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Coastal Systems and Low-Lying Areas

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Frequently Asked Questions

Executive Summary

Coastal systems are particularly sensitive to three key drivers related to climate change: sea level, ocean temperature, and ocean acidity (*very high confidence*). {5.3.2, 5.3.3.4, 5.3.3.5} Despite the lack of attribution of observed coastal changes, there is a long-term commitment to experience the impacts of sea level rise because of a delay in its response to temperature (*high confidence*). {5.5.8} In contrast, coral bleaching and species ranges can be attributed to ocean temperature change and ocean acidity. {5.4.2.2, 5.4.2.4} For many other coastal changes, the impacts of climate change are difficult to tease apart from human-related drivers (e.g., land use change, coastal development, pollution) (*robust evidence*, *high agreement*).

Coastal systems and low-lying areas will increasingly experience adverse impacts such as submergence, coastal flooding, and coastal erosion due to relative sea level rise (RSLR; *very high confidence*). In the absence of adaptation, beaches, sand dunes, and cliffs currently eroding will continue to do so under increasing sea level (*high confidence*). {5.4.2.1, 5.4.2.2} Large spatial variations in the projected sea level rise together with local factors means RSLR at the local scale can vary considerably from projected global mean sea level rise (GMSLR) (*very high confidence*). {5.3.2} Changes in storms and associated storm surges may further contribute to changes in sea level extremes but the small number of regional storm surge studies, and uncertainty in changes in tropical and mid-latitude cyclones at the regional scale, means that there is *low confidence* in projections of storm surge change {5.3.3.2} Both RSLR and impacts are also influenced by a variety of local processes unrelated to climate (e.g., subsidence, glacial isostatic adjustment, sediment transport, coastal development) (*very high confidence*).

Acidification and warming of coastal waters will continue with significant negative consequences for coastal ecosystems (*high confidence*). The increase in acidity will be higher in areas where eutrophication or coastal upwellings are an issue. It will have negative impacts for many calcifying organisms (*high confidence*). {5.4.2.2} Warming and acidification will lead to coral bleaching, mortality, and decreased constructional ability (*high confidence*), making coral reefs the most vulnerable marine ecosystem with little scope for adaptation. {5.4.2.4, Box CC-OA} Temperate seagrass and kelp ecosystems will decline with the increased frequency of heat waves and sea temperature extremes as well as through the impact of invasive subtropical species (*high confidence*). {5.4.2.3}

The population and assets exposed to coastal risks as well as human pressures on coastal ecosystems will increase significantly in the coming decades due to population growth, economic development, and urbanization (*high confidence*). The exposure of people and assets to coastal risks has been rapidly growing and this trend is expected to continue. {5.3.4.1, 5.4.3.1} Humans have been the primary drivers of changes in coastal aquifers, lagoons, estuaries, deltas, and wetlands (*very high confidence*) and are expected to further exacerbate human pressures on coastal ecosystems resulting from excess nutrient input, changes in runoff, and reduced sediment delivery (*high confidence*). {5.3.4.2, 5.3.4.3, 5.3.4.4}

For the 21st century, the benefits of protecting against increased coastal flooding and land loss due to submergence and erosion at the global scale are larger than the social and economic costs of inaction (*limited evidence*, *high agreement*). Without adaptation, hundreds of millions of people will be affected by coastal flooding and will be displaced due to land loss by year 2100; the majority of those affected are from East, Southeast, and South Asia (*high confidence*). {5.3.4.1, 5.4.3.1} At the same time, protecting against flooding and erosion is considered economically rational for most developed coastlines in many countries under all socioeconomic and sea level rise scenarios analyzed, including for the 21st century GMSLR of above 1 m (*limited evidence*, *high agreement*). {5.5.5}

The relative costs of adaptation vary strongly between and within regions and countries for the 21st century (*high confidence*). Some low-lying developing countries (e.g., Bangladesh, Vietnam) and small islands are expected to face very high impacts and associated annual damage and adaptation costs of several percentage points of gross domestic product (GDP). {5.5.5} Developing countries and small islands within the tropics dependent on coastal tourism will be impacted directly not only by future sea level rise and associated extremes but also by coral bleaching and ocean acidification and associated reductions in tourist arrivals (*high confidence*). {5.4.3.4}

The analysis and implementation of coastal adaptation toward climate-resilient and sustainable coasts has progressed more significantly in developed countries than in developing countries (*high confidence*). Given ample adaptation options, more proactive responses can be made and based on technological, policy related, financial, and institutional support. Observed successful adaptation includes major projects (e.g., Thames Estuary, Venice Lagoon, Delta Works) and specific practices in both developed countries (e.g., Netherlands, Australia) and developing countries (e.g., Bangladesh). {5.5.4.2} More countries and communities carry out coastal adaptation measures including those based on integrated coastal zone management, local communities, ecosystems, and disaster reduction, and these measures are mainstreamed into relevant strategies and management plans (*high confidence*). {5.5.4, 5.5.5}

5.1. Introduction

This chapter presents an updated picture of the impacts, vulnerability, and adaptation of coastal systems and low-lying areas to climate change, with sea level rise perceived as the most important risk for human systems. Unlike the coastal chapter in the previous assessment (Fourth Assessment Report, AR4), materials pertinent to the oceans are not covered here but in two new ocean chapters (Chapters 6 and 30). As in AR4, polar coasts are in another chapter (Chapter 28); small islands are also considered separately (Chapter 29) so an in-depth discussion is not provided herein.

The topics covered in this chapter follow the outline for sectoral chapters approved by the IPCC. An Executive Summary summarizes the key messages with a line of sight to the supporting sections in the chapter.

This chapter consists of six sections, with this first section dealing with progress in knowledge from AR4 to AR5 (Fifth Assessment Report), scope of chapter, and new developments. Section 5.2 defines the coastal systems and climate and non-climate drivers. The coastal systems include both natural systems and human systems, and this division is generally followed throughout the chapter. The climate and non-climate drivers are assessed in Section 5.3, followed by the impacts, vulnerabilities, and risks in Section 5.4. Section 5.5 deals with adaptation and managing risks. Information gaps, data gaps, and research needs are assessed in Section 5.6. There is one box on a specific example and reference to three cross-chapter boxes.

In AR4, the coastal chapter assessed the impact of climate change and a global sea level rise up to 0.59 m in the 2090s. The coastal systems were considered to be affected mainly by higher sea levels, increasing temperatures, changes in precipitation, larger storm surges, and increased ocean acidity. Human activities had continued to increase their pressure on the coasts with rapid urbanization in coastal areas and growth of megacities with consequences on coastal resources. Regionally, South, Southeast, and East Asia; Africa; and small islands were identified as most vulnerable. The AR4 chapter offered a range of adaptation measures, many under the Integrated Coastal Zone Management (ICZM) framework that could be carried out in both developed and developing countries, but recognized that the latter would face more challenges. Various issues on increasing the adaptive capacity or increasing the resilience of coastal communities were discussed. The unavoidability of sea level rise in the long term, even with stringent mitigation, was noted, with adaptation becoming an urgent issue.

A number of key issues related to the coasts have arisen since AR4. There is now better understanding of the natural systems, their ecosystem functions, their services and benefits to humanity, and how they can be affected by climate change. Their linkages landward to the watersheds and seaward to the seas and oceans need to be considered for a more integrated assessment of climate change impacts. The global mean sea level rise (GMSLR) is projected to be 0.28 to 0.98 m by 2100 (Table 5-2), although with regional variations and local factors the local sea level rise can be higher than that projected for the GMSLR. This has serious implications for coastal cities, deltas, and low-lying states. While higher rates of coastal erosion are generally expected under rising sea levels, the complex inter-relationships between the geomorphological and ecological attributes of the coastal system (Gilman et al., 2006; Haslett, 2009) and the relevant climate and oceanic processes need to be better established at regional and local scales. Such complex inter-relationships can be influenced by different methods and responses of coastal management.

Also of concern is ocean acidification. Together with warming, it causes coral reefs to lose their structural integrity, negatively implicating reef communities and shore protection (Sheppard et al., 2005; Manzello et al., 2008; see Boxes CC-OA, CC-CR). Acidification has potential impacts of reduced calcification in shellfish and impacts on commercial aquaculture (Barton et al., 2012). Since AR4, a significant number of new findings regarding the impacts of climate change on human settlements and key coastal systems such as rocky coasts, beaches, estuaries, deltas, salt marshes, mangroves, coral reefs, and submerged vegetation have become available and are reviewed in this chapter. However, uncertainties regarding projections of potential impacts on coastal systems remain generally high.

This chapter also provides advances in both vulnerability assessments and the identification of potential adaptation actions, costs, benefits, and trade-offs. A large number of new studies estimate the costs of inaction versus potential adaptation. Coastal adaptation has become more widely used, with a wider range of approaches and frameworks such as integrated coastal management, ecosystem-based adaptation, community-based adaptation, and disaster risk reduction and management.

Climate change will interact differently with the variety of human activities and other drivers of change along coastlines of developed and developing countries. For example, on the coastlines of developed countries, changes in weather and climate extremes and sea level rise may impact the demand for housing, recreational facilities, and construction of renewable energy infrastructure on the coast (Hadley, 2009), including critical infrastructures such as transportation, ports, and naval bases. Along the coasts of developing countries, weather and climate extremes affect a wide range of economic activities supporting coastal communities and pose an additional risk to many of the fastest growing low-lying urban areas, such as in Bangladesh and China (McGranahan et al., 2007; Smith, 2011).

5.2. Coastal Systems

Coastal systems and low-lying areas, also referred to as coasts in this assessment, include all areas near mean sea level. Generally, there is no single definition for the coast and the coastal zone/area, where the latter emphasizes the area or extent of the coastal ecosystems. In relation to exposure to potential sea level rise, the low-elevation coastal zone (LECZ) has been used in recent years with reference to specific area and population up to 10 m elevation (Vafeidis et al., 2011).

Coastal systems are conceptualized to consist of both natural and human systems (Figure 5-1). The natural systems include distinct coastal features and ecosystems such as rocky coasts, beaches, barriers and sand dunes, estuaries and lagoons, deltas, river mouths, wetlands, and coral reefs. These elements help define the seaward and landward boundaries of the coast. In spite of providing a wide variety of regulating, provisioning, supporting, and cultural services (MEA, 2005), they have

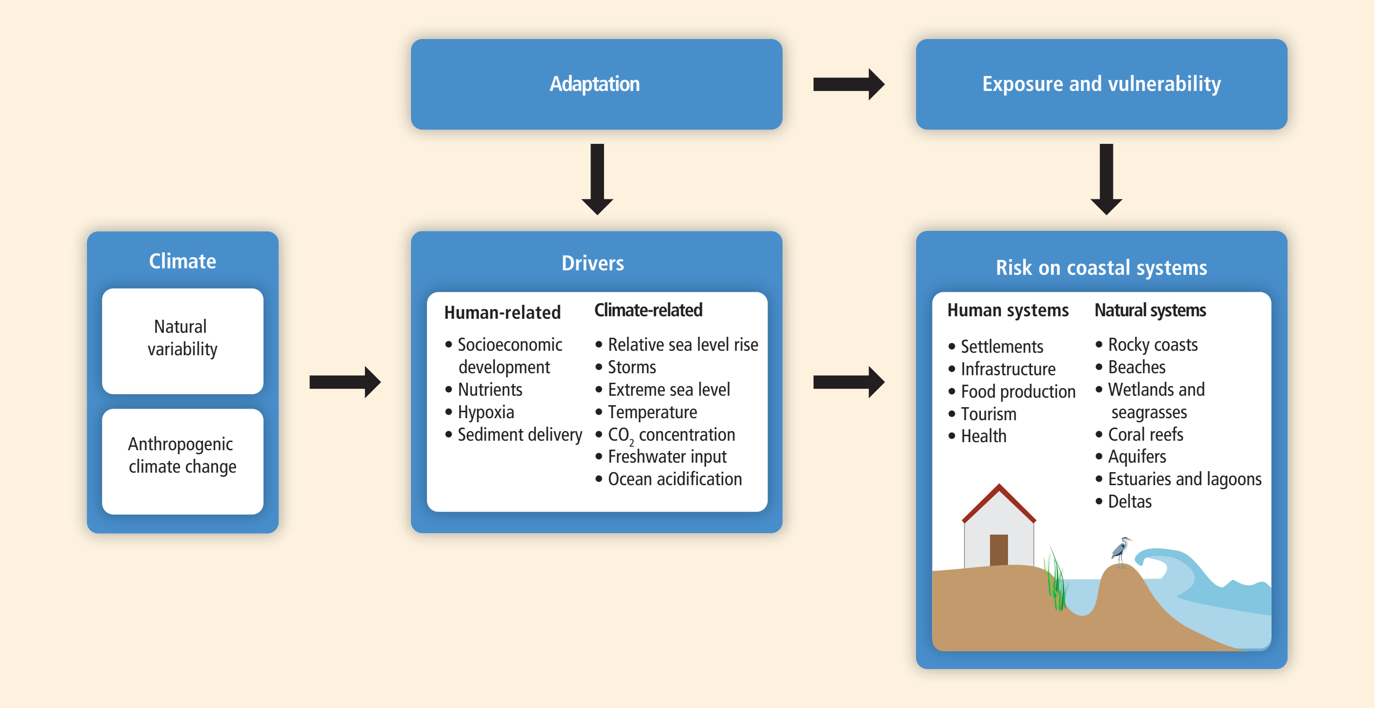

Figure 5-1 | Climate, just as anthropogenic or natural variability, affects both climate and human related drivers. Risk on coastal systems is the outcome of integrating drivers' associated hazards, exposure, and vulnerability. Adaptation options can be implemented either to modify the hazards or exposure and vulnerability, or both.

been altered and heavily influenced by human activities, with climate change constituting only one among many pressures these systems are facing. The human systems include the built environment (e.g., settlements, water, drainage, as well as transportation infrastructure and networks), human activities (e.g., tourism, aquaculture, fisheries), as well as formal and informal institutions that organize human activities (e.g., policies, laws, customs, norms, and culture). The human and natural systems form a tightly coupled socio-ecological system (Berkes and Folke, 1998; Hopkins et al., 2012).

5.3. Drivers

5.3.1. Introduction

In AR4, changes in climate drivers (i.e., any climate-induced factor that directly or indirectly causes a change), including sea level rise, were projected for different Special Report on Emissions Scenarios (SRES) emissions scenarios (IPCC, 2000). Consequently, to date, most of the impacts and vulnerability assessments of climate change in coastal areas are based on SRES A2, A1B, B2, and A1F1 scenarios. Since AR4 a new scenario process has been initiated to replace the SRES scenarios with Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) (Moss et al., 2010). The RCPs are scenarios specifying concentrations, rather than emissions, thereby avoiding differences in concentrations of long-lived greenhouse gas (GHG) and aerosol concentrations for the same emissions scenarios that can arise from the use of different models (van Vuuren et al., 2011). For a comparison between RCP and SRES scenarios, see WGI AR5 Box 1.2. In addition, Extended Concentration Pathways (ECPs) have been introduced for the 2100–2300 period (Meinhausen et al., 2011), providing the opportunity to assess the long-term commitment to sea level rise, which is *virtually certain* to continue beyond 2500 unless global temperature declines (WGI AR5 Chapter 1; Section 13.5.2).

The SSPs provide representative qualitative story lines (narratives) of world development together with quantitative pathways of key socioeconomic variables such as gross domestic product (GDP) and population. A preliminary list of five SSPs has been proposed (Arnell et al., 2011; O'Neill et al., 2012), and work to further refine them is ongoing (Kriegler et al. 2012; Van Vuuren et al., 2012). SSPs do not include assumptions on mitigation policy and are thus independent from RCPs in the sense that the same SSP may lead to different concentration levels and consequently rises in sea level depending on the level of mitigation reached (Arnell et al., 2011; O'Neill et al., 2012). Table 5-1 summarizes the main climate-related drivers for the coastal systems.

5.3.2. Relative Sea Level Rise

Assessments of coastal impacts, vulnerability, and adaptation need to consider relative sea level rise (RSLR), which includes climate-induced GMSLR (Section 5.3.2.1) and regional variations (Section 5.3.2.2) as well as local non-climate-related sea level changes (Section 5.3.2.3). RSLR poses a significant threat to coastal systems and low-lying areas around the globe, leading to inundation and erosion of coastlines and contamination of freshwater reserves and food crops (Nicholls, 2010). Sea level rise due to thermal expansion as the oceans warm, together with meltwater from glaciers, icecaps, and ice sheets of Greenland and Antarctica, are the major factors that contribute to RSLR globally. However, regional variations in the rate of rise occur because of ocean circulation patterns and interannual and decadal variability (e.g., Zhang

Table 5-1 | Main climate-related drivers for coastal systems, their trends due to climate change, and their main physical and ecosystem effects.

Climate-related driver	Physical/chemical effects	Trends	Projections	Progress since AR4
Sea level	Submergence, flood damage, erosion; saltwater intrusion; rising water tables/impeded drainage; wetland loss (and change).	Global mean sea level *very likely* increase (Section 5.3.2.2; WGI AR5 Sections 3.7.2, 3.7.3).	Global mean sea level *very likely* increase (see Table 5.1; WGI AR5 Section 13.5.1). Regional variability (Section 5.3.2.2; WGI AR5 Chapter 13).	Improved confidence in contributions to observed sea level. More information on regional and local sea level rise.
Storms: tropical cyclones (TCs), extratropical cyclones (ETCs)	Storm surges and storm waves, coastal flooding, erosion; saltwater intrusion; rising water tables/impeded drainage; wetland loss (and change). Coastal infrastructure damage and flood defense failure.	TCs (Box 5-1, WGI AR5 Section 2.6.3): *low confidence* in trends in frequency and intensity due to limitations in observations and regional variability. ETCs (Section 5.3.3.1; WGI AR5 Section 2.6.4): *likely* poleward movement of circulation features but *low confidence* in intensity changes.	TCs (Box 5-1): *likely* decrease to no change in frequency; *likely* increase in the most intense TCs. ETCs (Section 5.3.3.1): *high confidence* that reduction of ETCs will be small globally. *Low confidence* in changes in intensity.	Lowering of confidence of observed trends in TCs and ETCs since AR4. More basin-specific information on storm track changes.
Winds	Wind waves, storm surges, coastal currents, land coastal infrastructure damage.	*Low confidence* in trends in mean and extreme wind speeds (Section 5.3.3.2, SREX, WGI AR5 Section 3.4.5).	*Low confidence* in projected mean wind speeds. *Likely* increase in TC extreme wind speeds (Section 5.3.3.2, SREX).	Winds not specifically addressed in AR4.
Waves	Coastal erosion, overtopping and coastal flooding.	*Likely* positive trends in Hs in high latitudes (Section 5.3.3.2; WGI AR5 Section 3.4.5).	*Low confidence* for projections overall but *medium confidence* for Southern Ocean increases in Hs (Section 5.3.3.2).	Large increase in number of wave projection studies since AR4.
Extreme sea levels	Coastal flooding erosion, saltwater intrusion.	*High confidence* of increase due to global mean sea level rise (Section 5.3.3.3; WGI AR5 Chapter 13).	*High confidence* of increase due to global mean sea level rise, *low confidence* of changes due to storm changes (Section 5.3.3.3; WGI AR5 Section 13.5).	Local subsidence is an important contribution to regional sea level rise in many locations.
Sea surface temperature (SST)	Changes to stratification and circulation; reduced incidence of sea ice at higher latitudes; increased coral bleaching and mortality, poleward species migration; increased algal blooms.	*High confidence* that coastal SST increase is higher than global SST increase (Section 5.3.3.4).	*High confidence* that coastal SSTs will increase with projected temperature increase (Section 5.3.3.4).	Emerging information on coastal changes in SSTs.
Freshwater input	Altered flood risk in coastal lowlands; altered water quality/salinity; altered fluvial sediment supply; altered circulation and nutrient supply.	*Medium confidence* (*limited evidence*) in a net declining trend in annual volume of freshwater input (Section 5.3.3.6).	*Medium confidence* for general increase in high latitudes and wet tropics and decrease in other tropical regions (Section 5.3.3.6).	Emerging information on freshwater input.
Ocean acidity	Increased CO_2 fertilization; decreased seawater pH and carbonate ion concentration (or "ocean acidification").	*High confidence* of overall increase, with high local and regional variability (Section 5.3.3.5).	*High confidence* of increase at unprecedented rates but with local and regional variability (Box CC-OA).	Coastal ocean acidification not specifically addressed in AR4. Considerable progress made in chemical projections and biological impacts.

SREX = IPCC 2012 Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation.

and Church, 2012; Ganachaud et al., 2013) and glacial isostatic rebound and tectonic movement. Subsidence of coastal land from sediment compaction due to building loads, harbor dredging, changes in sediment supply that cause erosion/accretion, and subsurface resource extraction (e.g., groundwater, gas and petroleum; Syvitski et al., 2009) may also contribute to RSLR locally and therefore requires consideration in coastal impact studies. Sea level impacts are most pronounced during episodes of extreme sea levels and these are discussed in Section 5.3.3.

