g., RCP2.6) and high-end (e.g., RCP8.5) scenarios. What "sufficiently short" means depends on the location, because in locations where the internal sea-level variability is large as compared to the relative SLR it takes longer before the differences in sea-levels under low-end and high-end scenarios become apparent. We illustrate this effect with the new projections of this report (Sections 4.2.3.2 and 4.2.3.4) in Figure 4.15, which shows the year of scenarios divergence, defined here as the point in time when probability distributions of annual maximum sea levels for RCP2.6 and RCP8.5 start overlapping by less than 90%. For approximately half of the coastal sites with sufficient observational data, this is the case before 2045, but for 6% of locations this occurs later than 2055. The threshold of 90% is arbitrary; in practise this needs to be chosen based on risk preferences of the involved stakeholders.

But even before the year of scenario divergence is reached, a number of issues make it difficult to generate probabilistic predictions. This includes that seasonal to multi-decadal sea-level variability, which can dominate sea-level changes at these timescales are not well captured in available climate projections (Section 4.2). Furthermore, non-climatic drivers of local mean sea-level change such as vertical ground motion during or after earthquakes and human-induced subsidence (Section 4.2.2.5) are difficult to capture in a probabilistic framework (Hinkel, in review).

Whether the second condition can be met has been extensively discussed in previous IPCC reports (Carter et al., 2007). The main argument for assigning subjective probabilities is that otherwise the decision-makers may assume that all possible scenarios are equally probable (Schneider, 2001). Arguments against this include that the space of possible future emissions is insufficiently sampled by any number of scenarios, and that individuals may significantly disagree on subjective probabilities of emission scenarios (Lempert and Schlesinger, 2001; Stirling, 2010). For these reasons, only very few studies that assign subjective probabilities to emission scenarios are found in the literature (Woodward et al., 2014; Abadie, 2018).

A second criterion for choosing between expected utility and RDM approaches that has been discussed less prominently in the literature is the uncertainty tolerance of the involved stakeholders. If parties involved or affected by a decision have a low uncertainty tolerance, expected utility approaches are less suitable even if probabilistic predictions are available, because the goal of the uncertainty intolerant decision maker is to avoid major damages under most or all circumstances. An adaptation strategy developed based on the maximization of expect utility does not meet this goal, because worst-case damages occurring can exceed expected damages by orders of magnitude. For example, a cost-benefit analysis may find that a dike that protects against the 1,000-year flood has the highest expected utility, but the damages of a 10,000-year flood may still be unacceptable to society.

In summary, there is *high agreement* that RDM approaches are suitable for coastal decision analysis. Nonetheless, few applications are in the literature. For example, Brekelmans (2012) minimize the average and maximum regret across a range of SLR scenarios for dike rings and Lempert et al. (2013) apply RDM in Hoh-Chi-Minh City**.**

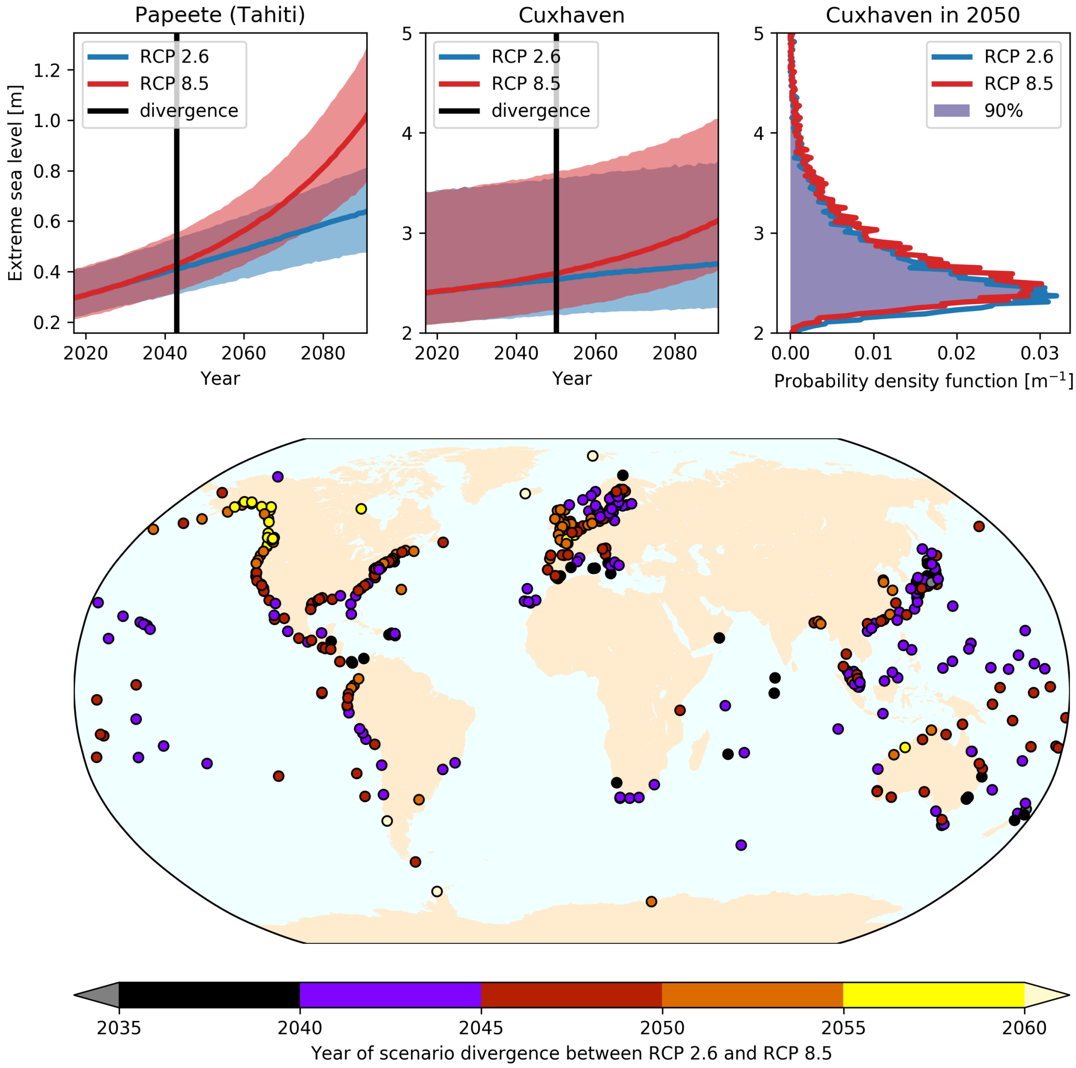


Figure 4.15: Scenario divergence for extreme sea level between RCP2.6 and RCP8.5. Upper left and middle panels indicate the median and 5%–95% range of future annual maximum sea level relative to the 1986–2005 baseline. Divergence is defined as the year where the probability functions for RCP2.6 and RCP8.5 overlap less than 90%, as illustrated in the upper right panel. The two stations have been chosen based on the large differences in sea level variability The bottom panel indicates the year of scenario divergence for all coastal sites with sufficient observational data.

4.4.4.3.3 Scenario-based cost-benefit analysis

Independent from the debate about whether to apply expected utility or robust decision making approaches there is an extensive literature that applies scenario-based cost-benefit analysis. For example, this approach has been applied for setting the safety standards of Dutch dike rings (Kind, 2014; Eijgenraam et al., 2016) exploring future protection alternatives for New York (Aerts et al., 2014), Ho Chi Minh City (Scussolini et al., 2017), and for many other locations. The application of cost-benefit analysis to compute an economically optimal height of a coastal protection structure has a long tradition dating back to the aftermath of the devastating coastal floods of 1953 in the Netherlands (van Dantzig, 1956). It continues to be widespread today, both because it is an integral part of the coastal risk management literature (Penning-Rowsell et al., 2014) and also legally prescribed for coastal adaptation in countries such as the US, the UK and The Netherlands.

Scenario-based cost-benefit analysis differs from cost-benefit analysis under risk discussed in the previous section in that cost-benefit analysis is not applied to rank alternatives across scenarios, but a “separate” cost-benefit analysis is applied within each emission or SLR scenario considered. While this identifies the optimal alternative under each scenario, it does not formally address the problem faced by a coastal decision maker, namely to decide across scenarios (Lincke and Hinkel, 2017). Nevertheless, the results of scenario-based cost-benefit analysis provide guidance for decisions and can also be used as inputs to the robust (Section 4.4.4.2.2) and flexible decision making (Section 4.4.4.2.4).

