

Chapter 5. Coastal Systems and Low-Lying Areas**Coordinating Lead Authors**

Poh Poh Wong (Singapore), Iñigo J. Losada (Spain)

Lead Authors

Jean-Pierre Gattuso (France), Jochen Hinkel (Germany), Abdellatif Khattabi (Morocco), Kathleen McInnes (Australia), Yoshiki Saito (Japan), Asbury Sallenger (USA)

Contributing Authors

So-Min Cheong (Republic of Korea), Kirstin Dow (USA), Carlos Duarte (Spain), Kris Ebi (USA), Lucy Faulkner (UK), Masahiko Isobe (Japan), Jack Middelburg (Netherlands), Susanne Moser (USA), Mark Pelling (UK), Edmund Penning-Rowsell (UK), Sybil Seitzinger (Sweden), Marcel Stive (Netherlands), Richard Tol (Netherlands), Athanasios Vafeidis (Greece)

Review Editors

Robert Nicholls (UK), Filipe Santos (Portugal)

Volunteer Chapter Scientist

Sara Amez (Spain)

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43
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45
46
47 **Coastal systems and low-lying areas will increasingly experience adverse impacts associated with**
48 **submergence and extreme sea level flooding due to relative sea level rise (*high confidence*).** Large spatial
49 variations in the projected sea level rise, together with local factors such as subsidence suggests that relative sea
50 level rise can be considerably larger than projected GMSL and therefore is an important consideration in impact
51 assessments (*very high confidence*) [5.3.1]. Changes in storms and associated storm surges may further contribute to
52 changes in sea level extremes but the small number of regional storm surge studies, limited spatial coverage and
53 different modelling approaches used means that there is *low confidence* in projections of storm surge [5.3.3.2].
54

1 **Acidification and warming of coastal waters will continue with significant consequences for coastal**
2 **ecosystems (*high confidence*)**. The increase in acidity will be higher in areas where eutrophication is an issue with
3 negative consequences for many calcifying organisms (*high confidence*) [5.4.2.2, 5.4.2.4]. The interaction of
4 acidification and warming exacerbates coral bleaching and mortality (*very high confidence*) [5.4.2.4, Box CC-OA].
5 Warming will cause a decline of vegetated coastal habitats across the temperate zone [5.4.2.3]. Temperate seagrass
6 and kelp ecosystems will decline with the increased frequency of heat waves and sea temperature extremes as well
7 as through the impact of invasive subtropical species (*high confidence*). The decline of seagrass and kelp habitats
8 will affect food webs, biodiversity and biogeochemical cycling in these ecosystems (*very high confidence*). In the
9 absence of adaptation, beaches, sand dunes and cliffs currently eroding will continue to do so under increasing sea
10 levels (*high confidence*) [5.4.2.1.-5.4.2.2.]. Increased human-induced drivers have been the primary drivers of
11 change in coastal aquifers, lagoons, estuaries, deltas and wetlands (*very high confidence*). Climate-induced drivers
12 will exacerbate currently existing problems in these natural systems (*very high confidence*) [5.4.2.3-5.4.2.7].
13

14 **The population and assets exposed to coastal risk as well as human pressures on coastal ecosystems will**
15 **increase significantly in the coming decades due to population growth, economic development, urbanization**
16 **and coast-ward migration of people (*high confidence*)**. Under medium population projections, the population
17 exposed to the 1 in 100 year coastal flood is expected to increase from 271 million in 2010 to 345 million in 2050
18 due to socio-economic development only [5.4.3.1]. This increase in coastal population is expected to further
19 exacerbate human pressures on coastal systems resulting from excess nutrient input, reduced run-off and sediment
20 delivery (*high confidence*) [5.3.4.3, 5.3.4.4, 5.3.4.5, 5.3.4.6].
21

22 **The costs of inaction are larger than the sum of adaptation and residual damage costs for the 21st century**
23 **and at the global scale (*high agreement*)**. Without adaptation, hundreds of million people will be affected by
24 coastal flooding and be displaced due to land loss through submergence and erosion by 2100; the majority of these
25 affected are from East, Southeast and South Asia (*high confidence*). [5.4.3.1]. Even with very extreme mean sea-
26 level rise of 1.3m by 2100, protection is considered economically rational for most developed coastlines in most
27 countries (*high agreement*) [5.5.3]. Under medium socio-economic development assumption, the expected direct
28 global annual cost of coastal flooding (adaptation and residual damage costs) may reach US\$300 billion per year in
29 2100 without adaptation and US\$90 billion per year with adaptation under a 1.26 m sea-level rise scenario [5.5.3]
30

31 **The impacts of climate change on coasts and the required level of adaptation vary strongly between regions**
32 **and countries (*high confidence*)**. While developed countries are expected to be able to adapt to even high levels of
33 sea-level rise, small island states and some low-lying developing countries are expected to face very high impacts
34 and associated annual damage and adaptation costs of several percentage points of GDP (*high agreement*) [5.5.3].
35 Developing countries and small island states within the tropics relying on coastal tourism, are impacted not only
36 directly by future sea-level rise and associated extremes but also by the impacts of coral bleaching and ocean
37 acidification and reductions in tourist flows from other-regions (*very high confidence*). [5.4.3.4]
38

39 **Since AR4, the analysis and implementation of coastal adaptation has progressed significantly but much**
40 **more effort is needed for a transition towards climate resilient and sustainable coasts (*very high confidence*)**.
41 The analysis of adaptation has progressed towards novel approaches such as robust decision making and adaptation
42 pathways that recognize that the deep uncertainty in projections of drivers does not have to be a barrier to adaptation
43 (*high confidence*) [5.5.2.2]. Adaptation analysis and implementation have also progressed towards considering the
44 institutional context and governance of adaptation, albeit many governance challenges related to vertical and
45 horizontal policy integration, political will and power relations remain (*very high confidence*) [5.5.2.3, 5.5.2.4].
46 Many countries, states/provinces, cities and communities are now carrying out adaptation activities including the
47 mainstreaming of coastal adaptation into relevant strategies and management plans (*very high confidence*) [5.5.4].
48

50 5.1. Introduction

51
52 This chapter presents an updated picture of the impacts, vulnerability and adaptation of coastal systems and low-
53 lying areas to climate change, with emphasis on sea-level rise. Unlike the coastal chapter in the previous assessment

1 (AR4), some materials pertinent to the oceans are not covered in this chapter but in two new ocean chapters
2 (Chapters 6 and 30).

3
4 The topics covered in this chapter follow the outline for sectoral chapters approved by the IPCC. An Executive
5 Summary summarizes the key messages with a line of sight to the supporting sections in the chapter.

6
7 This chapter comprises six sections with this first section dealing with progress in knowledge from AR4 to AR5
8 scope of chapter and new developments. Section 2 defines the coastal systems and climate and non-climate drivers.
9 The coastal systems include both natural systems and human systems and this division is generally followed
10 throughout the chapter. The climate and non-climate drivers are assessed in section 3, followed by the impacts,
11 vulnerabilities and risks in section 4. Section 5 deals with adaptation and managing risks. Information gaps, data
12 gaps and research needs are assessed in section 6. There are 8 boxes on specific topics or examples, including 3
13 cross-chapter boxes, distributed within the chapter.

14
15 In the AR4, the coasts chapter assessed the impact of climate change and global sea-level rise up to 0.6 m to 2100
16 The coastal systems were deemed be affected mainly by higher sea level, increasing temperature, changes in
17 precipitation, larger storm surges and reduction in ocean pH. Human activities had continued to increase their
18 pressure on the coasts with rapid urbanization in coastal areas and growth of megacities with consequences on the
19 coastal resources. Regionwise, South, Southeast and East Asia, Africa and small islands were identified most
20 vulnerable. The AR4 chapter offered a range of adaptation measures, many under the ICZM (integrated coastal zone
21 management) framework that could be carried out in the developed and developing countries, but recognized that
22 the latter would face more challenges. Various issues on increasing the adaptive capacity or increasing the resilience
23 of coastal communities were discussed. The unavoidability of sea level rise in the long term, even with stringent
24 mitigation was noted, and adaptation would become an urgent issue.

25
26 A number of key issues related to the coasts have arisen since the AR4. There is now better understanding of the
27 natural systems, their ecosystem functions, their services and benefits to humanity and how they can be affected by
28 climate change. Their linkages landward to the watersheds and seaward to the seas and oceans need to be considered
29 for a more integrated assessment of climate change impacts. GMSL are projected to be 0.46 to 0.96 cm by 2100
30 although regional variations in sea level rise may see values vary by up to 20% of GMSL for most countries and as
31 much as 50% for some (WG1 Chapter 13). This may have serious implications for coastal cities, deltas and low-
32 lying states. While higher rates of coastal erosion are generally expected under rising sea levels, the complex inter-
33 relationships between the geomorphological and ecological attributes of the coastal system and the relevant climate
34 and oceanic processes need to be better established at regional and local scales.

35
36 Also of concern is ocean acidification and potential impacts of reduced calcification in shellfish and impacts on
37 commercial aquaculture (Barton *et al.*, 2012). Together with warming, acidification also causes coral reefs to lose
38 their structural stability with negative implications for reef communities and shore protection (Sheppard *et al.*, 2005;
39 Manzello *et al.*, 2008; see also Box CC-OA). A significant number of new findings regarding the impacts of climate
40 change on human settlements, key coastal systems such as rocky coasts, beaches, estuaries, deltas, salt marshes,
41 mangroves, coral reefs and submerged vegetation have become available since the AR4 and are reviewed in this
42 chapter. However, uncertainties regarding projections of potential impacts on coastal systems remain high.

43
44 This chapter also provides advances in both vulnerability assessments and the identification of potential adaptation
45 actions, costs, benefits and tradeoffs. A larger number of new studies estimate the cost of inaction versus potential
46 adaptation. Coastal adaptation has become more acceptable and a wider range of approaches and frameworks such
47 as integrated coastal management, ecosystem-based adaptation, community-based adaptation and disaster risk
48 reduction and management are being used.

49
50 Climate change will interact differently with the variety of human activities and other drivers of change along
51 coastlines of developed and developing countries. For coastlines of developed countries, changes in weather and
52 climate extremes and sea-level rise may impact for example, demand for housing, recreational facilities and
53 construction of renewable energy infrastructure at the coast (Hadley, 2009). On coasts of developing countries,

1 weather and climate extremes put an additional risk to many of the fastest-growing coastal urban areas, such as in
2 Bangladesh and China (McGranahan *et al.*, 2007; Smith 2011).

5.2. Coastal Systems

7 Coastal systems and low-lying areas, also referred to as simply coasts in this assessment are areas near to mean sea
8 level. Generally, there is no single definition for the coasts and the coastal zone/area where the latter has an
9 emphasis on area or extent. In relation to exposure to potential sea-level rise, the LECZ (low-elevation coastal zone)
10 has been used in recent years with reference to specific area and population up to 10 m elevation (Vafeidis *et al.*,
11 2011). This chapter does not consider the polar coasts (chapter 28), small islands (chapter 29), many of which are
12 low-lying, or the region beyond the continental shelf (chapters 6 and 30).

14 The coastal systems are conceptualized to consist of both natural systems and human systems (Figure 5-1). The
15 natural systems include distinct coastal characterizations and ecosystems such as rocky coasts, beaches, barriers and
16 sand dunes, estuaries and lagoons, deltas, wetlands and coral reefs. These elements help to define the seaward and
17 landward boundaries of the coast. While they provide a wide variety of regulating, provisioning, supporting and
18 cultural services (MEA, 2005) they have been altered and heavily influenced by human activities with climate
19 change constituting only one amongst many pressures these systems are facing. The human systems include the built
20 environment (settlements, infrastructure and transport networks), human activities (e.g., tourism, aquaculture, etc) as
21 well as formal and informal institutions that organize human activities (e.g., policies, laws, customs, norms and
22 culture). Both systems together form a tightly coupled social-ecological system (SES) (Berkes and Folke, 1998;
23 Hopkins *et al.*, 2012).

25 [INSERT FIGURE 5-1 HERE

26 Figure 5-1: Schematic diagram indicating the elements of the coastal zone that are considered in this chapter.]

5.3. Drivers

5.3.1. Introduction

33 In TAR and AR4 changes in climate drivers (any climate-induced factor that directly or indirectly causes a change),
34 including sea level rise, were projected for different SRES emissions scenarios (Nakicenovic and Swart, 2000).
35 Consequently, to date, most of the impacts and vulnerability assessments of climate change in coastal areas are
36 based on SRES A2, A1B, B2 and A1F1 scenarios. Since AR4 a new scenario process has been initiated to replace
37 the SRES scenarios with Representative Concentration Pathways (RCPs) and Shared Socio-economic Pathways
38 (SSPs) (Moss *et al.*, 2010). The RCPs are scenarios specifying concentrations, rather than emissions, thereby
39 avoiding differences in concentrations of Long-Lived Greenhouse Gas and aerosol concentrations for the same
40 emissions scenarios that can arise from the use of different models (van Vuuren *et al.*, 2011). For a comparison
41 between RCP and SRES scenarios see WG1, Chapter 1, Box 1.2. In addition, Extended Concentration Pathways
42 (ECPs) have been introduced for the period 2100-2300 (Meinhausen *et al.* 2009) providing the opportunity to assess
43 the long-term commitment to sea-level rise, which is *very likely* to continue beyond 2500 unless global temperature
44 declines (WG1, Chap.1, 13.5.2).

46 The SSPs provide representative qualitative story lines (narratives) of world development together with quantitative
47 pathways of key socio-economic variables such as GDP and population (O'Neil *et al.*, 2011). A preliminary list of 5
48 SSPs have been proposed (Arnell *et al.*, 2011; O'Neil *et al.*, 2011) and will be discussed in 5.3.4.1 and work to
49 further refine these is ongoing (Kriegler *et al.* 2012; Van Vuuren *et al.*, 2012). SSPs do not include assumptions
50 about mitigation policy and are thus independent from RCPs in the sense that the same SSP may lead to different
51 concentration levels and hence rises in sea-level depending on the level of mitigation reached (Arnell *et al.*, 2011;
52 O'Neil *et al.*, 2011).

5.3.2. Relative Sea Level Rise

Relative sea level rise poses a significant threat to coastal systems and low-lying areas around the globe leading to inundation and erosion of coastlines, 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 relative sea level rise globally. However, the subsidence of coastal land due to sediment compaction, subsurface resource extraction (e.g. groundwater, gas and petroleum; Syvitski *et al.*, 2009), glacial isostatic rebound and tectonic movement may also contribute to relative sea level rise 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 5.3.3.

5.3.2.1. Global Mean Sea Level

Although sea level change can exhibit large regional variability on different time scales from factors such as climate variability and ocean circulation patterns, it is *very likely* that over the 20th Century, global mean sea level (GMSL) rose at a mean rate between 1.5 to 1.9 mm yr⁻¹ and since 1993, at a rate between 2.8 to 3.6 mm yr⁻¹. Ocean thermal expansion and melting of glaciers have been the largest contributors, accounting for over 80% of the MSL rise over the latter period (AR5, Chapter 13). Future contributions to GMSL rise during the 21st century will *very likely* exceed the observed rate for the period 1971–2010 for all RCP scenarios. Sea levels will continue to rise beyond the 21st Century. Projections for sea levels are available for 2200 to 2500 although these 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 which relate to atmospheric GHG concentrations <500 ppm, 500-700 and > 700 ppm respectively (13.5.2). Projections of GMSL for a range of time horizons are summarized in Table 5-1.

[INSERT TABLE 5-1 HERE]

Table 5-1: Projections of global mean sea level rise in metres relative to 1986–2005 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 is given whereas for projections from 2200 onwards, the range represents the model spread due to the small number of model projections available (source: WG1, Chapter 13).]

[INSERT TABLE 5-2 HERE]

Table 5-2: Main climate-related drivers for coastal systems, their trends due to climate change, and their main physical and ecosystem effects (↑ increase; ↓ decrease; ∅ no change; ? uncertain; ↔ regional variability).]

5.3.2.2. Regional Sea Level

The impacts of 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 interdecadal time periods. For example in the equatorial Pacific, sea levels can vary from the global mean by up to 40 cm due to 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 at the coast can arise from climate and ocean dynamical processes such as changes in winds and air pressure, air-sea heat and freshwater fluxes, ocean currents and their steric properties. Changes in gravitational processes due to the redistribution of water mass and changes in the shape of the sea floor also contribute. Although the vast majority of coastlines are experiencing sea level rise, coastlines near current and former glaciers and ice sheets are experiencing sea level fall. Under RCP4.5 and 8.5, it is *very likely* that about 72% and 77% respectively of the world's coastlines will experience a sea level change that is within ±20% of the GMSL change, although some coastlines may experience a rise of up to 50% above the GMSL (AR5, Chapter 13.6).