5.3.2.1. Global Mean Sea Level

It is *very likely* that global mean sea level rose at a mean rate of 1.7 [1.5 to 1.9] mm yr^{-1} between 1900 and 2010 and at a rate 3.2 [2.8 to 3.6] mm yr^{-1} from 1993 to 2010 (WGI AR5 Section 13.2.2). Ocean thermal expansion and melting of glaciers have been the largest contributors, accounting for more than 80% of the GMSLR over the latter period (WGI AR5 Section 13.3.1). Future rates of GMSLR during the 21st century are projected to exceed the observed rate for the period 1971–2010 of 2.0 [1.7 to 2.3] mm yr^{-1} for all RCP scenarios (WGI AR5 Table 13.1). Table 5-2 summarizes the *likely* ranges of 21st century GMSLR as established by the Working Group I contribution to this Assessment Report.

From a coastal risk management perspective (Nicholls et al., 2013) assessments of impacts, vulnerabilities, and adaptation have been using GMSLR scenarios above the ranges put forward by WGI reports of AR4 (Meehl et al., 2007; Table 10.7) and AR5 (WGI AR5 Table 13.5). The ranges estimated by WGI of AR4 and AR5 include only those components of GMSLR that can be quantified using process-based models (i.e., models derived from the laws of physics; WGI AR5 Glossary). The ranges given in AR4 thus explicitly excluded contributions to GMSLR resulting from changes in ice flows from the ice sheets of Greenland and Antarctica because at that time process-based models were not able to assess this with sufficient confidence (Meehl et al., 2007; WGI AR5 Section 4.4.5). Since then, understanding has increased and the *likely* range of GMSLR given in AR5 now includes ice sheet flow contributions. *Likely*, however, means that there is still a 0 to 33% probability of GMSLR beyond this range, and coastal risk management needs to consider this. WGI does not assign probabilities to GMSLR beyond the *likely* range, because this cannot be done with the available process-based models. WGI, however, assigns *medium confidence* that 21st century GMSLR does not exceed the likely range by several tenths of a meter (WGI AR5 Section 13.5.1). When using other approaches such as semi-empirical models, evidence from past climates and physical constraints on ice-sheet dynamics GMSLR upper bounds of up to 2.4 m by 2100 have been estimated, but there is *low agreement* on these higher estimates and no consensus on a 21st century upper bound (WGI AR5 Section 13.5.3). Coastal risk management is thus left to choose an upper bound of GMSLR to consider based on which level of risk is judged to be acceptable in the specific case. The Dutch Delta Programme, for example, considered a 21st century GMSLR of 1.3 m as the upper bound.

It is *virtually certain* that sea level rise will continue beyond the 21st century, although projections beyond 2100 are based on fewer and simpler models that include lower resolution coupled climate models for thermal expansion and ice sheet models coupled to climate models to project ice sheet contributions. The basis for the projections are the Extended Concentration Pathways (ECPs), and projections are provided for low, medium, and high scenarios that relate to atmospheric GHG concentrations <500, 500 to 700, and >700 ppm respectively (WGI AR5 Section 13.5.2). Projections of GMSLR up to 2500 are also summarized in Table 5-2.

5.3.2.2. Regional Sea Level

Sea level rise will not be uniform in space and time. Natural modes of climate variability influence sea levels in different regions of the globe and this will affect the rate of rise on interannual and interdecadal time periods. For example, in the equatorial Pacific, sea levels can vary from the global mean by up to 40 cm due to El Niño-Southern Oscillation (ENSO; e.g., Walsh et al., 2012) and this can strongly influence trends on decadal scales. Regional variations in the rate of sea level rise on the coast can arise from climate and ocean dynamic processes such as changes in winds and air pressure, air-sea heat and freshwater fluxes, and ocean currents and their steric properties (Timmermann et al., 2010; WGI AR5 FAQ 13.1). Although the vast majority of coastlines are experiencing sea level rise, coastlines near current and former glaciers and ice sheets are experiencing relative sea level fall (Milne et al., 2009; WGI AR5 FAQ 13.1). This is because the gravitational attraction of the ice sheet decreases as it melts and exerts less pull on the oceans and also because the land tends to rise as the ice melts, the shape of the sea floor changes under the reduced load of the ice sheets, and the change in mass distribution alters the Earth's rotation (WGI AR5 FAQ 13.1; Gomez et al., 2010). In terms of absolute sea level change, approximately 70% of the global coastlines are projected to experience sea level change that is within 20% of the global mean sea level change (WGI AR5 Section 13.6.5).

5.3.2.3. Local Sea Level

Besides the effect of long-term vertical land movement on regional sea level, RSLR can occur locally due to subsidence or uplifts of coastal plains as well as due to other natural causes. Natural subsidence can occur because of sediment compaction and loading, as in the Mississippi River, and other deltas (Törnqvist et al., 2008; Dokka, 2011; Marriner et al., 2012). Tectonic movements, both sustained and abrupt, have brought about relative sea level changes. The Great East Japan Earthquake in 2011 caused subsidence of up to 1.2 m of the Pacific coast of northeast Japan (Geospatial Information Authority of Japan, 2011). The Sumatra-Andaman earthquake in 2004 and subsequent earthquakes in 2005 produced vertical deformation ranging from uplift of 3 m to subsidence of 1 m (Briggs et al., 2006). These movements are especially important in coastal zones located near active plate margins.

Anthropogenic causes of RSLR include sediment consolidation from building loads, reduced sediment delivery to the coast, and extraction of subsurface resources such as gas, petroleum, and groundwater. Subsidence rates may also be sensitive to the rates of oil and gas removal (e.g., Kolker et al., 2011). Syvitski et al. (2009) estimate that the majority of the world's largest deltas are currently subsiding at rates that are considerably larger than the current rates of sea level rise because of coastal sediment starvation due to substantial dam building over the 20th century or sediment compaction through natural or anthropogenic activities. Many large cities on deltas and coastal plains have subsided during the last 100 years: ~4.4 m in eastern Tokyo, ~3 m in the Po delta, ~2.6 m in Shanghai, and ~1.6 m in Bangkok (Syvitski et al., 2009; Teatini et al., 2011). Loads from massive buildings and other large structures can also increase sediment compaction and subsidence (Mazzotti et al., 2009). RSLR can exceed GMSLR by an order of magnitude, reaching more than 10 cm yr^{-1}, and it is estimated that the delta surface

Table 5-2 | Projections of global mean sea level rise in meters relative to 1986–2005 are based on ocean thermal expansion calculated from climate models, the contributions from glaciers, Greenland and Antarctica from surface mass balance calculations using climate model temperature projections, the range of the contribution from Greenland and Antarctica due to dynamical processes, and the terrestrial contribution to sea levels, estimated from available studies. For sea levels up to and including 2100, the central values and the 5–95% range are given whereas for projections from 2200 onwards, the range represents the model spread due to the small number of model projections available and the high scenario includes projections based on RCP6.0 and RCP8.5. Source: WGI AR5 Summary for Policymakers and Sections 12.4.1, 13.5.1, and 13.5.4.

Emission scenario	Representative Concentration Pathway (RCP)	2100 CO$_2$ concentration (ppm)	Mean sea level rise (m)		Emission scenario	Mean sea level rise (m)		
			2046–2065	2100		2200	2300	2500
Low	2.6	421	0.24 [0.17–0.32]	0.44 [0.28–0.61]	Low	0.35–0.72	0.41–0.85	0.50–1.02
Medium low	4.5	538	0.26 [0.19–0.33]	0.53 [0.36–0.71]	Medium	0.26–1.09	0.27–1.51	0.18–2.32
Medium high	6.0	670	0.25 [0.18–0.32]	0.55 [0.38–0.73]	High	0.58–2.03	0.92–3.59	1.51–6.63
High	8.5	936	0.29 [0.22–0.38]	0.74 [0.52–0.98]				

area vulnerable to flooding could increase by 50% for 33 deltas around the world under the sea level rise as projected for 2100 by the IPCC AR4 (Syvitski et al., 2009).

Clearly large regional variations in the projected sea level rise, together with local factors such as subsidence, indicates that RSLR can be much larger than projected GMSLR and therefore is an important consideration in impact assessments (*very high confidence*).

5.3.3. Climate-Related Drivers

Increasing GHGs in the atmosphere produce changes in the climate system on a range of time scales that impact the coastal physical environment. On shorter time scales, physical coastal impacts such as inundation, erosion, and coastal flooding arise from severe storm-induced surges, wave overtopping, and rainfall runoff. On longer time scales, wind and wave climate change can cause changes in sediment transport at the coast and associated changes in erosion or accretion. Natural modes of climate variability, which can affect severe storm behavior and wind and wave climate, may also undergo anthropogenic changes in the future. Ocean and atmospheric temperature change can affect species distribution with impacts on coastal biodiversity. Carbon dioxide (CO_2) uptake in the ocean increases ocean acidity and reduces the saturation state of carbonate minerals, essential for shell and skeletal formation in many coastal species. Changes in freshwater input can alter coastal ocean salinity concentrations. Past and future changes to these physical drivers are discussed in this section (see also Table 5-1).

5.3.3.1. Severe Storms

Severe storms such as tropical and extratropical cyclones (ETCs) can generate storm surges over coastal seas. The severity of these depends on the storm track, regional bathymetry, nearshore hydrodynamics, and the contribution from waves. Globally there is *low confidence* regarding changes in tropical cyclone activity over the 20th century owing to changes in observational capabilities, although it is *virtually certain* that there has been an increase in the frequency and intensity of the strongest tropical cyclones in the North Atlantic since the 1970s (WGI AR5 Section 2.6). In the future, it is *likely* that the frequency of tropical cyclones globally will either decrease or remain unchanged, but there will be a *likely* increase in global mean tropical cyclone precipitation rates and maximum wind speed (WGI AR5 Section 14.6).

ETCs occur throughout the mid-latitudes of both hemispheres, and their development is linked to large-scale circulation patterns. Assessment of changes in these circulation features reveals a widening of the tropical belt, poleward shift of storm tracks and jet streams, and contraction of the polar vortex; this leads to the assessment that it is *likely* that, in a zonal mean sense, circulation features have moved poleward (WGI AR5 Sections 2.7.5 to 2.7.8) but there is *low confidence* regarding regional changes in intensity of ETCs (e.g., Seneviratne et al., 2012). With regard to future changes, a small poleward shift is *likely* in the Southern Hemisphere but changes in the Northern Hemisphere are basin specific and of *lower confidence* (WGI AR5 Section 14.6.3). Globally, it is *unlikely* that the number of ETCs will fall by more than a few percent due to anthropogenic climate change (*high confidence*; WGI AR5 Section 14.6.3).

5.3.3.2. Extreme Sea Levels

Extreme sea levels are those that arise from combinations of factors including astronomical tides, storm surges, wind waves and swell, and interannual variability in sea levels. Storm surges are caused by the falling atmospheric pressures and surface wind stress associated with storms such as tropical and ETCs and therefore may change if storms are affected by climate change. To date, however, observed trends in extreme sea levels are mainly consistent with mean sea level (MSL) trends (e.g., Marcos et al., 2009; Haigh et al., 2010; Menendez and Woodworth, 2010; Losada et al., 2013) indicating that MSL trends rather than changes in weather patterns are responsible.

Assuming that sea level extremes follow a simple extreme value distribution (i.e., a Gumbel distribution), and accounting for the uncertainty in projections of future sea level rise, Hunter (2012) has developed a technique for estimating a sea level allowance, that is, the minimum height that structures would need to be raised in a future period so that the number of exceedances of that height remains the same as under present climate conditions (Figure 5-2). Such an allowance can be factored into adaptive responses to rising sea levels. It should be noted, however, that extreme sea level distributions might not follow a simple Gumbel distribution (e.g., Tebaldi et al., 2012) owing to different factors influencing extreme levels that may not be measured by tide gauges (e.g., Hoeke et al., 2013).

Regarding future changes to storm surges, hydrodynamic models forced by climate models have been used in several extratropical regional studies such as the northeast Atlantic (e.g., Debenard and Roed, 2008; Wang et al., 2008; Sterl et al., 2009) and southern Australia (Colberg and McInnes, 2012). These studies show strong regional variability and sensitivity to the choice of Global Climate Model (GCM) or Regional Climate Model (RCM). The effect of future tropical cyclone changes on storm surges has also been investigated in a number of regions using a range of different methods. These include methods to stochastically generate and/or perturb cyclones within background environmental conditions that represent historical (e.g., Harper et al., 2009) and GCM-represented future conditions (e.g., Mousavi et al., 2011; Lin et al., 2012). Regional studies include Australia's tropical east coast (Harper et al., 2009), Louisiana (Smith et al., 2010), Gulf of Mexico (Mousavi et al., 2011), India (Unnikrishnan et al., 2011), and New York (Lin et al., 2012), and the details of the methods and findings vary considerably between the studies. While some studies indicate for some regions increase to extreme sea levels due to changes in storms, others indicate the opposite. In general, the small number of regional storm surge studies together with the different atmospheric forcing factors and modeling approaches means that there is *low confidence* in projections of storm surges due to changes in storm characteristics. However, observed upward trends in MSL together with projected increases for 2100 and beyond indicate that coastal systems and low-lying areas will increasingly experience extreme sea levels and their adverse impacts (*high confidence*) (see also WGI AR5 Section 13.7).

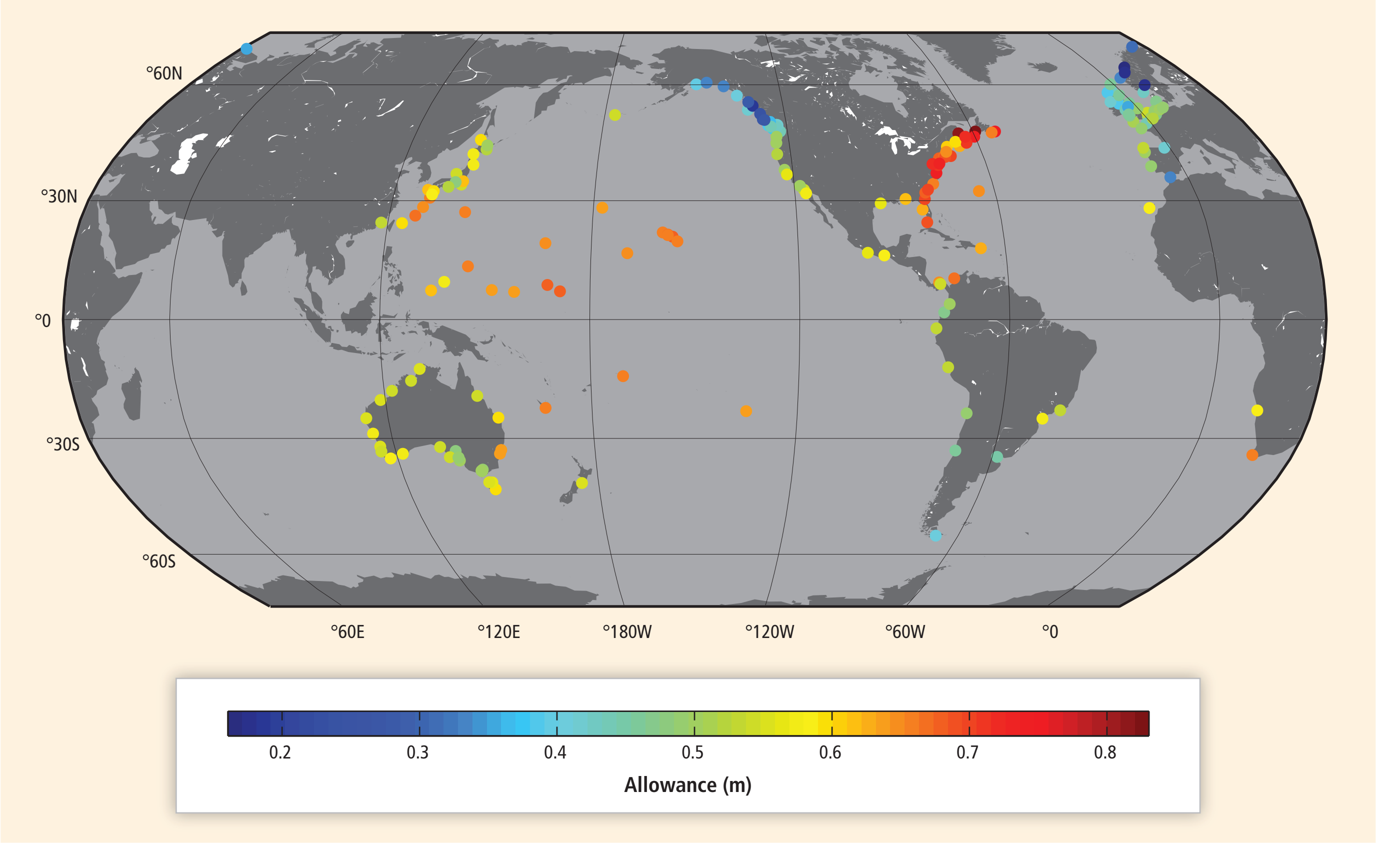

Figure 5-2 | The estimated increase in height (m) that flood protection structures would need to be raised in the 2081–2100 period to preserve the same frequency of exceedances that was experienced for the 1986–2005 period, shown for 182 tide gauge locations and assuming regionally varying relative sea level rise projections under an Representative Concentration Pathway 4.5 (RCP4.5) scenario (adapted from Hunter et al., 2013).

5.3.3.3. Winds and Waves

Changes in wind climate affect large-scale wave climate. Winds also influence longshore current regimes and hence upwelling systems (Narayan et al., 2010; Miranda et al., 2012; see also Sections 6.3.3, 6.3.5). Energy dissipation via wave breaking contributes to longshore and cross-shore currents, elevated coastal sea levels through wave set-up, and run-up and beach erosion. Changes to wind and wave climate therefore can affect sediment dynamics and shoreline processes (e.g., Aargaard et al., 2004; Reguero et al., 2013), and extreme winds and waves are a threat to coastal populations. The coastal impacts of wave climate change are also a function of wave direction and period as well as the coastline itself, which can influence shoaling and refraction. Long period swell, which dominates the wave energy field, poses a significant danger to coastal and offshore structures and shipping (e.g., Semedo et al., 2011) and can causes significant flooding of coastlines with steep shelf margins (Hoeke et al., 2013).

There is *low confidence* in trends calculated from measurements of mean and extreme winds and their causes due to the limited length of records and uncertainties associated with different wind measurement techniques (Seneviratne et al., 2012). However, there is increasing evidence for a strengthening wind stress field in the Southern Ocean since the early 1980s from atmospheric reanalyses, satellite observations, and island station data (WGI AR5 Section 3.4.5). Positive trends in wave height have been detected in the Northeast Atlantic over the 1958–2002 period based on reanalyses and ship observations and in the Southern Ocean between 1985 and 2008 based on satellite data (*medium confidence*) (WGI AR5 Section 3.4.6; see Table 5-2).

Projected changes in mean and extreme winds and waves were assigned *low confidence* (Seneviratne et al., 2012) owing to limited studies. Although there has been an increase in studies addressing future wave climate change (Hemer et al., 2013), generally *low confidence* remains in projected wave climate change (except for *medium confidence* over the Southern Ocean), and this is due to uncertainties in future winds, particularly those associated with storms (see WGI AR5 Section 13.7).

5.3.3.4. Sea Surface Temperature

Sea surface temperature (SST) has significantly warmed during the past 30 years along more than 70% of the world's coastlines, with highly heterogeneous rates of change both spatially and seasonally (Lima and Wethey, 2012). The average rate is 0.18 ± 0.16°C per decade and the average change in seasonal timing was -3.3 ± 4.4 days per decade. These values are larger than in the global ocean where the average of change is 0.11 [0.09 to 0.13]°C per decade in the upper 75 m of the ocean during the 1971–2010 period (WGI AR5 Section 3.2.2) and the seasonal shift is -2.3 days per decade (Lima and Wethey, 2012). Extreme events have also been reported. For example, the record high ocean temperatures along the western Australian coast during the austral summer of 2010/2011, with nearshore temperatures peaking at about 5°C above average, were unprecedented (Pearce and Feng, 2013). In summary, positive trends in coastal SSTs are seen on the majority of coastlines, and the rate of rise along coastlines is higher on average than the oceans (*high confidence*). Based on projected temperature increases there is *high confidence* that positive coastal SST trends will continue.

5.3.3.5. Ocean Acidification

Anthropogenic ocean acidification refers to the changes in the carbonate chemistry primarily due to the uptake of atmospheric CO_2 (Box CC-OA). Seawater pH exhibits a much larger spatial and temporal variability in coastal waters compared to open ocean owing to the variable contribution of processes other than CO_2 uptake (Duarte et al., 2013a) such as upwelling intensity (Feely et al., 2008; Box CC-UP), deposition of atmospheric nitrogen and sulfur (Doney et al., 2007), carbonate chemistry of riverine waters (Salisbury et al., 2008; Aufdenkampe et al., 2011), as well as inputs of nutrients and organic matter (Borges, 2011; Cai et al., 2011). For example, pH (NBS scale) ranges from 6 to 9 in 24 estuaries (Borges and Abril, 2011) and short-term (hours to weeks) changes of up to 0.5 pH units are not unusual in coastal ecosystems (Hofmann et al., 2011).

Few high-quality ocean acidification time series exceed 5 years in the coastal ocean (Wootton et al., 2008; Provoost et al., 2010; Waldbusser et al., 2010). Some exhibit considerable differences compared to open ocean stations, illustrating that anthropogenic ocean acidification can be lessened or enhanced by processes such as primary production, respiration, and calcification (Borges and Gypens, 2010; Kleypas et al., 2011).