Cost-benefit analysis comes along with several well-known limitations such as its sensitivity to discount rates and the difficulty to monetize ecological, cultural and other intangible benefits (Section 1.1.4) that have been widely discussed in previous IPCC reports (Chambwera et al., 2014; Kunreuther et al., 2014). Specifically, for the coastal context, uncertainties in model structure and parameters can result in large variations in the economically efficient solution (Oddo et al., 2017).

4.4.4.3.4 Flexible decision making

The objective of flexible decision making is to keep future alternatives open by favouring flexible alternatives over non-flexible ones. An alternative is said to be ‘flexible’ if it allows switching to other alternatives once the implemented alternative is no longer effective. For example, a flexible protection approach would be to build small dikes on foundations designed for higher dikes, in order to be able to raise dikes in the future when more is known about SLR. Such staged approach is generally suitable for coastal adaptation due to the long lead and life-times of many coastal adaptation measures and the deep uncertainties in future sea-levels (Hallegatte, 2009; Kelly, 2015).

A prominent and lightweight method that addresses the objective of flexibility is adaptation pathways analysis (Haasnoot et al., 2011; Haasnoot et al., 2012). The method graphically represents alternative combinations of measures over time together with information until when alternatives are effective (these points in time are called adaption tipping point), as well as possible alternatives then available. A completed adaptation pathways plan thus suggest policy actions for the short to medium term, within a longer-term pathway. As time and SLR progresses, monitoring may trigger a decision to select and prepare for switching to an alternative.

Adaptation pathway analysis has been widely applied both in the scientific literature as well as in practical cases. Prominent applications after AR5 include Indonesia (Butler et al., 2014), New York City (Rosenzweig and Solecki, 2014), Singapore (Buurman and Babovic, 2016) and Australia (Lin and Shullman, 2017). There is *high confidence* that the method is generally useful in interaction with decision-makers and other stakeholders, helping them to identify appropriate sequences of measures over time, avoiding lock-ins and showing decision-makers that there are several possible pathways leading to the same desired future (Haasnoot et al., 2012; Haasnoot et al., 2013; Brown et al., 2014; Werners et al., 2015). Experiences in Australia also show that municipalities applying this method need further assistance with stakeholder engagement processes in order to develop socially accepted pathways (Lin and Shullman, 2017).

While adaptation pathways analysis identifies adaptation pathway in terms of their flexibility, it cannot answer the question of economically efficient flexibility and timing of adaptation. Delaying decisions and opting for flexible measures may introduce extra costs, because flexible measures are often more expensive than inflexible ones and damages may occur whilst delaying the decision. An important consideration therefore is to balance the cost of delaying decisions with the benefits of deciding later when having more information at hand. This is precisely the decision problem methods such as real-options analysis (ROA) (Dixit et al., 1994) and decision tree analysis (DTA) (Conrad, 1980) can address. Application of these approaches are few in the SLR literature. For example, Woodward et al. (2014) applied real-option analysis to an area of the Thames Estuary in London, England, and Buurman and Babovic (2016) for the cases of Singapore, and Dawson et al. (2018) for coastal rail infrastructure in Southern England.

A requirement for applying ROA and DTA is to quantify today how much we will have learned at a given point in time in the future. The few application of these methods to SLR-related decisions in the literature have generally used ad-hoc assumptions. For example, Woodward et al. (2011) assumed either perfect learning (i.e., in 2040 we will be sure on which SLR trajectory we will be on) or no learning (i.e., uncertainty ranges and confidence in these remains as today). Others have derived learning rates from comparing past progress in SLR projections and then applying these to the future. An example is given by Dawson et al. (2018) who derive learning rates from the 2002 and 2009 SLR projections of the UK Climate Impacts Programme (UKCIP) and apply these for ROA.

4.4.4.3.5 Further methods and research needs

The three broad categories of decision analysis approaches organised above in terms of the three objectives of maximal expected utility, robustness and flexibility cover the main single-attribute decision analysis methods applicable to coastal adaptation. Another category of approaches called multi-criteria analysis (comprising multiple-objective and multiple-attribute decision making) is also suitable for coastal adaptation, because adaptation often involves stakeholders having distinct objectives and valuing alternatives differently (Oddo et al., 2017). Furthermore, methods can be combined. For example, in adaptation pathways analysis alternatives can be also characterized through multiple attributes such as costs, effectiveness, co-benefits, etc., which in turn can be used in a multi-attribute decision making method (Haasnoot et al., 2013). Other coastal examples include a combination of adaptation pathway and adaptive policymaking applied to the lower Rhine Delta in the Netherlands (Haasnoot et al., 2013) and a combination of adaptation pathways, adaptive planing and real-option analysis applied to coastal adaptation in Singapore (Buurman and Babovic, 2016).

In summary, three general gaps can be identified in the literature. First, the generation of sea level rise information is insufficiently coupled to the use of this information in decision-analysis. This constitutes a limitation, as different coastal decision contexts require different decision analysis methods, which in turn require different sea level rise information. Specifically, applications of decision analysis methods generally convert existing sea-level information to fit their method, often misinterpreting the information, making arbitrary assumptions or loosing essential information on the way (Hinkel et al., 2015; Bakker et al., 2017a; Van der Pol and Hinkel, 2018). Second, with the exception of adaptation pathway analysis, methods of robust and flexible decision making are under-represented in the literature despite their suitability (Van der Pol and Hinkel, 2018). A lot of the SLR decision literature focuses on scenario-based cost-benefit analysis, which does not address the problem of deep uncertainty coastal decision makers are facing. Third, research is necessary to compare the various methods, to identity which methods are best suitable in which situation and to develop consist categorisations of methods (Hallegatte et al., 2012; Haasnoot et al., 2013; Hinkel et al., 2015; Watkiss et al., 2015; Dittrich et al., 2016). Addressing those gaps requires a closer cooperation between SLR sciences and decision science. An underlying challenge is to design and integrate relevant formal decision-making approaches into the heterogeneous reality of local planning and decision-making cultures, institutions, processes and practices, often with community-specific needs and requirements.

4.4.4.4 Community-based Approaches and Methods

AR5 highlighted the emergence of community-based adaptation (CBa) and other bottom-up, reflexive and participatory decision-making processes in response to the increased complexity of management challenges due to climate change, development and other pressures. CBa is a form of adaptation that aims to reduce the risks of climate change to the world's poorest people by involving them in the practices and planning of adaptation. It adds to current approaches to adaptation by emphasizing the social, political, and economic drivers of vulnerability, by addressing climate risks and these drivers of vulnerability simultaneously and by highlighting the needs of vulnerable people (Jamero et al., 2017).

Many of the approaches and methods discussed in this section have application in both developed and developing country contexts. Moreover, community engagement and involvement is invariably an important and integral part of processes that apply the more formal assessment methodologies discussed above.

4.4.4.4.1 Integration, governance and other challenges and opportunities for community-based adaptation

In parallel with national-level planning, CBa adopts an integrated approach to adaptation planning, governance, and implementation, and as such is considered more effective than standalone efforts to reduce climate-related risks. Forsyth (2013) argues that CBA forms part of a trend of linking international development and climate change policies. This trend seeks to explain the risks posed by climate change more holistically within development contexts, and aims to increase the range and usefulness of adaptation options. Thus, CBa should not be viewed simplistically as an overly localist approach to risk assessment. Alignment of country-level policy processes under the 2030 Agenda for Sustainable Development, the Paris

Agreement and the Sendai Framework for Disaster Risk Reduction can help to advance climate-resilient development, by increasing coherence, efficiency and effectiveness in policy processes for improved outcomes. The approach to alignment will differ depending on the particular country context (Dazé, 2016).

CBa presents an opportunity for local-level participation in framing adaptation planning and activities, with wider transformative potential for governance at the local level (Archer et al., 2014). These include using CBa as part of a wider package of approaches, using institutional reform as an opportunity to integrate community perspectives, institutionalizing new actors and approaches as a mechanism for scaling up multi-stakeholder approaches, ensuring top-down planning approaches are connected to local dynamics, and using participatory research to facilitate local communities in shaping planning processes.