5.3.2.3. Local Sea Level

As well as long-term vertical land movements from GIA (glacial isostatic adjustment), relative sea level rise due to subsidence of coastal plains can occur through other natural causes. For example, tectonic movements, both sustained and abrupt, have brought about relative changes of sea level. The Tohoku earthquake in 2011 caused subsidence of up to 1.2 m along ~400 km of the Pacific coast of northeast Japan. 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 relative sea level rise 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.*, 2010). 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 delta plains have subsided during the last 100 years, by up to 5 m in eastern Tokyo, 3 m in Shanghai, 2 m in Bangkok, and 3 m in the Po delta (Nicholls, 2011; Teatini *et al.*, 2011). Loads from massive buildings and other large structures can also increase sediment compaction and subsidence (Mazzotti *et al.*, 2009). Relative sea level rise can exceed GMSL rise by an order of magnitude, reaching more than 10 cm/y and it is estimated that the delta surface area vulnerable to flooding could increase by 50% under projected sea-level rise in the twenty-first century (Syvitski *et al.*, 2009).

5.3.2.4. Summary

Observed trends in mean sea level together with projected increases for 2100 and beyond means that coastal systems and low-lying areas will increasingly experience adverse impacts associated with submergence (*high confidence*). Large spatial variations in the projected sea level rise, together with local factors such as subsidence suggests that relative sea level rise can be much larger than projected GMSL and therefore is an important consideration in impact assessments (*very high confidence*).

5.3.3. Climate-related Drivers

Increasing greenhouse gases 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 erosion. On longer time scales, changes in wind and wave climate can cause changes in sediment transport at the coast that may also lead to erosion or accretion. Natural modes of climate variability, which can affect severe storm behaviour and wind and wave climate, may also undergo anthropogenic changes in the future. Ocean temperatures can affect species distribution and lead to declines in some species thereby leading to changes in coastal biodiversity. CO₂ 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. Past and future changes to these physical drivers are discussed in this section.

5.3.3.1. Severe Storms

Severe storms lead to strong winds and regions of low pressure which, over coastal seas can generate storm surges and high waves. The severity of these depends also on the storm's track, regional bathymetry and nearshore hydrodynamics. Tropical cyclones pose a significant threat to coastal population (see Box 5-2), mostly due to the

1 associated storm surge, which may combine with fresh water flooding due to extreme rainfall (Rappaport, 2000) and
2 increase the extent of coastal flooding. Extratropical cyclones (ETCs) occur throughout the mid latitudes of both
3 hemispheres and their development is linked to large-scale circulation patterns. Assessment of changes in large-scale
4 climate circulation features indicate that there has been a widening of the tropical belt, poleward shift of storm tracks
5 and jet streams and contraction of the polar vortex leading to the assessment that it is *likely* that, in a zonal mean
6 sense, circulation features have moved poleward (Chapter 2). However, both Seneviratne *et al.* (2012) and AR5
7 concluded that there is *low confidence* regarding regional changes in intensity of extratropical cyclones. With
8 regards to future changes, models tend to agree on a southward shift in the SH storm track and a global reduction of
9 ETC numbers. However there is *high confidence* that the reduction in the global number of extra-tropical cyclones
10 due to global warming will be small (less than a few percent) and hence small compared to natural interannual
11 variability. There is *high confidence* that a small poleward shift is *likely* in the Southern Hemisphere (AR5 Chapter
12 14) but changes in the Northern Hemisphere are basin specific and of *lower confidence*. There is
13 also *low confidence* in the influence on extreme events of storm track changes.

16 5.3.3.2. Extreme Sea Levels

18 Extreme sea levels arise from combinations of factors that include astronomical tides, storm surges, wind and swell
19 waves, sea level variations due to interannual variability and Tsunamis, although the latter are tectonic and therefore
20 not related to climate. The frequency of extreme sea levels will be increased by relative sea level rise. Storm surges,
21 caused by falling atmospheric pressures and surface wind stress associated with storms, may also change if storms
22 are affected by climate change.

24 Recent global (e.g. Menendez and Woodworth, 2010) and regional studies (e.g. Marcos *et al.*, 2009; Haigh *et al.*,
25 2010, Losada *et al.* 2013) have found that observed trends in extreme sea levels are mainly consistent with mean sea
26 level trends (SREX, indicating that the increasing frequency of extreme events observed so far is related to rising
27 MSL and not to changes in the behaviour of severe storms. Observations of present sea level extremes due to
28 variability of tides and storm surges have been combined with projections of MSL and their uncertainties, to
29 estimate a “sea level allowance” (Hunter, 2012; Hunter *et al.*, 2012) . Assuming that sea level extremes follow a
30 simple extreme value distribution (i.e. a Gumbel distribution), projected MSL rises of 0.542 m (the projected MSL
31 rise for 1990-2100 under an A1FI scenario) and 1.0 m require an additional allowance of 26% and 44% MSL
32 respectively to preserve the current frequency of flooding events (Figure 5-2). Such an allowance can be factored
33 into adaptive responses to rising sea levels. It should be noted however that extreme sea level distributions may not
34 follow a simple Gumbel distribution (e.g. Tebaldi *et al.* 2012) due to different factors influencing extreme levels.

36 [INSERT FIGURE 5-2 HERE

37 Figure 5-2: Results of global analysis, indicated by dot diameter. a Factor by which frequency of flooding events
38 will increase with a rise in sea level of 0.5 metres (key is left-hand column of dots in the bottom left-hand corner). b
39 Sea-level rise allowance (metres) for 1990–2100 which conserves frequency of flooding events for the IPCC A1FI
40 Projection based on A1FI emission scenario and AR4-adjusted TAR projections (normal distribution with
41 $\Delta z=0.542$ m and $\sigma=0.168$ m); key is central column of dots in the bottom left-hand corner. c Sea-level rise
42 allowance (metres) for 21st century which conserves frequency of flooding events for the 1.0/1.0 m Projection,
43 based on post-AR4 results (raised cosine distribution with $\Delta z=1.0$ m and $W/2=1.0$ m); key is right-hand column of
44 dots in the bottom left-hand corner.]

46 Several regional studies have assessed future changes to storm surges using hydrodynamic models forced by climate
47 models. Extratropical studies show strong regional variability and sensitivity to the choice GCM or RCM (e.g.
48 Debenard and Roed, 2008; Wang *et al.*, 2008; Sterl *et al.*, 2009 for the northeast Atlantic and Colberg and McInnes;
49 2012 for the southern Australian coastline. The effect of tropical cyclone changes on storm surges have also been
50 investigated in a number of regions including Australia’s tropical east coast (Harper *et al.*; 2009), Louisiana (Smith
51 *et al.*, 2010), Gulf of Mexico, (Mousavi *et al.*, 2011), India, (Unnikrishnan *et al.*; 2011) and New York (Lin *et al.*,
52 2012), and methods used and findings vary considerably between the studies. For example Mousavi *et al.*, 2011
53 developed relationships between current climate cyclone intensities and SSTs and used the projected changes in
54 SSTs from climate models to scale the cyclone intensity whereas Lin *et al.*, (2012) use the cyclones simulated in

1 four climate models that were scaled-up to realistic cyclone numbers via a synthetic cyclone approach. Lin *et al.*,
2 (2012) found that 2 of their 4 models produced changes in storm surges comparable to the projected sea level rise
3 while changes in the other two models were dominated by sea level rise. Non-linear interactions between the storm
4 surge and increased sea level conditions were also highlighted in some studies (e.g. Smith *et al.*, 2010; Mousavi *et*
5 *al.*, 2012).

6
7 The small number of regional storm surge studies combined with the different atmospheric forcing factors and
8 modelling approaches means that there is *low confidence* in projections of storm surges. However, there is *high*
9 *confidence* that extremes will increase with GMSL rise, thereby leading to large increases in the frequency of
10 extreme sea level events by the end of the 21st century (see also Chapter 13).

11 12 13 5.3.3.3. *Winds and Waves*

14
15 In the context of coasts, wind climate determines large-scale wave climate change, which in turn shapes shorelines.
16 Winds influence longshore current regimes and hence upwelling systems (Narayan *et al.*, 2010; Miranda *et al.*,
17 2012; see also Chapter 6). Energy dissipation via wave breaking contributes to beach erosion, longshore currents,
18 and elevated coastal sea levels through wave set-up and run-up. Changes to wind and wave climate therefore can
19 affect sediment dynamics and shoreline processes (e.g. Aargaard *et al.*, 2004; Reguero *et al.*, 2012) while extreme
20 winds and waves associated with storms are a threat to coastal populations. In addition to shorter period wind waves
21 longer period swell, whose energy dominates the wave energy field, poses a significant danger to coastal and
22 offshore structures, (Semedo *et al.*, 2011) and can causes flooding of coastlines with steep shelf margins (Hoeke *et*
23 *al.* 2013). The coastal impacts of wave climate change are also a function of wave direction and period as well as the
24 coastline itself, which can influence shoaling and refraction.

25
26 For observed changes in wind, Seneviratne *et al.*, (2012) concluded that there is *low confidence* in trends calculated
27 from measurements of mean and extreme winds and their causes due to the limited length of records and
28 uncertainties associated with different wind measurement techniques. However, WG1 Chapter 3 notes increasing
29 evidence for a strengthening of the wind stress field in the Southern Ocean since the early 1980s from atmospheric
30 reanalyses, satellite observations and island station data. Regional wave climate is strongly related to modes of
31 climate variability (Seneviratne, 2012) and it is *likely* that there have been positive trends in the North Atlantic,
32 North Pacific and Southern Ocean (Chapter 3, see Table 5-1).

33
34 Projected changes in mean and extreme winds and waves were assigned *low confidence* (Seneviratne *et al.*, 2012)
35 owing to limited studies. Although there has been an increase in studies addressing wave climate change (Hemer *et*
36 *al.*, 2013), generally *low confidence* remains in projected wave climate change (except for *medium confidence* over
37 the southern ocean) and this is due to uncertainties in future winds, particularly those associated with storms (see
38 also Chapter 13.7).

39 40 41 5.3.3.4. *Sea Surface Temperature*

42
43 Sea surface temperature has significantly warmed during the past 30 years along more than 70% of the world's
44 coastlines, with highly heterogeneous rates of change both spatially and seasonally (Lima and Wethey, 2012). The
45 average rate is $0.18 \pm 0.16^\circ\text{C}$ per decade and the average change in seasonal timing was -3.3 ± 4.4 days per decade.
46 These values are larger than in the global ocean where the average of change is about 0.1°C per decade in the upper
47 75 m of the ocean during the period 1970-2009 (WGI, Chap. 3) and the seasonal shift is -2.3 days per decade (Lima
48 and Wethey, 2012). Extreme events have also been reported. For example, the record high ocean temperatures along
49 the Western Australian coast during the austral summer of 2010/2011, with nearshore temperatures peaking at about
50 5°C above average, were unprecedented (Pearce and Feng, 2013). In summary, positive trends in coastal SST's are
51 seen on the majority of coastlines and the rate of rise along coastlines is higher on average than the oceans (*high*
52 *confidence, limited evidence*). Based on projected temperature increases there is *high confidence* that coastal SST's
53 exhibiting positive trends will continue to do so.

5.3.3.5. Ocean Acidification

Anthropogenic ocean acidification refers to the changes in the carbonate chemistry primarily due to the uptake of atmospheric CO₂ (Box CC-OA). Seawater pH exhibits a much larger spatial and temporal variability in coastal waters compared to open ocean due to the variable contribution of processes other than CO₂ uptake (Duarte *et al.*, 2013) such as upwelling intensity (Feely *et al.*, 2008), deposition of atmospheric nitrogen and sulphur (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, 2012) 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 ocean acidification time series exceed more than 5 years in the coastal ocean (Wootton *et al.*, 2008; Provoost *et al.*, 2010; Waldbusser *et al.*, 2010). Some exhibit considerable differences with the open ocean stations illustrating the fact that anthropogenic ocean acidification can be lessened or enhanced by coastal biogeochemical processes (Borges and Gypens, 2010; Feely *et al.*, 2010).

In more recent years, a phosphorus removal policy limited primary production which led to a decrease in pH much larger than would be expected from the absorption of atmospheric CO₂ alone (-0.016 pH unit yr⁻¹). Under the IS92a CO₂ emission scenario, the global pH (total scale) of coastal waters has been projected 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 CO₂ emission scenario Cai *et al.* (2011) projected that the overall decline in 0.74 pH between pre-industrial time and 2100 in the Northern Gulf of Mexico, a value that is much greater than in the open ocean.

To summarise, seawater pH exhibits considerable temporal and spatial variability in coastal areas compared to open ocean due 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 and droughts, complex interactions between changing levels of CO₂, plant physiology and hence evapotranspiration (e.g. Gedney *et al.*, 2006; Betts *et al.*, 2007) and other human drivers such as land-use change, water withdrawal, dam building and other engineered modifications to waterways. Such changes can have multiple effects on coastal systems. Not only are changes in the quantity and quality of runoff relevant but also the temporal distribution. Sudden pulsed discharges of freshwater arising from meltwater or storm-induced runoff into marine systems may impact ecosystems unable to deal with low-salinity water and can affect the efficiency of estuaries to retain or filter material delivered by the rivers. This can result in the delivery of riverine nutrients to coastal sea systems that would otherwise have been processed during transit. Generally higher and more variable river runoff arises from lowered retention due to land clearing (Chapter 4) such as for agricultural purposes and this also associated with increased erosion and sediment yield.

An assessment of run-off 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 gauges and of these two thirds exhibited downward trends and one third upward trends (Dai *et al.*, 2009). Precipitation changes dominate the trends, which for flow discharging into the Pacific, Indian and Atlantic Oceans, is also correlated with ENSO. Positive trends in runoff are more prevalent in the Arctic in winter and spring associated with snow melt. While precipitation change dominates freshwater flows, decreasing trends in river discharge may be further enhanced by human pressures (Dai *et al.*, 2009; Chapter 3.2.3).

Average annual runoff is generally projected to increase at high latitudes and in the wet tropics and projected to decrease in most dry tropical regions (Chapter 3). Shifts to earlier peak flows are also projected in areas affected by snowmelt. However, there are some regions where there is considerable uncertainty in the magnitude and direction

1 of change, specifically south Asia and large parts of South America. Both the patterns of change and the uncertainty
2 is largely driven by projected changes in precipitation.

3
4 To summarise, there is *medium confidence (limited evidence)* in a net declining trend in freshwater input globally
5 although large regional variability exists. Trends are dominated by precipitation changes although human pressures
6 on water supply may enhance downward trends (*medium confidence*). Uncertainty in future changes in run-off is
7 linked to precipitation uncertainty. Runoff is generally projected to increase in high latitudes with earlier peak flows
8 and in the wet tropics and decrease in other tropical regions but with large uncertainty (*medium confidence*).

11 5.3.4. Human Drivers

12
13 Coastal systems are subject to a wide range of non climate-related drivers (e.g., Crain *et al.*, 2009) the impacts of
14 which can interact with climate-related drivers and confound efforts to attribute causes of changes. Some of the
15 major human drivers, i.e. human-induced factors that directly or indirectly cause changes, are briefly reviewed
16 below.

19 5.3.4.1. Socioeconomic Development

20
21 One of the most important drivers of coastal impacts is socio-economic development (SED). The current
22 understanding of possible future SED pathways is described through a preliminary set of five shared socio-economic
23 pathways (SSPs; Arnell *et al.*, 2011; O'Neil *et al.*, 2011). The highest GDP and lowest population numbers are
24 attained under SSP1 (called "Sustainability"), which reflects a world progressing towards sustainability with
25 reduced resource intensity and fossil fuel dependency, and SSP 5 (called "Conventional Development"), which
26 reflects a world oriented toward equitable rapid fossil fuel-dominated development. GDP is lowest and population
27 highest under SSP 3 ("Fragmentation"), which reflects a world fragmented into poor regions with low resource
28 intensity and moderately healthy regions with a high fossil fuel dependency. GDP and population under SSP 4
29 (Inequality) which is a highly unequal world both within and across countries, follows a similar but less extreme
30 trend compared to SSP 3. SSP 2 (Middle of the Road) reflects a world with medium assumptions between the other
31 four SSPs.

32
33 There is *very high confidence* that SED has been one of the major drivers of increasing coastal flood damage
34 through increasing exposure (IPCC SREX) and it is expected that this will also be a major driver of climate and sea-
35 level rise impacts during the 21st century (Nicholls and Cazenave, 2010). Currently, the Low Elevation Coastal Zone
36 (LECZ) constitutes 2% of world's land area but contains 10% of world's population (600 million) and 13% of
37 world's urban population (360 million) based on 2000 estimates (McGranahan *et al.*, 2007). Although these
38 estimates are subject to uncertainties (see Lichter *et al.*, 2011; Mondal and Tatem, 2012), they are indicative of the
39 high exposure of low-lying coastal regions. About 65% of the world's cities with populations of over 5 million are
40 located in the LECZ, including a large number of small island states and densely populated mega-deltas
41 (McGranahan *et al.*, 2007). The top 10 exposed cities in terms of exposed population are Mumbai, Guangzhou,
42 Shanghai, Miami, Ho Chi Minh City, Kolkata, Greater New York, Osaka-Kobe, Alexandria and New Orleans
43 (Hanson *et al.*, 2011). In terms of assets exposed, 60% are from the USA, Japan and the Netherlands (Hanson *et al.*,
44 2011). Comparatively, Asia demonstrates the greatest exposure in terms of population, assets and productivity and
45 the largest increases in exposure through socio-economic development is expected in Asia and Africa (Dasgupta,
46 2009; Hanson *et al.*, 2011; Kebede and Nicholls, 2012).