Under the IS92a CO_2 emission scenario, the global pH (total scale) of coastal waters has been projected to decrease from about 8.16 in the year 1850 to 7.83 in 2100 (Lerman et al., 2011) but with considerable spatial variability. For example, using the same CO_2 emission scenario, Cai et al. (2011) projected an overall decline of pH in the Northern Gulf of Mexico of 0.74 over the same period, a value that is much greater than that of the open ocean (Box CC-OA).

To summarize, seawater pH exhibits considerable temporal and spatial variability in coastal areas compared to open ocean owing to additional natural and human influences (*very high confidence*). Coastal acidification is projected to continue but with large and uncertain regional and local variations (*high confidence*).

5.3.3.6. Freshwater Input

Changes in river runoff arise from changes in climate drivers such as precipitation, complex interactions between changing levels of CO_2, plant physiology, and, consequently, evapotranspiration (e.g., Gedney et al., 2006; Betts et al., 2007) as well as human drivers such as land use change, water withdrawal, dam building, and other engineered modifications to waterways (see more detailed discussion in Chapter 3). An assessment of runoff trends in 925 of the world's largest ocean-reaching rivers, which account for about 73% of global total runoff, indicates that from 1948–2004 statistically significant trends were present in only one-third of the top 200 rivers and, of these, two-thirds exhibited downward trends and one-third upward trends (Dai et al., 2009). While precipitation changes dominate freshwater flows, decreasing trends in river discharges may be further enhanced as a result of human pressures (Dai et al., 2009; Section 3.2.3).

Average annual runoff is generally projected to increase at high latitudes and in the wet tropics and to decrease in most dry tropical regions (Section 3.4.5). Shifts to earlier peak flows are also projected in areas affected by snowmelt (Adam et al, 2009). However, there are some regions where there is considerable uncertainty in the magnitude and direction of change, specifically South Asia and large parts of South America. Both the patterns of change and the uncertainty are largely driven by projected changes in precipitation.

To summarize, there is *medium confidence* (*limited evidence*, *high agreement*) in a net declining trend in freshwater input globally, although large regional variability exists. Trends are dominated by precipitation changes although human pressures on water supply may enhance downward trends (*medium confidence*). Uncertainty in future changes in runoff is linked to precipitation uncertainty. Runoff is generally projected to increase in high latitudes with earlier peak flows and in the wet tropics and decrease in other tropical regions, however, with large uncertainty (*medium confidence*).

5.3.4. Human-Related Drivers

Coastal systems are subject to a wide range of human-related or anthropogenic drivers (e.g., Crain et al., 2009) that interact with climate-related drivers and confound efforts to attribute impacts to climate change. Some of the major terrestrially based human drivers that directly or indirectly cause changes are briefly reviewed. Related drivers in the marine environment are discussed in Sections 6.4 and 30.6.

5.3.4.1. Socioeconomic Development

Socioeconomic development (SED) drives coastal impacts in several ways. SED influences the number of people and the value of assets exposed to coastal hazards. Since AR4, a number of studies have estimated the influence of future sea level rise and associated hazards on coastal population and assets. Although these estimates are subject to uncertainties associated with global elevation and population data sets (Lichter et al., 2011; Mondal and Tatem, 2012), all the studies indicate high and growing exposure of low-lying coastal areas. The Low Elevation Coastal Zone (LECZ) constitutes 2% of the world's land area but contains 10% of the world's population (600 million) and 13% of the world's urban population (360 million), based on year 2000 estimates (McGranahan et al., 2007). About 65% of the world's cities with populations of greater than 5 million are located in the LECZ (McGranahan et al., 2007). The global population exposed to the 1-in-100-year extreme sea level (i.e., the sea level that has a 1% chance of being exceeded every year) has increased by 95% from 1970 to 2010, with about 270 million people and US$13 trillion worth of assets being exposed to the 1-in-100-year extreme sea level in 2010 (Jongman et al., 2012). In 2002, about US$1.9 trillion worth of assets below the 1-in-100-year extreme sea level were concentrated in the following 10 port cities: Miami (USA), New York-Newark (USA), New Orleans (USA), Osaka-Kobe (Japan), Tokyo (Japan), Amsterdam (Netherlands), Rotterdam (Netherlands), Nagoya (Japan), Virginia Beach (USA), and Guangzhou (China) (Hanson et al., 2011). Compared to other regions, Asia exhibits the greatest exposure in terms of population and assets (Jongman et al., 2012).

For many locations, population and assets exposure is growing faster than the national average trends owing to coastward migration, coastal industrialization, and urbanization (e.g., McGranahan et al., 2007; Seto, 2011; Smith, 2011; see also Chapter 8; *high confidence*). Coastal net migration has largely taken place in flood- and cyclone-prone areas, which poses a challenge for adaptation (de Sherbinin et al., 2011). These processes and associated land use changes are driven by a combination of many social, economic, and institutional factors including taxes, subsidies, insurance schemes, aesthetic and recreational attractiveness of the coast, and increased mobility (Bagstad et al., 2007; Palmer et al., 2011). In China, the country with the largest exposed population, urbanization and land reclamation are the major drivers of coastal land use change (Zhu et al., 2012). Although coastal migration is expected to continue in the coming decades, it is difficult to capture this process in global scenarios, as the drivers of migration and urbanization are complex and variable (Black et al., 2011).

SED also influences the capacity to adapt. Poor people living in urban informal settlements, of which there are about 1 billion worldwide, are particularly vulnerable to weather and climate impacts (de Sherbinin et al., 2011; Handmer et al., 2012). The top five nations classified by population in coastal low-lying areas are developing and newly industrialized countries: Bangladesh, China, Vietnam, India, and Indonesia (McGranahan et al., 2007; Bollman et al., 2010; Jongman et al., 2012). SED and associated land reclamation are also major drivers of the destruction of coastal wetlands, which also makes human settlements more vulnerable because wetlands act as natural buffers reducing wave and storm impacts on the coast (e.g., Crain et al., 2009; Shepard et al., 2011; Arkema et al., 2013; Duarte et al., 2013b). Finally, socioeconomic development is expected to exacerbate further a number of human pressures on coastal systems related to nutrient loads, hypoxia, and sediment delivery, which is discussed in the following subsections.

5.3.4.2. Nutrients

Increased river nutrient (nitrogen, phosphorus) loads to coasts in many regions are observed, and simulated by regional and global models (Alexander et al., 2008; Seitzinger et al., 2010). Anthropogenic global loads of dissolved inorganic nutrients (DIN, DIP) are two to three times larger than those of natural sources (Seitzinger et al., 2010), causing coastal ecosystem degradation (Sections 5.3.4.3, 5.4.2.6). Large variations exist in magnitude and relative sources of nutrient loads. Anthropogenic sources are related primarily to fertilizer use in agriculture and fossil fuel emissions (NO_x) (Galloway et al., 2004; Bouwman et al., 2009).
Future trends depend on measures available to optimize nutrient use in crop production and minimize loss to rivers from agriculture (crop, livestock), sewage, and NO_x emissions. In scenarios with little emphasis on nutrient management, global nutrient discharge increases (DIN 29%, DIP 64%) between 2000 and 2050 (Seitzinger et al., 2010). With ambitious nutrient management, global DIN loads decrease slightly and DIP increases (35%). Climate change is projected to change water runoff (Chapter 3) that influences river nutrient loads. Studies of climate change effects related to increased watershed nutrient sources are needed. In summary, nutrient loads have increased in many world regions (*high confidence*); future increases will depend largely on nutrient management practices (*medium confidence*).

5.3.4.3. Hypoxia

The presence of excessive nutrients in coastal waters, which causes eutrophication and the subsequent decomposition of organic matter, is the primary cause of decreased oxygen concentration (hypoxia). Globally, upwelling of low oxygen waters (e.g., Grantham et al., 2004) and ocean warming, which decreases the solubility of oxygen in seawater (Shaffer et al., 2009), are secondary drivers but can be locally important. The oxygen decline rate is greater in coastal waters than in the open ocean (Gilbert et al., 2010). Hypoxia poses a serious threat to marine life, which is exacerbated when combined with elevated temperature (Vaquer-Sunyer and Duarte, 2011; see also Section 6.3.3). The number of so-called "dead zones" has approximately doubled each decade since 1960 (Diaz and Rosenberg, 2008). Fishery catches from these areas are generally lower than predicted from nutrient loading alone (Breitburg et al., 2009). Although non-climate anthropogenic factors are responsible for virtually all hypoxia in estuaries and inner continental shelves, climate drivers such as ocean warming, altered hydrological cycles, and coastal current shifts and changes in upwellings may interact with eutrophication in the next decades (Rabalais et al., 2010; Meire et al., 2013; *high confidence*).

5.3.4.4. Sediment Delivery

Human activities in drainage basins and coastal plains have impacted the coastal zone by changing the delivery of sediment to the coast. Sediment trapping behind dams, water diversion for irrigation, and sand and gravel mining in river channels all contribute to decrease sediment delivery, whereas soil erosion due to land use changes helps increase it (Syvitski, 2008; Walling, 2006). It is estimated that the global discharge of riverine sediment was 16 to 19 Gt yr^{-1} in the 1950s before widespread dam construction (e.g., Syvitski et al., 2005; Milliman and Farnsworth, 2011) and it has decreased to 12 to 13 Gt yr^{-1} (Syvitski and Kettner, 2011). Out of 145 major rivers with mostly more than 25 years of record, only seven showed evidence of an increase in sediment flux while 68 showed significant downward trends (Walling and Fang, 2003). The number of dams has increased continuously and their distribution has expanded globally. As of early 2011, the world has an estimated 16.7 million reservoirs larger than 0.01 ha (Lehner et al., 2011). Globally, 34 rivers with drainage basins of 19 million km^2 in total show a 75% reduction in sediment discharge over the past 50 years (Milliman and Farnsworth, 2011). Reservoir trapping of sediments is estimated globally as 3.6 Gt yr^{-1} to more than 5 Gt yr^{-1} (Syvitski et al., 2005; Milliman and Farnsworth, 2011; Walling, 2012). Human pressure is the main driver of the observed declining trend in sediment delivery to the coast (*high agreement*).

5.4. Impacts, Vulnerabilities, and Risks

5.4.1. Introduction

This subsection briefly introduces the diverse approaches and methods applied in the literature on coastal impact, vulnerability, and risk. The following subsections then assess this literature related to coastal natural systems (Section 5.4.2) and coastal human systems (Section 5.4.3). Much of this literature focuses on RSLR and extreme sea level events as the main drivers. The main biophysical impacts of this driver are increasing flood damage, dry-land loss due to submergence and erosion, wetland loss and change, saltwater intrusion into surface and ground water, and rising water tables and impeded drainage (Table 5-3).

Impacts and risks are assessed using a wide variety of approaches from the local to global scale. Sea level rise exposure approaches are applied at all scales to assess values exposed to sea level rise (e.g., people, assets, ecosystems, or geomorphological units). Submergence exposure approaches assess exposure to permanent inundation under a given sea level rise (e.g., Dasgupta et al., 2009; Boateng, 2012) whereas flood exposure approaches assess exposure to temporary inundation during a coastal flood event by combining the extreme water level of the flood event with a given level of sea level rise (e.g., Dasgupta et al., 2011; Kebede and Nicholls, 2012).

Indicator-based approaches are also used at all scales to aggregate data on the current state of the coastal systems into vulnerability indices (Gornitz, 1991; Hinkel, 2011), based on either biophysical exposure or hazard variables (e.g., Bosom and Jimenez, 2011; Yin et al., 2012), socioeconomic variables representing a social group's capacity to adapt (e.g., Cinner et al., 2012), or both kinds of variables (e.g., Bjarnadottir et al., 2011; Li and Li, 2011; Yoo et al., 2011).

At local scales (<100 km coastal length), process-based models are applied to assess flooding, erosion, and wetland impacts. Approaches include assessments of flood damage of single extreme water level events using numerical inundation models (e.g., Lewis et al., 2011; Xia et al., 2011). Erosion impacts are assessed using either numerical morphodynamic models (e.g., Jiménez et al., 2009; Ranasinghe et al., 2012) or simple geometric profile relationships such as the Bruun Rule (Bruun, 1962). For ecosystem impacts ecological landscape simulation models are used to predict habitat change due to sea level rise and other factors (e.g., Costanza et al., 1990).

At regional to global scales, numerical process-based models are not available for assessing the impacts of RSLR and extreme sea level events due to data and computational limits. Global scale assessments of coastal impacts have been conducted with the models Climate Framework for Uncertainty, Negotiation and Distribution (FUND) and Dynamic and Interactive Coastal Vulnerability Assessment (DIVA). FUND is an integrated assessment model with a coastal impact component that includes country-level cost functions for dry-land loss, wetland loss, forced migration, and dike construction (Tol, 2002). DIVA is a dedicated coastal impact model employing subnational coastal data (Vafeidis et al., 2008) and considering additional impacts such as coastal flooding and erosion as well as adaptation in terms of protection via dikes and nourishment (Hinkel and Klein, 2009). DIVA assesses coastal flood risk based on hydrologically connected elevation and extreme water level distributions

Frequently Asked Questions

FAQ 5.1 | How does climate change affect coastal marine ecosystems?

The major climate-related drivers on marine coastal ecosystems are sea level rise, ocean warming, and ocean acidification.

Rising sea level impacts marine ecosystems by drowning some plants and animals as well as by inducing changes of parameters such as available light, salinity, and temperature. The impact of sea level is related mostly to the capacity of animals (e.g., corals) and plants (e.g., mangroves) to keep up with the vertical rise of the sea. Mangroves and coastal wetlands can be sensitive to these shifts and could leak some of their stored compounds, adding to the atmospheric supply of these greenhouse gases.

Warmer temperatures have direct impacts on species adjusted to specific and sometimes narrow temperature ranges. They raise the metabolism of species exposed to the higher temperatures and can be fatal to those already living at the upper end of their temperature range. Warmer temperatures cause coral bleaching, which weakens those animals and makes them vulnerable to mortality. The geographical distribution of many species of marine plants and animals shifts towards the poles in response to warmer temperatures.

When atmospheric carbon dioxide is absorbed into the ocean, it reacts to produce carbonic acid, which increases the acidity of seawater and diminishes the amount of a key building block (carbonate) used by marine 'calcifiers' such as shellfish and corals to make their shells and skeletons and may ultimately weaken or dissolve them. Ocean acidification has a number of other impacts, many of which are still poorly understood.

Table 5-3 | Main impacts of relative sea level rise. Source: Adapted from Nicholls et al. (2010).

Biophysical impacts of relative sea level rise	Other climate-related drivers	Other human drivers
Dryland loss due to erosion	Sediment supply, wave and storm climate	Activities altering sediment supply (e.g., sand mining)
Dryland loss due to submergence	Wave and storm climate, morphological change, sediment supply	Sediment supply, flood management, morphological change, land claim
Wetland loss and change	Sediment supply, CO_2 fertilization	Sediment supply, migration space, direct destruction
Increased flood damage through extreme sea level events (storm surges, tropical cyclones, etc.)	Wave and storm climate, morphological change, sediment supply	Sediment supply, flood management, morphological change, land claim
Saltwater intrusion into surface waters (backwater effect)	Runoff	Catchment management and land use (e.g., sand mining and dretching)
Saltwater intrusion into groundwaters leading to rising water tables and impeded drainage	Precipitation	Land use, aquifer use

(Hinkel et al., 2013) and erosion based on a combination of the Bruun Rule and a simplified version of the Aggregated Scale Morphological Interaction between a Tidal inlet and the Adjacent coast (ASMITA) model for tidal basins (Nicholls et al., 2011). The results of these models are discussed in Sections 5.4.3.1 and 5.5.5.

For impacts on natural systems, the key climate-related drivers considered are temperature, ocean acidification, and sea level. A variety of approaches are applied including field observations of ecosystem features (e.g., biodiversity, reproduction) and functioning (e.g., calcification, primary production), remote sensing (e.g., extent of coral bleaching, surface area of vegetated habitats), and perturbation experiments in the laboratory and in the field.

5.4.2. Natural Systems

Coastal ecosystems are experiencing large cumulative impacts related to human activities (Halpern et al., 2008) arising from both land- and ocean-based anthropogenic drivers. Anthropogenic drivers associated with global climate change are distributed widely and are an important component of cumulative impacts experienced by coastal ecosystems. There is no wetland, mangrove, estuary, rocky shore, or coral reef that is not exhibiting some degree of impact. Overexploitation and habitat destruction are often the primary causes of historical changes in coastal systems leading to declines in diversity, structure, and functioning (Lotze et al., 2006). Further, extreme climate events generate changes to both the mean and the variance of climatic variables over ecological time scales.

5.4.2.1. Beaches, Barriers, and Sand Dunes

Beaches, barriers, and sand dunes are about half as common as rocky coasts (Bird, 2000; Davis and FitzGerald, 2004) and often exhibit distinct and seasonal changes. Owing to their aesthetic qualities, they are highly valued for recreation and residences.

5.4.2.1.1. Observed impacts

Globally, beaches and dunes have in general undergone net erosion over the past century or longer (e.g., for an overview, see Bird, 2000). A number of studies have investigated shoreline change by comparing historical maps and imagery, available since about the mid-19th century with more recent maps and imagery to quantify combined climate and non-climate changes. For example, along the U.S. Mid-Atlantic and New England coasts the long-term rate of erosion, based on 21,184 transects equally spaced along more than 1000 km of coast, is 0.5 ± 0.09 m yr^{-1}, with 65% of transects showing net erosion (Hapke et al., 2011). A similar study by Webb and Kench (2010) in the central Pacific utilized historical aerial photographs and satellite images to show physical changes in 27 islets located in four atolls over a 19- to 61-year period. The analysis highlighted the dynamic nature of sea level rise response in the recent past, with physical changes in shoreline progradation and displacement influencing whether the island area increased (46%), remained stable (46%), or decreased (14%).

Attributing shoreline changes to climate change is still difficult owing to the multiple natural and anthropogenic drivers contributing to coastal erosion. For example, rotation of pocket beaches (i.e., where one end of the beach accretes while the other erodes and then the pattern reverses) in southeast Australia is closely related to interannual changes in swell direction (Harley et al., 2010). Additional processes, unrelated to climate change, that contribute to coastal change include dams capturing fluvial sand (e.g., in Morocco; Chaibi and Sedrati, 2009). Statistically linking sea level rise to observed magnitudes of beach erosion has had some success, although the coastal sea level change signal is often small when compared to other processes (e.g., Leatherman et al., 2000a,b; Sallenger et al., 2000; Zhang et al., 2004). A Bayesian network incorporating a variety of factors affecting coastal change, including RSLR, has been successful in hindcasting shoreline change, and can be used to evaluate the probability of future shoreline change (Gutierrez et al., 2011).

While some coastal systems may be able to undergo landward retreat under rising sea levels, others will experience coastal squeeze, which occurs when an eroding shoreline approaches hard, immobile structures such as seawalls or resistant natural cliffs. In these instances the beaches will narrow owing to the resulting sediment deficit and produce adverse impacts such as habitat destruction, impacting the survivability of a variety of organisms (Jackson and McIlvenny, 2011). With such a manifestation of coastal squeeze, sand dunes will ultimately be removed as the beach erodes and narrows. Extreme storms can erode and completely remove dunes, degrading land elevations and exposing them to inundation and further change if recovery does not occur before the next storm (Plant et al., 2010). Even in the absence of hard obstructions, barrier island erosion and narrowing can occur, as a result of rising sea level and recurrent storms, as in the Chandeleur Islands and Isles Dernieres, Louisiana, USA (Penland et al., 2005).

5.4.2.1.2. Projected impacts

With projected GMSLR (see Section 5.3.3), inundation and erosion may become detectable and progressively important. In the first instance, Frequently Asked Questions

FAQ 5.2 | How is climate change influencing coastal erosion?

Coastal erosion is influenced by many factors: sea level, currents, winds, and waves (especially during storms, which add energy to these effects). Erosion of river deltas is also influenced by precipitation patterns inland which change patterns of freshwater input, runoff, and sediment delivery from upstream. All of these components of coastal erosion are impacted by climate change.

Based on the simplest model, a rise in mean sea level usually causes the shoreline to recede inland due to coastal erosion. Increasing wave heights can cause coastal sand bars to move away from the shore and out to sea. High storm surges (sea levels raised by storm winds and atmospheric pressure) also tend to move coastal sand offshore. Higher waves and surges increase the probability that coastal sand barriers and dunes will be over-washed or breached. More energetic and/or frequent storms exacerbate all these effects.

Changes in wave direction caused by shifting climate may produce movement of sand and sediment to different places on the shore, changing subsequent patterns of erosion.

the impacts will be apparent through sea level rise which, combined with storm surge, will make extreme water levels higher and more frequent and therefore enable greater attack on beaches and dunes (Tebaldi et al., 2012).

The Bruun rule (a simple rule based on the assumption that to maintain an equilibrium cross-shore profile under rising sea levels, the coastline will move landwards a distance of approximately 100 times the vertical sea level rise; Bruun, 1962) has been used by many researchers to calculate erosion by sea level rise. However, there is disagreement about whether the Bruun rule is appropriate (Cooper and Pilkey, 2004; Woodroffe and Murray-Wallace, 2012), and how to calculate the amount of retreat remains controversial (Gutierrez et al., 2011; Ranasinghe et al., 2012). An increase in storm intensity and ocean swell may accelerate erosion of beaches, barriers, and dunes, although in some places beach response to sea level rise could be more complex than just a simple retreat (Irish et al., 2010).