While integrating CBa into local and district level plans is regarded as one of the most effective ways to support the most vulnerable communities to adapt to the impacts of climate change, practical approaches for integration reflecting realities and priorities of the communities on the ground have always been a challenge (Möller et al., 2014). It is not probable that CBa interventions will support pro-poor development without attention being paid to the necessarily multi-level nature of adaptation policy and programming, and the links between mitigation and adaptation politics and practice (Dodman and Mitlin, 2013). CBa can benefit from taking on board the considered experience of participatory development to date, particularly in relation to local involvement in project planning and implementation, as well as acknowledging the specific challenges raised by climate change. The need for distributed risk governance and citizen engagement is increasingly recognised, but few empirical studies systematically assess interactions between citizens and municipalities in climate risk management and adaptation. Brink and Wamsler (2018) mapped adaptation interactions and analysed how responsibilities for climate adaptation manifest and are (re)negotiated. They found that adaptation planners rarely consider collaborations with citizens, and advocated for fostering collaborations with citizens through proactive engagement and by promoting equity, clear lines of responsibility, nature-based approaches and systematic adaptation mainstreaming.

4.4.4.4.2 Participatory approaches and tools

Communities have many opportunities to use participatory approaches when deciding how best to respond to climate change. Such approaches are most effective when designed and planned as a long-term-process that: (1) empowers people to handle by themselves the challenges and influence the direction of their interventions, leading to joint decision-making about what can be achieved and how; and (2) uses the inputs and opinions of stakeholders in the community to achieve an externally pre-established goal, such as that defined by government at the national level (Kearney et al., 2007).

Participatory approaches have been used by communities in activities such as needs assessment, design and management of protective barriers, monitoring sea level changes, teaching and training on the basics of climate change and its impacts on the coasts, research and conflict management (Pedrosa and Pereira, 2006). These areas involved a range of stakeholders (e.g. multi-level workshops, for example: public sector senior managers, practitioners and community members, youth, parents, senior citizens, disabled citizens, diverse ethnic backgrounds, and higher education staff and students) involving sharing of knowledge and experience in coastal projects, working in teams on practical tasks, the use of visualization and analytical tools, and the development of shared understanding of climate change specifically, sea level rise and their implications to coastal development (Fortes, 2018). Hence, participatory approaches take the form of simply being informed (passive participation), or answers are provided stakeholders (participation by consultation), or participation in the discussion and analysis of predetermined objectives set by the community (participation by collaboration), or primary stakeholders initiate the process and take part in the analysis and evaluation, leading to joint decision-making about empowerment participation (Tufte and Mefalopulos, 2009).

In the context of community participation in Bangladesh to cope with sea-level rise, and to enhance community resilient capacity, Haque et al. (2016) show that local-level CBa approach and community involvement in decision-making processes are very effective in resilience building among the most vulnerable segment of the society. Community participation can be integrated in the broader national strategies for developing effective adaptation as well as social- ecological resilience system, while multilevel social networks are essential for developing social capital for supporting the legal, political, and financial frameworks that enhance community resilience. Integration of indigenous knowledge and learning from local communities into wider national policies can help ensure pro-poor climate governance.

The warning (based on a review of community-based adaptation research in the Canadian Arctic) of Ford et al. (2016b) against assuming that research has a positive role to play in community adaptation just because it utilizes participatory approaches has wide implications: Participation in CBa research can perpetuate the privilege of Western knowledge over local values and indigenous knowledge and can further marginalize communities if power relations are not addressed. Moreover, CBa does not necessarily prevent maladaptation.

Treating sea level rise as a social-ecological phenomenon, rather than just as a physical or ecological problem, has the potential to overcome the barriers to engagement with underrepresented communities, including through race-aware adaptation planning that encourages discussions at the onset of project formation to include issues of power and racial inequalities. Hardy et al. (2017) show that the practice of race-aware adaptation planning offers pathways to resist "passive indifference" and inequalities that perpetuate differentiated vulnerability to sea level rise. Coastal adaptation can benefit from technical knowledge being merged with lessons learnt through an adaptive management cycle to meet both short-term decision objectives and long-term adaptation goals. For example, Nagy et al. (2015) used a risk-based and participatory approach to assess climate vulnerability and improve governance in coastal Uruguay. It included a stakeholder-driven Vulnerability Reduction Assessment and multicriteria approaches to adaptation within a participatory bottom-up and top-down process.

Cities are increasingly involved in planning for climate change adaptation. However, the extent and role of public participation in such efforts remains poorly theorized and understudied (Sarzynski, 2015). Broto et al. (2015) has provided an appraisal of participatory urban planning for adaptation in practice, building upon a participatory experience in Maputo, a coastal city in Mozambique. They found that such bottom-up planning may lead to a more inclusive, and potentially fairer, society. Importantly, the timescales of development are longer than those of participatory urban planning. This may lead to loss of momentum within the community. Moreover, participatory planning processes require a partnership built on mutual trust and understanding between local institutions and communities. An appropriate process of institutional support needs to be in place, but local governments often have difficulty integrating climate change knowledge as well as delivering adaptation interventions.

Garschagen et al. (Submitted) used a participatory scenario-based approach to decipher the adaptation-development-nexus and its potential future trajectories for four coastal megacities. The approach was useful in convening a transdisciplinary learning and reflection process that shed light not only on the enablers but also barriers of transformation. Participatory Three-Dimensional Modelling (P3DM) has helped integrate indigenous and scientific knowledge systems (Piccolella, 2013). It added credibility to locally produced content and provided a platform for multi-stakeholder dialogue, while minimising the risk that perverse power dynamics would jeopardise the effectiveness of the participatory process. The combination of the community discussion with demonstrations of 'what if' scenarios of sea-level rise confirmed that P3DM is able to bridge top- down and bottom-up approaches to coastal CBa by creating a space for mutual learning. Treuer (2017) reports the findings of an immersive simulation experiment that accelerated 348 South Florida homeowners through thirty-five years of sea level rise. Levels of concern, and willingness to move, increased with higher sea levels, and was consistent across age, income, political identity, and other demographic divisions.

Small-group deliberation focused on local problem-solving may be an effective tool for reducing the polarizing effects of cultural worldviews on decision-making. Akerlof et al. (2016) used a community deliberative event with small-group discussions as a strategy to depolarize perceptions of sea-level rise risk. The approach significantly increased topic knowledge among all participants and, among those with a worldview predisposing them to lower risk perceptions, significantly increased problem identification and concern about impacts.

4.4.4.4.3 Community visioning and pathways

To overcome difficulties to build public support for flood-related policy and action, adaptation scenarios and 3D landscape visualizations were used in a visioning process to explore a range of alternative response options to sea level rise for the 100,000 citizens of Delta, a low-lying municipality at the mouth of the Fraser River delta. A large portion of the community is at considerable risk from climate change induced sea level rise and storm surges. The findings were used to support decision-making and further policy development for flood management in the municipality (Barron, undated).

Kench et al. (2018) challenge existing narratives of island loss by showing that island expansion has been the most common physical alteration throughout Tuvalu over the past four decades, despite sea level rising. The results are used to project future landform availability and consider opportunities for a vastly more nuanced and creative set of adaptation pathways for atoll nations.

Residents of a small town in coastal Australia used their photographs and accompanying narratives to both vision (by elucidating their current experiences) and re-envision (in advocating for different futures) their everyday experiences of adapting to flooding. The photoelicitation process provided different outcomes than conventional interviews, focus groups and questionnaires (O'Neill and Graham, 2016).

Brown et al. (2017) explored the lessons of coastal planning and development for the implementation of proactive adaptation in order to identify and open up windows of opportunity in current decision-making, to better design and implement proactive adaptation. They found that the windows of opportunity concept can aid practitioners and policymakers to identify instances where decision-making can be reframed or transformed to better enable proactive adaptation. Reframing of existing policies or creation of new transformative approaches can help build both the social capital and practical mechanisms required to deliver proactive adaptation. The transition from current to proactive adaptation requires shifts in decision framing, the pre-conditions and processes and outcomes association with identifying and opening adaptation spaces. Identifying windows of opportunity and understanding how they operate can support sustainability and adaptation mainstreaming and dynamic adaptation pathway approaches to help deliver the transformational change necessary for sustainable coastal adaptation to climate change.