47
48 For many locations there is *high confidence* that coastal population and assets exposure is growing faster than the
49 national average trends due to coastward migration, coastal industrialization and urbanization (e.g. McGranahan *et*
50 *al.*, 2007; Smith, 2011; Seto, 2011; WG2 Ch. 8). Coastal net migration has largely taken place in flood- and
51 cyclone-prone areas, which poses a challenge for adaptation (de Sherbinin *et al.*, 2012). These processes and
52 associated land use changes are driven by a combination of many social, economic, and institutional factors
53 including taxes, subsidies, insurance schemes, aesthetic and recreational attractiveness of the coast and increased
54 mobility (Bagstadt *et al.*, 2007; Palmer *et al.*, 2011). In China, the country with the highest exposed population,

1 urbanization and land reclamation are the major drivers of coastal land-use change (Zhu *et al.*, 2012). Although
2 coastal migration is expected to continue in the coming decades, it is difficult to capture this process in global
3 scenarios as the drivers of migration and urbanization are complex and variable (Black *et al.* 2011).

4
5 Socio-economic development also determines the future capacity to adapt. Poor people living in urban informal
6 settlements, of which there are about 1 billion worldwide, are particularly vulnerable to weather and climate impacts
7 (Handmer *et al.*, 2012; de Sherbinin *et al.*, 2012). Of the top ten nations classified by population and proportion of
8 population in coastal low-lying areas the majority are in developing countries (Bollman *et al.*, 2010). SED and
9 associated land reclamation are also major drivers of the destruction of coastal wetlands, which also makes human
10 settlements more vulnerable since wetlands act as natural buffers reducing wave and storm impacts on the coast
11 (e.g., Crain *et al.*, 2009; Shepard *et al.*, 2011). Finally, socio-economic development is expected to further
12 exacerbate a number of human pressures on coastal systems related to changes in freshwater input, water-diversion,
13 nutrients and hypoxia, which will be discussed in the following sections.

14
15 [INSERT TABLE 5-3 HERE

16 Table 5-3: Top ten nations with the largest populations and the highest proportions of population in low-lying
17 coastal areas (Countries with fewer than 100,000 inhabitants are not included; 15 SIDs (Small Island Developing
18 States) with total of 423,000 inhabitants are also excluded). Source: Bollman *et al.*, 2010.]

19 20 21 5.3.4.2. *Nutrients*

22
23 Increased nutrient (i.e. nitrogen, phosphorus) loads to coastal systems in many world regions are observed and
24 simulated by regional and global watershed models ((Alexander *et al.*, 2008; Howarth *et al.*, 1996; Seitzinger *et al.*,
25 2010). River transported anthropogenic nutrients are primarily due to increased fertilizer use for food production and
26 fossil fuel emissions (NOx) (Bouwman *et al.*, 2009; Galloway *et al.*, 2004).

27
28 Anthropogenic global loads of biologically reactive dissolved inorganic N and P (DIN, DIP) are about 2 to 3 times
29 larger than natural sources (Seitzinger *et al.*, 2010) resulting in degradation of coastal ecosystems, including
30 hypoxia. Large variations exist between rivers in the magnitude of nutrient loads and their relative sources. Future
31 trends depend on measures to optimize nutrient use in food production and minimize nutrient loss to rivers from
32 agriculture, sewage, and NOx emissions. Using the Millennium Ecosystem Assessment (MEA) scenario with little
33 emphasis on nutrient management, DIN and DIP global discharge increase by about 30% and 55%, respectively,
34 between 2000 and 2050 (Seitzinger *et al.*, 2010). In the most ambitious MEA nutrient management scenario, global
35 river DIN loads decrease slightly and DIP increases by 35%. In summary, nutrient loads have increased in many
36 regions of the world (*high confidence*).

37 38 39 5.3.4.3. *Hypoxia*

40
41 The presence of excessive nutrients in coastal waters, which causes eutrophication and the subsequent
42 decomposition of organic matter is the primary cause of decreased oxygen concentration (hypoxia). Upwelling of
43 low oxygen waters (e.g., Grantham *et al.*, 2004) and ocean warming, which decreases the solubility of oxygen in
44 seawater (Shaffer *et al.*, 2009) are secondary drivers. The oxygen decline rate is greater in the coastal rather than the
45 open ocean (Gilbert *et al.*, 2010). Hypoxia poses a serious threat to marine life, which is exacerbated when
46 combined with elevated temperature (Vaquer-Sunyer and Duarte, 2010). The number of so-called “dead zones” has
47 approximately doubled each decade since 1960 (Diaz and Rosenberg, 2008). Fisheries catches from these areas are
48 generally lower than predicted from nutrient loading alone (Breitburg *et al.*, 2009). Although non-climate
49 anthropogenic factors are responsible for virtually all hypoxia in estuaries and inner continental shelves, climate
50 drivers such as ocean warming, altered hydrological cycles and coastal currents shifts due to changes in wind
51 patterns may interact with eutrophication in the next decades (Rabalais *et al.*, 2010) (*high confidence*).

5.3.4.4. Sediment Delivery

Human activities in drainage basins and coastal plains have impacted the coastal zone by changing sediment delivery to the coast. Sediment trapping behind dams, water diversion for irrigation, and sand and gravel mining in river channels all act to decrease sediment delivery, whereas soil erosion due to land-use changes acts to increase it. In the 1950s, before widespread dam construction, the global discharge of riverine sediment was estimated to have been ~20 Gt yr⁻¹ (e.g., Syvitski *et al.*, 2005; Milliman and Farnsworth, 2011), and it has decreased to 12–13 Gt yr⁻¹ (Syvitski and Kettner, 2011). Out of 145 major rivers, only 7 showed evidence of an increase in sediment flux while 68 showed significant downward trends (Walling and Fang, 2003). Two stages of drainage basin development have been identified in patterns of sediment delivery: an increase in the early stage due to soil erosion followed by a decrease in later stages due mainly to dam construction (Syvitski, 2008). 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 with a combined storage capacity of approximately 8070 km³ (Lehner *et al.*, 2011). Human pressure is the main driver of the observed declining trend in sediment delivery to the coast (*high agreement*). Reduction of sediment delivery to the coast has impacts on river deltas, contributes to shoreline erosion and threatens mangroves and wetlands (Syvitski, 2008) whereas increase delivery due to soil erosion impacts coastal ecosystems.

5.4. Impacts, Vulnerabilities, and Risks

5.4.1. Introduction

The distinction in the meaning of the terms vulnerability and risk is often unclear in current literature (Ch. 1; SREX; WG2 Glossary), with both terms used interchangeably to describe identical methodological approaches (Hinkel, 2010; Wolf, 2011). Therefore in this chapter, literature assessing vulnerability and risk will be treated together. Diverse approaches are applied for assessing impacts, vulnerability and risk. For impacts on natural systems, the key drivers considered are temperature, ocean acidification and sea level and 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. For impacts on human systems, most approaches focus on relative sea-level rise and can be distinguished in terms of the main biophysical impacts they address (Table 5-4).

[INSERT TABLE 5-4 HERE]

Table 5-4: Main impacts of relative sea-level rise. Adapted from Nicholls 2002 and Nicholls *et al.* 2010.]

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 level of sea level rise (e.g., Dasgupta *et al.*, 2008; 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.*, 2009; 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 (Hinkel, 2012), based on either biophysical exposure or hazard variables (e.g., Yin *et al.*, 2012; Bosom and Jimenez, 2011), 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; Yoo *et al.*, 2012; Li and Li, 2012).

At local scales (10-100 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 *hydrodynamic/inundation models* (e.g., Xia *et al.*, 2011; Lewis *et al.*, 2011). *Morphodynamic models* are applied to assess impacts of RSLR on coastal erosion (Jiménez *et al.* 2009; Ranasinghe *et al.* 2012). 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, Costanza and Ruth, 1998).

1
2 For assessing the impacts of sea level rise at regional to global scales (>1000 km coastal length), heuristic, statistical
3 and economic models together with damage functions are used, as detailed process-based models are not available
4 due to data and computational limits. Global scales assessments have been conducted with the Integrated
5 Assessment Model FUND (Anthoff *et al.*, 2010) and the impact model DIVA (Hinkel and Klein, 2009). These
6 models and their results are discussed in 5.4.3.1 and 5.5.3.
7

8 In the impacts on, vulnerabilities of and risks to biophysical systems (5.4.2) and for human systems (5.4.3) are
9 covered. For biophysical systems, we start with impacts on smaller scale systems (e.g., beaches, wetlands, etc.) and
10 proceed to larger scale and compound systems (estuaries and deltas). For human systems, we start with impacts on
11 human settlements as a whole followed by impacts on key sectors that support human settlements. Where possible,
12 all subsections address drivers, observed and projected changes.
13

14 15 **5.4.2. Natural Systems**

16 Coastal ecosystems are experiencing large cumulative impact of human activities (Halpern *et al.*, 2008) arising from
17 both land- and ocean-based anthropogenic drivers. Anthropogenic drivers associated with global climate change are
18 distributed widely and are an important component of cumulative impacts experienced by coastal ecosystems. There
19 are few wetlands, mangroves, estuaries, rocky shores or coral reefs that are not exhibiting some degree of impact.
20 Overexploitation and habitat destruction are often the primary causes of historical changes in coastal systems and
21 eutrophication has largely followed rather than driven observed declines in diversity, structure, and functioning
22 (Lotze *et al.*, 2006). Further, extreme climate events generate changes to both the mean and the variance of climatic
23 variables over ecological time scales.
24
25

26 27 **5.4.2.1. Beaches, Barriers, and Sand Dunes**

28
29 Beaches, barriers and sand dunes constitute about one-third of world's coasts. These dynamic systems often exhibit
30 distinct diurnal and seasonal changes. Due to their attractive attributes, they are highly valued for their recreational
31 and residential value.
32
33

34 **Observed impacts**

35
36 Globally beaches and dunes have in general undergone net erosion over the past century or longer (e.g. see Bird,
37 2000 for an overview). This erosion is due to a variety of processes with some climate related: rising sea levels
38 (Ranasinghe and Stive, 2009); increases in the frequency of extreme water levels with sea-level rise (Tebaldi *et al.*,
39 2012); wave propagation caused by sea-level changes realigning shorelines (Tamura *et al.*, 2010); sustained changes
40 in the direction of mean wave energy (Reguero *et al.*, 2013); increased storm waves (Stutz and Pilkey, 2011) and
41 changes in the loss of natural protective structures such as coral reefs (Greville and Mimura, 2008) or mangrove
42 forests (Bongaerts *et al.*, 2010). These processes may act at different time scales.
43

44 Reasonably accurate maps have been available since about the mid-19th century to compare with more recent maps
45 and imagery to quantify combined climate and non-climate changes. For example, along the U.S. Mid-Atlantic and
46 New England coasts the long-term rate of erosion is 0.5 ± 0.09 m yr⁻¹ and 68% showed net erosion based on over
47 21,000 measurement locations equally spaced along more than 1,000 km of coast (Hapke *et al.*, 2011). However, a
48 survey using historical aerial photographs and satellite images of 27 atoll islands in the central Pacific showed that
49 86% of the islands have remained stable or increased in area over a 19 to 61 year period, contradicting the
50 widespread perception that small islands are eroding with sea-level rise (Webb and Kench, 2010).
51

52 Attributing shoreline changes to climate change is still difficult due to the multiple natural and anthropogenic drivers
53 contributing to coastal erosion. For example, rotation of pocket beaches (i.e. where one end of the beach accretes
54 while the other erodes and then the pattern reverses) of Southeast Australia is closely related to interannual changes

1 in swell direction (Harley *et al.*, 2010). Additional processes, unrelated to climate change, that contribute to coastal
2 change, include dams capturing fluvial sand (e.g., in Morocco, Chaibi and Sedrati, 2009). Statistically linking sea-
3 level rise to observed magnitudes of beach erosion has been challenging as the coastal sea-level change signal is
4 small relative to other processes (e.g. Sallenger *et al.*, 2000; Leatherman *et al.*, 2000a; 2000b). A Bayesian network
5 incorporating a variety of factors affecting coastal change including relative sea-level rise, has been successful in
6 hindcasting shoreline change, and, hence, may be useful in forecasting change (Gutierrez *et al.*, 2011).

7
8 One observed impact of net erosion is clear. Where an eroding shoreline approaches hard, immobile, structures like
9 seawalls or resistant natural cliffs, the beaches will narrow due to coastal squeeze that removes the sands and
10 associated habitats, and potentially steepens the beach slope, impacting the survivability of a variety of organisms
11 (Jackson and McIlvenny, 2011). With coastal squeeze, sand dunes will ultimately be removed as the beach erodes
12 and narrows. Extreme storms can erode and completely remove dunes, degrading land elevations and exposing them
13 to inundation and further change if recovery does not occur before the next storm (Plant *et al.*, 2010).

14 15 16 *Projected impacts*

17
18 Projected sea-level rise may approach 1 m or more by 2100, and in the intervening time the resulting inundation and
19 erosion may become detectable and progressively important. The impacts will *likely* be first apparent by sea-level
20 rise adding to storm surge, making extreme water levels higher and more frequent to attack beaches and dunes
21 (Tebaldi *et al.*, 2012).

22
23 Some investigators have used the Bruun rule to calculate erosion by sea-level rise (Bruun, 1962), although there is
24 disagreement about whether the Bruun rule is appropriate (Cooper and Pilkey, 2004; Woodroffe and Murray-
25 Wallace 2012). How to calculate the amount of retreat remains controversial (Gutierrez *et al.*, 2011; Ranasinghe *et*
26 *al.*, 2012). An increase in storm intensity and ocean swell may accelerate erosion of beaches, barriers and dunes
27 although in places beach response to sea-level rise could be more complex than simple retreat (Irish *et al.*, 2010).

28
29 Coastal squeeze will *likely* accelerate with a rising sea level. In many locales, locating sufficient sand to artificially
30 rebuild beaches and dunes will *likely* become increasingly difficult as present supplies near to project sites are
31 depleted. New generation models are emerging to estimate the costs of saving oceanfront homes through beach
32 nourishment relative to the structures cost (McNamara *et al.*, 2011). In the absence of adaptation measures, beaches
33 and sand dunes currently affected by erosion will continue to do so under increasing sea levels (*high confidence*).

34 35 36 *5.4.2.2. Rocky Shores*

37
38 According to Davis and FitzGerald (2004) three-quarters of the world's coasts are rocky. They vary from
39 consolidated sediments (lithified coasts) to unconsolidated sediments (unlithified coasts), with different strengths
40 and typically having an abrasional shore platform at their base. They are characterized by very strong environmental
41 gradients, especially in the intertidal zone where challenges are posed by both aquatic and aerial climatic regimes,
42 such as temperature and desiccation

43 44 45 *Observed impacts*

46
47 Cliffs and platforms are erosional features and any change in the climate system that increases the efficiency of
48 processes to act on them, such as relative sea level rise will lead to increased rates of erosion (Naylor *et al.*, 2010).
49 Other significant climate drivers include mid-latitude storminess, wave climate and rainfall regime on cliff dynamics
50 and retreat rates (Brooks and Spencer, 2012). Precipitation and frost appear to have a limited role in cliff retreat
51 (Dornbusch *et al.*, 2008).

1 Cliffs and platforms have reduced resilience to climate change impacts; once platforms are lowered or cliffs retreat,
2 it is difficult to rebuild them (Naylor *et al.*, 2010). For cohesive clay coasts, rising sea level will usually result in
3 accelerated rates of bluff recession, especially if the rise is rapid (Trenhaile, 2010).

4
5 Changes in the abundance and distribution of rocky shore animals and algae in rocky shores have long been
6 recognized (Hawkins *et al.*, 2008) and perturbation experiments provided information about environmental limits,
7 acclimation and adaptation, particularly to changes in temperature (Somero, 2012). The challenge is to distinguish
8 the response that are due to climatic drivers from those due non-climatic drivers, or to natural temporal and spatial
9 fluctuations.