Coastal squeeze is expected to accelerate with a rising sea level. In many locations, finding sufficient sand to rebuild beaches and dunes artificially will become increasingly difficult and expensive as present supplies near project sites are depleted (*high confidence*). New generation models are emerging to estimate the costs of saving oceanfront homes through beach nourishment relative to the structures cost (McNamara et al., 2011). In the absence of adaptation measures, beaches and sand dunes currently affected by erosion will continue to be affected under increasing sea levels (*high confidence*).

5.4.2.2. Rocky Coasts

Rocky coasts with shore platforms form about three-fourths of the world's coasts (Davis and FitzGerald, 2004; Jackson and McIlvenny, 2011) and are characterized by very strong environmental gradients, especially in the intertidal zone where both marine and atmospheric climate regime changes can pose challenges.

5.4.2.2.1. Observed impacts

Cliffs and platforms are erosional features and any change that increases the efficiency of processes acting on them, such as RSLR, storminess, wave energy, and weathering regimes, increases erosion (Naylor et al., 2010). Their responses vary, owing to different lithology (e.g., hard rock vs. non-lithified soft rock) and profiles (e.g., plunging cliffs or cliffs with shore platforms). Cliffs and platforms have reduced resilience to climate change impacts; once platforms are lowered or cliffs have retreated, it is difficult to rebuild them (Naylor et al., 2010). On the decadal scale, for example, the retreat of soft rock cliffs in East Anglia, UK, has been linked to the North Atlantic Oscillation (NAO) phases with high energetics (Brooks and Spencer, 2013).

Changes in the abundance and distribution of rocky shore animals and algae have long been recognized (Hawkins et al., 2008), and perturbation experiments provide information about environmental limits, acclimation, and adaptation, particularly to changes in temperature (Somero, 2012). The challenge is to attribute the changes to climate-related drivers, human-related drivers, and to natural fluctuations.

The range limits of many intertidal species have shifted by up to 50 km per decade over the past 30 years in the North Pacific and North Atlantic, much faster than most recorded shifts of terrestrial species (Helmuth et al., 2006; Box CC-MB). However, the distribution of some species has not changed in recent decades, which may be due to weak local warming (Rivadeneira and Fernández, 2005) or overriding effects of variables such as timing of low tide; hydrographic features; lack of suitable substrate; poor larval dispersal; and effects of food supply, predation, and competition (Helmuth et al., 2002, 2006; Poloczanska et al., 2011).

The dramatic decline of biodiversity in mussel beds of the Californian coast has been attributed to large-scale processes associated with climate-related drivers (59% mean loss in species richness, comparing 2002 to historical data (1960s to 1970s); Smith et al., 2006) (*high* *confidence*). Warming reduced predator-free space on rocky shores, leading to a decrease of the vertical extent of mussel beds by 51% in 52 years in the Salish Sea, and to the disappearance of reproductive populations of mussels (Harley, 2011). Unusually high air or water temperature led to mass mortalities, for example, of mussels on the California coast (Harley, 2008) and gorgonians in the northwestern Mediterranean (Garrabou et al., 2009).

Rocky shores are one of the few ecosystems for which field evidence of the effects of ocean acidification is available. Observational and modeling analysis have shown that the community structure of a site of the northeast Pacific shifted from a mussel to an algal-barnacle dominated community between 2000 and 2008 (Wootton et al., 2008), in relation with rapidly declining pH (Wootton and Pfister, 2012).

5.4.2.2.2. Projected impacts

Modeled relationships suggest that soft-rock recession rates depends on the relative change in sea level rise while cliff retreat depends both on total elevation change of sea level and on the rate of sea level rise (Ashton et al., 2011). In a modeling study, Trenhaile (2010) found sea level rise to trigger faster rates of cliff recession, especially in coasts that are already retreating fast. In addition, based on modeling cliff dynamics with contemporary and historic data of soft cliff retreat along Suffolk Coast, UK, rapid retreat is associated with accelerating sea level rise (Brooks and Spencer, 2013). However, coasts currently retreating slowly would experience the largest proportional increase in retreat rates. Increases in storminess have smaller effects on rocky shores (Dawson et al., 2009; Trenhaile, 2011).

Few projections of the effect of climate change on rocky shores have considered the effects of direct and indirect species interactions (Poloczanska et al., 2008; Harley, 2011) and the effects of multiple drivers (Helmuth et al., 2006). The abundance and distribution of rocky shore species will continue to change in a warming world (*high confidence*). For example, the long-term consequences of ocean warming on mussel beds of the northeast Pacific are both positive (increased growth) and negative (increased susceptibility to stress and of exposure to predation) (Smith et al., 2006; Menge et al., 2008; *medium confidence*). Extrapolations of ecosystem change based on temperature-focused studies alone are likely to be conservative, as hypoxia (Grantham et al., 2004) or ocean acidification (Feely et al., 2008) are also known to occur in this region.

Observations performed near natural CO_2 vents in the Mediterranean Sea show that diversity, biomass, and trophic complexity of rocky shore communities will decrease at future pH levels (Barry et al., 2011; Kroeker et al., 2011; *high confidence*). An abundant food supply appears to enable mussels of the Baltic Sea to tolerate low pH (Thomsen et al., 2010, 2013) at the cost of increased energy expenditure. Model projections that include the interactive effects of ocean warming and acidification suggest that a population of barnacle of the English Channel will become extinct 10 years earlier than it would with warming alone (Findlay et al., 2010; *medium confidence*). Ocean acidification may also exacerbate mass mortality events in the Mediterranean Sea (Rodolfo-Metalpa et al., 2011; *limited evidence*, *medium agreement*).

In summary, rocky shores are among the better-understood coastal ecosystems in terms of potential impacts of climate variability and change. The most prominent effects are range shifts of species in response to ocean warming (*high confidence*) and changes in species distribution and abundance (*high confidence*) mostly in relation to ocean warming and acidification.

5.4.2.3. Wetlands and Seagrass Beds

Vegetated coastal habitats and coastal wetlands (mangrove forests, salt marshes, seagrass meadows, and macroalgal beds) extend from the intertidal to the subtidal areas in coastal areas, where they form key ecosystems.

5.4.2.3.1. Observed impacts

Vegetated coastal habitats are declining globally (Duarte et al., 2005), rendering shorelines more vulnerable to erosion due to increased sea level rise and increased wave action (e.g., Alongi, 2008) and leading to the loss of carbon stored in sediments. Together, the loss of coastal wetlands and seagrass meadows results in the release of 0.04 to 0.28 PgC annually from organic deposits (Pendleton et al., 2012). Recognition of the important consequences of the losses of these habitats for coastal protection and carbon burial (Duarte et al., 2013a) has led to large-scale reforestation efforts in some nations (e.g., Thailand, India, Vietnam).

The response of saltmarshes to sea level rise involves landward migration of salt-marsh vegetation zones, submergence at lower elevations, and drowning of interior marshes. Ocean warming is leading to range shifts in vegetated coastal habitats. The poleward limit of mangrove forests is generally set by the 20°C mean winter isotherm (Duke et al., 1998). Accordingly, migration of the isotherm with climate change (Burrows et al., 2011) should lead to a poleward expansion of mangrove forests, as observed in the Gulf of Mexico (Perry and Mendelssohn, 2009; Comeaux et al., 2011; Raabe et al., 2012) and New Zealand (Stokes et al., 2010), leading to increased sediment accretion (*medium confidence*).

Seagrass meadows are already under stress due to climate change (*high confidence*), particularly where maximum temperatures already approach their physiological limit. Heat waves lead to widespread seagrass mortality, as documented for *Zostera* species in the Atlantic (Reusch et al., 2005) and *Posidonia* meadows in the Mediterranean Sea (Marbà and Duarte, 2010) and Australia (Rasheed and Unsworth, 2011; *high confidence*). Warming also favors flowering of *P. oceanica* (Diaz-Almela et al., 2007), but the increased recruitment rate is insufficient to compensate for the losses resulting from elevated temperatures (Diaz-Almela et al., 2009).

Kelp forests have been reported to decline in temperate areas in both hemispheres (Fernández, 2011; Johnson et al., 2011; Wernberg et al., 2011a,b), a loss involving climate change (*high confidence*). Decline in kelp populations attributed to ocean warming has been reported in southern Australia (Johnson et al., 2011; Wernberg et al., 2011a,b) and the North Coast of Spain (Fernández, 2011). The spread of subtropical invasive macroalgal species may be facilitated by climate change, adding to the stresses experienced by temperate seagrass meadows due to ocean warming (*medium evidence*, *high agreement*).

5.4.2.3.2. Projected impacts

Ocean acidification (Section 5.3.3.5; Box CC-OA) is expected to enhance the production of seagrass, macroalgae, salt-marsh plants, and mangrove trees through the fertilization effect of CO_2 (Hemminga and Duarte, 2000; Wu et al., 2008; McKee et al., 2012; *high confidence*). Increased CO_2 concentrations may have already increased seagrass photosynthetic rates by 20% (Hemminga and Duarte, 2000; Hendriks et al., 2010; *limited evidence, high agreement*).

Coupling of downscaled model projections using the SRES A1B scenario in the western Mediterranean with relationships between mortality rates and maximum seawater temperature led Jordá et al. (2012) to conclude that seagrass meadows may become functionally extinct by 2050–2060 (*high confidence*). Poleward range shifts in vegetated coastal habitats are expected to continue with climate change (*high confidence*).

Although elevated CO_2 and ocean acidification are expected to increase productivity of vegetated coastal habitats in the future, there is *limited evidence* that elevated CO_2 will increase seagrass survival or resistance to warming (Alexandre et al., 2012; Jordá et al., 2012).

Coastal wetlands and seagrass meadows experience coastal squeeze in urbanized coastlines, with no opportunity to migrate inland with rising sea levels. However, increased CO_2 and warming can stimulate marsh elevation gain, counterbalancing moderate increases in sea level rise rates (Langley et al., 2009; Kirwan and Mudd, 2012). Climate change is expected to increase carbon burial rates on salt marshes during the first half of the 21st century, provided sufficient sediment supply, with carbon-climate feedbacks diminishing over time (Kirwan and Mudd, 2012; *medium confidence*).

In summary, climate change will contribute to the continued decline in the extent of seagrasses and kelps in the temperate zone (*medium confidence*) and the range of seagrasses, mangroves, and kelp in the Northern Hemisphere will expand poleward (*high confidence*). The limited positive impact of warming and increased CO_2 on vegetated ecosystems will be insufficient to compensate the decline of their extent resulting from other human drivers such as land use change (*very high confidence*).

5.4.2.4. Coral Reefs

Coral reefs are shallow-water ecosystems made of calcium carbonate secreted by reef-building corals and algae. They are among the most diverse ecosystems and provide key services to humans (Box CC-CR).

5.4.2.4.1. Observed impacts

Mass coral bleaching coincided with positive temperature anomalies over the past 30 years, sometimes followed by mass mortality (Kleypas et al., 2008; *very high confidence*). More than 80% of corals bleached during the 2005 event in the Caribbean and more than 40% died (Eakin et al., 2010). Bleaching events and their recovery are variable in time and space: 7% of the reef locations exhibited at least one bleaching between 1985 and 1994 compared to 38% in the 1995–2004 period, most of which occurred during the 1997–98 El Niño event (Figure 5-3). Recovery from the 1998 global bleaching event was generally variable in the Indian Ocean, absent in the western Atlantic, and no clear trends elsewhere (Baker et al., 2008). Warming has caused a poleward range expansion of some corals (Greenstein and Pandolfi, 2008; Yamano et al., 2011; *high confidence*).

Persistence of coral reefs depends on the balance between the production and erosion of calcium carbonate and on coral settlement, both of which are affected by ocean acidification (Section 5.3.3.5; Box CC-OA). Experimental data show that ocean acidification generally decreases calcification (Andersson et al., 2011; Kroeker et al., 2013) and promotes dissolution of calcium carbonate and bioerosion (Tribollet et al., 2009; Wisshak et al., 2012), leading to poorly cemented reefs (Manzello et al., 2008); it also negatively affects early life history stages, which could reduce the number of larval settlers (Albright, 2011).

Coral cover and calcification have decreased in recent decades (e.g., Gardner et al., 2003; De'ath et al., 2009, 2012; Manzello, 2010; Box CC-CR; *very high confidence*) but attribution to climate-related and human-related drivers is difficult. Globally, the primary climate-related driver appears to be ocean warming rather than ocean acidification, cyclonic activity, and changes in freshwater input (Cooper et al., 2012; De'ath et al., 2012; *medium confidence*). Sea level rise also controls reef growth but, within the uncertainties of past sea level rise and coral reef growth, most coral reefs seem to have kept pace with the recent sea level rise (Buddemeier and Smith, 1988; Brown et al., 2011).

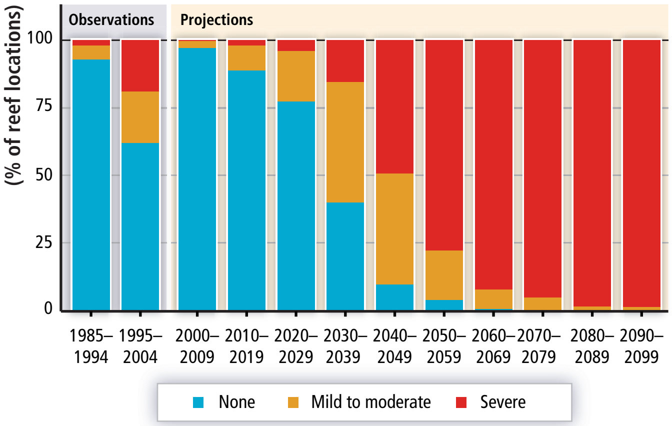

Figure 5-3 | Percent of reef locations (1° × 1° grid cells which have at least one reef) that experience no bleaching, at least one mild bleaching event, or at least one severe bleaching event for each decade. Observed bleaching events are summarized from the ReefBase data set (Kleypas et al., 2008). In the observations, some of the "no bleaching" cells may have experienced bleaching but it was either not observed or not reported. Modeled bleaching events are averages of data from four ensemble runs of the Community Climate System Model version 3 using the Special Report on Emissions Scenarios (SRES) A1B scenario and the standard degree heating month formula (Teneva et al., 2011). The labels of values ≤1% are not shown.

5.4.2.4.2. Projected impacts

Coral bleaching and mortality will increase in frequency and magnitude over the next decades (*very high confidence*). Under the A1B CO_2 emission scenario, 99% of the reef locations will experience at least one severe bleaching event between 2090 and 2099 (Figure 5-3), with *limited evidence* and *low agreement* that coral acclimation and/or adaptation will limit this trend (Logan et al., 2014). The onset of annual bleaching event under RCP8.5 is delayed by more than 2 decades in about 23% of reef locations compared to RCP6.0 (van Hooidonk et al., 2013).

Ocean warming and acidification have synergistic effects in several reef-builders (Reynaud et al., 2003; Anthony et al., 2008). They will increase coral mortality, reduce calcification and the strength of calcified organisms, and enhance skeletal dissolution (Manzello et al., 2008; *high confidence*). Reefs will transition from a condition of net accretion to one of net erosion (Andersson and Gledhill, 2013; *high confidence*) and will be more susceptible to breakage. The onset of global dissolution is at an atmospheric CO_2 of 560 ppm (Silverman et al., 2009; *medium confidence*) and dissolution will be widespread in 2100 (RCP8.5 emission scenario, Dove et al., 2013; *medium confidence*). The observed poleward range extension will be limited by ocean acidification (Yara et al., 2012; Couce et al., 2013) and may be followed by equatorial range retractions (Kiessling et al., 2012).

The maximum rate of vertical accretion has been variable regionally during the last deglaciation (about 20 mm yr^{-1}; Dullo, 2005; Montaggioni, 2005) and has not enabled all coral reefs to keep up with sea level rise. Some reefs kept up, even when the eustatic sea level rise exceeded 40 mm yr^{-1} (Camoin et al., 2012). A number of coral reefs could therefore keep up with the maximum rate of sea level rise of 15.1 mm yr^{-1} projected for the end of the century (WGI AR5 Table 13.5; *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*).

In summary, ocean warming is the primary cause of mass coral bleaching and mortality (*very high confidence*), which, together with ocean acidification, deteriorates the balance between coral reef construction and erosion (*high confidence*). The magnitude of these effects depends on future rates of warming and acidification (*very high confidence*), with a limited moderating role owing to biological acclimation and adaptation (*medium confidence*).

5.4.2.5. Coastal Aquifers

Coastal aquifers are of strategic importance for the water supply of highly populated coastal areas, especially in small islands (Section 29.3).

5.4.2.5.1. Observed impacts

Temperature and evaporation rise, precipitation changes, and extended droughts affecting aquifer recharge can contribute to saltwater intrusion (Section 3.2.4). Rising sea levels and overwash from waves or storm surge are also relevant, especially in low-lying areas and islands (Terry and Falkland, 2010; White and Falkland, 2010; see also Section 29.3).

Aquifers on the coasts of the USA have experienced increased levels of salinity largely due to excessive water extraction (Barlow and Reichard, 2010). Natural drivers combined with over-extraction, pollution, mining, and erosion compound groundwater supply problems in small islands in the Pacific, Indian, and Atlantic Oceans (White et al., 2007; White and Falkland, 2010). This increased usage of groundwater resources globally has, over the last century, led to a reduction in groundwater quality, including increased salinization (*very high confidence*).

Attribution of saline intrusion to incremental sea level rise is still not sufficiently supported (Rozell and Wong, 2010; White and Falkland 2010). In small islands, observed saltwater intrusion due to flooding and overwash under storm events cannot be attributed to climate change (Section 29.3.2; *limited evidence*, *high agreement*).

5.4.2.5.2. Projected impacts

Available information on projected impacts on coastal aquifers is limited (Section 3.4.6). Rozell and Wong (2010) assessed the impact of rising sea levels on fresh water resources on Shelter Island (USA) for two different combinations of precipitation change and sea level rise. Projected impacts were highly dependent on local conditions. Ferguson and Gleeson (2012) concluded that the direct impact of groundwater extraction in the USA has been and will be much more significant than the impact of a 0.59 m sea level rise by the end of the 21st century under a wide range of hydrogeological conditions and population densities.

Saltwater intrusion is generally a very slow process; as a consequence, reaching equilibrium may take several centuries limiting the reversibility of the process in the near term (Webb and Howard, 2011).

Human-induced pressure will continue to be the main driver for aquifer salinization during the next century (*high confidence*). Changing precipitation, increased storminess, and sea level rise will exacerbate these problems (*limited evidence*, *high agreement*).

5.4.2.6. Estuaries and Lagoons

Coastal lagoons are shallow water bodies separated from the ocean by a barrier and connected at least intermittently to the ocean, while estuaries, where fresh and saltwater mix, are the primary conduit for nutrients, particulates, and organisms from land to the sea.

5.4.2.6.1. Observed impacts

Sediment accumulation in estuaries is high, heterogeneous, and habitat-specific and directly affected by human drivers, such as dredging and canalization, and indirectly via habitat loss, changes in sea level, storminess, and freshwater and sediment supply by rivers (Syvitski et al., 2005; Swanson and Wilson, 2008). Coastal lagoons are also susceptible to alterations of sediment input and erosional processes driven by changes in sea level, precipitation, and storminess (Pickey and Young, 2009). Droughts, floods, and sea level rise impact estuarine circulation, tidal characteristics, suspended matter, and hence turbidity with consequences for biological communities, particularly in microtidal systems. Climate change and habitat modification (e.g., dams and obstructions) impact fish species such as salmon and eels that pass through estuaries (Lassalle and Rochard, 2009).

Enhanced nutrient delivery (Section 5.3.4.3) has resulted in major changes in biogeochemical processes, community structure, metabolic balance, and CO_2 exchange (Howarth et al., 2011; Canuel et al., 2012; Statham, 2012), including enhanced primary production which has affected coastal fishery yield (Nixon, 1982; Savage et al., 2012). Eutrophication has modified the food-web structure (*high confidence*) and led to more intense and long lasting hypoxia (Section 5.3.4.4), more frequent occurrence of harmful algal blooms (Breitburg et al., 2009; Howarth et al., 2011; *medium confidence*), and to enhanced emission of nitrous oxide (de Bie et al., 2002; Kroeze et al., 2010; *high confidence*).

In summary, there is *very high confidence* that humans have impacted lagoons and estuaries.

5.4.2.6.2. Projected impacts

The increase of atmospheric CO_2 levels will reduce the efflux of CO_2 from estuaries (Borges, 2005; Chen and Borges, 2009; *high confidence*). Its impact on the pH of estuarine and lagoon waters will generally be limited because other drivers are usually more important (Section 5.3.3.4 and Box CC-OA; *high confidence*). For example, freshwater flow in the Scheldt estuary was the main factor controlling pH, directly via a decreased supply of dissolved inorganic carbon and total alkalinity, and, indirectly, via decreased input ammonia loadings and lower rates of nitrification (Hofmann et al., 2009).