Hay et al. (2018) call for increased understanding of the longer term habitability of atolls and islands. Changes in habitability occur as a result of the interplay between atmospheric, oceanic, social and economic conditions over the long-term. While a focus on resilience tends to favour responses that consider only the short-term, a longer term perspective is critical when considering strategic responses, such as international migration as an adaption option for countries facing severe declines in habitability. The drivers of declining habitability include increasing population density, economic vulnerability, and incidence of pests and disease. For example, rural-urban and outer- to capital-island migration to locations lacking in infrastructure and other support services can reduce habitability.

4.4.4.4.4 Consensus building and decision making

Poorly planned participatory processes, and the lack of context-specific approaches in their use, hamper efforts to strengthen the resilience of communities. Nkoana et al. (2018) identified best practices in the use of context-specific and culturally-sensitive climate change adaptation tools. These included the use of a livelihoods approach to engage communities, recognition of local champions from within the community, and two-way climate change risk communication instead of a one-sided information sharing approach. Fortes (2018) also advocates for constant dialogue among community and other relevant stakeholders in order to clarify the problem(s) to be addressed and subsequently initiating the iterative adaptive management cycle where problems are resolved through more informed decision making. Gorddard et al. (2016) argue that decision makers tend to frame adaptation as a decision problem, whereby the responses to impacts of change are addressed within existing decision processes centred on defining the decision problem and selecting options. As this approach is constrained by societal values and principles, regulations and norms and the state of knowledge, it is unsuitable for addressing complex, contested, cross-scale problems. But simply broadening the decision-making perspective to account for institutions and values is insufficient (Gorddard et al., 2016). When they analysed the influence of values, rules and knowledge on decision making and decision contexts for three adaptation projects that responded to sea level rise they found that linking these systems facilitates adaptation practitioners structuring adaptation as a process of co-evolutionary change that enables a broader set of social issues and change processes to be considered.

In a study of local adaptation planning processes in Vanuatu, Granderson (2017) found a marked difference in how actors contextualized and prioritized risks. Villagers assessed current impacts and risks from climate change in relation to wider socio-economic changes, and prioritized maintaining their way of life. In contrast, practitioners in civil society organizations (CSO) adopted a technocratic approach, drawing on climate science and focusing not only on the severity of risks but also on the potential need for external interventions. Explanations for climate-related changes, and notions of causality, also differed among villagers and CSO actors. Such differences in actors' values and politics highlight the need for open and inclusive dialogue that provides space for alternative understandings of risk, and for adaptation strategies that ensure community buy-in.

An Urgency, Barriers, and Risk (UBR) Framework assisted stakeholders in Miami Beach, Florida, to recognize and respond to barriers encountered in adapting to sea level rise (Treuer, 2017). The Framework provides a structure for dynamically tracking and analyzing the interaction between pressures driving policy change, decision makers, and barriers within the adaptation process. Three lessons were learned in its use: (1) Barriers to achieving consensus appeared towards the end of the agenda setting phase and early in implementation, when newly engaged stakeholders recognized and opposed specific adaptation actions; (2) Facilitation—based on the Netherlands approach to third-party facilitation in difficult, experimental climate adaptive water management projects—proved successful in overcoming barriers; and (3) Adaptation actions that address sea level rise risks at multiple timeframes were more successful.

Based on a study of a vulnerable, low-lying coastal area in northern Portugal, Campos et al. (2016) showed that participatory action research (PAR) was able to trigger new dynamics for collective decision-making that supported a sustainable direction in transformational adaptation. PAR uncovered the intricacies of planning and political processes, including the context-specific challenges for implementation. These include difficulties in translating decisions resulting from participative processes into effective policies. By building a support base from a wide group of stakeholders, PAR encourages socio-political legitimacy and trust for the results, such as the prioritization of adaptation options. PAR and transition management can complement each other in transition studies. By being more pragmatic, PAR can influence incrementally transformative changes that are guided by transition management's long-term design for governing sustainable transitions.

PAR projects in several coastal communities in New-Brunswick and Quebec were found to provide noticeable short-term benefits and strengthen long-term community governance, and adaptation capacity and resilience (Chouinard et al., 2015; Chouinard et al., 2017). Vulnerabilities and adaptation options are best evaluated with active community participation and informationexchange between scientists and local stakeholders. Such engagement can co-produce new knowledge and identify priorities that improve community adaptation plans and provisions. Less costly and more appropriate adaptation options can be identified and selected that suit local circumstances and align with community values and aspirations. Such 'tailored' solutions are more likely to be accepted by the community and their governing authorities. In practice, however, translating such initiatives into tangible decisions takes time. Furthermore, the retreat option invaribly remains contentious and highly emotional (Chouinard et al., 2015; Chouinard et al., 2017).

The foregoing confirm the SR1.5 conclusion that adaptation planning and interventions grounded on community values, coping strategies and decision-making structures cannot work in isolation at the community level since factors beyond the control of the community scale, such as governance and policy context, affect the ability to reduce vulnerability to climate change (*robust evidence, high agreement*).

4.4.4.4.5 Learning from monitoring and evaluation

As evident from AR5, there are few examples of literature, understanding and application related to this topic. Moreover, it is difficult to identify good practices as CBA activities appear very similar to standard development work (Jamero et al., 2017). Importantly, community-based monitoring and evaluation initiatives, including participatory monitoring and evaluation, help ensure increased authenticity of locally relevant findings and improve local capacity. Mathew et al. (2016) review and provide examples of such initiatives. Jhan (2017) has developed a modified Analysis-Awareness-Action framework to evaluate local climate change adaptation in four coastal townships along the vulnerable southwest coast of Taiwan in order to derive recommendations for local adaptation framework development. He found that a constructive dialogue and participatory processes are in order to increase community engagement in local adaptation. Improvements included engaging other local organisations and private actors, developing specialist organisations, legislative acts, and considering multiple objectives in formulation of adaptation actions to eliminate the potential conflict of interest.

The use of adaptation pathways implies a systematic monitoring effort to inform future adaptation decisions, with the monitoring feeding into a long-term collaborative learning process between multiple actors at various levels. Hermans et al. (2017) have developed an approach based around the conceptual core offered by adaptive policy pathways methods and their notion of signposts and triggers. This is embedded in a wider approach that revisits the critical assumptions in underlying basic policies, looks forward to future adaptation decisions, and incorporates reciprocity in the organization of monitoring and evaluation. The usefulness and practical feasibility of the approach were assessed using the Delta Programme in the Netherlands. This incorporated adaptation pathways in its adaptive delta management planning approach. The results suggest that the approach proposed by Hermans et al. (2017) adds value to existing monitoring practices. They also identified different types of signposts - technical signposts, in particular, need to be distinguished from political ones, and require different learning processes with different types of actors.

4.4.5 Implementing Sea Level Rise Responses at the Local Level: Enablers, Barriers and Lessons Learned

4.4.5.1 Introduction

Local governments around the world are playing key roles in adaptation efforts by responding to and producing innovative responses to climate change in the coastal zone. Local government is located at the closest interface to local communities and the environment, and is often best placed to respond to the hazards and risks generated by SLR, coastal inundation, erosion and flooding. Local government can deliver adaptation strategies from above and co-ordinate bottom-up action (Porter et al., 2015). Local governments responsible for the public decision-making in the coastal zone have a long history of adapting to environmental change because coasts are highly dynamic spaces. However, climate change is creating new challenges due to the way in which it shapes economic, social, environmental and political relations in the coastal zone and local governments face numerous political, institutional, social, economic, financial and environmental constraints in reducing coastal risks and building resilience. Some of the key issues that have been faced by local communities and their governing authorities in responding to SLR are outlined below. A synthesis of post-AR5 insights about enablers, barriers and lessons learned from efforts to implement SLR responses is presented at the end of this section.