10
11 Helmuth *et al.* (2006) reported shifts of range limits of many intertidal species of up to 50 km per decade, much
12 faster than most recorded shifts of terrestrial species. However, the geographical distribution of some species has not
13 changed in recent decades, may be due to weak local warming (Rivadeneira and Fernández, 2005) or overriding
14 effects of variables such as timing of low tide, hydrographic features, lack of suitable substrata, poor larval dispersal,
15 and effects of food supply, predation and competition (Helmuth *et al.*, 2002, 2006; Poloczanska *et al.*, 2011).

16
17 The dramatic decline of biodiversity in mussel beds of the Californian coast, with a 59% loss in species richness
18 between the 1960s and 2002, has been attributed to large-scale processes associated with climate change (*high*
19 *confidence*; Smith *et al.*, 2002). A strong impact of temperature and food availability was shown in mussels on the
20 coast of Oregon, with higher growth during warm than cool events (Menge *et al.*, 2008). Warming also reduced
21 predator-free space on rocky shores, which lead to a decrease of the vertical extent of mussel beds by 51% in 52
22 years in the Salish Sea, and the disappearance of reproductive populations of mussels at several sites, illustrating the
23 alteration of interspecific interactions by climate change (Harley, 2011).

24
25 Rocky shores are one of the few ecosystems for which field evidence of the effects of ocean acidification is
26 available. Observational and modeling analysis have shown that the community structure of a rocky shore site of the
27 NE Pacific shifted from a mussel to an algal-barnacle-dominated community between 2000 and 2008 (Wootton *et al.*,
28 2008), in relation with rapidly declining pH (Wootton and Pfister, 2012).

30 31 *Projected impacts*

32
33 Based on contemporary and historic data for shoreline retreat the major driver appears to be sea-level rise (Brooks
34 and Spencer, 2012). Soft-rock recession rates can be estimated by using square root of the relative change in sea-
35 level rise rate while cliff retreat depends not only on total elevation change of sea level but also on the rate of sea-
36 level rise (Ashton *et al.*, 2011).

37
38 In a modelling study, Trenhaile (2011) found sea-level rise to trigger faster rates of cliff recession, especially in
39 coasts that are already retreating fast. However, results further suggested that coasts currently retreating slowly
40 would experience the largest proportional increases in retreat rates. Increases in storminess appear to have smaller
41 effects on rocky shores (Trenhaile, 2011; Dawson *et al.*, 2009). Using existing topographical data and a digital
42 elevation model, the intertidal areas of rocky shore in Scotland are estimated to decrease by 10-27% with a 0.3 sea-
43 level rise (Jackson and MacIlvenny, 2011).

44
45 Most projections of the effect of climate change on rocky shore ecosystems have used a climate envelope approach
46 using environmental tolerances obtained in laboratory perturbation experiments and assuming that species will
47 remain in their bioclimatic envelope as climatic stressors change. Few have considered the effects of direct and
48 indirect species interactions (Poloczanska *et al.*, 2008; Harley *et al.*, 2011) and the effects of multiple stressors
49 (Helmuth *et al.* 2006).

50
51 The abundance and distribution of rocky shore species will continue to vary in a warming world (*high confidence*).
52 The likely long-term consequences of ocean warming on mussel beds of the NE Pacific are both positive (increased
53 growth) and negative (increased susceptibility to stress and of exposure to predation)(*medium confidence*; Smith *et*

1 *al.*, 2002; Menge *et al.*, 2008). Importantly, these projections are conservative as they do not consider hypoxia
2 (Grantham *et al.*, 2004) or ocean acidification (Feely *et al.*, 2008) which is known to occur in this area.
3

4 Despite some shortcomings (Riebesell, 2008), observations performed near natural CO₂ vents in the Mediterranean
5 Sea show that diversity, biomass, and trophic complexity rocky shore communities will decrease at future pH levels
6 (*high confidence*; Barry *et al.*, 2011; Kroeker *et al.*, 2011). An abundant food supply tolerance appears to enable
7 mussels of the Baltic Sea to tolerate low pH (Thomsen *et al.*, 2010, 2012) at the cost of increased energy
8 expenditure. Model projections that assume a linear increase in temperature and ocean acidity, and include the
9 interactive effects of temperature and pH suggests that a local population of a barnacle will become extinct in the
10 English Channel 10 years earlier than would occur if there was only global warming and no concomitant decrease in
11 pH (*medium confidence*; Findlay *et al.*, 2010).
12

13 Rising sea level is the major driver for rocky shores retreat (*robust evidence*). With coral reefs, rocky shores are the
14 coastal ecosystem for which there is most evidence of the impacts of climate change. The most prominent effects are
15 range shifts of species in response to ocean warming (*high confidence*) and changes in biodiversity (*high*
16 *confidence*) in relation to ocean warming and acidification.
17

18 5.4.2.3. Wetland and Seagrasses Beds

19 Vegetated coastal habitats, including mangrove forests, salt marshes, seagrass meadows and macroalgal beds occur
20 as a thin vegetation belt fringing the shoreline (Hemminga and Duarte 2000). Coastal wetlands are prominent
21 features and important habitats in the intertidal zone along the coastline, including mangrove forests and tidal
22 marshes. Seagrass meadows and macroalgal beds extend from the intertidal to the subtidal areas in coastal areas.
23
24
25

26 *Observed impacts*

27 Mangrove forests, salt marshes and seagrass meadows are declining globally (Duarte *et al.*, 2005), rendering
28 shorelines more vulnerable to erosion due increased sea level rise and increased wave action (e.g., Alongi, 2008) and
29 leading to the loss of carbon stored in sediments. Together, the loss of coastal wetlands and seagrass meadows
30 results in the release of 0.04 to 0.28 Pg C annually from organic deposits (Pendleton *et al.* 2012).
31

32 Recognition of the important consequences of the loss of mangrove forests, salt marshes and seagrass meadows for
33 coastal protection and carbon burial, has led to large-scale reforestation efforts in some nations (e.g. Thailand, India,
34 Vietnam).
35

36 The response of saltmarsh to sea level rise involves landward migration of salt marsh vegetation zones and
37 submergence at lower elevations and drowning of interior marshes. Ocean warming is leading to range shifts in
38 vegetated coastal habitats. The poleward limit of mangrove forests is generally set by the 20 °C mean winter
39 isotherm (Duke *et al.*, 1998). Accordingly, migration of the isotherm with climate change (Burrows *et al.*, 2011)
40 should lead to a poleward expansion of mangrove forests, as observed in the Gulf of Mexico (Perry and
41 Mendelssohn, 2009; Comeaux *et al.*, 2011, Raabe *et al.* 2012), and New Zealand (Stokes *et al.*, 2010), where it leads
42 to increased sediment accretion (*medium confidence*).
43
44

45 Seagrass meadows are already under stress due to climate change (*high confidence*), particularly where maximum
46 temperatures already approach their physiological limit. Heat waves lead to widespread seagrass mortality, as
47 documented for *Zostera* species in the Atlantic (Reusch *et al.*, 2005), and *Posidonia* meadows in the Mediterranean
48 Sea (Marbà and Duarte, 2010) and Australia (Rasheed and Unsworth, 2011) (*high confidence*). Warming also
49 favours flowering of *P. oceanica* (Diaz-Almela *et al.*, 2007), but the increased recruitment rate is insufficient to
50 compensate for the losses resulting from elevated temperature (Diaz-Almela *et al.*, 2009).
51

52 Kelp forests have been reported to decline in temperate areas in both hemispheres (Johnson *et al.* 2011, Wernberg *et al.*
53 2011a,b, Fernández *et al.* 2011), a loss believed to involve climate change (*high confidence*). Decline in kelp
54 populations attributed to ocean warming has been reported in southern Australia (Johnson *et al.* 2011, Wernberg *et*

1 *al.* 2011a,b) and the North Coast of Spain (Fernández *et al.* 2011). The spread of subtropical invasive macroalgal
2 species is believed to be facilitated by climate change, adding to the stresses temperate seagrass meadows
3 experience from ocean warming (*medium evidence, high agreement*).

4 5 6 *Projected impacts*

7
8 Ocean acidification (5.3.34; Box CC-OA) is expected to enhance the production of seagrass (Duarte, 2000, McKee
9 *et al.* 2012) and macroalgae (Wu *et al.*, 2008) through the fertilization effect of CO₂. Increased CO₂ concentrations
10 may have already increased seagrass photosynthetic rates by 20% (Hemminga and Duarte, 2000; Hendriks *et al.*,
11 2010) (*limited evidence, high agreement*).

12
13 Coupling of downscaled model projections using the A1B scenario in the Western Mediterranean along with
14 empirically-determined relationships between mortality rates and maximum seawater temperature led Jordá *et al.*
15 (2012) to conclude that seagrass, *Posidonia oceanica*, meadows may become functionally extinct by 2050 to 2060
16 (*high confidence*). Poleward range shifts in vegetated coastal habitats is expected to continue with climate change
17 (*high confidence*). Reduced ice cover and retreat of coastal glaciers may facilitate the expansion of seagrass
18 meadows and kelp forests along the Arctic (Krause-Jensen *et al.* 2012; *medium confidence*), with cascading effects
19 on the coastal Arctic ecosystem (Krause-Jensen *et al.* 2012).

20
21 Elevated CO₂ and ocean acidification are expected to lead to increased productivity of vegetated coastal habitats in
22 the future (Duarte *et al.* 2000) (*high confidence*). However, there is *limited evidence* that elevated CO₂ may increase
23 seagrass survival or resistance to warming (Alexandre *et al.*, 2012; Jordá *et al.*, 2012).

24
25 Coastal wetlands and seagrass meadows experience coastal squeeze in urbanized coastlines, with no opportunity to
26 migrate inland with rising sea levels. However, increased CO₂ and warming can stimulate marsh elevation gain,
27 counterbalancing moderate increases in rates of sea-level rise (Langley *et al.*, 2009; Kirwan and Mudd, 2012). The
28 net impact of climate change on salt-marsh accretion will be to increase carbon burial rates in the first half of the
29 twenty-first century, with carbon–climate feedbacks diminishing over time (Kirwan and Mudd, 2012) (*medium*
30 *confidence*).

31
32 In summary, climate change will significantly contribute to the continued decline in the extent of seagrass and kelps
33 in the temperate zone (*medium confidence*) and the range of seagrass, mangroves and kelp in the northern
34 hemisphere will expand poleward (*high confidence*). The limited positive impact of warming and increased CO₂ on
35 some vegetated ecosystems will be insufficient to compensate the decline of their extent resulting from other human
36 drivers such as land use change (*very high confidence*).

37 38 39 5.4.2.4. Coral Reefs

40
41 Coral reefs are shallow-water structures made of calcium carbonate mostly secreted by reef-building corals and
42 encrusting macroalgae. They are among the most diverse ecosystems and are sources of many benefits through key
43 services provided to humans.

44 45 46 *Observed impacts*

47
48 Coral reefs are susceptible to climate-related and non climate-related processes (see Box CC-CR). Mass coral
49 bleaching has occurred in association with positive temperature anomalies over the past 30 years, sometimes
50 followed by mass mortality (Hoegh-Guldberg, 1999; Kleypas *et al.*, 2008; Baker *et al.*, 2008). Bleaching events are
51 variable in time and space: 7% of the grid cells comprising reefs exhibited at least one bleaching event in 1985-1994
52 compared to 38% in the subsequent decade due to intense El Niño events. Recovery from the 1998 global bleaching
53 event was generally slow in the Indian Ocean (about 1% yr⁻¹), absent in the western Atlantic and variable elsewhere
54 (Baker *et al.*, 2008).

1
2 Warming causes a poleward range expansion of some corals (*high confidence*; Greenstein and Pandolfi, 2008;
3 Yamano *et al.*, 2011). The paleontological record suggests that the observed poleward range extension may soon be
4 followed by equatorial range retractions (Kiessling *et al.*, 2012). Several reef crises of the last 500 Myr were at least
5 partially governed by ocean acidification and warming (Kiessling and Simpson, 2011). Ocean acidification (5.3.3.5,
6 Box CC-OA) has become a recent source of concern because persistence of coral reefs directly depends on the
7 balance between the production and erosion of calcium carbonate (Andersson and Gledhill, 2013). It generally
8 decreases calcification (Kroeker *et al.*, in press) and promotes dissolution of calcium carbonate and bioerosion
9 (Tribollet *et al.*, 2009; Wisshak *et al.*, 2012), leading to a transition from net accretion to net erosion and to poorly
10 cemented reefs (Manzello *et al.*, 2008).

11
12 Lower pH decreases calcification in many reef-building corals and coralline algae (Andersson *et al.*, 2011) and may
13 have already decreased (e.g., Gattuso *et al.*, 1999; Silverman *et al.*, 2009) and most (e.g., De'ath *et al.*, 2009,
14 Manzello, 2010) retrospective studies show decreased calcification in recent decades. Attribution has proven
15 difficult but warming rather than acidification appears to be the primary driver (*medium confidence*; Cooper *et al.*,
16 2012).

17
18 Climate-related drivers other than ocean warming and acidification do not seem to have led to any obvious changes
19 since the industrial revolution (*high confidence*). Coral reef growth is intimately linked to sea level but, within the
20 uncertainties of past sea level rise and coral reef growth, most coral reefs seem to have kept pace with the recent sea-
21 level rise (Buddemeier and Smith, 1988).

22 23 24 *Projected impacts*

25
26 The frequency and magnitude of coral bleaching and mortality will increase in the next few decades (*very high*
27 *confidence*; Hoegh-Guldberg, 1999; Donner *et al.*, 2009; Chapter 30, 30.8.2). Under the A1B CO₂ emission
28 scenario, 99% of the grid cells experience at least one severe bleaching event over 2090-2099 (Figure 5-3; Teneva *et*
29 *al.*, 2011). Half of the coral reefs may avoid high frequency bleaching through 2100 assuming hypothetical
30 acclimation and/or adaptation (*limited evidence, low agreement*; Logan *et al.*, sbm).

31
32 [INSERT FIGURE 5-3 HERE

33 Figure 5-3: Percent of reef locations (1°x1° grid cells which have coral reefs) that experience no bleaching, at least
34 one mild bleaching event, or at least one severe bleaching event for each decade. Observed bleaching events are
35 summarized from the ReefBase dataset (Kleypas *et al.* 2008). In the observations, some of the “no bleaching” cells
36 may have experienced bleaching but it was either not observed or not reported. Modeled bleaching events are
37 averages of data from four ensemble runs of the Community Climate System Model version 3 using the SRES A1B
38 CO₂ scenario and the standard degree heating month formula (Teneva *et al.*, 2011). The labels of values ≤ 1% are
39 not shown.]

40
41 Ocean acidification reduces biodiversity and favours seagrasses and fleshy algae against corals (Fabricius *et al.*,
42 2011). Since the effects of elevated temperature and acidity are synergistic in several reef-builders (Reynaud *et al.*,
43 2003; Anthony *et al.*, 2008), their combined impact may be larger than those observed near CO₂ vents today (*high*
44 *confidence*). Ocean warming and acidification expected under RCP 8.5 will reduce calcification, elevate coral
45 mortality and enhance sediment dissolution (*high confidence*; Manzello *et al.*, 2008). Coral reefs may stop growing
46 and start dissolving when atmospheric CO₂ reaches 560 ppm due to the combined effects of both drivers (*medium*
47 *evidence*; Silverman *et al.*, 2009).

48
49 The maximum rate of vertical accretion has been variable regionally during the last deglaciation (about 20 mm yr⁻¹;
50 Dullo, 2005; Montaggioni *et al.*, 2005) and has not enabled all coral reefs to keep-up with sea level rise. Some reefs
51 kept-up, even when the eustatic sea level rise exceeded 40 mm yr⁻¹ (Camoin *et al.*, 2012). Therefore, a number of
52 coral reefs could keep up with the maximum rate of sea level rise of 15.1 mm yr⁻¹ projected at the end of the century
53 (WGI, Table 13.5; *medium confidence*). A lower net accretion than during the Holocene, as reported for Caribbean

1 reefs (Perry *et al.*, 2013) weaken this capability. *high confidence* Reef submergence would increase turbidity leading
2 to increased stress (Storlazzi *et al.*, 2011).

3
4 In summary, climate-related drivers are the primary cause of mass coral bleaching and mortality (*very high*
5 *confidence*) and deteriorate the balance between coral reef construction and erosion (*high confidence*). The future
6 magnitude of these effects will depend on the rates of warming and acidification (*very high confidence*), with a
7 moderating role of biological acclimation and adaptation which appears limited (*medium confidence*).

10 5.4.2.5. Coastal Aquifers

11
12 A coastal aquifer is an underground layer of water-bearing permeable rock or unconsolidated materials from which
13 groundwater can be extracted. Consequently, they are of strategic importance for the water supply of highly
14 populated coastal areas, especially in small islands (Chap. 29, 29.3).