Changes in sea level and hydrology could affect lagoons and estuaries in multiple ways. Sea level rise will impact sediment redistribution, the partitioning of habitats within estuaries, salinity, tidal range, and submergence periods (Anthony et al., 2009; *high confidence*). Lagoons may shrink because landward migration is restricted due to human occupation or extend due to the drowning of marshes (Anthony et al., 2009; Pilkey and Young, 2009; Stutz and Pilkey, 2011). Salinity, primary production, biodiversity, fisheries, and aquaculture may be impacted by changes in water discharge, withdrawals and precipitation-evaporation balance (Webster and Harris, 2004; Smith et al., 2005; Anthony et al., 2009; Canu et al., 2010). Altered riverine discharge and warming may lead to enhanced thermal and/or salinity stratification of estuaries and lagoons. This has consequences for biogeochemical processes, organism distribution patterns, and frequency and duration of hypoxia (Diaz and Rosenberg, 2008; Rabalais et al., 2009; Hong and Shen, 2012; *medium confidence*). Stronger winds and droughts may reduce the extent, duration, and frequency of estuarine stratification, counteracting the decrease in oxygen concentration (Rabalais et al., 2009; *medium confidence*).

Changes in storm events may also alter the sediment deposition-erosion balance of lagoons and estuaries (Pilkey and Young, 2009), the structure and functioning of biological communities via the transport of communities and/or of their resources, and the underwater light climate (Wetz and Paerl, 2008; Canuel et al., 2012; *medium confidence*). Changes in precipitation extremes and freshwater supply may induce fluctuations in salinity with the associated adverse impacts on biodiversity, benthic macrofauna, and ecosystem functions (Jeppesen et al., 2007; Fujii and Raffaelli, 2008; Levinton et al., 2011; Pollack et al., 2011). Warming may directly affect most biological processes and the trophic status of coastal ecosystems, and higher carbon dioxide emission (Canuel et al., 2012; *limited evidence*, *medium agreement*). Warming may lengthen the duration of phytoplankton production season (Cloern and Jassby, 2008; *medium confidence*).

Any change in the primary production of lagoons might impact fisheries, as primary production and fisheries yield are correlated (Nixon, 1982; *limited evidence*, *medium agreement*). For example, seawater warming and changes in seasonal patterns of precipitations projected in the Venice lagoon, using the SRES A2 emission scenario for the period 2071–2100, may lead to a reduction in plankton production, with a decline of habitat suitability for clam growth and aquaculture (Canu et al., 2010).

Finally, projected changes in climate-related drivers such as warming, storms, sea level, and runoff will interact with non-climate human drivers (e.g., eutrophication, damming) and will have consequences for ecosystem functioning and services of lagoons and estuaries (*high confidence*).

In summary, the primary drivers of change in lagoons and estuaries are human-related rather than climate-related drivers (*very high confidence*). Future changes in climate-related drivers such as warming, acidification, waves, storms, sea level, and runoff will have consequences on the functions and services of ecosystems in lagoons and estuaries (*high confidence*) but the impacts cannot be assessed at the global scale as the key drivers operate at a local to regional scale.

5.4.2.7. Deltas

Characterized by the interplay between rivers, lands, and oceans and influenced by a combination of river, tidal, and wave processes, deltas are coastal complexes that combine natural systems in diverse habitats (e.g., tidal flats, salt marshes, mangroves, beaches, estuaries, low-lying wetlands) and human systems (e.g., houses, agriculture, aquaculture, industry, and transport). They are low-lying coastal landforms formed by riverine sediments in the areas around river mouths, mostly during the last 6000–8000 years of relatively stable sea level and have a population density more than 10 times the world average (Ericson et al., 2006; Foufoula-Georgiou et al., 2011). As low-lying plains, deltas are highly sensitive to changes in sea level. They are subject to climatic impacts from rivers upstream (e.g., freshwater input) and oceans downstream (e.g., sea level changes, waves) as well as within the deltas themselves. At the same time, they are affected by human activities such as land use changes, dam construction, irrigation, mining, extraction of subsurface resources, and urbanization (Nicholls et al., 2007).

5.4.2.7.1. Observed impacts

The combined impact of sediment reduction, RSLR, and land use changes in delta and river management on channels and banks has led to the widespread degradation of deltas (*very high confidence*). The changes of sediment delivery from rivers due to dams, irrigation, and embankments/dikes create an imbalance in sediment budget in the coastal zones. Degradation of beaches, mangroves, tidal flats, and subaqueous delta fronts along deltaic coasts has been reported in many deltas (e.g., Nile and Ebro; Sanchez-Arcilla et al., 1998; Po, Simeoni and Corbau, 2009; Krishna-Godavari, Nageswara Rao et al., 2010; Changjiang, Yang et al., 2011; Huanghe, Chu et al., 1996; *very high confidence*). Deltaic coasts naturally evolve by seaward migration of the shoreline, forming a delta plain. However, decreasing sediment discharge during the last 50 years has decreased the growth of deltaic land, even reversing it in some locations (e.g., Nile, Godavari, Huanghe). Artificial reinforcement of natural levees also has reduced the inter-distributory basin sedimentation in most deltas, resulting in wetland loss.

The major impacts of sea level rise are changes in coastal wetlands, increased coastal flooding, increased coastal erosion, and saltwater intrusion into estuaries and deltas (Mcleod et al., 2010), which are exacerbated by increased human-induced drivers (*very high confidence*). Ground subsidence amplifies these hazards in farms and cities on deltaic plains through RSLR (Day and Giosan, 2008; Mazzotti et al., 2009). RSLR due to subsidence has induced wetland loss and shoreline retreat (e.g., the Mississippi delta; Morton et al., 2005; Chao Phraya delta, Saito et al., 2007; *high confidence*). Episodic events superimpose their effects on these underlying impacts and accelerate land loss (*high confidence*) (e.g., Hurricanes Katrina and Rita in 2005; Barras et al., 2008). To forestall submergence and frequent flooding, many delta cities now depend on a substantial infrastructure for flood defense and water management (Nicholls et al., 2010).

Deltas are impacted by river floods and oceanic storm surges (*very high confidence*). Tropical cyclones are noteworthy for their damages to deltas, for example, the Mississippi delta by Hurricane Katrina in 2005 (Barras et al., 2008), the Irrawaddy delta by Cyclone Nargis in 2008, and the Ganges-Brahmaputra delta by Cyclone Gorky in 1991 and Cyclone Sidr in 2007 (Murray et al., 2012; see also Box CC-TC). A detailed study of 33 deltas around the world found that 85% of them had experienced severe flooding in the past decade, causing the temporary submergence of 260,000 km^2 (Syvitski et al., 2009).

5.4.2.7.2. Projected impacts

The projected natural impacts on deltas under changing global climate are caused mainly by extreme precipitation-induced floods and sea level rise. These will result in increased coastal flooding, decreased wetland areas, increased coastal erosion, and increased salinization of cultivated land and groundwater (McLeod et al., 2010; Day et al., 2011; Box CC-TC; *high confidence*). The surface area of flooding in 33 deltas around the world is estimated to increase by 50% under sea level rise estimations as projected for 2100 by the IPCC AR4 (Syvitski et al., 2009). Non-climatic drivers (e.g., reduction in sediment delivery, subsidence, and land use changes) rather than climatic drivers have affected deltas for the last 50 years (Syvitski, 2008; *very high confidence*). Densely populated deltas are particularly vulnerable owing to further population growth together with the above-described impacts. The impacts beyond 2100 show a more complex and enhanced flood risk on deltas (e.g., Katsman et al., 2011).

In summary, increased human drivers have been primary causes in changes of deltas (e.g., land use, subsidence, coastal erosion) for at least the last 50 years (*very high confidence*). There is *high agreement* that future sea level rise will exacerbate the problems of increased anthropogenic degradation in deltas.

5.4.3. Human Systems

5.4.3.1. Human Settlements

Important direct effects of climate change on coastal settlements include dry-land loss due to erosion and submergence, damage of extreme events (such as wind storms, storm surges, floods, heat extremes, and droughts) on built environments, effects on health (food- and water-borne disease), effects on energy use, effects on water availability and resources, and loss of cultural heritage (Hunt and Watkiss, 2010). Since AR4, a large number of regional, national, and subnational scale studies on coastal impacts have been conducted. These are covered in the respective regional chapters. At the global scale, studies have focused either on exposure to sea level rise or extreme water levels or on the physical impacts of flooding, submergence, and erosion.

5.4.3.1.1. Projected exposure

Coastal flood risks are strongly influenced by the growing exposure of population and assets. The population exposed to the 1-in-100-year coastal flood is projected to increase from about 270 million in 2010 to 350 million in 2050 due to socioeconomic development only (UN medium fertility projections) (Jongman et al., 2012). Population growth, economic growth, and urbanization will be the most important drivers of increased exposure in densely populated areas (Hanson et al., 2011; Seto, 2011; see also Chapter 14; *high confidence*). For 136 port cities above 1 million inhabitants, the number of people exposed to a 1-in-100-year extreme sea level is expected to increase from 39 million in 2005 to 59 million by 2070 through 0.5 m GMSLR alone and to 148 million if socioeconomic development (UN medium population projections) is considered (Hanson et al., 2011). Human-induced subsidence alone is expected to increase the global economic exposure of 136 major port cities by around 14% from 2005 to 2070 although this driver only applies to 36 of the cities (Hanson et al., 2011). As a result of socioeconomic development Asia is expected to continue to have the largest exposed population and sub-Saharan Africa the largest increases in exposure (Dasgupta et al., 2009; Vafeidis et al., 2011; Jongman et al., 2012).

5.4.3.1.2. Projected impacts and risks

Exposure estimates, however, give an incomplete picture of coastal risks to human settlements because they do not consider existing or future adaptation measures that protect the exposed population and assets against coastal hazards (Hallegatte et al., 2013; Hinkel et al., 2013). Although the global potential impacts of coastal flood damage and land loss on human settlements in the 21st century are substantial, these impacts can be reduced considerably through coastal protection (*limited evidence*, *high agreement*). Nicholls et al. (2011) estimate that without

Figure 5-4 | The 20 coastal cities where average annual losses (AALs) increase most (in relative terms in 2050 compared with 2005) in the case of optimistic sea level rise, if adaptation maintains only current defense standards or flood probability (PD) (Hallegatte et al., 2013).

protection 72 to 187 million people would be displaced due to land loss due to submergence and erosion by 2100 assuming GMSLRs of 0.5 to 2.0 m by 2100. Upgrading coastal defenses and nourishing beaches would reduce these impacts roughly by three orders of magnitude. Hinkel et al. (2013) estimate the number of people flooded annually in 2100 to reach 117 to 262 million per year in 2100 without upgrading protection and two orders of magnitude smaller with dike (levee) upgrades, given GMSLRs of 0.6 to 1.3 m by 2100. The major driver of increasing risks to human settlements in the next decades is socioeconomic development. When upgrading flood defenses to maintain a constant probability of flooding, average annual losses (AALs) in the 136 largest coastal cities are expected to increase ninefold from 2005 to 2050 due to socioeconomic development, only another 12% due to subsidence, and 2 to 8% due to GMSLRs of 0.2 to 0.4 m (Hallegate et al., 2013; Figure 5-4).

Despite the delayed response of sea level rise to global warming levels (WGI AR5 Section 13.5.4) mitigation may limit 21st century impacts of increased coastal flood damage, dry-land loss, and wetland loss substantially (*limited evidence*, *medium agreement*) albeit numbers are difficult to compare owing to differences in scenarios, baselines, and adaptation assumptions. Tol (2007) finds that stabilizing CO_2 concentration at 550 ppm reduces global impacts on wetlands and dry lands by about 10% in 2100 compared to a scenario of unmitigated emissions. Hinkel et al. (2013) report that stabilizing emissions at 450 ppm CO_2-eq reduces the average number of people flooded in 2100 by about 30% compared to a baseline where emissions increase to about 25 Gt C-eq in 2100. Arnell et al. (2013) find that an emissions pathway peaking in 2016 and declining at 5% per year thereafter reduces flood risk by 58 to 66% compared to an unmitigated A1B scenario. All three studies only consider the effects of mitigation during the 21st century and assume low or no contribution of ice sheets to GMSLR. Mitigation is expected to be more effective when considering impacts beyond 2100 and higher contributions of ice sheets (Section 5.5.8).

Global studies confirm AR4 findings that there are substantial regional differences in coastal vulnerability and expected impacts (*high confidence*). Most countries in South, Southeast, and East Asia are particularly vulnerable to sea level rise due to rapid economic growth and coastward migration of people into urban coastal areas together with high rates of anthropogenic subsidence in deltas where many of the densely populated areas are located (Nicholls and Cazenave, 2010). At the same time, economic growth in these countries increases the monetary capacity to adapt (Nicholls et al., 2010). In contrast, although many African countries experience a similar trend in rapid urban coastal growth, the level of economic development is generally lower and consequently the monetary capacity to adapt is smaller (Kebede and Nicholls, 2012; Hinkel et al., 2013).

In summary, while there is *high agreement* on some general findings, only a small fraction of the underlying uncertainty has been explored, which means evidence is limited. Gaps remain with respect to impacts of possible large contributions of the ice sheets of Greenland and Antarctica to GMSLR (WGI AR5 Sections 13.4.3, 13.4.4), regional patterns of climate-induced sea level rise, subsidence, and socioeconomic change and migration. Many studies rely on few or only a single socioeconomic scenario. Few studies consider adaptation and those that do generally ignore the wider range of adaptation measures beyond hard protection options. Integrated studies considering the interactions between a wide range of RSLR impacts (Table 5-3) as well as trade-offs between diverse adaptation options are missing.

5.4.3.2. Industry, Infrastructure, Transport, and Network Industries

Coastal industries, their supporting infrastructure including transport (ports, roads, rail, airports), power and water supply, storm water, and sewerage are highly sensitive to a range of extreme weather and climate events including temporary and permanent flooding arising from extreme precipitation, high winds, storm surges, and sea level rise (Horton et al. 2010; Handmer et al. 2012; Hanson and Nicholls, 2012; Aerts et al. 2013; *high confidence*). Most industrial facilities, infrastructure, and networks are designed for service lives extending over several decades. In fact, many bridges, ports, and road and railway lines remain in their original design location for centuries even if the infrastructure on them has been rehabilitated or replaced several times. Certain facilities, such as new nuclear power plants, are designed to last even well beyond the 22nd century (Wilby et al., 2011).

As the need to locate most of these industries and networks in coastal areas will remain and probably increase due to coastal development (Section 5.4.3.1), considering climate variability and climate change drivers in life cycle assessment of industry, infrastructure, and transport and network industries is of utmost importance (*high confidence*).

5.4.3.2.1. Observed impacts

Climate impacts on coastal industries and infrastructures vary considerably depending on geographical location, associated weather and climate, and specific composition of industries within particular coastal regions (*high confidence*).

Over the last 10 years an extensive number of climate-related extreme events (Coumou and Rahmstorf, 2012) illustrate the potential for impacts on coastal industry, infrastructure, transport, and network industry. Severe storms with associated winds, waves, rain, lightning, and storm surges have been particularly disruptive to transport and power and water supplies (Jacob et al., 2007; USCCSP, 2008; Horton et al., 2010; *high confidence*). In such network configurations, flooding of even the smallest component of an intermodal system can result in a much larger system disruption. Even though a transportation terminal may not be affected, the access roads to it could be, thus forcing the terminal to cease or reduce operation. Disruption to port activities in one location can disrupt supply chains, which can have far reaching consequences (Becker et al. 2012, 2013). Existing experience has also shown that impacts of hurricanes and flooding on underground infrastructure can have long-term effects (Chisolm and Matthews, 2012).

Hurricanes like Katrina (2005) caused US$100 million of damage to Mississippi's ports and Sandy (2012) led to a week-long shut-down of the Port of New York, generating economic damages reaching US$50 billion (Becker et al., 2012). These have shown the critical need to better prepare coastal human settlements and associated network infrastructures and industries for future extreme weather impacts and climate change (Aerts et al., 2013; *high confidence*).

5.4.3.2.2. Projected impacts

Although there is *robust evidence* of the impacts and consequences of extreme events on coastal infrastructure and industrial facilities, there are limited assessments on projected impacts of long-term changes (*high agreement*). Besides, while there is an important amount of non-journal literature on projected impacts of sea level rise and increasing flooding levels on certain coastal infrastructures (USCCSP, 2008; USACE, 2011; McEvoy and Mullet, 2013), limited peer review information is available.

Vulnerability to flooding of railroads, tunnels, ports, roads, and industrial facilities at low-lying areas will be exacerbated by rising sea levels or more frequent or intense storms, causing more frequent and more serious disruption of services and damages under extreme sea levels unless adaptation is enforced (Esteban et al., 2010, 2012; Wilby et al., 2011; Aerts et al., 2013; *high confidence*).

Furthermore, sea level rise will reduce extreme flood return periods and therefore increase the need for adaptation of infrastructure such as airports, tunnels, coastal protections, and ship terminals to extreme sea level impacts (Jacob et al., 2007; Becker et al., 2013).

It is estimated that a hypothetical 1 m RSLR projected for the Gulf Coast region between Alabama and Houston over the next 50 to 100 years would permanently flood a third of the region's roads as well as putting more than 70% of the region's ports at risk (USCCSP, 2008).

The estimated costs of climate change to Alaska's public infrastructure could add US$3.6 to 6.1 billion (+10 to 20% above normal wear and tear) from now to 2030 and US$5.6 to 7.6 billion (+10 to 12%) from now to 2080 (Larsen et al., 2008). Higher costs of climate change for coastal infrastructure are expected due to its proximity to the marine environment. Other projected impacts are beneficial for the transportation system. For example, decline of Arctic sea-ice coverage could extend seasonal accessibility to high-latitude shipping routes such as the northwest shipping route that connects the Atlantic to the North Pacific.

Hanson et al. (2011) presents a first estimate of the exposure of the world's large port cities to coastal flooding due to sea level rise and storm surge in the 2070s. The analysis suggests that the total value of assets exposed in 2005 across all cities considered is estimated to be US$3000 billion, corresponding to around 5% of global GDP in 2005. By the 2070s, and assuming a homogeneous global sea level rise of 0.5 m, increased extreme water levels up to 10%, and a fixed subsidence rate in susceptible cities with respect to today's values, asset exposure is estimated to increase to approximately 9% of projected global GDP in this period.

Coastal infrastructural instability may result from natural hazards triggered by groundwater-level (GWL) variations resulting from rising sea level. For earthquake-prone coasts, this could be exacerbated by earthquake liquefaction if GWL increases with sea level rise (Yasuhara et al., 2007). Increasing sea levels, surges, and waves can also lead to a stability loss of coastal structures (Headland et al., 2011).

Other impacts may arise in coastal industries in high latitudes affected by permafrost thaw causing ground instability and erosion, thereby affecting transport safety and the industries that rely on such travel in these regions (e.g., Pearce et al., 2010).

5.4.3.3. Fisheries, Aquaculture, and Agriculture

Fisheries and aquaculture and the associated post-harvest activities globally create millions of jobs (Daw et al., 2009; Sumaila et al., 2011) and contribute significantly to the dietary animal protein of millions of people and to the world merchandise trade (FAO, 2010, 2012; see also Section 6.4.1.1). In addition to small-scale fisheries and aquaculture, which are important for the food security and economy of coastal communities (Bell et al., 2009), coastal zones also support significant agricultural activities, for example, rice production in the low-lying deltaic regions of Asia (Wassmann et al., 2009).

5.4.3.3.1. Observed impacts

Climate variability and change impact both fishers' livelihoods (Badjeck et al., 2010) and fish production (Barange and Perry, 2009) (Section 6.5.3). In the North Sea, ocean warming over the 1977–2002 period led to relatively increased distribution ranges of some fish species (Hiddink and Hofstede, 2008), and demersal fish assemblage deepened in response to climate change (Dulvy et al., 2008). In southeastern Australia, Last et al. (2011) found an increasing abundance of 45 fish species of warm temperate origin, which they linked to the observed strengthening of the East Australian Current (EAC) bringing warm waters further south (Ridgeway, 2007). A study (Sherman et al., 2009) of the impact of sea surface temperature changes on the fisheries yields of 63 large marine ecosystems over a 25-year period shows a positive relationship for the northeast Atlantic large marine ecosystems, due to zooplankton biomass increases (Section 6.5.3). Distributional effects are very important for migratory pelagic fisheries, such as tuna (see Table 29-2). Impacts of climate change on aquaculture (*Mytilus edulis* and *Salmo salar*) in the UK and Ireland have been difficult to discern from natural environmental variability (Callaway et al., 2012).

Seawater inundation has become a major problem for traditional agriculture in Bangladesh (Rahman et al., 2009), and in low-lying island nations (e.g., Lata and Nunn, 2012). The combination of rice yield reduction induced by climate change and inundation of lands by seawater causes an important reduction in production (Chen et al., 2012).