4.4.5.2 Accounting for the Rate and Extent of Sea Level Rise

Considering rates of change affects the projected optimal adaptation strategy. Adaptation to a new climate state, instead of adaptation to ongoing rates of change, may produce inaccurate estimates of damages to the social systems and their ability to respond to external pressures. Shayegh et al. (2016) confirm this by determining the optimal investment taking into account the interplay among physical and economic factors governing coastal development decisions, including rate of sea level rise, land slope, discount rate, and depreciation rate. Optimal investment strategies depend on taking into account future rates of sea level rise, as well as social and political constraints.

Planners and decision makers who face risks arising from elevated sea levels are now provided with vastly improved hazard data and tools (see Section 4.2). While sea level rise is widely identified in adaptation plans for US coastal cities that are considered at high risk and vulnerable to rising sea levels, the overall quality of the plans to address it requires significant improvement (Fu et al., 2016). Localities lack the necessary information and incentives to plan for such an emerging agenda.

4.4.5.3 Accounting for Uncertainty

The process of decision making using adaptive pathways approaches is increasingly being used to plan for adaptation over time. It requires risk and uncertainty considerations to be transparent in the scenarios used in adaptive planning. In this regard, Stephens et al. (2017) have developed a framework for uncertainty identification and management within coastal hazard assessments. It can better inform identification of trigger points for adaptation pathways planning and their expected time range, compared to traditional coastal flooding hazard assessments.

In theory, application of adaptation pathways can also help ensure more implementable adaptation planning (Barnett et al., 2014). However, developing pathways toward transformation is especially difficult in coastal regions where there are often multiple contested resource uses and rights, with diverse decision makers and rules, and where high uncertainty is generated by differences in stakeholders' values, understanding of future sea levels, and ways of adapting (Abel et al., 2016).

Those charged with developing and implementing coastal planning policies can recognise, communicate, and seek to overcome uncertainty. This can involve: 1) acknowledging and communicating uncertainties in existing and projected rates of sea level rise; 2) engaging in site-specific mapping based upon best available scientific information; 3) incorporating probabilities of extreme weather events; 4) resolving whether coastal engineering solutions are included in mapping; 5) ensuring that mapping includes areas required for future ecosystem migration; 6) managing discretion in planning and policy decision making processes; 7) creating flexible policies which can be updated in line with scientific developments; and 8) balancing the need for consistency with the ability to apply developments in science and technology (Bell et al., 2014).

A qualitative analysis of climate change adaptation initiatives in the small island nation of Kiribati revealed that adopting a culturally appropriate short-term (approximately 20 years) planning horizon may help reduce uncertainty and the trade-offs between adaptation options. In the short-term, the range of sea level projections may be small enough to not seriously confound adaptation decisions. But decisions can be regularly revisited, based on data collected on their effectiveness and reviews of the latest global sea level data and projections (Donner and Webber, 2014).

Thorarinsdottir et al. (2017) used two illustrative examples—Bergen on Norway's west coast and Esbjerg on the west coast of Denmark—to highlight how technical efforts to understand and quantify uncertainties in hydrologic projections can be coupled with concrete decision-problems framed by the needs of the end-users using statistical formulations. They found that failing to take uncertainty into account can result in the median-projected damage costs being an order of magnitude smaller.

The Adaptive Delta Management approach used in the Netherlands accommodates uncertainty in future climate and socio-economic changes. Key points of the approach are: 1) linking short-term decisions with long-term tasking around flood and drought risk management; 2) incorporating flexibility in possible adaptation strategies; 3) working with multiple adaptation strategies through adaptation pathways; and 4) linking different investment agendas. It provides greater transparency to decision-makers and stakeholders, as demonstrated for the management of flood risk and resilience in Dordrecht (Gersonius et al., 2016).

Construction of a consensus estimate from divergent expert assessments of rates of sea level rise can be subject to considerable structural (and deep) uncertainty (Bakker et al., 2017b). As a result, a robust strategy (See Section 4.4.4.3), i.e., one that performs well over a wide range of plausible futures/views, may be preferable over optimal strategies. Effective communication of deep uncertainties depends strongly on the decision-context. Therefore, an efficient representation requires a tight interaction between decision analysts, scientists, and decision makers.

4.4.5.3.1 Barriers

The call for monitoring and evaluation of adaptation pathways stems first and foremost from the expectation that adaptation pathways are being implemented and that the developed plans help identify the variables that need to be monitored (Hermans et al., 2017). However, Wise et al. (2014) suggest that adaptation plans are often not implemented and, if they are, it is only the smaller incremental measures within those plans. van der Brugge and Roosjen (2015) explain how the presumed implementation and effectiveness of adaptation pathways might be due to the changes in institutional and socio-cultural structures required for the implementation of adaptation strategies. This implementation problem is not unique to adaptation pathways (Hermans et al., 2017).

4.4.5.3.2 Adaptive decision making

The AR5-cycle reported the emerging realization in the scientific and policy arena of the need to think adaptation and resilience policies and practices in a dynamic way (Brown et al., 2014), in order to 1) reflect the evolving nature of exposure and vulnerability (Denton et al., 2014), 2) improve the projection of climate change impacts (Cardona et al., 2012), 3) start anticipating the risks of maladaptation (Cardona et al., 2012; Noble et al., 2014), and (iv) enhance flexibility to allow better addressing climate change uncertainty (O'Brien et al., 2012; Noble et al., 2014). The 'adaptation pathway' approach thus gained attention, calling for 'cautious and staged implementation' (Kelly, 2015), for instance, long-term adaptation strategy based upon decision cycles that, over time, explore and sequence a set of possible actions based on alternative external, uncertain developments (Haasnoot et al., 2013; Barnett et al., 2014; Wise et al., 2014). The AR5-cycle recognizes the context-specific nature of adaptation pathways, that reflect 'competing prioritized values and objectives, and different visions of development that can change over time' (O'Brien et al., 2012, p. 440). Such a shift in adaptation thinking carries a real potential for a better integration of SLR and gradual changes more broadly. Until very recent works however, adaptation pathways have been described in a very general, theoretical way, with rare practical examples (Denton et al., 2014). The recent literature provides a better understanding of the dynamics of exposure and vulnerability, as well as first practical examples of adaptation pathways.

4.4.5.4 Accounting for Dynamics of Exposure and Vulnerability, and Path-dependency

4.4.5.4.1 Uncertainty manifestation in the policy system

In response to uncertain environmental and socio-economic change, those managing flood risk are urged to develop adaptive plans to ensure communities' long-term sustainable economic development (Hallegatte et al., 2015). However, there are challenges in developing and implementing such plans to address changing climate impacts and socio-economic conditions, including; dealing with uncertainty and the need to do so; understanding and acknowledging different types of uncertainty; making robust and adaptive decisions that can cope with uncertainties about the future, and shifting planning practice from static to dynamic approaches (Lawrence and Haasnoot, 2017).

4.4.5.4.2 Transformation, tipping points, and the acceleration of adaptation practice

Burch et al. (2017) discuss the emerging literature on transformative adaptation (Kates et al., 2012; Pelling et al., 2015) when paired with broader studies of development path shifts and sustainability transitions, suggests that the following are examples of actions or approaches that might push communities towards a tipping point' into a fundamentally more desirable state:

- Transformations in organizational methodology, major investments in capacity, new skills and ways of working (Pelling et al., 2015).
- Consideration of long-term (future) and irregular risks along with immediate risks (ibid.).
- Engaging with a diversity of actors and interests, both within and among organizations (ibid.) in a way that may trigger the imaginations of stakeholders and create excitement (Dempsey et al., 2011).
- Actions that do not simply consider key areas such as urban form, transportation, energy systems etc. but explicitly target the linkages among them (McCormick et al., 2013).
- Iterative, adaptive management that is based on monitoring and evaluation of key indicators (Burch et al., 2014).
- Framing climate change adaptation (or mitigation) in the context of sustainability/sustainable development, so as to capitalize on synergies and align the efforts with a wider variety of stakeholders (Shaw et al., 2014).
- These early suggestions of approaches that might lead to transformative adaptation reinforce the notion that transformation can be pursued through addressing the root causes of unsustainability, identifying tipping points that can act as leverage points, and by employing a social–ecological systems lens to reveal strategies that create synergies (and avoid trade-offs) with other priorities, (Burch et al., 2017).