17 *Observed impacts*

18
19 Coastal aquifers are very sensitive to a range of climate and non climate-related drivers. Temperature and
20 evaporation rise, changes in precipitation and extended droughts that affect aquifer recharge are some of the factors
21 that can contribute to displacement of fresh groundwater by more saline water. Rising sea levels and partial or
22 complete overwash from storm waves or storm surge are also relevant drivers, especially in low-lying areas and
23 islands (Terry and Falkland, 2010, White and Falkland, 2010, Post and Abarca, 2010).

24
25 Combined with this, excessive groundwater extraction for coastal settlements and agriculture causes intrusion of
26 saline water from the ocean or from deeper, more saline layers below the aquifer. For example, coastal aquifers on
27 the east and west coasts of the US have experienced increased levels of salinity largely due to excessive
28 anthropogenic water extraction (Barlow and Reichard, 2011). The combination of natural with anthropogenic drivers
29 of over-extraction, pollution, mining for building and erosion due to shoreline works compound groundwater supply
30 problems in small tropical islands in the Pacific, Indian and Atlantic Oceans (White *et al.*, 2007; White and
31 Falkland, 2010). Detailed information on salinization observations in small islands can be found in Chapter 29.

32
33 Attribution of saline intrusion to incremental sea level rise is still not sufficiently supported (Rozell and Wong,
34 2010; White and Falkland 2010). In small islands, observed saltwater intrusion due to flooding and overwash under
35 storm events cannot be attributed to climate change (Chap. 29). Furthermore, Werner (2010) noted that there are
36 fundamental knowledge gaps that impede assessment of changes in seawater intrusion, which are mostly due to
37 uncertainties in the predictive capabilities of the models, limitations in the assessment of small-scale processes and
38 difficulties in characterizing the marine-groundwater interactions.

41 *Projected impacts*

42
43 The assessment of climate change impacts that may arise from changes in ground water recharge and sea level rise is
44 still challenging, limiting the work currently available on climate change projected impacts on coastal aquifers.
45 Rozell and Wong, 2010 assessed the impact of rising sea levels on fresh water resources on Shelter Island (USA) for
46 two different combinations of precipitation change and sea level rise. Results show that projected impacts were
47 highly dependent on local conditions. Based on a simplified analytical model Ferguson and Gleeson (2012)
48 concluded that the direct impact of groundwater extraction has been and will be much more significant than the
49 impact of sea level rise under a wide range of hydrogeologic conditions and population densities.

50
51 In summary, there is *very high confidence* that increased usage of groundwater resources for agriculture and coastal
52 settlements globally has led to a reduction in groundwater quality, including increased salinization (*high agreement*,
53 *robust evidence*). Human-induced pressure will continue to be the main driver for aquifer salinization (*high*

1 *agreement*). Climate change through changing patterns of precipitation, increased storminess and sea level rise will
2 exacerbate these problems (*high agreement, limited evidence*).
3
4

5 5.4.2.6. Estuaries and Lagoons 6

7 Coastal lagoons are shallow water bodies separated from the ocean by a barrier and connected at least intermittently
8 to the ocean, while estuaries are the primary conduit for water, nutrients and particulates from land to the sea.
9

10 11 *Observed impacts* 12

13 Sediment accumulation in estuaries is generally very high because of riverine particle delivery but heterogeneous
14 and habitat-specific. Changes in sediment accumulation is directly affected by human drivers, such as dredging, and
15 indirectly via habitat loss, changes in sea-level, storminess and sediment supply by rivers (Syvitski *et al.*, 2005).
16 Coastal lagoons are also highly susceptible to alterations of sediment input and erosional processes driven by
17 changes in sea level, precipitation, and storminess (Pickey and Young, 2009). Estuarine water with low tidal range
18 are strongly affected by changes in run-off since the residence time depends on the relative strengths of runoff and
19 tidal forcing and governs many ecosystem processes including nutrient processing, the metabolic balance, carbon
20 dioxide exchange and hypoxia (Howarth *et al.*, 2009; Canuel *et al.*, 2012). River floods and other runoff events have
21 been reported to impact estuarine communities and deliver large quantities of organic matter to coastal systems,
22 controlling the cycling of organic matter and nutrients (Canuel *et al.*, 2012; Statham, 2012).
23

24 Enhanced nutrient delivery (5.3.4.3) has resulted in major changes in biogeochemical processes, community
25 structure and ecosystem functions (Howarth *et al.* 2009), including enhanced primary production which has affected
26 coastal fishery yield (Nixon, 1982; Savage *et al.*, 2012). Eutrophication has modified food-web structure (*high*
27 *confidence*) and led to more intense and longer lasting hypoxia (5.3.4.4), more frequent occurrence of harmful algal
28 blooms (*high confidence*; Breitburg *et al.*, 2009; Howarth *et al.*, 2009) and to enhanced emission of nitrous oxide
29 (*high confidence*; Kroeze *et al.*, 2010; de Bie *et al.*, 2002).
30
31

32 *Projected impacts* 33

34 The increase of atmospheric carbon dioxide levels will reduce the efflux of CO₂ from estuaries (Borges, 2005; Chen
35 and Borges, 2009; *high confidence*). Its impact on the pH of estuarine and lagoon waters will generally be limited
36 because other drivers are generally more important (*high confidence*; 5.3.3.4 and Box CC-OA). For example, recent
37 changes in the freshwater flow in the Scheldt estuary was the main factor controlling pH, either directly via a
38 decreased supply of dissolved inorganic carbon and total alkalinity, and, indirectly, via the decreased input ammonia
39 loadings and lower rates of nitrification (Hofmann *et al.*, 2009).
40

41 Sea-level rise will have likely impact sediment redistribution, the partitioning of habitats within estuaries and
42 landward lagoon extension (*high confidence*; Anthony *et al.*, 2009) Lagoons may shrink because landward migration
43 is restricted due to human occupation on the landward side (Pilkey and Young, 2009; Anthony *et al.*, 2010; Stutz
44 and Pilkey, 2011).
45

46 Changes in hydrology could affect lagoons and estuaries in multiple ways. The water residence time could either
47 increase or decrease, depending on direction and magnitude of changes in discharge and precipitation-evaporation
48 balance (Anthony *et al.*, 2009) with diverging impacts on primary production, fisheries and aquaculture (Smith *et*
49 *al.*, 2005b; Webster and Harris, 2004; Canu *et al.*, 2010). Altered riverine discharge may affect estuarine
50 stratification with consequences for ecosystem metabolic balances, intensity and occurrence of biogeochemical
51 processes, organism distribution patterns and frequency and duration of hypoxia (Hong and Shen, 2012; Rabalais *et*
52 *al.*, 2009). However, stronger winds and droughts may reduce the extent, duration and frequency of estuarine
53 stratification, counteracting the decrease in oxygen concentration (*medium confidence*; Rabalais *et al.*, 2009).
54 Changes in precipitation extremes and freshwater supply may induce dramatic fluctuations in salinity with

1 associated diverse impacts on benthic macrofauna and ecosystem functions (Pollack *et al.*, 2011; Levinton *et al.*,
2 2011; Fujii and Raffaelli, 2008; Jeppesen *et al.*, 2007).

3
4 Warming will lead to enhanced stratification of estuaries and lagoons, increasing hypoxia (*medium confidence*; Diaz
5 and Rosenberg, 2008; Rabalais *et al.*, 2009). It will also directly affect most biological processes and the trophic
6 status of coastal ecosystem, and higher carbon dioxide emission (*limited evidence, medium agreement*; Canuel *et al.*,
7 2011). Warming will lengthen the duration of phytoplankton production season (Cloern and Jassby, 2008; *medium*
8 *confidence*).

9
10 Changes in storm events would alter the extent and duration of estuarine stratification (Hong and Shen, 2012), the
11 sediment deposition-erosion balance of lagoons and estuaries (Pilkey and Young, 2009), the structure and
12 functioning of biological communities via the transport of communities and/or of their resources, and the underwater
13 light climate (*medium confidence*; Wetz and Paerl, 2008; Canuel *et al.*, 2012).

14
15 Finally, any change in the primary production of lagoons will impact fisheries as there is an empirical correlation
16 between primary production and fisheries yield (*limited evidence, medium agreement*; Nixon, 1982). For example,
17 seawater warming and changes in seasonal patterns of precipitations projected in the Venice lagoon using the SRES
18 A2 CO₂ emission scenario for the period 2071-2100, leads to a reduction in plankton production, a decline of habitat
19 suitability for clam growth and aquaculture (Canu *et al.*, 2010).

20
21 In summary, the primary drivers of change in lagoons and estuaries are human drivers rather than climate change
22 (*very high confidence*). Future changes in climate-related drivers such as warming, acidification, waves, storms, sea
23 level and run-off will have consequences on the functions and services of ecosystems in lagoons and estuaries (*high*
24 *confidence*) but the impacts cannot be assessed at the global scale as the key drivers operate at a local to regional
25 scale.

26 27 28 5.4.2.7. Deltas

29
30 Deltas are low-lying coastal landforms formed by riverine sediments in the areas around river mouths, mostly during
31 the last 6000–7000 years of relatively stable sea level. They are characterized by interplay between rivers, lands, and
32 oceans and are influenced by a combination of river, tidal, and wave processes. Deltas are a coastal complex that
33 combines natural systems in diverse habitats (e.g., tidal flats, salt marshes, mangroves, beaches, estuaries, low-lying
34 wetlands) and human systems (e.g., houses, agriculture, aquaculture, industry, and transport). They have a
35 population density more than 10 times the world average (Ericson *et al.*, 2006; Foufoula-Georgiou *et al.*, 2011). As
36 low-lying plains, deltas are highly sensitive to changes in sea level. Deltas are subject to climatic impacts from
37 rivers upstream (e.g., freshwater input) and oceans downstream (e.g., sea-level changes, waves) as well as within the
38 deltas themselves. At the same time, they are affected by human activities such as land-use changes, dam
39 construction, irrigation, mining, extraction of subsurface resources, and urbanization (Nicholls *et al.*, 2007).

40 41 42 *Observed impacts*

43
44 The combined impact of sediment reduction, relative sea-level rise, land-use changes in deltas, and river
45 management on channels and banks has led to the widespread degradation of deltas (*very high confidence*).
46 Decreased sediment discharge due to dam construction and irrigation creates an imbalance in sediment budget in
47 coastal zones. Degradation of beaches, mangroves, tidal flats, and subaqueous delta front along deltaic coasts has
48 been reported in many deltas (*very high confidence*)(e.g., Nile and Ebro, Sanchez-Arcilla *et al.*, 1998; Po, Simeoni
49 and Corbau, 2009; Krishna-Godavari, Nageswara Rao *et al.*, 2010; Changjiang, Yang *et al.*, 2011; Huanghe, Chu *et*
50 *al.*, 1996). Deltaic coasts naturally evolve by seaward migration of the shoreline, forming a delta plain; however,
51 decreasing sediment discharge during the last 50 years has decreased the growth of deltaic land, even reversing it in
52 some locations (e.g., Nile, Godavari, Huanghe). Artificial reinforcement of natural levees also has reduced the
53 interdistributary basin sedimentation in most deltas, resulting in wetland loss.

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

10
11 Deltas are substantially impacted by river floods and oceanic storm surges and tsunamis (*very high confidence*).
12 Tropical cyclones are noteworthy for their damages to deltas, e.g., the Mississippi delta by Hurricane Katrina in
13 2005 (Barras *et al.*, 2006), the Irrawaddy delta by Cyclone Nargis in 2008, and the Ganges-Brahmaputra delta by
14 Cyclone Gorky in 1991 and Cyclone Sidr in 2007 (Murray *et al.*, 2012)(Box CC-TC). A detailed study of 33 deltas
15 around the world found that 85% of the deltas had experienced severe flooding in the past decade, causing the
16 temporary submergence of 260,000 km² (Syvitski *et al.*, 2009).

17 18 19 *Projected impacts*

20
21 The projected natural impacts on deltas under changing global climate are caused mainly by extreme- precipitation
22 induced floods, sea-level rise, and accompanying changes of waves and storm surges. These will result in increased
23 coastal flooding, decreased wetland areas, increased coastal erosion, and increased salinization of cultivated land
24 and groundwater (*high confidence*) (McLeod *et al.*, 2010; Day *et al.*, 2011) (Box CC-TC). The surface area of
25 flooding in 33 deltas around the world is projected to increase by 50% under the future sea-level rise projected for
26 2100 using the IPCC AR4 scenario (Syvitski *et al.*, 2009). Non-climatic drivers (e.g., reduction in sediment
27 delivery, subsidence, and land-use changes) more than climatic drives have affected deltas for the last 50 years (*very*
28 *high confidence*) (Syvitski, 2008). Densely populated deltas are particularly vulnerable due to further population
29 growth together with the above-described impacts. The impacts of further sea-level rise beyond 2100 show a more
30 complex and enhanced flood risk on deltas (e.g., Katsman *et al.*, 2011).

31
32 In summary, there is *very high confidence* that increased human drivers are the primary cause in changes of deltas
33 (*high agreement, robust evidence*). There is *high agreement* that future climate changes through sea-level rise and
34 increased storminess will exacerbate the problems in deltas with the increase of further human stress.

35 36 37 **5.4.3. Human Systems**

38 39 *5.4.3.1. Human Settlements*

40
41 The most important effects of climate change on coastal settlements include dry land loss due to erosion and
42 submergence, damage of extreme events on built infrastructure (such as wind storms, storm surges, floods, heat
43 extremes and droughts), effects on health, food and water-borne disease, effects on energy use, and effects on water
44 availability and resources (Hunt and Watkiss, 2010). Assessments of climate impacts on settlements have almost
45 exclusively focused on the impacts of sea level rise and coastal flood events. A large number of regional, national
46 and sub-national scale studies have been conducted and Tables 5-4 and 5-5 highlight some of these studies. A
47 comprehensive account of impacts, vulnerabilities and risks in specific regions is given in the Regional Chapters. At
48 the global scale, studies have focused either on exposure to sea-level rise or extreme water levels or on the physical
49 impacts of flooding, submergence and erosion.

50
51 [INSERT TABLE 5-5 HERE]

52 Table 5-5: Summary of Coastal Vulnerability Assessments conducted at national or regional scale. Studies that
53 either costed (Adapt\$) or considered adaptation options (Adapt) are indicated. In studies that have considered

1 adaptation: WOA=without adaptation; WA=with adaptation. CVI=Coastal Vulnerability Index; GIS=Geographic
2 Information System, DIVA=Dynamic Interactive Vulnerability Assessment model. RSLR=relative sea level rise.]
3

4 Exposure studies confirm the findings of AR4 that coastal vulnerability and risks are strongly influenced by non-
5 climatic drivers. The population exposed to the 1 in 100 year coastal flood is projected to increase from 271 million
6 in 2010 to 345 million in 2050 due to socio-economic development only (UN medium fertility projections)
7 (Jongman *et al.*, 2012). For coastal cities there is *high confidence* that population growth, economic growth and
8 urbanization are the most important drivers of increased exposure (Seto, 2011; Hanson *et al.*, 2011; Chapter 14). For
9 136 port cities above one million inhabitants the number of people exposed to a 1 in 100 year coastal flood event is
10 expected to increase from 39 million in 2005 to 59 million by 2070 through 0.5 m global mean sea level rise alone
11 and to 148 million if socio-economic development (UN medium population projections) is considered on top of this
12 (Hanson *et al.*, 2011). Asia is expected to continue to have the largest exposed population, North America and Asia
13 the largest economic exposure and North and Sub-Saharan Africa the largest increases in exposure (Dasgupta *et al.*,
14 2009; Vafeidis *et al.*, 2011; Jongman *et al.*, 2012). As urban population represents increasing proportion of world
15 populations, urban floods will account for an increasing percentage of total flood impact as seen in Pakistan,
16 Australia and Brazil (Jha *et al.*, 2011).
17

18 For deltas, another major driver of increases in exposure is relative sea-level rise due to subsidence. 85% of the
19 world's largest deltas have experienced severe flooding in the last decade and the area exposed to flooding could
20 increase by more than 50% by 2100 under current projections of sea-level rise (Syvitski *et al.*, 2009). Under medium
21 UN population projections, human-induced subsidence alone is expected to increase the global economic exposure
22 of 136 major port cities by around 14% although this driver only applies to 36 of the cities (Hanson *et al.*, 2011).
23

24 While some literature does not make a clear cut between exposure and impacts (e.g., Dasgupta *et al.*, 2007; Brecht *et al.*,
25 2012), it is important to distinguish these concepts, as exposure estimates do not consider existing or future
26 adaptation measures that protect the exposed population and assets against coastal risk (Hinkel, 2012). Since AR4, a
27 number of studies, listed in Table 5-5, have provided global assessments of coastal impacts on human settlements
28 including the effects of adaptation. All of these studies also assess monetary costs of impacts and adaptation (5.5.3.).
29 While there is *limited evidence* (few studies and models) three findings emerge.
30

31 First, while the global potential impacts of coastal flood damage and land loss on human settlements in the 21st
32 century are substantial, impacts can be reduced substantially through coastal protection (*limited evidence, high*
33 *agreement*). Nicholls *et al.* (2011) estimated that without protection 72-187 million people would be displaced due
34 to land loss due to submergence and erosion by 2100 assuming sea level increases of 0.5-2.0 m by 2100. Upgrading
35 coastal defenses and nourishing beaches would reduce these impacts roughly by three orders of magnitude. Hinkel *et al.*
36 (2012) estimate the number of people flooded annually in 2100 to reach 170-260 million per year in 2100
37 without upgrading protection and two orders of magnitude smaller with dike (levee) upgrades, assuming global
38 mean sea-level rises of 0.6-1.3 m by 2100.
39

40 Second, despite the delayed response of sea-level rise to global warming levels (WG1, Chapter 3) mitigation may
41 limit 21st century impacts of increased coastal flood damage, dry land loss and wetland loss substantially (*limited*
42 *evidence, medium agreement*) albeit there is *little agreement* on the exact numbers. Nicholls and Lowe (2004)
43 estimated that stabilizing emission at 550 ppm reduces the annual number of people flooded a factor 50% in 2110
44 compared to a scenario of unmitigated emissions. Tol (2007) found that stabilizing emissions at 550 ppm reduces
45 global impacts on wetlands and drylands by about 10% in 2100 compared to scenario of unmitigated emissions.
46 Hinkel *et al.* (2012) reported that stabilizing emissions at 450 ppm-CO₂-eq reduces flood risks in 2100 by 23-29%.
47 All three studies only consider the effects of mitigation during the 21st century and due to the thermal expansion
48 component of sea level rise. Mitigation is expected to be more effective when considering impacts beyond 2100 and
49 other components of sea level rise (WG1 Chapter 13).
50

51 Third, studies confirm AR4 findings that there are substantial regional differences in coastal vulnerability and
52 expected impacts (*limited evidence, high agreement*). Most countries in South, South East and East Asia are
53 particularly vulnerable to sea-level rise due to rapid economic growth and coastward migration of people into urban
54 coastal areas together with high rates of anthropogenic subsidence in deltas where many of the densely populated

1 areas are located (Nicholls and Cazenave, 2010). At the same time, economic growth also increases the capacity to
2 adapt and the benefits of adaptation are also highest in these regions (Nicholls *et al.*, 2010). On the contrary, while
3 many African countries experience a similar trend in rapid urban coastal growth, the level of economic development
4 is generally lower and hence the capacity to adapt is smaller (Hinkel *et al.*, 2011; Kebede and Nicholls, 2012).