5.4.3.3.2. Projected impacts

Fisheries may be impacted either negatively or positively (Hare et al., 2010; Meynecke and Lee, 2011; Cinner et al., 2012) depending on the latitude, location, and climatic factors. Climate change can impact the pattern of marine biodiversity through changes in species' distributions, and may lead to large-scale redistribution of global catch potential depending on regions (Cheung et al., 2009, 2010). Narita et al. (2012) estimated that the global economic costs of production loss of molluscs due to ocean acidification (Section 5.3.3.5) by the year 2100 based on IPCC IS92a business-as-usual scenario could be higher than US$100 billion. As a result of increased sea temperatures, the reduction in coral cover in the Caribbean basin and its associated fisheries production is expected to lead to a net revenue loss by 2015 (Trotman et al., 2009). Economic losses in landed catch value and the costs of adapting fisheries resulting from a 2°C global temperature increase by 2050 have been estimated at US$10 to 31 billion globally (Sumaila et al., 2011). For aquaculture, negative impacts of rising ocean temperatures will be felt in the temperate regions whereas positive impacts will be felt in the tropical and subtropical regions (De Silva and Soto, 2009). Changes to the atmosphere-ocean in the Pacific Island countries are likely to affect coral reef fisheries by a decrease of 20% by 2050 and coastal aquaculture may be less efficient (Bell et al., 2013).

In summary, changes have occurred to the distribution of fish species (*medium confidence*) with evidence of poleward expansion of temperate species (*limited evidence*, *high agreement*). Tropical and subtropical aquaculture has not been adversely affected by rising ocean temperatures to date (*limited evidence*, *high agreement*). Coastal agriculture has experienced negative impacts (*medium confidence*) due mainly to increased frequency of submersion of agricultural land by saltwater inundation (*limited evidence*, *high agreement*).

5.4.3.4. Coastal Tourism and Recreation

Coastal tourism is the largest component of the global tourism industry. Over 60% of Europeans opt for beach holidays and beach tourism provides more than 80% of U.S. tourism receipts (UNEP, 2009). More than 100 countries benefit from the recreational value provided by their coral reefs, which contributed US$11.5 billion to global tourism (Burke et al., 2011).

5.4.3.4.1. Observed impacts

Observed significant impacts on coastal tourism have occurred from direct impacts of extreme events on tourist infrastructure (e.g., beach resorts, roads), indirect impacts of extreme events (e.g., coastal erosion, coral bleaching), and short-term adverse tourist perception after the occurrence of extreme events (e.g., flooding, tropical storms, storm surges) (Phillips and Jones, 2006; Scott et al., 2008; IPCC, 2012, Section 4.3.5.3). Recent observed climate change impacts on the Great Barrier Reef include coral bleaching in the summers of 1997–1998, 2001–2002, and 2005–2006 and extreme events including floods and cyclones (Tropical cyclones Larry in 2006, Hamish in 2009, and Yasi in 2011). The stakeholders show a high level of concern for climate change, and various resilience initiatives have been proposed and developed by the Great Barrier Reef Marine Park Authority (Biggs, 2011; GBRMPA, 2012).

5.4.3.4.1. Projected impacts

To provide some idea of climate change impacts on coastal destinations, many studies have been carried out on projecting tourism demand, for example, in Europe (Perch-Nielson et al., 2010), in the Baltic region (Haller et al., 2011), in the Mediterranean (Moreno and Amelung, 2009a), and in 51 countries worldwide (Perch-Nielson, 2010). The studies provide varying details, although it is difficult to draw overarching conclusions on tourism demand for coastal destinations. With increased temperature in mid-latitude countries and coupled with increased storms in tropical areas, tourist flows could decrease from mid-latitude countries to tropical coastal regions with large developing countries and small island nations most affected (Perch-Nielson, 2010). The Mediterranean would likewise be affected in summer (Moreno and Amelung, 2009a). In contrast, less is known about the relationship between the impacts of climate change and specific tourist behavior, activities, or flows to coastal destinations (Moreno and Amelung, 2009b; see Section10.6.2). Usually tourists do not consider climate variability or climate change in their holidays (Hares et al., 2009) although there are a few studies that show the contrary (Cambers, 2009; Alvarez-Diaz et al., 2010).

As for future impacts on coastal tourism, there is *high confidence* in the impacts of extreme events and sea level rise aggravating coastal erosion. A scenario of 1-m sea level rise by 2100 would be a potential risk to Caribbean tourism (Scott et al., 2012). The presence of coastal tourism infrastructure will continue to exacerbate beach reduction and coastal ecosystems squeeze under rising sea levels, as exemplified in Martinique (Schleupner, 2008). Carbonate reef structures would degrade under a scenario of at least 2°C by 2050–2100 with serious consequences for tourism destinations in Australia, the Caribbean, and other small islands (Hoegh-Gulberg et al., 2007; see Box CC-CR).

The costs of future climate change impacts on coastal tourism are enormous. For example, in the Caribbean community countries, rebuilding costs of tourist resorts are estimated US$10 to 23.3 billion in 2050. A hypothetical 1-m sea level rise would result in the loss or damage of 21 airports, inundation of land surrounding 35 ports, and at least 149 multi-million dollar tourism resorts damaged or lost from erosion to the coastal beach areas (Simpson et al., 2010).

In summary, while coastal tourism can be related to climate change impacts, it is more difficult to relate tourism demand directly to climate change. Coastal tourism continues to be highly vulnerable to weather, climate extremes, and rising sea levels with the additional sensitivity to ocean temperature and acidity for the sectors that rely on reef tourism (*high confidence*). Developing countries and small island states within the tropics relying on coastal tourism are most vulnerable to present and future weather and climate extremes, future sea level rise, and the added impacts of coral bleaching and ocean acidification (*high confidence*).

5.4.3.5. Health

The relationship between health of coastal populations and climate change include direct linkages (e.g., floods, droughts, storm surges, and extreme temperatures) and indirect linkages (e.g., changes in the transmission of vector-, food-, and water-borne infectious diseases and increased salinization of coastal land that affects food production and freshwater supply and ecosystem health). Coastal and particularly informal settlements concentrate injury risk and death from storm surges and rainfall flooding (Handmer et al., 2012). This section deals with human health in the context of the coastal zone, while Chapter 11 addresses general health issues and Section 6.4.2.3 deals with health issues associated with ocean changes. Understanding the relationship between climate and health is often confounded by socioeconomic factors that influence coastal settlement patterns and the capacity of authorities to respond to health-related issues (Baulcomb, 2011).

5.4.3.5.1. Observed impacts

Mortality risk in coastal areas is related to exposure and vulnerability of coastal populations to climate hazards (e.g., Myung and Jang, 2011). A regional analysis of changes in exposure, vulnerability, and risk indicates that although exposure to flood and cyclone hazards has increased since 1980, the risk of mortality has generally fallen. The reductions reflect a strengthening of the countries' capacity to respond to disasters (Box 5-1). However, mortality is still rising in the countries with the weakest risk governance capacities (UNISDR, 2011).

Coastal regions face a range of climate-sensitive diseases. Increased saline intrusion is linked to increased hypertension disease (Vineis et al., 2011), with greater occurrence in pregnant women living in coastal regions compared to further inland (Khan et al., 2008). Increasing temperature, humidity, and rainfall can increase vector-borne diseases such as malaria, dengue, leishmaniasis, and chikungunya (Pialoux et al., 2007; Stratten et al., 2008; Kolivras, 2010; van Kleef et al., 2010) and diarrhea, infectious gastrointestinal disease, rotovirus, and salmonella (e.g., Hashizume et al., 2007; Zhang et al., 2007, 2010; Chou et al., 2010; Onozuka et al., 2010). The parasitic disease schistosomiasis, endemic in many tropical and small island coastal regions (Section 29.3.3.2), is also sensitive to temperature increase (Mangal et al., 2008). Vibrio outbreaks (e.g., cholera) are sensitive to rainfall and SST (e.g., Koelle et al., 2005), and recent increased vibrio outbreaks in the Baltic have been linked to heat waves and low salinity (Baker-Austin et al., 2013). Harmful algal blooms (HABs) outbreaks (e.g., ciguatera) have been linked to SST variability (e.g., Erdner et al., 2008; Jaykus et al., 2008). However, in general there is *limited evidence* and *low confidence* in how global climate change will impact HABs (Section 6.4.2.3), suggesting the need for increased monitoring (Hallegraeff, 2010). Nontoxic blooms of high biomass can reduce biodiversity through oxygen depletion and shading (Erdner et al., 2008), with consequences for ecosystem and human nutrition and health.

5.4.3.5.2. Projected impacts

Under future climate conditions, expansion of brackish and saline water bodies in coastal areas under projected sea level rise may increase the incidence of vector-borne diseases (Ramasamy and Surendran, 2011), diarrhea, and hypertension (Vineis et al., 2011). Human responses to climate change may also influence outcomes on health; however, limited empirical climate-health data increases uncertainties on such projections (Kolstad and Johansson, 2011).

Evidence continues to emerge of the relation between climate and diseases that affect human health in the coastal zone including air and water temperature, rainfall, humidity, and coastal salinity. However, the relations are often complex and vary between diseases and even regionally for the same disease. The interplay between climate and human systems with regard to health impacts is poorly understood and this continues to confound reliable projections of health impacts (*robust evidence*, *high agreement*).

5.4.4. Summary: Detection and Attribution

There is *high confidence* in the attribution to climate change of observed coastal impacts that are sensitive to ocean temperature change, such as coral bleaching and movements in species ranges. However, for many other coastal changes, the impacts of climate change are difficult to tease apart from human-related drivers (e.g., land use change, coastal development, pollution). Figure 5-5 shows changes of major phenomena observed in coastal systems and low-lying areas. Horizontal and vertical axes indicate the degree of confidence in detection of trends for phenomena, which are elements sensitive to climate change, and the degree of confidence in attribution of phenomena to climate change, respectively. Mainly phenomena with *high* to *very high confidence* in trend detection are illustrated in this figure.

The increase of coral bleaching and the shift in distribution and range limits of some species are attributed to climate change with *high confidence.* Mass coral bleaching coincided with positive temperature anomalies over the past 30 years. A poleward expansion of mangrove forests and some corals, and shifts of range limits of many intertidal species, are also attributed. Vegetated coastal habitats are declining globally. Coral cover and calcification have decreased in recent decades. Elevated temperatures along with ocean acidification reduce the calcification rate of corals. Although the attribution of decreased calcification to either climate- or human-related drivers is difficult, we have *medium confidence* that the primary climate-related driver is ocean warming globally. Seagrass meadows are already under stress due to climate change, particularly where maximum temperatures already approach their physiological limit. However, the decline of the distribution of mangroves and salt marshes is mainly linked with human activities, for example, deforestation and reclamation. Therefore the degree of their attribution to climate change is *very low*.

Globally beaches and shorelines have, in general, undergone net erosion over the past century or longer. There is *high confidence* in detection of increased beach erosion globally. However, attributing shoreline changes to climate change is still difficult owing to the multiple natural and human-related drivers contributing to coastal erosion (e.g., subsidence, decreased sediment delivery, land use change). There is *high confidence* that human pressures, for example, increased usage of surface water and groundwater resources for agriculture and coastal settlements, and river channel deepening, have led to increased saltwater intrusion and *low confidence* in attribution of saltwater intrusion to climate change.

The population living in coastal lowlands is increasing and more than 270 million people in 2010 are already exposed to flooding by the 1-in-100-year coastal flood (Mimura, 2013). Population growth and land subsidence in coastal lowlands are the major causes; therefore, there is *very low* attribution to climate change.

5.5. Adaptation and Managing Risks

5.5.1. Introduction

Coastal adaptation and risk management refer to a wide range of human activities related to the social and institutional processes of framing the

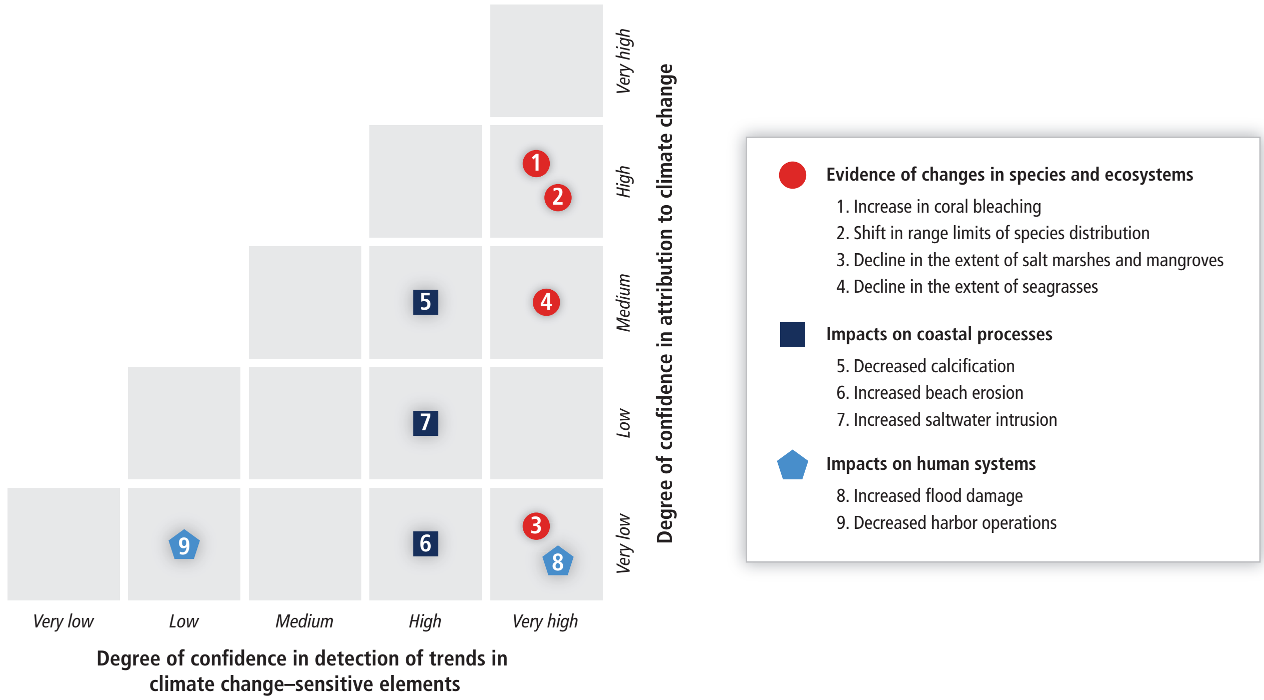

Figure 5-5 | Summary of detection and attribution in coastal areas.

Frequently Asked Questions

FAQ 5.3 | How can coastal communities plan for and adapt to the impacts of climate change, in particular sea level rise?

Planning by coastal communities that considers the impacts of climate change reduces the risk of harm from those impacts. In particular, proactive planning reduces the need for reactive response to the damage caused by extreme events. Handling things after the fact can be more expensive and less effective.

An increasing focus of coastal use planning is on precautionary measures, that is, measures taken even if the cause and effect of climate change is not established scientifically. These measures can include things like enhancing coastal vegetation and protecting coral reefs. For many regions, an important focus of coastal use planning is to use the coast as a natural system to buffer coastal communities from inundation, working with nature rather than against it, as in the Netherlands.

While the details and implementation of such planning take place at local and regional levels, coastal land management is normally supported by legislation at the national level. For many developing countries, planning at the grass roots level does not exist or is not yet feasible.

The approaches available to help coastal communities adapt to the impacts of climate change fall into three general categories:

1. Protection of people, property, and infrastructure is a typical first response. This includes "hard" measures such as building seawalls and other barriers, along with various measures to protect critical infrastructure. "Soft" protection measures are increasingly favored. These include enhancing coastal vegetation and other coastal management programs to reduce erosion and enhance the coast as a barrier to storm surges.
2. Accommodation is a more adaptive approach involving changes to human activities and infrastructure. These include retrofitting buildings to make them more resistant to the consequences of sea level rise, raising low-lying bridges, or increasing physical shelter capacity to handle needs caused by severe weather. Soft accommodation measures include adjustments to land use planning and insurance programs.
3. Managed retreat involves moving away from the coast and may be the only viable option when nothing else is possible.

Some combination of these three approaches may be appropriate, depending on the physical realities and societal values of a particular coastal community. The choices need to be reviewed and adjusted as circumstances change over time.

adaptation problem, identifying and appraising adaptation options, implementing options, and monitoring and evaluating outcomes (Chapters 2, 14, 15, 16, and 17). The governance of this process is challenging due to the complex, nonlinear dynamics of the coastal socio-ecological systems (Rosenzweig et al., 2011) as well as the presence of multiple management goals, competing preferences of stakeholders, and social conflicts involved (Hopkins et al., 2012). In many instances, coastal adaptation may thus be characterized to be a "wicked problem" (Rittel and Webber, 1973), in the sense that there is often no clear agreement about what exactly the adaptation problem is and there is uncertainty and ambiguity as to how improvements might be made (Moser et al., 2012).

Since AR4, the set of adaptation measures considered has been expanded specifically toward ecosystem-based measures (Section 5.5.2); novel approaches for appraising coastal adaptation decisions have been applied (Section 5.5.3.1) and the analysis of adaptation governance and the institutional context in which decisions are taken has progressed (Section 5.5.3.2). Progress has also been made in better integrating adaptation practices within existing policy frameworks (Section 5.5.4.1) as well as in implementing adaptation and identifying good practices (Section 5.5.4.2). A number of studies have also explored the global costs and benefits of coastal adaptation (Section 5.5.5); opportunities, constraints, and limits of coastal adaptation (Section 5.5.6); linkages between coastal adaptation and mitigation (Section 5.5.7); and the long-term commitment to coastal adaptation (Section 5.5.8).

5.5.2. Adaptation Measures

A detailed discussion on general adaptation needs and measures can be found in Chapter 14. As a first approximation, adaptation measures were classified into institutional and social measures (Section 14.3.2.1), technological and engineered measures (Section 14.3.2.2), and ecosystem-based adaptation measures (Section 14.3.2.3). In terms of coastal adaptation, most of the existing measures can be included within this classification.

The IPCC classification of coastal adaptation strategies consisting of retreat, accommodation, and protection (Nicholls et al., 2007) is now widely used and applied in both developed and developing countries (Boateng, 2010; Linham and Nicholls, 2012). This trilogy of strategies has expanded into broad approaches of retreat, defend, and attack (Peel, 2010). Protection aims at advancing or holding existing defense lines by means of different options such as land claim; beach and dune nourishment; the construction of artificial dunes and hard structures such as seawalls, sea dikes, and storm surge barriers; or removing invasive and restoring native species. Accommodation is achieved by increasing flexibility, flood proofing, flood-resistant agriculture, flood hazard mapping, the implementation of flood warning systems, or replacing armored with living shorelines. Retreat options include allowing wetlands to migrate inland, shoreline setbacks, and managed realignment by, for example, breaching coastal defenses allowing the creation of an intertidal habitat. The appropriate measure may depend on several factors requiring a careful decision-making and governance process (Section 5.5.3).

Since AR4, coastal adaptation options have been revised and summarized in several guidebooks (EPA, 2009; USAID, 2009; UNEP, 2010) including best practice examples. Especially relevant has been the growth of Community Based Adaptation (CBA) measures (*robust evidence*, *high agreement*). Table 5-4 compiles different examples of CBA measures in countries such as Bangladesh, India, and the Philippines.

Ecosystem-based adaptation is increasingly attracting attention (Munroe et al., 2011). Adaptation measures based on the protection and restoration of relevant coastal natural systems such as mangroves (Schmitt et al., 2013), oyster reefs (Beck et al., 2011), and salt marshes (Barbier et al., 2011) are seen as no- or low-regret options irrespective of future climate (Cheong et al., 2013; *medium evidence*, *high agreement*). Further work is still needed in order to make reliable quantitative estimates and predictions of the capability of some of these ecosystems to reduce wave, storm surge, and sea level rise impacts and in order to provide reliable cost-benefit analysis of how they compare to other measures based on traditional engineering approaches.

5.5.3. Adaptation Decision Making and Governance

Since AR4, progress has been made in understanding coastal adaptation decisions and governance. For a general treatment of adaptation decision making and governance, see Chapters 2, 15, and 17.

5.5.3.1. Decision Analysis

One specific quality of many coastal adaptation decisions is that these involve options with long (i.e., 30 and more years) investment time scales (e.g., land use planning, flood defenses, construction of housing, and transportation infrastructure; Section 5.5.2). For such decisions, standard methods that rely on probability distribution of outcomes, such as cost-benefit analysis under uncertainty, cannot be applied because of the difficulties, both in theory and practice, to associate probabilities to future levels of GHG emissions, which determine the level of impacts and outcomes (Lempert and Schlesinger, 2001; Hallegate, 2009; see also Section 17.3.6.2).

Alternative approaches that represent uncertainty not through a single probability distribution but through a range of scenarios have thus been applied to long-term coastal adaptation. Robust decision making (RDM), for example, refers to approaches where options that work well over a wide range of these scenarios are preferred (Lempert and Schlesinger, 2000; Lempert and Collins, 2007). RDM in this sense has been applied to, e.g., the Port of Los Angeles infrastructure (Lempert et al., 2012).

Another set of approaches uses the criterion of flexibility to decide between alternative strategies. Flexible and reversible options are favored over non-flexible and non-reversible ones and decisions are delayed to keep future options open (Hallegate, 2009). The adaptation pathways approach, for example, implements the criterion of flexibility by characterizing alternative strategies in terms of two attributes: (1) adaptation tipping points (ATPs), which are points beyond which strategies are no longer effective (Kwadijk et al., 2010); and (2) what alternative strategies are available once a tipping point has been reached (Haasnoot et al., 2013). Importantly, the exact time when an ATP is reached does not matter; it is rather the flexibility of having alternative strategies available that is driving the decision. Prominent applications of this approach include the Thames Estuary 2100 Plan (Penning-Roswell et al., 2012; Box 5-1), the Dutch Delta Programme (Kabat et al., 2009), and the New York City Panel on Climate Change (Rosenzweig et al., 2011).