4.4.5.4.3 Potential for transformation

Also, Burch et al. (2017) were discussed the tipping toward transformation "progress, patterns and potential for climate change adaptation in the global south" In response to observed and projected climate change impacts, major donors are funding an abundance of climate change research. This is to capturing the broader trends and patterns across south cases. Furthermore, he recognizes that transformational approaches are difficult to implement for a variety of reasons. Kates et al. (2012) mention a key obstacle for transformative adaptation is uncertainty around the severity of climate impacts and purported benefits of adaptation. This includes uncertainty around the costs of transformation, which are often unknown but presumed to be high, compared to the ability to calculate the costs of incremental adaptation. Burch et al. (2017) also stated that: finally, there is a host of institutional barriers, ranging from cultural norms to existing complex legal systems. These barriers certainly exist in the countries in which the projects and adaptation options were conducted.

Building on the above insights, what are the key enablers and barriers faced by local government in seeking to implement SLR responses in practice?

4.4.5.5 Enablers and Barriers for Implementing Sea Level Rise Responses at the Local Level: A Synthesis of Post-AR5 Literature

Local governments are experimenting with and implementing different solutions to the challenges of SLR, coastal erosion and inundation. Enablers and barriers to climate adaptation that have emerged from a review of post 2015 literature on local government responses to climate change challenges in the coastal zone are presented below, in no particular order of importance.

4.4.5.5.1 Enablers for implementing sea level rise responses at the local level

Governance structures and institutional arrangements that support participatory governance: Participation of multiple actors in both formal and informal networks plays an important role in adapting to climate change in the coastal zone. It builds trust and relations between the state and citizens and this generates significant benefits (Dyckman et al., 2014; Colenbrander and Sowman, 2015; Dutra et al., 2015; Sowman et al., 2016; Van Putten et al., 2016; New Zealand Government, 2017). Support for a culture of open and transparent management processes and communication by local government builds trust, legitimises decisions and lends support for science being used in decision making (Dutra et al., 2015).

Presence of committees or networks of actors that champion innovation for climate adaptation and build partnerships: Leaders and champions embedded in networks of actors, including creative and experienced coastal zone managers, can have a valuable impact in supporting innovation. These networks of actors can act as bridging organisations, particularly between the state and citizens, and lead to the building of trust (Dyckman et al., 2014; Sowman et al., 2016).

Efforts by legal teams who can interpret legislation in innovative and socially and environmentally just ways: Legislation is being challenged by the complexity of rights and responsibilities arising from the impacts of climate change on the coastal zone (Dyckman et al., 2014; Sowman et al., 2016). Having legal teams who understand how to interpret, apply and reform legislation in ways that create the legal space and legal support to address these challenges enables better coastal risk governance (Smith et al., 2016b; Whittal, 2016).

Policy space for local government to develop policy and frameworks to guide risk assessment and undertake adaptation planning: Creating space within existing intitutional arrangements to address novel challenges being generated by climate change enables SLR responses. San Francisco has developed a coastal risk strategy as part of its 100 Resilient Cities programme so as to integrate coastal risk into its resilience building programme (City and County of San Francisco, 2016). The development of set back lines in South Africa has been enabled through policy space created by national legislation (Desportes and Colenbrander, 2016).

Availability of and access to relevant and meaningful scientific knowledge: Climate adaptation innovation is facilitated where local governments have access to scientific knowledge that is relevant, meaningful and which has been translated into a form that is aligned with and relevant to the local context and local challenges (Dyckman et al., 2014; Dutra et al., 2015; New Zealand Government, 2017; Rosenzweig and Solecki, 2018). The accessibility of climate science is one of the most important shifts that has occurred since the IPCC 5th Assessment. This has helped to address technical-cognitive barriers to adaptation in local authorities (Porter et al., 2015).

Evidence of the co-production of knowledge: Where knowledge is co-produced by multiple actors, drawing on expert, tacit, indigenous and local knowledge, it is more probable that climate adaptation interventions are to be accepted, successful, and lead to a lower transfer of risk (Dutra et al., 2015; City and County of San Francisco, 2016; Desportes and Colenbrander, 2016; Betzold and Mohamed, 2017; New Zealand Government, 2017; Onat et al., 2018). The sharing of experiences by story-telling has been successful because stories engage actors, help them to visualise the problem, see the problem from someone's else's position, and enable them to understand that they are pursuing a common goal (Dutra et al., 2015; Elrick-Barr et al., 2017). Integrating 'modern' and traditional or indigenous knowledge is important in supporting climate adaptation in contexts where dual governance systems exist (Dutra et al., 2015; Betzold and Mohamed, 2017; New Zealand Government, 2017).

Flexible governance structures and organizational arrangements that support experimentation and enable decision making in the face of uncertainty: The importance of being able to make decisions in the face of uncertainty about SLR risks, given the limits of science, is key to enabling identification of appropriate interventions and adaptation pathways. Local governments cannot wait until they know for certain what the best way forward is, they have to act, learning by doing and developing dynamic adaptive pathways, that enable change as interventions are no longer appropriate or as the risk changes (Dutra et al., 2015; New Zealand Government, 2017).

Support for a learning by doing approach: Local governments that support a learning by doing (social learning) and experimental approach are able to be more innovative and pro-active in the climate adaptation space. This is evident in Australia, New Zealand, South Africa and USA (Dyckman et al., 2014; Dutra et al., 2015; Douwes, 2016; New Zealand Government, 2017). In Australia in the SEQ Healthy Waterways, and in the Fitzroy Partnership (Queensland), highly effective social learning occurred when a community member who was engaged in innovative practices shared their knowledge with other community members (Dutra et al., 2015). This 'learning from each other' is valuable as it can encourage behaviour change. This is also evident in the Palmiet Rehabilitation Project and Take Back our Rivers Programme in Durban, South Africa.

Use of shadow systems to support innovation: Informal or shadow systems provide opportunities for innovation and change beyond the formal institutional arrangements in local government. They produce informal spaces of information and knowledge exchange across operations which facilitates the introduction of new ideas and practice. The value of shadow systems has been seen in the development and application of Durban's Municipal Climate Protection Programme, South Africa (Leck and Roberts, 2015).

Integrating climate change concerns with broader societal challenges within local governments, particularly those related to resilience: Local governments embed coastal climate change adaptation into broader city-wide programmes. A key element of success in Clarence City, Tasmania, Australia, for incorporating climate change into council decision making was to integrate biophysical, socio-economic and climate change information and then relate this combined knowledge to broader community issues (Dutra et al., 2015). In other local governments climate adaptation has been reframed as a resilience issue as this has greater political traction and may attract resources and funding (Porter et al., 2015; City and County of San Francisco, 2016; Hinkel et al., 2018). In South Africa, coastal climate adaptation is framed within the country's transformation agenda, needing to ensure development co-benefits.

Ability to design, construct and finance a wide range of hard and soft technical interventions: Hard interventions (usually seawalls, bulkheads, revetments, jetties, and groins) are being more typically employed when there are no other practible means to address coastal inundation or erosion. Overall there has been a shift towards soft interventions (usually dune rehabilitation, beach nourishment and vegetation), due to their low cost, environmental benefits and ease of implementation. The concept of a Living Shoreline concept has been effective in some states in the USA, such as Maryland, where local government has worked with local stakeholders, including property owners and conservation organizations to replace hard protective works with alternative ecosystem based measures that are are preferred by local communities as well as being legally defensable (Dyckman et al., 2014). Sand nourishment has been shown to be successful and economically viable with environmental costs that can be mitigated in two different coastal settings in Portugal and Netherlands (Stronkhorst et al., 2018). Local governments in Australia, the Niger Delta and Bangladesh have developed desalination techniques and have supported changes in agricultural methods (agiculture to aquaculture) or by planting salt resistant crops to support the productivity of land in the coastal zone or raising the land through controlled sedimentation and tidal river management (Musa et al., 2016; City of Greater Geraldton, 2018; Hinkel et al., 2018).

Capacity to implement and enforce legislation: Local governments can implement SLR responses if they have the political will, resources and local legislative backing to ensure compliance with climate adaptation strategies and policies. Some states in the USA use 'policing provisions' to implement coastal adaptation. In Rhode Island, once a house is part of an active beach, an order or removal is issued under the rolling easement policy and the structure is condemned by building inspectors who withdraw the septic tank licence, which means that the house has to be removed. Thus they use sanitation by-laws and legislation to compel coastal retreat.