5
6 Many gaps remain. The available studies have only explored a small fraction of the underlying uncertainty. Only
7 few assessments consider global mean sea-level rise scenarios beyond the range given in AR4, thus excluding the
8 impacts of a possible large contribution of the ice sheets of Greenland and Antarctica to global mean sea-level rise
9 (Sect. 5.3.2, and WG1 Ch. 13). Studies considering regional patterns of climate-induced sea-level rise as well as
10 human-induced subsidence are few. Many studies rely on few or only a single socio-economic scenario. Few studies
11 consider adaptation and those that do generally ignore the wider range of adaptation options beyond hard protection
12 options. Integrated studies assessing multiple hazards, multiple impacts and trade-offs between adaptation options
13 are rare.

14
15 _____ START BOX 5-1 HERE _____

16 17 **Box 5-1. Coastal Megacities**

18
19 Large coastal urban areas offer both concentrated risk and resources for living with and adapting to the impacts of
20 climate change. When climate related disasters hit megacities costs can be very high: Storm Sandy is estimated to
21 have resulted in more than US\$100 billion of damages for New York and its hinterland. When impacts reach these
22 levels, and when strategic infrastructure is damaged, losses in large cities are capable of impacting on regional and
23 global economies through the disruption of globalized flows of goods, resources and capital. Large-scale coastal
24 urbanization is most concentrated in south and southeast Asia. Asia is also a world region with high exposure to
25 climate and weather related hazards and the potential for these to be compounded by geophysical hazards, and those
26 more directly caused by human action such as subsidence.

27
28 Of 21 megacities worldwide defined by having populations in excess of 10 million, 14 are in the coastal zone –
29 within 100km and 50m elevation from the coast (Figure 5-4) and it is anticipated that the number of coastal
30 megacities will continue to grow, especially in Africa and Asia. Growth will be largely through planned
31 development but may also feature of unplanned, spontaneous and often illegal development – with implications for
32 the limits and scope of adaptive capacity and management. Growth in neighbouring urban regions offers the
33 prospect of mega-cities or mega-urban-regions, currently the largest is the Hong Kong-Shenzhen-Guangzhou region
34 in China, with a population of 120 million. Many other large coastal cities (e.g., Cairo, London and Sao Paulo) offer
35 important lessons on planning and risk management at scales that indicate the importance of a flexible approach to
36 the study of coastal mega-urbanization.

37
38 [INSERT FIGURE 5-4 HERE

39 Figure 5-4: Mega-urbanisation of on the coast. Source: Blackburn S and Marques da Silva C (2013) Mega-
40 urbanisation on the coast: Global context and key trends in the twenty-first century, in Pelling M and Blackburn S
41 (eds) Megacities and the Coast: Risk, Resilience and Transformation, Earthscan: London.]

42
43 Contemporary approaches to risk management acknowledge the need for soft risk reduction measures such as
44 education, good governance, and risk communication, being applied in conjunction with hard engineering solutions
45 such as sea walls, groynes and levees and green-engineered equivalents. However applying these principles in
46 megacities is challenging, requiring collaboration between a multitude of stakeholders. These include actors
47 operating at all scales from the international (in the case of large land-owning corporations and supranational
48 donors) to the individual. Good governance is key to risk management, but there is much debate over precisely what
49 this entails and its limitations.

50
51 The prospect of dangerous climate change bringing increasing rates of sea-level rise and coastal storminess by mid
52 century asks serious questions of urban planners today. This is especially so in places where these hazard drivers are
53 exacerbated by local conditions, for example of subsidence. Middle-income countries experiencing the most rapid
54 mega-urban expansion also possess an opportunity to plan now for potential risk mid-century and beyond. It is more

1 difficult still to confront the challenge of retrofitting or redesigning cities where current land-use will configure
2 future risk. The next decade is likely to be critical for realigning urban planning, reaching out to informal and
3 regulating market-led developments. Responding to dangerous climate change requires joined-up risk management
4 that can consider transformational adaptation with considerable local impacts on the way cities are imagined,
5 governed and shaped, alongside contemporary, incremental adaptation options.

6
7 _____ END BOX 5-1 HERE _____
8
9

10 5.4.3.2. *Industry, Infrastructure, Transport, and Network Industries*

11
12 There is *high confidence* that coastal industries, their supporting infrastructure including transport (ports, roads, rail,
13 airports), power and water supply, storm water and sewerage are sensitive to a range of extreme weather and climate
14 events (Handmer *et al.* 2012) and many of these are projected to change over the coming decades (Seneviratne *et al.*,
15 2012). This is especially relevant considering the fact that most industrial facilities, infrastructure and networks are
16 designed for life cycles extending over several decades, even extending well into the twenty-second horizon such as
17 new nuclear power plants (Wilby *et al.* 2011).

18
19 Table 5-6 summarizes potential impacts of sea level rise, coastal floods and storms on critical coastal infrastructure
20 in the communications, energy, transportation and water waste sectors.

21
22 [INSERT TABLE 5-6 HERE

23 Table 5-6: Impacts of sea level rise, coastal floods, and storms on critical coastal infrastructure by sector. Sources:
24 Horton and Rosenzweig (2010), Zimmerman and Faris (2010).]
25

26 Severe storms with associated winds, waves, rain, lightning and storm surges are particularly disruptive to transport
27 and power and water supplies. In such network configurations, flooding of even the smallest component of an
28 intermodal system can result in a much larger system disruption. For instance, even though a transportation terminal
29 may not be affected, the access roads to it could be, thus forcing the terminal to cease or reduce operation (CCSP,
30 2008). Sea transport accounts for more than 80% of global goods trade (by volume) and so disruption to port
31 activities in one location can disrupt supply chains, which can have far reaching consequences (Handmer *et al.*,
32 2012).

33
34 Some low-lying railroads, tunnels, ports and roads are already vulnerable to flooding and rising sea levels (5.3.3.2)
35 will exacerbate the situation by causing more frequent and more serious disruption of transportation services under
36 extreme sea levels unless adaptation is enforced. Furthermore, sea-level rise will reduce the extreme flood return
37 periods and will lower the design critical elevations of infrastructure such as airports, tunnels, coastal protections
38 and ship terminals (Jacob *et al.*, 2007). Coastal infrastructural instability may result from natural hazards triggered
39 by groundwater-level (GWL) variations resulting from rising sea level. For earthquake-prone coasts, this could be
40 exacerbated by earthquake liquefaction if GWL increases with sea-level rise (Yasuhara *et al.*, 2007). Other impacts
41 may arise in coastal industries in high latitudes affected by permafrost thaw causing ground stability and erosion
42 thereby affecting transport safety and the industries that rely on such travel in these regions (e.g., Pearce *et al.*,
43 2010).

44
45 There is *high confidence* that climate impacts on coastal industries vary considerably depending on geographical
46 location, associated weather and climate and specific composition of industries within particular coastal regions.

47
48 While there is *robust evidence* of the impacts and consequences of extreme events on coastal infrastructure and
49 industrial facilities there are limited assessments on projected impacts. For example, it is estimated that a
50 hypothetical 1 m rise in relative sea level projected for the Gulf Coast region between Alabama and Houston over
51 the next 50-100 years would permanently flood a third of the region's roads as well as putting more than 70% of the
52 regions ports at risk (CCSP, 2008).

1 Although not completely coastal, the estimated costs of climate change to Alaska's public infrastructure could add
2 US\$3.6-6.1 billion (+10% to 20% above normal wear and tear) from now to 2030 and US\$5.6-7.6 billion (+10% to
3 12%) from now to 2080 (Larsen *et al.*, 2008). Higher costs of climate change for coastal infrastructure are expected
4 due to its proximity to the marine environment. Other projected impacts are beneficial for the transportation system.
5 For example, decline of Arctic sea-ice coverage could extend seasonal accessibility to high-latitude shipping routes
6 such as the northwest shipping route that connects the Atlantic to the North Pacific (MCCIP, 2008).

7
8 Hanson *et al.* (2011) presents a first estimate of the exposure of the world's large port cities to coastal flooding due
9 to sea-level rise and storm surge in the 2070s. The analysis suggests that the total value of assets exposed in 2005
10 across all cities considered is estimated to be US\$3,000 billion; corresponding to around 5% of global GDP in 2005.
11 By the 2070s, and assuming a homogeneous global sea level rise of 0.5 m, increased extreme water levels up to a
12 10% and a fixed subsidence rate in susceptible cities with respects today values, asset exposure is estimated to
13 increase to approximately 9% of projected global GDP in this period.

14 15 16 5.4.3.3. Fisheries, Aquaculture, and Agriculture

17
18 The coastal zone supports significant fisheries, aquaculture and agricultural activities. Fisheries and aquaculture
19 globally employ 43.5 million people (Daw *et al.*, 2009) and contribute for more than 20% to the dietary animal
20 protein of nearly 1.5 billion people (FAO, 2010). Rice production, the world's number one food crop, is a major
21 crop grown in the low-lying deltaic regions of Asia (Wassman *et al.*, 2009).

22 23 24 *Observed impacts*

25
26 Climate variability and change impact both fishermen livelihoods (Badjeck *et al.*, 2010) and fish production
27 (Barange and Perry, 2009). In the North Sea, ocean warming over the period 1977-2002 led to 8 times more fish
28 species (Hiddink and Hofstede, 2008). In southeastern Australia, Last *et al.* (2011) found an increasing abundance of
29 45 fish species of warm temperate origin (Ridgeway, 2007), a decline abundance for 9 species, and predicted the
30 potential for longer term detrimental effects for cool temperate species endemic to the region. Impacts of climate
31 change on aquaculture (*Mytilus edulis* and *Salmo salar*) in the UK and Ireland have been difficult to discern from
32 natural environmental variability (Callaway *et al.*, 2009).

33
34 The impact of sea surface temperature changes on fisheries yields over the last 25 years is negative for the Northeast
35 Atlantic large marine ecosystems, and positive for the Indian Ocean (Sherman *et al.*, 2009). In coastal Louisiana,
36 saltwater intrusion was found to reduce the population size of the freshwater western mosquitofish (*Gambusia*
37 *affinis*) (Purcell *et al.*, 2010). Eutrophication and hypoxia give rise to frequency and intensity of harmful algal
38 blooms (MEA, 2005). A combination of factors renders the Pacific coast and coastal estuaries particularly
39 vulnerable to acidified water (Newton *et al.*, 2010).

40
41 The combination of rice yield reduction induced by climate change and inundation of lands by seawater causes an
42 important reduction in production (Chen *et al.*, 2012). Seawater inundation has become a major problem for
43 traditional agriculture in Bangladesh (Rahman *et al.*, 2011), and in low-lying island nations (e.g. Lata and Nunn,
44 2012).

45 46 47 *Projected impacts*

48
49 Fisheries may be impacted either negatively or positively (Cinner *et al.*, 2012; Meynecke and Lee, 2011; Hare *et al.*,
50 2010) depending on the latitude, location and climatic factor. Using a partial-equilibrium analysis, Narita *et al.*
51 (2012) estimated that the global economic costs of production loss of mollusks due to ocean acidification by the year
52 2100 could be over 100 billion USD. Warming ocean temperatures can lead to the migration of the sea urchin
53 (*Centrostephanus rogersii*-*Diadematidae*) in Australia (Ling *et al.*, 2009). For aquaculture, negative impacts of

1 rising ocean temperatures will be felt in the temperate regions whereas positive impacts will be felt in the tropical
2 and subtropical regions (De Silva and Soto, 2009).

3
4 In summary, there is *medium confidence* that changes have occurred to the distribution of fish species with evidence
5 of poleward expansion of temperate species (*high agreement, limited evidence*). There is *limited evidence* to suggest
6 that tropical and subtropical aquaculture has not been adversely affected by rising ocean temperatures to date. There
7 is also *medium confidence* that coastal agriculture has experienced negative impacts due mainly to increased
8 frequency of submersion of agricultural land by saltwater inundation (*high agreement, limited evidence*).

10 11 5.4.3.4. Coastal Tourism and Recreation

12
13 Coastal tourism is the largest component of the global tourism industry. More than 60% of Europeans opt for beach
14 holidays and beach tourism provides more than 80% of US tourism receipts (UNEP, 2009). More than 100 countries
15 benefit from the recreational value provided by their coral reefs which contributed US\$11.5 billion to global tourism
16 (Burke *et al.*, 2011).

17 18 19 *Observed impacts*

20
21 Observed significant impacts on coastal tourism have occurred from changes in extreme events (e.g. flooding,
22 tropical storms, storm surges, heat waves) and climate variability (e.g. drought and prevailing winds accelerating
23 coastal erosion) which can cause damage to infrastructure and tourist attractions (Scott *et al.*, 2008; Bender *et al.*,
24 2010; Knutson *et al.*, 2010). Observed climate change impacts on the Great Barrier Reef include the coral bleaching
25 episodes in 1998 and 2002 due to higher summer sea temperatures, more severe storms, rising sea levels and coastal
26 erosion although tourists show a low level of climate change concern with respect to coral bleaching (Zeppel, 2012).

27 28 29 *Projected impacts*

30
31 In order to provide some idea of climate change impacts on coastal destinations, many studies have been made on
32 projecting tourism demand, for example, in Europe (Perch-Nielson *et al.*, 2010), East Anglia, UK (Coombes *et al.*,
33 2009), the Baltic region (Haller *et al.*, 2011) and beach tourism in the Mediterranean (Moreno and Amelung, 2009a)
34 and in 51 countries worldwide (Perch-Nielson, 2010). The studies provide varying details but it is difficult to draw
35 overarching conclusions on tourism demand for coastal destinations. Less is known about the relationship between
36 the impacts of climate change and specific tourist behaviour, activities or flows to coastal destinations (Moreno and
37 Amelung, 2009b) (see Chapter 10). Usually tourists do not consider climate variability or climate change in their
38 holidays *et al.* although there are a few studies to show on the contrary (Alvarez-Diaz *et al.*, 2010; Cambers, 2009).

39
40 As for future impacts on coastal tourism, there is *high confidence* in the impacts of extreme events and sea level rise
41 aggravating coastal erosion. A scenario of 1 m sea level rise would be a potential risk to 906 major coastal resort
42 properties in 19 countries in the Caribbean (Scott *et al.*, 2012). The presence of coastal tourism infrastructure will
43 continue to exacerbate beach reduction and coastal ecosystems squeeze under rising sea levels, as exemplified in
44 Martinique (Schleupner, 2008). Carbonate reef structures would degrade under a scenario of at least 2°C by 2050 to
45 2100 with serious consequences for tourism destinations in Australia, Caribbean and other small island nations
46 (Hoegh-Gulberg *et al.*, 2007). Ocean acidification would add its toll to coral reefs (Box CC-CR).