5.5.3.2. Institution and Governance Analysis

Decisions are made within a context. Institution and governance analysis comprise a variety of approaches that aim at describing this context as well as at explaining the emergence and performance of institutions and governance structures (GS). Institution analysis is particularly relevant to coastal adaptation, because deciding between options and implementing them is an ongoing process involving complex inter-linkages between public and private decisions at multiple levels of decision making and in the context of other issues, existing policies, conflicting interests, and diverse GS (e.g, Few et al., 2007; Urwin and Jordan, 2008; Hinkel et al., 2010; see also Sections 2.2.2, 2.2.3). The non-consideration of this context may hinder or mislead adaptation decisions and implementations as reported by the emerging literature on barriers to adaptation (Section 5.5.5). Institution analysis strives to understand how this context shapes decisions, and insights gained may be employed to craft effective institutions and policies for adaptation.

For coastal adaptation, the effectiveness of existing GS is often hindered owing to a lack of horizontal (i.e., within the same level of decision making) and vertical (i.e., between different levels of decision making) integration of organizations and policies (*high confidence*). Storbjörk and Hedren (2011), for example, report on a weak vertical administrative interplay in coastal GS in Sweden. In the UK, the effectiveness of local GS of Coastal Partnership is found to be limited because these are poorly integrated with higher level policies (Stojanovic and Barker, 2008). In the UK, national level coastal recommendations are difficult to translate into local level actions (Few et al., 2007) and, in the USA, coastal policies often have ambiguous or contradictory goals (Bagstad et al., 2007). In a number of African cases, coastal policies are found not to take into account longer term climate change (Bunce et al., 2010).

Box 5-1 | London’s Thames Estuary 2100 Plan: Adaptive Management for the Long Term

The Environment Agency in Britain has recently developed the Thames Estuary 2100 plan (TE2100) to manage future flood threat to London (Environment Agency, 2012). The motivation was a fear that due to accelerated climate change-induced sea level rise the time could already be too short for replacing the Thames Barrier (completed in 1982) and other measures that protect London, because such major engineering schemes take 25 to 30 years to plan and implement. An adaptive plan that manages risk in an iterative way was adopted based on the adaptation pathway approach (Penning-Rowsell et al., 2012; see also Section 5.5.3.1; Figure 5-6). This plan includes maintaining the existing system in the first 25 years, then enhancing the existing defenses in a carefully planned way over the next 25 to 60 years, including selectively raising defenses and possibly over-rotating the Barrier to raise protection standards. Finally, in the longer term (beyond 2070) there will be the need to plan for more substantial measures if sea level rise accelerates. This might include a new barrier, with even higher protection standards, probably nearer to the sea, or even a coastal barrage. In the meantime the adaptive approach requires careful monitoring of the drivers of risk in the Estuary to ensure that flood management authorities are not taken by surprise and forced into emergency measures.

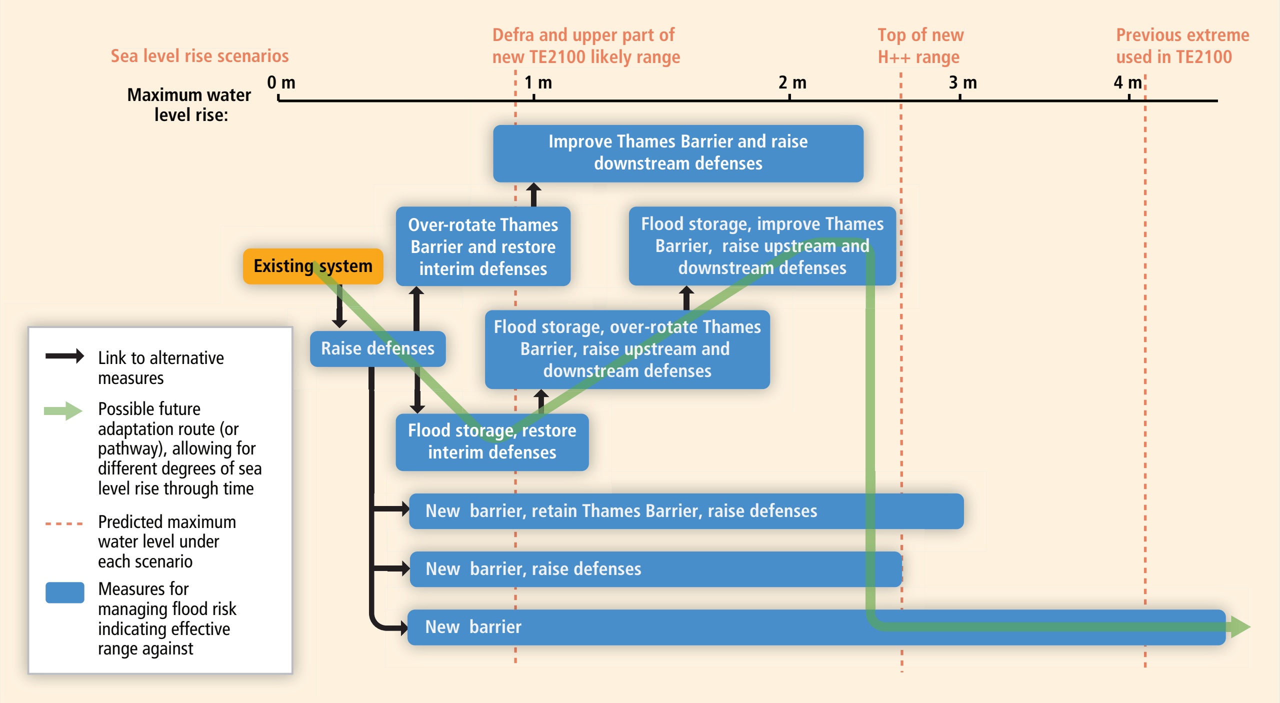

Figure 5-6 | Adaptation measures and pathways considered in the TE2100 project. The boxes show the measures and the range of sea level rise over which the measures are effective. The black arrows link to alternative measures that may be applied once a measure is no longer effective. The red lines show various 21st century sea level rise scenarios used in the analysis including a conservative estimate of about 0.9 m by the UK Department for Environment Food and Rural Affairs ('Defra and upper part of new TE2100 likely range'), a high-level scenario ('Top of new H++ range'), and an extreme scenario of over 4 meters ('previous extreme used in TE2100'). The fat green line shows a possible future adaptation route (or pathway), allowing for different degrees of sea level rise through time (adapted from Lowe et al., 2009).

Governance issues are particularly challenging when considering planned retreat (*medium evidence*). While managed realignment is on the political agenda in Germany and the UK, the political costs of doing so are high, as both the existing GS as well as public opinion are geared toward protection (e.g., Tunstall and Tapsell, 2007), so that short election cycles do not provide incentives for politicians to undertake actions that may produce benefits in the long term (Few et al., 2007; Rupp-Armstrong and Nicholls, 2007). Along the Queensland coast in Australia the option of planned retreat is disappearing because of rapid coastal development and liability laws favoring development. To prevent this, risks and responsibilities would need to be redistributed from the governments to the beneficiaries of this development (Abel et al., 2011).

While institutional factors are decisive in enabling coastal adaptation (*high confidence*), the role of institutions in coastal adaptation is generally under-researched. The majority of studies are descriptive. Institutional analysis striving to understand which GS emerge and are effective depending on both biophysical and social system characteristics as found in the fields of socio-ecological systems (Dietz et al., 2003; Folke et al., 2005; Ostrom 2007, 2009) and institutional economics (Hagedorn et al., 2002; Bougherara et al., 2009) are practically nonexistent.

5.5.4. Implementation and Practice

Since AR4, more experience has been gained in coastal adaptation implementation and practice. Generally, adaptation is not carried out stand-alone but in the context of already existing policy and practice frameworks. Section 5.5.4.1 assesses frameworks that are particularly relevant for coastal adaptation, and Section 5.5.4.2 assesses the experience as well as principles and compiled best practice guidelines.

5.5.4.1. Frameworks

The issues for coastal adaptation are not radically different from issues encountered within ICZM, which offers an enabling environment for adaptation practice (Celliers et al., 2013). ICZM is a long-term, institutionalized and iterative process that promotes the integration of coastal activities, relevant policymakers, practitioners, and scientists across coastal sectors, space and organizations with a view to use coastal resources in a sustainable way (Christie et al., 2005; Kay and Alder, 2005; Sales, 2009; WGII AR5 Glossary). Considering climate change in this framework does not mean radical changes to ICZM, because ICZM already emphasizes the integration of coastal issues across sectors and policy domains as well as the long-term perspective (e.g., Hofstede, 2008; Falaleeva et al., 2011). The major difference of coastal adaptation from ICZM is coping with greater uncertainty, longer time frames in planning (beyond 30 years), and long-term commitments inherent to climate change (Tobey et al. 2010). So far, however, there is *limited evidence* and *low agreement* on the effectiveness of ICZM alone or combined with climate change adaptation. Even though ICZM has been applied throughout the world for over 40 years, many obstacles to its successful implementation still remain (*high confidence*). Generally, there is a lack of empirical research evaluating ICZM (Stojanovic et al., 2004; Stojanovic and Ballinger, 2009). A recent review of ICZM in Europe concluded that the complexity of coastal regulations, demographic deficits, lack of sustainable finance and a failure to involve communities, business, and industry hinder its implementation (Shipman and Stojanovic, 2007). Developing countries in particular struggle to meet the goals of ICZM owing to a lack of qualified human resources, a lack of human, legal, and institutional capacities (Isager, 2008; González-Riancho et al., 2009), difficulties in integrating policy across multiple coastal agencies (Martinez et al., 2011; Ibrahim and Shaw, 2012), power (abuse) of the majority political party or political leaders (Isager, 2008; Tabet and Fanning, 2012), the lack of long-term financial commitment of donors (González-Riancho et al., 2009; Ibrahim and Shaw, 2012), and a lack of knowledge regarding the coastal system (González-Riancho et al., 2009).

Another prominent framework used for coastal adaptation practice is adaptive management (AM), which has been developed as a response to the deep uncertainty characterizing ecosystem management, where it is often impossible to predict outcomes of management interventions. AM thus aims to test management hypothesis by implementing them, monitoring their outcomes and learning from these to refine the management hypothesis to be applied (Holling, 1978; Walters, 1986). There are numerous applications of AM to coastal management (e.g., Walters, 1997; Marchand et al., 2011; Mulder et al., 2011), but there is *limited evidence* of its long-term effectiveness. Limitations of AM are also notable, such as the potential high cost of experimentation and a range of institutional barriers hindering the delivery of flexible management approaches (e.g., McLain and Lee, 1996).

Community-based adaptation (CBA) refers to the generation and implementation of locally driven adaptation strategies that address both climate change impacts and development deficits for the climate-vulnerable poor and that aim to strengthen the adaptive capacity of local people to climate and non-climate risk factors (Nicholls et al., 2007; Reid et al., 2009; Ayers and Dodman, 2010; Ayers and Huq, 2013; see also Sections 14.2.1, 15.4.3.1, 24.4.6.5). CBA is a bottom-up approach to adaptation involving all relevant stakeholders, especially local communities (Ayers and Huq, 2009; UNDP, 2010; Riadh et al., 2012) (Table 5-4). As such, CBA approaches have been developed through active participatory processes with local stakeholders (Ayers and Forsyth, 2009), and operated on a learning-by-doing, bottom-up, empowerment paradigm (Kates, 2000; Huq and Reid, 2007).

CBA experiences emphasize that it is important to understand a community's unique perception of its adaptive capacities in order to identify useful solutions (Parvin et al., 2008; Badjeck et al., 2010; Paul and Routray, 2010) and that scientific and technical information on anticipated coastal climate impacts needs to be translated into a suitable language and format that allows people to be able to participate in adaptation planning (Saroar and Routray, 2010). Furthermore, effective CBA needs to consider measures that cut across sectors and technological, social, and institutional processes, as technology by itself is only one component of successful adaptation (Pelling, 2011; Rawlani and Sovacool, 2011; Sovacool et al., 2011).

Efforts are also being made to integrate climate change adaptation into Disaster Risk Reduction (DRR) frameworks (Mercer, 2010; Polack, 2010; Romieu et al., 2010; Gero et al., 2011) and adaptation practice is likely to move forward as climate change adaptation (CCA) converges with disaster risk reduction (UNISDR, 2009; Setiadi et al., 2010; Tran and Nitivattananon, 2011; Hay, 2012). In Japan, for example, coastal climate change adaptation has been mainstreamed into the framework of Coastal Disaster Management in the aftermath of the 2011 Tohoku Earthquake Tsunami. The priority of upgrading coastal defenses in the face of sea level rise is thereby judged from the potential damage on the assets in predicted inundation areas on the one hand as well as from the age and earthquake resistance of the coastal structures on the other hand (Central Disaster Management Council, 2011; Committee on Adaptation Strategy for Global Warming in the Coastal Zone, 2011). Other important policy and practice frameworks in place in the coastal zone include poverty reduction and development (Mitchell et al., 2010).

5.5.4.2. Principles, Guidance, and Experiences

Much of the observed adaptation practice deals with the coastal hazards of erosion and flooding (Hanak and Moreno, 2012). In many

Table 5-4 | Community-based adaptation measures.

Impact	Type of option	Measures	Brief description	References
Increased salinity	New and diversified livelihoods	Saline-tolerant crop cultivation	Farmer production of saline-tolerant multi-vegetable varieties and non-rice crops	Ahmed (2010); Rabbani et al. (2013)
	New and diversified livelihoods	Keora nursery	Mangrove fruit production to develop local female entrepreneurship	Ahmed (2010)
	New and diversified livelihoods	Crab fattening	Collection, rearing, and feeding of crabs for 15 days to increase local market value	Pouliotte et al. (2009)
	Structural	Homestead protection	Houses constructed on raised foundations to mitigate salinity ingress	Ayers and Forsyth (2009)
Flooding/ inundation	Socio-technical	Disaster management committees	Multi-community stakeholder committees established to discuss disaster preparedness and response on a monthly basis	Ahammad (2011)
	Socio-technical	Early flood warning systems	Established systems converted into a language and format understood by local communities; warning dissemination through community radio services	Ahmed (2005); Saroar and Routray (2010)
	New and diversified livelihoods	Aquaculture: cage and integrated approaches	Small-scale fish culture in cages on submerged agriculture land; aquaculture integrated with other livelihood practices	Pomeroy et al. (2006); Pouliotte et al. (2009); Khan et al. (2012)
	New and diversified livelihoods	Embankment cropping	Growing different vegetable varieties around heightened shrimp enclosures/coastal polders for productive use of fallow land	Ahmed (2010)
	New and diversified livelihoods	Hydroponics	Cultivating vegetables and other crops on floating gardens	Ayers and Forsyth (2009); Ahmed (2010); Dev (2013)
Cyclones/ storm surges	Structural/hard	Homestead reinforcement	Low-cost retrofitting to strengthen existing household structures, especially roofs; strict implementation of building codes	Sales (2009); Ahmed (2010)
	Structural/soft	Homestead ecosystem protection	Plantation of specific fruit trees around homestead area	Haq et al. (2012)
	Structural/hard	Underground bunker construction	Underground bunker established, providing protected storage space for valuable community assets	Raihan et al. (2010)
Sea level rise	Institutional	Risk insurance mechanisms	Farmers educated on comprehensive risk insurance, focusing on sea level rise and coastal agriculture	Khan et al. (2012)
Multi-coastal impacts	Institutional	Integrating climate change into education	Formal and informal teacher training and curriculum development on climate change, vulnerability, and risk management	Ahmed (2010)
	Institutional	Integrated coastal zone management (ICZM) plan	ICZM plan development at local institutional level, including land and sea use zoning for ecosystem conservation	Sales (2009)
	Structural/soft	Restoration, regeneration and management of coastal habitats	Community-led reforestation and afforestation of mangrove plantations, including integration of aquaculture and farming to increase household income levels	Rawlani and Sovacool, (2011); Sovacool et al. (2012)
	Institutional	Community participation in local government decision-making	Active female participation in local government planning and budgeting processes to facilitate delivery of priority coastal adaptation needs	Faulkner and Ali (2012)
	Institutional/ socio-technical	Improved research and knowledge management	Establishment of research centers; community-based monitoring of changes in coastal areas	Sales (2009); Rawlani and Sovacool (2011)

parts of the world, small island indigenous communities address climate change consequences based on their own traditional knowledge (Percival, 2008; Langton et al., 2012; Nakashima et al., 2012). Long-term adaptation to sea level rise has been confined to a few major projects such as the Venice Lagoon project, the Thames Estuary 2100 project (Box 5-1), and the Delta Programme, Netherlands (Norman, 2009).

Through the Delta Programme, the Dutch government has set out far-reaching recommendations on how to keep the country flood-proof over the 21st century taking into account a sea level rise as high as 0.65 to 1.3 m by 2100. These recommendations constitute a paradigm shift from "fighting" the forces of nature with engineered structures to "working with nature" and providing "room for river" instead (Kabat et al., 2009). The recommendations include soft and environmentally friendly solutions such as preserving land from development to accommodate increased river inundation, maintaining coastal protection by beach nourishment, improving the standards of flood protection, and putting in place the necessary political-administrative, legal, and financial resources (Stive et al., 2011).

From adaptation experiences, good practices (practices that have shown consistently better results and could be used as benchmark) have been derived. For some European cases, for example, McInnes (2006) has collected good practices for coastlines facing coastal erosion, flooding, and landslide events. In the California adaptation study that includes coasts, the lessons learnt include using best available science, decision on goals and early actions, locating relevant partners, identification and elimination of regulatory barriers, and encouragement of introduction of new state mandates and guidelines (Bedsworth and Hanak, 2010). Boateng (2010) presented 15 case studies from 12 countries of best practice in coastal adaptation to help coastal managers and policymakers. Bangladesh provides good examples on awareness raising, disaster warning and control, and protective building measures (Martinez et al., 2011). In general, documentation on good adaptation practices for coasts is improving.

In addition, numerous principles have been set forward. In a broad-scale assessment of climate change threats to Australia's coastal ecosystems, seven principles in adaptation were suggested: clearly defined goals by location, thorough understanding of connectivity within and between ecosystems, consideration of non-climatic drivers, involvement of all relevant stakeholders, easily available and shared data, re-thinking of existing policy and planning constraints, and adaptation at local/regional scales (Hadwen et al., 2011). Based on Oxfam's adaptation programs in South Asia that include coastal communities, additional principles presented include a focus on the poor, vulnerable, and marginalized; community or local ownership; flexible and responsive implementation; and preparation for future and capacity building at multiple levels (Sterrett, 2011). An assessment of worldwide case studies indicates the importance of knowledge transfer of good practice methods for scaling up adaptation strategies in and between regions and beyond the national scale (Martinez et al., 2011).

Further principles reported include: Information on efficient adaptation options alone (as assessed through DA approaches) may not fully serve the needs of managers and must to be supplemented by financial and technical assistance as well as boundary organizations that serve as an interface between science and practice (Tribbia and Moser, 2008). The adaptation and decision-making processes should be participatory and inclusive, integrating all relevant stakeholders in a way that is culturally appropriate (Milligan et al., 2009; Nunn, 2009). The adaptation processes should foster mutual learning, experimentation, and deliberation among stakeholders and researchers (Fazey et al., 2010; Kenter et al., 2011). For example, neither scientific climate knowledge alone nor indigenous knowledge alone is considered sufficient for coastal adaptation (Sales, 2009; Dodman and Mitlin, 2011; Bormann et al., 2012). Finally, since coastal systems are complex, diverse, and dynamic, their governance requires experimentation and learning by doing (Jentoft, 2007).

In summary, a wealth of adaptation activities can now be observed in the coastal zone that depend on technology, policy, financial, and institutional support, and are supported by documentation on good practices (*very high confidence*). ICZM, with its emphasis on integration, is likely to remain a major framework for coastal adaptation. While there is *high agreement* on adaptation principles, there is to date little systematic review of and hence *limited evidence* on why a given principle or approach is effective in a given context (and not in another), which emphasizes the need for research to better understand this context (Section 5.5.3.2). Some of the literature on adaptation practice needs to be treated with caution, because normative principles that have been established *ex ante* are not systematically distinguished from *ex post* evaluations of the experiences carried out. Despite the wealth of coastal adaptation activities, it must, however, be emphasized that meeting the multiple goals of coastal adaptation, improving governance, accounting for the most vulnerable populations and sectors and fully integrating consideration of natural ecosystems is still largely aspirational. Meanwhile, development continues in high-risk coastal areas, coastal ecosystems continue to degrade in many regions, coastal freshwater resources are being overexploited in many highly populated areas, and vulnerability to coastal disasters grows (e.g., Shipman and Stojanovic, 2007; McFadden, 2008; Jentoft, 2009; Mercer, 2010).

5.5.5. Global Adaptation Costs and Benefits

This section reports on studies that provide internally consistent estimates of the direct costs of sea level rise impacts and adaptation at global scales. These studies have used the models FUND and DIVA, which are described in Section 5.4.1. Studies that use computable general equilibrium models and growth models to estimate the indirect and dynamic costs of climate change, including sea level rise, are reviewed in Chapter 10.