Support by local government for community based approaches in the absence of local government capacity: In many contexts, particularly in the developing world, local government does not have the capacity or financial resources to implement climate adaptation alone and hence partners with local communities. In the Niger Delta where a lack of resources and local government capacity has led to local actors addressing climate change impacts, a range of sustainable responses include planting of bamboo trees for erosion control, raising of houses onto stilts, use of sandbags as bridges and dikes (flood control), use of flood receptor pits as temporary flood water reservoirs, and community legislation against sand mining and indiscriminate tree felling have been implemented (Musa et al., 2016, p. 221). Micronesian responses in the Pacific Islands to coastal change reveal both pragmatic and cultural resistance responses to rising sea level by communities, demonstrating the value of integrating traditional responses with local government responses (Nunn et al., 2017b). Community based adaptation in the Solomon Islands in the Pacific has revealed that function-based factors (the ability to access and use resources) and cognitive factors (which are drawn from value and belief systems) have played a critical role. These factors have increased the capacity of communities to engage with external organisations to plan with and obtain resources for adaptation, that is constructed on their own terms (Warrick et al., 2017). Social workers and the social work education they support has also proven to be a valuable resource for climate adaptation that is socially and environmentally just in poorer communities (Joseph, 2017). Strengthening local organisation effectiveness, most particularly in managing and using international funds being allocated to climate adaptation, and building knowledge about the development co-benefits of adaptation, as well as building partnerships between local government and local organisations was considered critical to adaptation in South Africa (Baudoin and Ziervogel, 2017).

Using planning as a climate adaptation instrument: Across the literature, it is evident that local governments are employing planning as an instrument in their practices for climate adaptation (see Section 4.4.4.1).

Capacity in spatial knowledge production, management and dissemination: The production of spatial knowledge plays a significant role in climate adaptation efforts of local governments in the coastal zone. Coastal hazard, risk and vulnerability assessments are used extensively and are mapped using GIS and remote sensing to reveal the extent of coastal flooding and inundation under different scenarios in different contexts (City and County of San Francisco, 2016; Musa et al., 2016; New Zealand Government, 2017).

4.4.5.5.2 Barriers for implementing sea level rise responses at the local level

Uncertainty about climate change impacts: Uncertainty about climate change and its impacts, including SLR risks, makes it very difficult to plan and design successful interventions. Climate uncertainty is combined with socio-economic and political uncertainty over the longer term, which makes it difficult to assess the level of protection that will be required (Dyckman et al., 2014; City and County of San Francisco, 2016).

Availability, accessibility and accuracy of climate knowledge: There have been significant improvements in the accessibility of scientific knowledge that is relevant and can be applied in locality-specific adaptation planning. However, the barrier is how to translate this knowledge into tangible adaptation practices and meaningful action on the ground (Porter et al., 2015).

Politics of knowledge: Knowledge about SLR (scientific, local and indigenous knowledges) can be marginalized in decision making processes that are dominated by narrow interests and agendas, as reflected in some decision-making processes in Australia (Dutra et al., 2015).

Integration of knowledge between natural and social sciences: It is challenging to foster inter- and trans-disciplinary ways of working. This is evident in coastal risk and vulnerability assessments where the social and political economy/political ecology dimensions of vulnerability are not well understood or represented (Dutra et al., 2015). Adaptation officers in local governments in the UK struggle to obtain information on the economic costs of climate change, which would assist them in building a business case for climate adaptation and mitigation (Porter et al., 2015).

Lack of integration between sectors or departments in local government: Compartmentalisation of organisations, particularly local government departments and sectors means that legal frameworks or rules, practices and interventions are located in specific sub-domains that leads to poor and non-integrated outcomes and weak co-ordination in coastal zone management (Dyckman et al., 2014; Dutra et al., 2015). The lack of integration across local government sectors in cities in diverse coastal contexts impedes climate adaptation (Romero-Lankao et al., 2018).

The struggle for communities to understand and grasp the significance of SLR risk: Cognitive styles have been found to shape people's ability to shift their attitudes and behavior and can be an impediment to new knowledge about climate risk (Dutra et al., 2015). Those who live further from the coast may have little concern about being impacted by coastal risk and hence collectively less interest is invested in climate adaptation. This reveals a high level of geographical variation in knowledge and experience of coastal risk and hence responses need to be context specific. However, this impacts on local government in securing support across their local jurisdiction to implement SLR responses (New Zealand Government, 2017).

Perceived inequality produced through investment on coastal adaptation: Conflict arises from the distribution of public money between the coastal actors receiving public support for adaptation and non-coastal actors paying to cover climate adaptation through taxes. This produces political dilemmas associated with public spending, especially in the developing world context where other development demands are considered more pressing and urgent, as demonstrated in cases in the Netherlands, Catalonia, and coastal states in the USA.

Lack of integration of interventions: Interventions in climate adaptation can be ad hoc, particularly when they are driven by actors outside of the state pursuing narrow private interests, and this can lead to a transfer of risk. There is a widespread challenge to enable positive interventions in one part of the coastal zone whilst avoiding maladaptations in another part. Poor integration of interventions has occurred in the City of Cape Town (Sowman et al., 2016) and the Niger Delta (Musa et al., 2016). Some technical interventions, such as the total exclusion barrage system, a tool kit employed in estuaries, have not been successful and have led to maladaptations in Canada, the United Kingdom and France (Kidd et al., 2017). Similar concerns about the transfer of risk have been raised by the environmental sector in Ho Chi Minh City in Vietnam where a ring dike, designed to protect the city, could increase flooding in rural hinterlands (Hinkel et al., 2018).

Policy and practice not always formalized or well integrated into legal system: Instruments and tools for climate adaptation lack legal support. When they are approved by state legislature they are often difficult to implement, they take time to be taken up in legislation, and they can be contradictory or vague (Dyckman et al., 2014; Colenbrander and Sowman, 2015). Regulation, when innovative may not translate into practical, implementable and judicially supported interventions or tools (Dyckman et al., 2014).

Dominant interests and agendas: Legislation, policies and practices to enable adaptation are often in conflict with other powerful economic and political interests. Dominant actors in the political economy prioritise unfettered coastal property development, extractive industries, tourism infrastructure and facilities at the coast, among other things, that can undermine efforts to reduce coastal risk and build resilience. It is challenging for local government officials to convince politicians and their constituents that meeting long term needs rather than short term gains reflects good governance (Dyckman et al., 2014).

Long time frame needed to implement effective SLR responses is countered by short term political cycles: Political cycles in local government, and at all scales of government, are short term and with new elections, which often bring in new governments or shift local politics, implementation plans go back to square one (Dutra et al., 2015; Porter et al., 2015).

Mismatch between management, organisational structures and ecosystem boundaries and scales of governance: Governance structures and institutional arrangements are political and administrative boundaries do not overlap with ecosystem boundaries. Different spheres of government implement legislation and policy at different scales. For example, regional policy frameworks may reduce risk at the regional scale, but often do not provide the detail necessary to reduce risk a local scale (Dutra et al., 2015),

Lack of capacity and finance (funding): A lack of human capacity impacts on climate adaptation as coastal managers are required to meet their daily tasks, as well as addressing the new challenges produced by climate change (Dutra et al., 2015; New Zealand Government, 2017) Local governments may have to pick up coastal programmes when higher levels of the state no longer fund programmes that they originally initiated. In the UK, budget cuts and lack of political will at central government level have undermined local governments' attempts to deliver even basic statutory responsibilities, let alone those related to climate adaptation (Porter et al., 2015). Both developed and developing countries face 'adaptation deficits' which make investment and commitment to future climate adaptation even more challenging (Dyckman et al., 2014; Porter et al., 2015). In Ho Chi MinH City in Vietnam the city has not been able to secure funds for flood protection interventions, even with the high levels of flooding and damage during the monsoon season (Hinkel et al., 2018; Hoque et al., 2018). High costs of adaptation and financial constraints is severely constraining adaptation efforts in Small Island Developing States. Where funding exists this is highly skewed in distribution (Robinson and Dornan, 2017).

Lack of integration and contradictions between legal frameworks: Regulatory innovation can create conflict between and within state laws at different scales and across different sectors (Dyckman et al., 2014; Hinkel et al., 2018).