47
48 The costs of future climate change impacts on coastal tourism are enormous. For example, in the Caribbean region, a
49 hypothetical 1-m sea-level rise would result in the loss or damage of 21 CARICOM airports, inundation of land
50 surrounding 35 ports, and at least 149 multi-million dollar tourism resorts damaged or lost from erosion to the
51 coastal beach areas.(Simpson *et al.*, 2011).

52
53 In summary, while coastal tourism can be related to climate change impacts, it is more difficult to relate tourism
54 demand directly to climate change. Coastal tourism continues to be highly vulnerable to weather and climate

1 extremes and rising sea levels with the additional sensitivity to ocean temperature and acidity for the sectors that
2 rely on reef tourism (*high confidence*). Developing countries and small island states within the tropics relying on
3 coastal tourism, are most vulnerable to present and future weather and climate extremes, future sea level rise and the
4 added impacts of coral bleaching and ocean acidification (*very high confidence*).

7 5.4.3.5. Health

9 The relationship between health of coastal populations and climate change include direct linkages (e.g. floods,
10 droughts, storm surges and extreme temperatures) and indirect linkages (e.g. changes in the transmission of vector,
11 food and water borne infectious diseases and increased salinisation of coastal land that affects food production and
12 freshwater supply). Coastal settlements, and in particular informal settlements, concentrate the risks of injury and
13 death due to the risk of storm surges and flooding from rainfall and storm surge (Handmer et al, 2012). This section
14 deals with human health in the context of the coastal zone, while Chapter 11 addresses general health issues and
15 Chapter 6 deals with health issues associated with ocean changes. Understanding the relationship between climate
16 and health is often confounded by socio-economic factors that influence coastal settlement patterns and the level and
17 organisation of the response of authorities to health related issues (Baulcomb, 2011).

19 Mortality risk in coastal areas is related to exposure and vulnerability of coastal populations to climate hazards.
20 Recent modeling of trends in these components highlights that mortality risk is highest in countries with low GDP
21 and weak governance. A regional analysis of changes in exposure, vulnerability and risk indicates that although
22 exposure to flood and cyclone hazards has increased since 1980, the risk of mortality has generally fallen. The
23 reductions reflect strengthening of countries' capacity to respond to disasters (Box 5-1). However, mortality is still
24 rising in the countries with the weakest risk governance capacities (UNISDR, 2011).

26 Coastal regions face a range of diseases that are sensitive to climate. Increased saline intrusion of coastal land
27 through rising sea levels and changes to river flow is linked to increased incidence of hypertension disease (Vineas
28 et al, 2011). For example, in Bangladesh, higher rates of maternal hypertension disorders have been identified in
29 pregnant women living in coastal regions compared to further inland (Khan et al, 2008). Increasing temperature,
30 humidity and rainfall can increase suitable mosquito habitats, shorten the breeding cycles and reduce the time to
31 infection by vector-borne diseases such as malaria, dengue, leishmaniasis and chikungunya. (Stratten *et al.*, 2008;
32 van Kleef *et al.*, 2010; Pialoux et al, 2007, Kolivras, 2010) and infectious diseases such as diarrhoea, infectious
33 gastrointestinal disease, rotovirus and salmonella (e.g. Chou *et al.*, 2011, Hashizume *et al.*, 2007; 2008a Zhang *et al.*
34 *et al.*, 2007, 2010; Onozuka *et al.*, 2010). The parasitic disease, Schistosomiasis, is endemic in many tropical and small
35 island coastal regions (Chapter 29) and infection rates have been found to increase linearly with temperature to 30°C
36 but reduce beyond 35°C, because of increased mortality in the snail intermediate host. (Mangal *et al.* 2008).

38 Cholera outbreaks are also linked to rainfall, patterns and other seasonal climate patterns (e.g. Hashizume et al,
39 2008b, 2010) and variations in SST (e.g. Koelle et al, 2005). Outbreaks of toxins generated by Harmful Algal
40 Blooms (HABs) such as ciguatera have been linked to SST variability (e.g. Jaykus *et al.*, 2008; Erdner *et al.*, 2011).
41 However, in general there is *limited evidence* and *low confidence* in how global climate change will impact HABs
42 (Chapter 6). The potential impacts of HABs in human health and different ecosystem services suggests increased
43 monitoring of significant range extensions and associated increases in biotoxins is necessary (Hallegraeff, 2010).
44 Nontoxic blooms that grow to high biomass also can have detrimental effects on biodiversity through oxygen
45 depletion and physical shading of the benthos (Erdner *et al.*, 2011) with consequences for ecosystem health, human
46 nutrition and health.

48 Under future climate conditions, expansion of brackish and saline water bodies in coastal areas under projected sea
49 level rise may increase the incidence of associated vector-borne diseases (Ramasamy and Surendran, 2011) and
50 salinity-related diseases such as diarrhea and hypertension (Vineas et al, 2011). Human responses to climate change
51 also may influence outcomes on health. However, sparsity of empirical climate-health data increases
52 uncertainties around such projections (Kolstad and Johansson (2011)).

1 Evidence continues to emerge of relationships between many diseases that affect human health in the coastal zone
2 and climate including changes in air and water temperature, rainfall and humidity, coastal salinity and increased
3 salinisation of coastal land. However, the relationships are often complex and vary between diseases and even
4 regionally for the same disease. The interplay between climate and human systems with regards to health impacts is
5 poorly understood and this continues to confound reliable projections of health impacts. (*high agreement, robust*
6 *evidence*).

7 8 9 **5.4.4. Summary: Detection and Attribution**

10
11 Coastal systems, consisting of natural and human systems, have been heavily influenced by human activities
12 including those associated with climate changes (*high agreement, robust evidence*).

13
14 Coastal ecosystems such as rocky shores and coral reefs show the most evidence of the impacts of climate change
15 (5.4.2.2, 5.4.2.4), the most prominent effects being the range shifts of species in response to ocean warming (*high*
16 *confidence*), changes in biodiversity (*high confidence*) in relation to ocean warming and acidification, and mass
17 coral bleaching and mortality in response to ocean warming (*very high confidence*). Decreased calcification in many
18 reef-building corals and coralline algae is reported widely (*high confidence*), however its attribution to either
19 warming or acidification has proven difficult (*medium confidence*)(5.4.2.4). Ocean warming is also leading to range
20 shifts in mangrove forests and seagrass meadows (*medium confidence*)(5.4.2.3). Seagrass meadows are already
21 under stress due to ocean warming (*high confidence*), and in particular heat waves, which lead to widespread
22 seagrass mortality (*high confidence*). Kelp forests have been reported to decline in temperate areas in both
23 hemispheres, attributed to ocean warming (*high confidence*)(5.4.2.3). The spread of subtropical invasive macroalgal
24 species is believed to be facilitated by climate change, adding to the stresses temperate seagrass meadows
25 experience from ocean warming (*medium evidence, high agreement*)(5.4.2.3). The changes of the distribution of fish
26 species with evidence of poleward expansion of temperate species have occurred (*medium confidence*)(5.4.3.3).
27 There is *limited evidence* to suggest that tropical and subtropical aquaculture has been adversely affected by rising
28 ocean temperatures to date (5.4.3.3).

29
30 Though the range shift of mangroves is recognized, mangrove forests and seagrass meadows are declining globally
31 (*very high confidence*) mainly due to land-use changes and coastal erosion (5.4.2.3). Widespread erosion of beaches
32 and dunes has been observed over the past century or more (*robust evidence*) (*very high confidence*). However
33 attributing shoreline changes to climate change is difficult due to the multiple natural and anthropogenic drivers
34 contributing to coastal erosion (*low confidence*) (5.4.2.1). There is *very high confidence* that increased usage of
35 groundwater resources for agriculture and coastal settlements globally has led to a reduction in groundwater quality,
36 including increased salinization (*high agreement, robust evidence*), however, attribution to climate change is *low*
37 (5.4.2.5), human drivers being the primary cause in these changes and degradation of highly-populated deltas and
38 lowlands around estuaries and lagoons (*high agreement, robust evidence*)(5.4.2.7).

39
40 Exposure studies confirm the findings of AR4 that coastal vulnerability and risks are strongly influenced by non-
41 climatic drivers. Population of people living in coastal lowlands is increasing and more than 270 million people in
42 2010 are already exposed to flooding by the 1 in 100 year coastal flood (5.4.3.1)(*very high confidence*). Population
43 growth and land subsidence in coastal lowlands are the major cause and there is *very low attribution* to climate
44 changes. The interplay between climate and human systems with regards to health impacts is poorly understood
45 (*high agreement, robust evidence*)(5.4.3.5).

46
47 The coastal systems are affected by both climate-related and human drivers, and complex interactions of both.
48 Though there is *high* attribution to climate changes as coral bleaching and species shift, most of causes in other
49 changes to the coastal system are attributed to mainly human activities (human drivers). Further analysis will be
50 required to more clearly discriminate the relative contributions from human and climate-related drivers.

51 [INSERT FIGURE 5-5 HERE

52 Figure 5-5: Summary of detection and attribution in coastal areas.]

5.5. Adaptation and Managing Risks

This section assesses the literature on available on approaches for appraising and implementing coastal adaptation (5.5.1), adaptation options (5.5.2), costs and benefits of coastal adaptation (5.5.3), observed coastal adaptation practice (5.5.4), observed barriers to coastal adaptation (5.5.5), and finally linkages between coastal adaptation and mitigation (5.5.6).

5.5.1. Framing and Approaches

5.5.1.1. Overview of Approaches

Adaptation in general and coastal adaptation in particular are broad concepts referring to a wide range of human activities related to the process of framing the adaptation issue, assessing adaptation (i.e., identifying and analyzing adaptation options), implementing options and monitoring and evaluating these (e.g., UKCIP, 2003; PROVIA, 2013). As a result, a wide variety of approaches are applied (Chapters 2, 15, 16 and 17 for a comprehensive account).

For coastal adaptation, the literature on approaches falls into three categories: decision-analytical approaches, approaches of institutional and governance analysis and practical approaches that cover all stages of the adaptation process.

5.5.1.2. Decision Analysis

Decision-analytical (DA) approaches analyse a particular decision using formal methods in order to identify preferable actions from a set of alternative actions (also called options, alternatives or strategies) given some evaluation criteria. This section highlights some paradigmatic applications of DA methods to coastal adaptation; for a compressive treatment see Chapter 2 (Foundations for decision-making) and Chapter 17 (Economics of Adaptation).

Many standard methods for decision-making under uncertainty use the criterion of optimality (e.g., optimum utility, optimal cost-benefit ratio, etc). These methods cannot be applied for long-term adaptation decisions as they require the computation of expected utility or expected benefits, which is not possible in principle (Lempert and Schlesinger, 2001; Hinkel and Bisaro, 2013). As many coastal decisions involve options with investment time scales of 30 to over 100 years (e.g., land-use planning, flood defenses, construction of housing and transportation infrastructure; see 5.5.2), DA approaches beyond optimization are required (Hallegate, 2009).

Robust decision-making (RDM) refers to a range of alternative approaches that replace the evaluation criterion of optimality with the criterion of robustness. Uncertainty is not represented through a single probability distribution but through a range of alternative scenarios and robust strategies that work well over a wide range of these scenarios are preferred (Lempert and Schlesinger, 2000; Lempert and Collins, 2007). Application of RDM to Port of Los Angeles infrastructure is one of the few applications to coastal adaptation (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 implements the criterion of flexibility by characterizing alternative strategies in terms of two attributes: i) adaptation tipping points (ATP), which are points beyond which strategies are no longer effective (Kwadijk *et al.*, 2010), and ii) what alternative strategies are available once a tipping point has been reached (Haasnoot *et al.*, 2012). 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

1 approach include the Thames Estuary 2100 Plan (Low *et al.*, 2009; Penning-Roswell *et al.* 2011; Box 5-2), the
2 Dutch Delta Programme (Kabat *et al.*, 2009; Box 5-3) and the New York City Panel on Climate Change
3 (Rosenzweig *et al.*, 2011).

4
5 These and other approaches may also be embedded into multi-criteria-analysis (MCA), which considers multiple
6 criteria that may include robustness and flexibility. The application of MCA to coastal decisions is wide spread.
7 Another response to the deep uncertainty characterizing future climate drives is adaptive management, which is the
8 idea of practicing adaptation and evaluating outcomes *ext-post* instead of analyzing decisions *ex-ante*; (e.g. practical
9 approaches in 5.5.2.4).

10 11 12 5.5.1.3. Institutional and Governance Analysis

13
14 Institutional and governance analysis (IA) comprise a variety of approaches that aim at describing and explaining
15 the emergence and performance of institutions and governance structures (GS) (Hinkel and Bisaro, 2013). IA is
16 particularly relevant to coastal adaptation, because deciding between options and implementing them is an ongoing
17 process involving complex inter-linkages between public and private decisions at multiple levels of decision making
18 and in the context of other issues, existing policies, conflicting interests and diverse GS (e.g. Few *et al.*, 2007; Urwin
19 and Jordan, 2008; Hinkel *et al.*, 2009). The non-consideration of this context may hinder or mislead adaptation
20 decisions and implementations (5.5.5). IA strives to understand this context and insights gained may be employed to
21 craft effective institutions and policies for adaptation.

22
23 For coastal adaptation, there is *high confidence* that the effectiveness of existing GS is hindered due to a lack of
24 horizontal and vertical integration of organizations and policies. Weak vertical administrative interplay in Sweden
25 (Storbjörk and Hedren (2011)); poor integration in higher-level governance and limited effectiveness of institutional
26 arrangements of Coastal Partnership in UK (Stojanovic and Barker, 2008); difficulty to translate national level
27 recommendations into local level actions in the UK (Few *et al.*, 2007); coastal policies with ambiguous or
28 contradictory goals (Bagstadt *et al.*, 2007) and fragmented economic incentives in the US (Seto, 2011) or coastal
29 policies not taken into account longer-term climate change in a number of African cases (Bunce *et al.*, 2010) are a
30 few examples.

31
32 There is *medium evidence* that governance issues are particularly challenging when considering planned retreat.
33 While managed realignment is on the political agenda in Germany and the UK, the political costs of doing so are
34 high as both the existing GS as well as public opinion are geared towards protection, so that short election cycles do
35 not provide incentives for politicians to undertake actions that may produce benefits in the long term (Few *et al.*,
36 2007; Rupp-Armstrong and Nicholls, 2007). Along the coast of South East Queensland, Australia, the option of
37 planned retreat is disappearing because of rapid coastal development favored by liability laws. To prevent this, risks
38 and responsibilities would need to be redistributed from governments to beneficiaries of development (Abel *et al.*,
39 2011).

40
41 While there is *high confidence* that many institutional factors are decisive in enabling coastal adaptation, the role of
42 coastal institutions in adaptation is generally under-researched. Contextually differentiated institutional analysis
43 considering both biophysical and social system characteristics (Dietz *et al.*, 2003; Ostrom, 2009) as found in the
44 fields of socio-ecological systems (Folke *et al.*, 2005; Ostrom 2007, 2009) and new institutional economics
45 (Hagedorn *et al.*, 2002; Bougherara *et al.*, 2009; Ostrom, 2005, Geels, 2011) are practically non-existent.
46 Most work focuses on Australia, US, Germany and the UK with little work on developing countries.

47 48 49 5.5.1.4. Approaches to Adaptation Practice

50
51 Generally, approaches to adaptation practice build on already existing policy and practice frameworks and cover the
52 whole adaptation processes from framing the issue and analyzing options to implementing adaptation actions and
53 monitoring and evaluation.