Generally, cost estimates are difficult to compare across studies owing to differences in scenarios used, impacts and adaptation options considered, methodologies applied, and baseline conditions assumed. Global adaptation costs have only been assessed for protection via dikes and nourishment. Nicholls et al. (2011) estimate annual adaptation cost in terms of dike construction, dike maintenance, and nourishment to be US$25 to 270 billion per year in 2100 under a 0.5 to 2.0 m GMSLR for 2005–2100. Anthoff et al. (2010) estimate the net present value of dike construction costs for 2005–2100 to be US$80 to 120 billion for 0.5 m GMSLR and US$900 to 1100 billion for a 2 m GMSLR, respectively.

The available global studies show that it is economically rational to protect large parts of the world's coastline during the 21st century against sea level rise impacts of increased coastal flood damage and land loss (Nicholls and Tol, 2006; Anthoff et al., 2010; Hinkel et al., 2013; *limited evidence*, *high agreement*). For dry land and wetlands loss, the FUND model shows that cost-benefit analysis would justify protecting 80% of the exposed coast in all but 15 countries under a GMSLR of 20 to 40 cm per century (Nicholls and Tol, 2006). Using the same method, Nicholls et al. (2008) show that under extreme GMSLR of up to 4 m in 2100, this fraction would drop to 30% to 50%. For coastal flooding, an application of DIVA shows that, for 21st century GMSLR scenarios of 60 to 126 cm, the global costs of protection through dikes (levees) are much lower than the costs of damages avoided through adaptation (Hinkel et al., 2013).

At the same time, costs and benefits of sea level rise impacts and adaptation vary strongly between regions and countries with some developing countries and small islands reaching limits of adaption or not being able to bear the costs of impacts and adaptation (*limited evidence*, *high agreement*) (Section 29.6.2.1). The cost of 1 m of GMSLR in 2100 (considering land loss due to submergence and protection costs) is projected to be above 1% of national GDP for Micronesia, Palau, the Bahamas, and Mozambique (Anthoff et al., 2010). For coastal flooding, annual damage and protection costs are projected to amount to several percentages of the national GDP for small island states such as Kiribati, the Solomon Islands, Vanuatu, and Tuvalu under GMSLR projections of 0.6 to 1.3 m by 2100 (Hinkel et al., 2013). Further substantial costs arise, particularly for developing countries owing to their current adaptation deficit (i.e., coastal defenses are not adapted to the current climate variability), which is not well understood and requires further analysis (Parry et al., 2009). For example, the adaption deficit of Africa with regard to coastal flooding is estimated at US$300 billion (Hinkel et al., 2011) and that of Bangladesh with respect to cyclones at US$25 billion (World Bank, 2011).

Several methodological gaps remain. As there are so few studies on the costs and benefits of sea level rise at a global level, uncertainties are largely unknown and the need for further research is great. The socioeconomic drivers, sea level rise scenarios, and impacts considered as well as damages and losses valued are incomplete. For example, costs of salinity intrusion, land loss due to increased coastal erosion, cost of forced migration due to permanent inundation, the backwater effect, and the impact of sea level rise in combination with other drivers on ecosystems have not been assessed at global scales (Section 5.5.5). Generally for sea level rise impacts, it is difficult to establish a "no adaptation" baseline and the choice of the baseline changes damage costs (Yohe et al., 2011).

Another gap is related to the fact that global studies have focused on protection via hard structures while many more potentially cheaper or socially preferable measures are available including "soft" protection, retreat, and accommodation measures (Section 5.1). Future work needs to consider trade-offs between all available measures. Hard protection measures, for example, may incur additional costs on adjacent unprotected coasts (Brown et al., 2013) or destroy coastal wetlands through coastal squeeze (Section 5.4.2.3). While the costs of "soft" protection measures such as ecosystem-based adaptation (EBA) are largely unknown (Linham and Nicholls, 2010; Engineers Australia, 2012), these may provide additional benefits in the form of a variety of ecosystem services (Alongi, 2008; IUCN, 2008; Anthony et al., 2009; Vignola et al., 2009; Pérez et al., 2010; Espinosa-Romero et al., 2011; McGinnis and McGinnis, 2011; Zeitlin et al., 2012). Finally, it must be noted that protection also further attracts people and development to the floodplain, which in turn increases the risk of potential catastrophic consequence in the case of defense failure. This is particularly true for many coastal cities such as London, Tokyo, Shanghai, Hamburg, and Rotterdam that already rely heavily on coastal defenses (Nicholls et al., 2007).

5.5.6. Adaptation Opportunities, Constraints, and Limits

There is a growing recognition of the potential co-benefits and new opportunities that can be achieved by mainstreaming adaptation with existing local to national goals and priorities (Section 14.3.4). DRR and adaptation share the common goals of reducing vulnerability against impacts of extreme events while creating strategies that limit risk from hazards (IPCC, 2012). This is especially true in coastal areas where extreme flooding events due to severe storm surges are one of the main sources of hazard. Besides, integrating adaptation with national and local planning can also contribute to building resilience in coastal areas.

EBA is considered to be an emerging adaptation opportunity (Munroe et al. 2011) (Section 16.6, Box CC-EA). In coastal areas, the conservation or restoration of habitats (e.g., mangroves, wetlands, and deltas) can provide effective measures against storm surge, saline intrusion, and coastal erosion by using their physical characteristics, biodiversity, and the ecosystem services they provide as a means for adaptation (Borsje et al., 2011; Jones et al., 2012; Cheong et al., 2013; Duarte et al., 2013b; see also Section 5.5.7).

Since AR4, a variety of studies have been published providing a better understanding of the nature of the constraints and limits to adaptation, both generally (Sections 16.3, 16.4) and more specifically in the coastal sector (e.g., Ledoux et al., 2005; Moser et al., 2008; Tribbia and Moser, 2008; Bedsworth and Hanak, 2010; Frazier et al., 2010; Saroar and Routray, 2010; Mozumber et al., 2011; Storbjörk and Hedrén, 2011; Lata and Nunn, 2012).

Constraints specific to coastal adaptation are polarized views in the community regarding the risk of sea level rise and concerns regarding the fairness of retreat schemes in Australia (Ryan et al., 2011); lack of awareness of sea level rise risks and spiritual beliefs in Fiji (Lata and Nunn, 2012); insufficient budget for the development of adaptation policies and other currently pressing issues in the USA (Tribbia and Moser, 2008; Mozumber et al., 2011); distinct preferences for retreat options depending on several social and exposure conditions in Bangladesh (Saroar and Routray, 2010); and the need to provide compensatory habitats under the Habitats Regulations and lack of local public support in the UK (Ledoux et al., 2005). Other relevant constraints include the lack of locally relevant information, resource tenure, and political will, especially critical in developing countries (*robust evidence*, *high agreement*). Besides, a gap exists between the useful climate information provided by scientists and the one demanded by decision makers.

Different constraints typically do not act in isolation, but in interacting bundles (*robust evidence*, *high agreement*). Therefore it is difficult to predict which constraints matter most in any specific context but instead multiple constraints need to be addressed if adaptation is to move successfully through the different stages of the management process (Moser and Ekstrom, 2010; Londsdale et al., 2010; Storbjörk, 2010; *medium evidence*, *high agreement*). Besides, some factors can act as enablers and add to the adaptation capacity, while acting as constraints for others (Burch, 2010; Storbjörk, 2010; *medium evidence*, *high agreement*).

Finally, a common concern emerging from the literature reviews (Biesbroek et al., 2010; Ekstrom et al., 2011) is that some critical constraints arise from the interactions across policy domains, existing laws and regulations, and long-term impacts of past decisions and policies (*low evidence*, *high agreement*).

A limit is reached when adaptation efforts are unable to provide an acceptable level of security from risks to existing objectives and values and prevent the loss of key attributes, components, or services of an ecosystem (Box 16-1; Sections 16.2, 16.5) and may arise as a result of most of the constraints described above.

Regarding coastal areas, it is widely recognized that biophysical limitations arise, for example, in small island developing states where adaptation through retreat to increasing impact of sea level rise in conjunction with storm surges and flooding is not an option due to limited high land availability, creating a temporary and eventually permanent human displacement from low-lying areas (Pelling and Uitto, 2001; *medium evidence*, *high agreement*). Nicholls et al. (2011) show that only a limited number of adaptation options are available for specific coastal areas if sea level exceeds a certain threshold (1 m) at the end of the century.

Regarding natural (unassisted) adaptation, several researchers have examined biophysical limits, for example, of coastal marshes (Craft et al., 2009; Langley et al., 2009; Mudd et al., 2009; Kirwan et al., 2010), and found that under certain nonlinear feedbacks among inundation, plant growth, organic matter accretion, and sediment deposition coastal wetlands can adapt to conservative rates of sea level rise (SRES A1B) if suspended sediment surpasses a certain threshold. In contrast, even coastal marshes with high sediment supplies will submerge near the end of the 21st century under scenarios of more rapid sea level rise (e.g., those that include ice sheet melting).

Increased ocean acidification is expected to limit adaptation of coral reefs to climate change (Boxes CC-OA and CC-CR).

5.5.7. Synergies and Trade-offs between Mitigation and Adaptation

Klein et al. (2007, p. 749) defined trade-offs between mitigation and adaptation as the "balancing of adaptation and mitigation when it is not possible to carry out both activities fully at the same time (e.g., due to financial or other constraints)." Successful adaptive coastal management of climate risks will involve assessing and minimizing potential trade-offs with other non-climate policy goals (e.g., economic development, enhancement of coastal tourism) and interactions between adaptation and mitigation (e.g., Brown et al., 2002; Tol, 2007; Barbier et al., 2008; Bunce et al., 2010).

Adaptation will be the predominant approach to reducing climate risks to coastal communities, populations, resources, and activities over the 21st century as large increases in sea level rise cannot be ruled out (WGI AR5 Section 13.5.2) and because of the time lag between emissions reductions, temperature changes, and impacts on global sea levels (Nicholls et al., 2007, 2011; see also Section 5.5.7). Still, positive synergies and complementarities between mitigation and adaptation in the coastal sector exist.

Since AR4, a series of studies have pointed out that marine vegetated habitats (seagrasses, salt marshes, macroalgae, or mangroves) contribute to almost 50% of the total organic carbon burial in ocean sediments leading to the so-called Blue Carbon (coastal carbon stocks) strategies (Nellemann et al., 2009; McLeod et al., 2011; Duarte et al., 2013b). These strategies aim at exploring and implementing the necessary mechanisms allowing Blue Carbon to become part of emission and mitigation protocols along with other carbon-binding ecosystems such as rainforests (Nellemann et al., 2009). Besides, marine vegetated habitats provide additional functions including the buffering of impacts against storm surges and waves, soil preservation, raising the seafloor, and shelter for fish nursery or habitat protection (Alongi, 2002; Kennedy and Björk, 2009; Duarte et al., 2013b). Consequently, restoration or ecosystem engineering of marine vegetated areas can be considered as a good example of positive synergies between adaptation and mitigation in coastal areas (Borsje et al., 2011; Jones et al., 2012; Duarte et al., 2013b) and should be further explored to be considered as a valid alternative in the portfolio of measures for climate change mitigation and adaptation. Only recently results have been presented on the role of a 1700 ha seagrass restoration in carbon storage in sediments of shallow coastal ecosystems in Virginia (USA). Restored seagrass meadows are expected to accumulate carbon at a rate comparable to ranges measured in natural seagrass meadows within 12 years of seeding, providing an estimated social cost of US$4.10 ha^{-1} yr^{-1} (Greiner et al., 2013).

Many coastal zone-based activities and various coastal management strategies involve emissions of GHGs. Reduction or cessation of some of them may have positive implications for both mitigation and adaptation. Limiting offshore oil production may imply a net reduction in GHG emissions depending on what form of energy replaces it, but also a reduced risk of oil spills, a reduction of stresses on the marine/coastal ecosystems, and variable socioeconomic impacts on human communities and public health (O'Rourke and Connolly, 2003). This may result in reduced vulnerability or increased resilience and consequently could prove positive for adaptation. However, this measure would increase the vulnerability of countries whose economies are highly dependent on oil extraction.

Some coastal adaptation options may have potentially negative implications on mitigation. Relocation of infrastructure and development out of the coastal floodplains (retreat) will imply increase in one-time GHG emissions due to rebuilding of structures and possible increase in low-density urban development and ongoing transportation-related emissions (Biesbroek et al., 2010). The building or upgrading of coastal protection structures or ports will also imply an increased energy use and GHG emissions related to construction (e.g., cement production) (Boden et al., 2011).

Similarly, actions beneficial for mitigation may result in potential negative impacts for adaptation. A more compact coastal urban design, increasing development in floodplains (Giridharan et al., 2007), or the development of marine renewable energy (Boehlert and Gill, 2010) may introduce additional drivers on coastal systems reducing coastal resilience and adaptive capacity.

5.5.8. Long-Term Commitment to Sea Level Rise and Adaptation

In AR4, both WGI and WGII highlighted the long-term commitment to sea level rise (Meehl et al., 2007; Nicholls et al., 2007), which means that sea levels will continue to rise for centuries due to global warming until reaching equilibrium conditions even if climate forcing is stabilized, because there is a delay in the response of sea level rise to global warming (WGI AR5 Section13.4.1). WGI AR5 has now assessed GMSLR until 2500 and this shows that even with aggressive mitigation measures (RCP2.6), sea level continues to rise after 2100 (Table 5-1; see also WGI AR5 Sections 13.5.1, 13.5.4). With more moderate (RCP4.5.) and little (RCP8.5) mitigation, larger ongoing increases in sea level are expected, lasting for several centuries. Note that the ranges given after 2100 are only model spread and not likely ranges. Looking beyond 2500, Levermann et al. (2013) project that GMSL will rise on average by about 2.3 m per degree Celsius of global warming within the next 2000 years. Under present levels of global warming, this means that we have already committed to a long-term sea level rise of 1.3 m above current levels (Strauss, 2013). For other climate-related drivers, responses to global warming levels are more immediate. For ocean acidification, for example, pH rise would cease several decades after strict CO_2 emission reductions begin (Bernie et al. 2010; see also Section 19.7.1).

This long-term commitment to sea level rise means that there is also a long-term commitment to sea level rise impacts and adaptation. Few studies have considered this and, from a methodological point of view, it is difficult to look at socioeconomic conditions and human responses on such large temporal scales. A limited number of studies have estimated the effects of mitigation on coastal impacts on human settlements and adaptation for the 21st century (Section 5.4.3.1). These studies show that despite the delayed response of sea level rise to global warming, mitigation can reduce impacts significantly already during the 21st century. These studies also show that for most urban areas, coastal protection is cost-efficient in reducing impacts during the 21st century (Section 5.5.5). Past and current adaptation practice also confirms this: cities such as Tokyo and Shanghai have protected themselves against local sea level rise of several meters during the 20th century and the Dutch and UK governments have decided that they can protect urban Netherlands and London against 21st century sea level rise above 1 m (Section 5.5.4). Not protecting cities such as Amsterdam, Rotterdam, and London during the 21st century is not an option. On the other hand, there are coastal areas such as small islands where protecting against several meters of sea level rise in the long term is not a viable option. Failing to mitigate, thus increasingly commits us to a world where densely populated areas lock into a trajectory of increasingly costly hard defenses and rising residual risks on the one hand and less densely populated areas being abandoned on the other hand. Mitigation thus plays, in the long term, a very important role in avoiding climate change impacts in coastal areas by reducing the rate of sea level rise and providing more time for long-term strategic adaptation measures to be adopted. However, even if anthropogenic CO_2 emissions were reduced to zero, sea levels would continue to rise for centuries, making adaptation in coastal areas inevitable.

5.6. Information Gaps, Data Gaps, and Research Needs

This chapter has updated knowledge on the impacts of climate change on the coastal systems not in isolation but also from the perspective of overexploitation and degradation that have been responsible for most of the historical changes. There is a better understanding of the varying impacts of weather and climate extremes and long-term sea level rise on human systems.

That sea levels will rise is a confident projection of climate science but uncertainties around the magnitude of future sea level rise remain large. The rates and magnitude of sea level rise are summarized in Table 5-1 but, under present levels of global warming, we are already committed to 1.3 m future sea level rise above current levels (Section 5.5.8). However, many sea level rise assessments are not provided at spatial or temporal scales most relevant for decision makers who require information on baseline conditions and projections of change (Kettle, 2012) of RSLR (i.e., including local subsidence) for vulnerability assessment and adaptation planning.

Generally, quantitative predictions of future coastal change remain difficult despite the application of improvements in technology—for example, aerial photographs, satellite imagery, Light Detection And Ranging (LiDAR; Sesil et al., 2009; Revell et al., 2011; Pe'eri and Long, 2012)—to investigate and characterize large-scale shoreline changes. There is incomplete understanding of coastal changes over the decade and century time scales (Woodroffe and Murray-Wallace, 2012). Shoreline response is more complex than simple submergence because of factors such as sediment supply, mobilization and storage, offshore geology, engineering structures, and wave forcing (Ashton et al., 2011). The projection of the future impacts of climate change on natural systems is often hampered by the lack of sufficiently detailed data at the required levels of space and time. Although observations have been made on impacts on beaches, rocky coasts, wetlands, coastal aquifers, delta areas, or river mouths by multi-drivers of climate and human-induced origin, there is still an incomplete understanding of the relative role played by each of these drivers and, especially of their combined effect. Uncertainties are even higher when it comes to the evaluation of projected impacts.

For coastal ecosystems, more work needs to be done to develop predictive models based on findings from multi-stressor experiments, both in the field and in the laboratory. Reliable predictions require information on multifactorial experiments performed on communities (preferably in the field), and on time scales of months to years in order to take into consideration the processes of biological acclimation and adaptation.

Although sea level is projected to rise in the future, there are significant gaps in vulnerability assessment of other specific coastal impacts. For example, the modeling of diseases that could affect coastal areas is based mainly on the mean values of climate. Also, despite tourism being one of the most important industries in the coastal areas, not enough is known about tourists' reactions to projected climatic change (Moreno and Amelung, 2009b) or required adaptation measures for port facilities (UNCTAD, 2009).

A wide range of coastal management frameworks and measures is available and used in coastal adaptation to climate change, and the scope for their integration has increased by combining scenarios of climate change and socioeconomic conditions and risk assessment (Kirshen et al., 2012). While various adaptation measures are available, at the local level, there remains insufficient information on assessment of adaptation options, particularly in developing countries.

Data and knowledge gaps exist or their reliability is insufficient. Despite the availability of potentially useful climate information, a gap exists between what is useful information for scientists and for decision makers. For example, at the project level, engineers may have difficulties to "plug in" climate projections presented by scientists. The proposed actions to improve usability include varying levels of interaction, customization, value-adding, retailing, and wholesaling (Lemos et al., 2012) so that data and methods can be more openly accessible to fellow scientists, users, and the public (Kleiner, 2011).

Coastal systems are affected by human and climate drivers and there are also complex interactions between the two. In general, certain components of coastal systems are sensitive and attributable to climate drivers while others are not clearly discernible. For example, data are available on the range shift in coastal plant and animal species and the role of higher temperatures on coral bleaching (see Box CC-CR). However, in many cases in the human systems, the detectable changes can be largely attributed to human drivers (Section 5.3.4). Reducing our knowledge gaps on the understanding of the processes inducing changes would help to respond to them more efficiently.

The economics of coastal adaptation are under-researched. More comprehensive assessments of valuation of coastal ecosystem services, adaptation costs, and benefits that simultaneously consider both the gradual impact of land loss due to sea level rise and the stochastic impacts of extreme water levels (storm surges, cyclones) are needed, as well as other impacts such as saltwater intrusion, wetlands loss and change, and backwater effects. Assessments should also consider a more comprehensive range of adaptation options and strategies, including "soft" protection, accommodation, and retreat options as well as the trade-offs between these.

Governance of coastal adaptation and the role of institutions in the transition toward sustainable coasts are under-researched. While institutional factors are recognized to be decisive in constraining and enabling coastal adaptation, most work remains descriptive. There is a great need for dedicated social science research aimed at understanding institutional change and which institutional arrangements are effective in which socioeconomic and biophysical contexts (Kay, 2012; see also Sections 5.5.3, 5.5.4).

Developing a coastal adaptation knowledge network between scientists, policymakers, stakeholders, and the general public could be considered a priority area for large coastal areas or regional areas affected by climate change and sea level rise. This is well developed in the USA, European Union, the Mediterranean, and Australia but less so in the developing countries, except in certain regions, for example, Caribbean islands and the Pacific Islands.

Future research needs for coastal adaptation are identified by several developments in climate science. Based on the Li et al. (2011) survey of the foci of climate research in the 21st century, the implications for coasts would be on biodiversity and flooding. Future technological advances may be significant—for example, new forms of energy and food production and information and communication technology (ICT) for risk monitoring (Delta Commission, 2008; Campbell et al., 2009; Zevenbergen et al., 2013)—and these would be useful for flood risks and food production in deltas and coastal systems (aquaculture).

With recent adverse climatic and environmental events on coasts, adaptation demands different decision regimes (Kiker et al., 2010) but adaptation, mitigation, and avoidance measures still require integrating research that includes natural and social sciences (CCSP, 2009). Although many gaps still remain, there is nevertheless a greater foundation of climate change research on coasts across a wide range of fields (Grieneisen and Zhang, 2011) upon which scientists, policymakers, and the public may find improved solutions for coastal adaptation.

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