Fragmentation through decentralised governance structures: Governance structures which result from decentralization can lead to fragmentation and a lack of accountability and responsibility for climate adaptation, and separation of taxation powers from implementation responsibilities (Solecki et al., 2017). This hampers implementation of adaptation as it falls between the gaps in organisational responsibility, where responsibility and blame is shifted, and contradictory policy approaches produce conflict in fragmented government settings (Den Uyl and Russel, 2018).

Property rights and adaptation along already highly developed coastlines: Expectations of property use and value limit local government's authority to zone property to manage coastal impacts, including planned retreat. Some sectors of local government prioritize short term interests in economic growth at the coast, and this tends to encourage development patterns that extract maximum vaue from coastal property development, which impacts the ability of local government to pursue strategies such as managed retreat or avoid new development in exposed localities. Conserving coastal land is challenging as in many cases it is prohibitively expensive for local governments to acquire land (Dyckman et al., 2014).

Social and political conflict and inequality: There is limited understanding about how socio-political relations produce unequal and uneven landscapes of vulnerability, risk and adaptation prospects in the coastal zone. Resultant conflict reflects divergent spatial and social outcomes of socio-ecological change and vulnerability. Understanding how inequality is entrenched and fostered by prevailing SLR responses is necessary to address the distributional and procedural injustices that some adaptation efforts perpetuate. This is evident in Hoque et al. (2018) research in Banglandesh, which focuses on the factors that marginalize some social groups, stratified by wealth status, gender, ethnicity and other demographic factors. Social conflict is also sparked by concerns such as who should absorb the consequences of SLR, and how public expenditure should be allocated given the scope of pressing developmental needs. The private sector, insurance companies and their clients are also questioning how the climate risks and the costs of mitigating it, should be distributed.

Socio-political assessments in spatial knowledge production: Notwithstanding advances in the mapping of coastal hazards, vulnerability and risk, the social assessment of vulnerability and risk needs further development and integration into spatial risk modelling (City and County of San Francisco, 2016; Musa et al., 2016; New Zealand Government, 2017). A better understanding of the socio-spatial-temporal dimensions of intersecting disadvantage improves technical risk analyses, revealing why some individuals or communities are more vulnerable to disasters (O'Hare and White, 2018).

Corruption, crime and social deviance: More research needs to be conducted on the impact of corruption, crime, and social deviance on local adaptation efforts (Mansur et al., 2018).

4.4.5.5.3 Lessons learned from efforts to implement sea level rise responses at the local level

Local governments are integrating provisions to implement SLR responses into their main functions including land use planning, service and infrastructure provision and maintenance, resource management, development approvals in the coastal zone, community development, asset and flood risk management and disaster risk management (Dyckman et al., 2014; Colenbrander and Sowman, 2015; Dutra et al., 2015; Porter et al., 2015; New Zealand Government, 2017). However, this is being achieved with varying levels of success, with adaptation deficits, lack of resources and capacity, and other development challenges being commonplace, which compete for limited resources, impeding adaptation efforts, particularly in developing countries. In many cases, coastlines are already heavily developed which creates path dependencies for how adaptation can take place, particularly as a result of the dominant influence of private property rights.

Nonetheless, the knowledge and action of individuals and communities in responding to climate change, through community based adaption and community resilience, has always been and is becoming increasingly important in coastal zones, revealing the value of partnerships, and communities' ability to adapt, often in the face of limited local government capacity. Local government responses reflect the broad approaches of avoid, accommodate, protect, retreat and advance in the face of SLR. Their responses reflect both short term coping strategies where they are 'managing and mitigating the dangers', and to a lesser extent longer-term transformative strategies and approaches which aim to meet more than just climate change goals. The context and particularities of place shape the possibilities and nature of response to climate change in the coastal zone. It is therefore essential to evaluate responses to coastal risk in relation to different socio-economic, environmental and political contexts, to be able to draw meaningful 'universal' lessons from climate adaptation at the local scale. What stands out as being foundational for enabling effective local implementation of SLR responses, is the value of participatory governance, the co-production and integration of scientific, local and indigenous knowledges, and the institutionalization of practical implementation measures. It is through such deliberative processes, which address the socio-political, economic and environmental dimensions and trade-offs in more value-based, open, negotiated and equal ways, that the greatest gains have been made in climate adaptation in the coastal zone.

4.4.7 Climate Resilient Development Pathways

[PLACEHOLDER FOR FINAL DRAFT]

[START FAQ 4.1 HERE]

FAQ 4.1: What challenges does certain sea level rise present to coastal communities?

It is certain that Global Mean Sea Level is rising. It will continue to do so for centuries. Human well-being and sustainable development aspirations are at risk because many people, assets and vital resources are concentrated along low-lying coasts around the world. Many coastal communities have started to consider the implications of sea level rise. Measures are being taken to address coastal hazards exacerbated by rising sea level, such as storm surges, coastal flooding, and salinization. However, in general, coastal communities are still ill-prepared for the rise in sea level.

Scientific evidence about sea level rise is clear: Global Mean Sea Level rose by 0.17 m between 1902 and 2010. It is projected to rise by 0.97 m by 2100 if global greenhouse gas emissions are not curbed (median RCP8.5). It could rise to 5 m by 2300, depending on the level of greenhouse gas emissions and the response of the Antarctic ice sheet, which are both highly uncertain. Even if efforts to mitigate emissions are very effective, extreme sea-level events that have been rare over the last century will become common before 2100, due to global warming and sea level rise, and even by 2050 in many locations. Without resolute adaptation, hazard impacts compounded by sea level rise, such as flooding, will become severe and commonplace along low-lying coasts.

Choices being made now about how to respond to sea level rise profoundly influence the trajectory of future exposure and vulnerability to sea level rise. If concerted mitigation and adaptation efforts are delayed, risks will get progressively worse as sea level rises at an accelerating pace. Prospects for global climate-resilience and sustainable development therefore depend in large part on coastal nations, cities and communities taking urgent and sustained action to mitigate greenhouse gas emissions and adapt to sea level rise. Such actions will ‘buy time’ and allow for adjustments in responses to sea level rise by mid-century and beyond, depending how sea level rise unfolds.

Sea level rise will vary regionally and locally, and will be especially challenging for people living along the low-lying shorelines of islands, deltas, and coastal cities and towns, from the Tropics to Polar regions. Action to reduce risks related to sea level rise takes different forms. ‘Hard protection’, like seawalls, can hold back the sea up to a point. Such protection is feasible and affordable in low-lying coastal areas that are densely populated and intensively developed, as is the case for many coastal cities and some small islands. Maintaining healthy coastal ecosystems, like mangroves, seagrass beds or coral reefs, can provide ‘soft protection’ and other benefits. Sea level rise can also be ‘accommodated’ by raising buildings on the shoreline, for example. Land can be reclaimed from the sea by building outwards and upwards, a response that addresses sea level rise by ‘advancement’. Residual risk remains even after such responses are implemented. The consequences can be disastrous if sea level rise and associated extreme sea level events exceed design standards—as demonstrated by the 1953 North Sea floods and after Hurricane Katrina in 2005 when protective works failed. ‘Retreat’ from the shoreline is the only way to eliminate such risk. For those unable to afford protection, accommodation or advancement measures, or when such measures are no longer viable or effective, displacement is inevitable; unless people choose to migrate or planned relocation is initiated. Such dire prospects face millions of people living on low-lying islands, including Small Island Developing States, some densely populated but less intensively developed deltas, rural coastal villages and towns, and Arctic communities who already face melting ice and unprecedented changes in weather. The resultant impacts on distinctive cultures and ways of life could be devastating. Difficult trade-offs are therefore inevitable when making social choices about rising sea level. Institutionalising processes that lead to fair and just outcomes is extremely challenging, but vitally important.

Rising sea levels thus present a monumental challenge to the global community, and to coastal nations, small islands, cities and communities. Moreover, this challenge will become more severe over time, with profound ethical, cultural, social, economic, political, environmental, technological and administrative implications. Societal choices that are made in the coming decade or two about how to mitigate greenhouse gas emissions, and adapt to rising seas, will shape the habitability of low-lying coasts, livelihood prospects and human well-being for centuries to come.

[END FAQ4.1 HERE]

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