1 Integrated Coastal Zone Management (ICZM) is a long-term, institutionalized and iterative process that promotes
2 the integration of coastal activities of relevant policy makers, practitioners and scientist across coastal sectors, space
3 and organizations with a view to use coastal resources in a sustainable way (Hiledebrand and Norrena, 1992;
4 Sorenses 1993; Sterr *et al.*, 2003; Sales, 2009; Christie *et al.*, 2005; WG2 Glossary). Considering climate change in
5 this framework does not mean radical changes to ICZM, because ICZM already emphasizes the integration of
6 coastal issues across sectors and policy domains as well as the long-term perspective (e.g., Hofstede, 2008;
7 Falaleeva *et al.*, 2011), but there is need to extend decision making horizons (Tobey *et al.* 2010).
8

9 So far, however, there is *limited evidence* of the effectiveness of ICZM combined with climate change adaptation.
10 ICZM itself has been applied throughout the world for over 40 years and while demonstrable benefits are reported
11 (e.g., Stojanovic and Ballinger, 2009) many obstacles to its successful implementation still remain (*high*
12 *confidence*). A recent review of ICZM in Europe concluded that the complexity of coastal regulations, demographic
13 deficits, lack of sustainable finance and a failure to involve communities, business and industry hinder its
14 implementation (Shipman and Stojanovic, 2007). Developing countries also struggle to meet the goals of ICZM due
15 to many factors (Box 5-4).
16

17 Another prominent framework used for coastal adaptation practice is adaptive management (AM), which has been
18 developed as a response to the deep uncertainty characterizing ecosystem management, where it is often impossible
19 to predict outcomes of management interventions (Holling, 1968; Walters, 1986). There are numerous applications
20 of AM to coastal management (e.g., Walters, 1997; Marchand, 2011, Mulder *et al.*, 2011), but as the majority of
21 these are very recent, there is *limited evidence* of its long-term effectiveness. Limitations of AM are also apparent
22 such as the potential high cost of experimentation and a range of institutional barriers hindering the delivery of
23 flexible management approaches (e.g. Gunderson *et al.*, 1995, McLain and Lee, 1996; Johnson 1999).
24

25 Community-based adaptation (CBA) refers to the generation and implementation of locally-driven adaptation
26 strategies that address both climate change impacts and development deficits for the climate vulnerable poor and
27 strengthen the adaptive capacity of local people to climate and non-climate risk factors (Reid *et al.*, 2009; Nicholls
28 *et al.*, 2007; Ayers and Dodman, 2010; Ayers and Huq, 2013; WG2 AR5 Chapter 14, 14.2.1; Chapter 15, 15.4.3.1;
29 Chapter 24, 24.4.6.5). CBA approaches have been developed through active participatory processes with local
30 stakeholders (Ayers and Forsyth, 2009), and operating on a learning-by-doing, bottom up, empowerment paradigm
31 (Huq and Reid, 2007; Kates, 2000). CBA experiences emphasize that it is important to understand a community's
32 unique perceptions of their adaptive capacities in order to identify useful solutions (Parvin *et al.*, 2008; Paul and
33 Routray, 2010; Badjeck *et al.*, 2009) and that scientific and technical information on anticipated coastal climate
34 impacts needs to be translated into a suitable language and format that allows people to be able to participate in
35 adaptation planning (Saroar and Routray, 2010). Further, effective CBA needs to consider measures that cut across
36 sectors and technological, social and institutional processes; technology by itself is only one component of
37 successful adaptation. (Sovacool *et al.*, 2011; Rawlani and Sovacool, 2011; Pelling, 2011; Gibbs, 2009).
38

39 Other important policy and practice frameworks in place in the coastal zone include poverty reduction, development
40 and Disaster Risk Reduction (Romieu *et al.*, 2010; Mercer, 2010; Mitchell *et al.*, 2010; Polack, 2010; Gero *et al.*,
41 2011; Kirshen *et al.*, 2011; Halpern *et al.*, 2008b)
42

43 Across these and other approaches there is *high agreement* on the following three principles. One, information on
44 efficient adaptation options alone (as assessed through DA approaches) may not fully serve managers need and
45 requires to be supplemented by financial and technical assistance as well as boundary organizations which serve as
46 an interface between science and practice (Tribbia and Moser, 2008). Two, the adaptation and decision making
47 processes should be participatory and inclusive, integrating all relevant stakeholders (Dolan and Walker, 2004;
48 O'Riordan and Ward, 1997; Milligan *et al.*, 2009). Three, the adaptation processes must be set up to foster mutual
49 learning, experimentation and deliberation amongst stakeholder and researchers (Fazey *et al.*, 2010; Kenter *et al.*,
50 2011). Neither scientific climate knowledge alone nor indigenous knowledge alone is sufficient (Sales, 2009;
51 Dodman and Mitland, 2011; Bormann *et al.*, 2012). Coastal adaptation is increasingly acknowledged to be a "wicked
52 problem" (Rittel and Webber, 1973), in the sense that there is often no clear agreement about what exactly the
53 adaptation problem is and there is uncertainty and ambiguity as to how improvements might be made (Moser *et al.*

1 2012). As coastal systems are complex, diverse and dynamic, their governance needs experimentation and learning
2 by doing (Jentoft, 2006).

3
4 While there is *high agreement* on these principles, there is little systematic review and hence *limited evidence* on
5 why a given approach is effective in a given context (and not in another). The need for systematic evaluation and
6 institutional research targeted at a differentiated understanding of these approaches is high. Furthermore, despite
7 experimentation with these approaches, meeting the multiple goals, improving governance, accounting for the most
8 vulnerable populations and sectors and fully integrating consideration of natural ecosystems is still largely
9 aspirational. Meanwhile development in high risk areas grows, coastal ecosystems continue to degrade in many
10 regions, coastal freshwater resources are being overdrawn in many highly populated areas, and vulnerability to
11 coastal disasters grow (e.g., Jentoft, 2009; McFadden, 2008; Mercer, 2010; Shipman and Stojanovic, 2007).

14 5.5.2. *Adaptation Options*

15
16 Selecting appropriate adaptation options can be challenging considering the ample range of options available. A
17 detailed discussion on general adaptation needs and options can be found in (chapter 16). As a first approximation,
18 adaptation options were classified into: institutional and social options (14.3.2.1), technological and engineered
19 options (14.3.2.2) and ecosystem-based adaptation options (14.3.2.3). In terms of coastal adaptation, most of the
20 existing options can be included within this classification.

21
22 The IPCC classification of coastal adaptation strategies consisting of retreat, accommodation and protection
23 (Nicholls *et al.*, 2007) is now widely used and applied in both developed and developing countries (Boateng, 2010;
24 Linham and Nicholls, 2012). This trilogy of strategies has also been translated as retreat, defend or attack (Peel,
25 2010). Protection aims at advancing or holding existing defence lines by different options such as: land claim, beach
26 and dune nourishment, the construction of artificial dunes, hard structures such as sea walls, sea dikes and storm
27 surge barriers or removing invasive and restore native species. Accommodation is achieved, increasing flexibility,
28 by flood proofing, flood agriculture, flood hazard mapping, the implementation of flood warning systems or
29 replacing armoured by living shorelines. Retreat options include allowing wetlands to migrate inland, shoreline
30 setbacks and managed realignment, for example, by breaching coastal defences allowing the creation of an intertidal
31 habitat.

32
33 Since AR4 coastal adaptation options have been revised and summarized in several guidebooks (USAID, 2009;
34 EPA, 2009; UNEP, 2010). Especially relevant has been the growth of Community Based Adaptation options. Table
35 5-7 compiles different examples, of options implemented to address climate change impacts in coastal areas.

36
37 [INSERT TABLE 5-7 HERE

38 Table 5-7: Community-based adaptation options.]

41 5.5.3. *Global Adaptation Costs and Benefits*

42
43 Since AR4, only a few studies have been published that provide comprehensive and internally consistent estimates
44 of the costs of sea-level rise and adaptation at global scales. These relying either on the FUND (Anthoff *et al.*, 2010;
45 Nicholls and Tol, 2009) or the DIVA model (Hinkel and Klein, 2009) and are listed in Table 5-5 and discussed here.

46
47 Generally, cost estimates are difficult to compare across studies due to differences in scenarios used, impacts and
48 adaptation options considered, methodologies applied and baseline conditions assumed. No study covers all of the
49 major sea-level rise impacts as reported in Table 5-4. All of these studies use the direct cost method, in which
50 exogenous prices for adaptation options and damages are taken from data of the respective markets. For wetland
51 loss, direct costs are used too but the “prices” are taken from monetary valuation studies for non-market goods and
52 services (Woodward and Wui, 2001; Brander *et al.*, 2006; Barbier, 2012). Some studies use computable general
53 equilibrium models and growth models to study the indirect and dynamic costs of climate change, including sea
54 level rise. These studies are reviewed in Chapter 10.

1
2 There is *high agreement* that the cost of sea-level rise (sum of adaptation and residual damage cost) are smaller with
3 coastal protection than without for the 21st century and the global scale, when considering the impacts of increased
4 coastal flood damage and land loss due to erosion. (Nicholls and Tol, 2006; Anthoff *et al.*, 2010; Hinkel *et al.*,
5 2012). *Evidence is low*, however, as only a few studies are available. Considering dryland and wetland loss only, the
6 FUND model shows that under a GMSLR of 20-40cm per century it would be economically justified to protect 80%
7 of the exposed coast in all but 15 countries (Nicholls and Tol, 2006) and even under an extreme GMSLR of 6m per
8 century 50% of today's coastline would still be worth protecting (Nicholls *et al.*, 2008). Considering flood damage
9 only, an application of DIVA shows that for 21st century global mean SEA LEVEL RISE scenarios of 60-126cm,
10 upgraded protection through dikes (levees) may reduce total costs by factors 3 to 5 as compared to no upgrades in
11 protection (Hinkel *et al.*, 2012).
12

13 There is also *high agreement* that costs and benefits of sea-level rise impacts and adaptation vary strongly between
14 regions and countries and that some developing countries and Small Island States may reach their limits of adaptive
15 capacity or may not be able to bear the costs of impacts and adaptation without external support (Chapter 29,
16 29.6.2.1). Even with protection, the cost of land loss due to submergence are projected to be above 1% of national
17 GDP for Micronesia, Palau, the Bahamas and Mozambique under 1m of sea level rise (Anthoff *et al.*, 2010). For
18 coastal flooding, annual damage and protection cost are projected to lie between 5% and 9% of national GDP for
19 Kiribati, the Solomon Islands, Vanuatu and Tuvalu in 2100 under 64 cm of global mean sea-level rise (Hinkel *et al.*,
20 2012). Further substantial costs arise particularly for developing countries due to their current adaptation deficit (i.e.
21 coastal defenses are not adapted to the current climate variability), which is not well understood and requires further
22 analysis (Parry *et al.*, 2009). For example, the adaption deficit of Africa with regards to coastal flooding is estimated
23 to US \$300 billion (1995 prices; Hinkel *et al.*, 2011) and that of Bangladesh with respect to cyclones to US\$ 25
24 billion (2009 prices; World Bank, 2011).
25

26 Several methodological issues and gaps remain. As there are so few studies of the costs and benefits of sea-level rise
27 at a global level, *evidence is low*. Uncertainties are largely unknown and the need for further research is large.
28 Impacts considered and damages and losses valued are incomplete. For example, costs of salinity intrusion, land loss
29 due to increased coastal erosion, the backwater effect and the impact of sea-level rise in combination with other
30 drivers on ecosystems have not been assessed at global scales (see Table 5-4). Generally for sea-level rise impacts, it
31 is difficult to establish a “no adaptation” baseline and the choice of the baseline changes damage costs (Yohe *et al.*,
32 2011).
33

34 Furthermore, assessments have focused on protection via hard structures but many more adaptation options are
35 available including, “soft” protection, retreat and accommodation options (Klein *et al.*, 2001; Sect. 5.1) and future
36 work needs to consider these. While the costs of “soft” protection options are largely unknown (Linham and
37 Nicholls 2010), these may provide additional benefits. For example, ecosystem-based adaptation options, also
38 preserve and restore coastal ecosystems whilst protecting against impacts (Espinosa-Romero *et al.*, 2011; McGinnis
39 and McGinnis, 2011; Pérez *et al.*, 2010; Anthony *et al.*, 2009; Alongi, 2008; Zeitlin *et al.*, 2012; Vignola *et al.*,
40 2009; IUCN, 2008). Finally, it must be noted that protection also further attracts people and development to the
41 floodplain, which together with protection levels leads to ever increasing residual risks with potential catastrophic
42 consequence in the case of defense failure. This is particularly true for many coastal cities such as London, Tokyo,
43 Shanghai, Hamburg and Rotterdam that already rely heavily on coastal defenses (Nicholls *et al.*, 2007).
44

45 [INSERT TABLE 5-8 HERE

46 Table 5-8: Global assessments of costs of sea-level rise.]
47
48

49 5.5.4. *Adaptation Practice*

50

51 Observed adaptation practice generally refers to the body of commonly used actions and measures for climate
52 change adaptation and differs from approaches (5.5.1) and options (5.5.2).
53

1 Much of the observed adaptation practice deals mainly with coastal hazards such as coastal erosion and coastal
2 flooding, although imperfect at times (Hanak and Moreno 2012). In many parts of the world, small island
3 indigenous communities address climate change consequences based on their own traditional knowledge (Percival,
4 2008; Langton *et al.*, 2012; Nakashima *et al.*, 2012).

5
6 Adaptation to sea level rise presents challenges on the ground as past adaptation to hazards may not be ecologically
7 sustainable or economically affordable in light of some high-end sea level rise projections. Long-term adaptation to
8 sea level rise has been confined to few major projects such as the Venice Lagoon project, the Thames Estuary 2100
9 project, London, and the Delta Works, Netherlands, (Norman, 2009) (Boxes 5-2 and 5-3). In addition, the complex
10 nature of coasts as a socio-ecological system (5.2) makes adaptation practice challenging (Rosenzweig *et al.*, 2011).

11 _____ START BOX 5-2 HERE _____
12
13

14 **Box 5-2. London's Themes Estuary 2100 Plan: Adaptive Management for the Long Term**

15
16 The Environment Agency in Britain, which has the main responsibility for flood risk management in England and
17 Wales, has recently undertaken the project Themes Estuary 2100 (TE2100) to investigate the future flood threat to
18 London (Environment Agency, 2012). The motivation was a fear that due to accelerated climate change-induced
19 sea-level rise time could already be too short for replacing the Thames Barrier (build in 1982) and other measures
20 that protect London, because such major engineering schemes take 25 to 30 years to plan and implement.

21
22 The US\$20 million TE2100 project was designed to assess combinations of non-structural and structural
23 engineering measures. Over a period of five years, many disciplines were involved, including engineers, economists,
24 ecologists, geomorphologists and sociologists. The TE2100 Plan was developed in stages, with substantial
25 involvement of the Estuary's stakeholders, using multi-criteria analysis to choose between the many competing
26 options.

27
28 The main findings were:

- 29 • Anticipated sea-level rise is expected not to outstrip the existing defences in the short term: so there is time
30 to plan future flood risk reduction measures.
- 31 • The Thames Barrier has a very high design standard (1 to 5,000 years), higher than had been originally
32 anticipated: such key assets need to be made to last as long as possible.
- 33 • The Estuary is geomorphologically stable: a sudden change in its character and hence the risk of flooding is
34 unlikely.
- 35 • The area affected contains as high density of with immensely valuable London properties, and developing
36 substantially: risk is rising rapidly.

37
38 As a result an adaptive plan that manages risk in an iterative way was adopted, with numerous and diverse kinds of
39 measures spread over the next 50 to 100 years, "pulling down" risk to acceptable levels (Figure 5-6). This plan
40 includes an adaptive approach to managing the existing flood defence 'assets' (walls, barriers, gates) in a carefully
41 planned way over the next 100 years (Penning-Rowsell *et al.*, 2012). During this time they will all need replacing,
42 and could at the same time be enhanced. The plan also includes a strategy to restrict development in the flood risk
43 areas, so that the time available for implementing major new works is not eroded by rapidly increasing risk. Finally,
44 in the longer term (beyond c. 2070) there will be the need to plan for more substantial measures if sea-level rise
45 accelerates. This might include a replacement of the Thames Barrier, with higher protection standards, probably
46 nearer to the sea. In the meantime the adaptive approach requires careful monitoring of the drivers of risk in the
47 Estuary to ensure that flood management authorities are not taken by surprise and forced into emergency measures.

48
49 [INSERT FIGURE 5-6 HERE

50 Figure 5-6: Adaptation measures and pathways considered in the TE2100 project. The boxed show the measures and
51 extend over the range of sea level rise they are effective. The blue arrows link to alternative measures that may be
52 applied once a measure is no longer effective. The red lines show the various sea-level rise scenarios used in the
53 analysis. The fat green line shows a possible future adaptation pathway in the unlikely event of extreme change (>4
54 m rise).]

1
2 _____ END BOX 5-2 HERE _____
3

4 To date, certain principles and good practices (methods that have shown consistently better results and could be used
5 as benchmark) can be derived from many observed examples of coastal adaptation. In a broad-scale assessment of
6 climate change threats to Australia's coastal ecosystems, seven principles in adaptation were suggested: clearly
7 defined goals for location, thorough understanding of connectivity within and between ecosystems, consideration of
8 non-climatic drivers, involvement of all relevant stakeholders, easily available and shared data, re-thinking of
9 existing policy and planning constraints and adaptation at local/regional scales (Hawden *et al.*, 2011). Based on
10 Oxfam's adaptation programmes in South Asia that include coastal communities, additional principles include a
11 focus on the poor, vulnerable and marginalized, community or local ownership, flexible and responsive
12 implementation, preparation for future and capacity building at multiple levels (Sterrett, *et al.*, 2011). An assessment
13 of worldwide case studies indicates the importance of knowledge transfer of good practice methods for scaling up
14 adaptation strategies in and between regions and beyond the national scale (Martinez *et al.*, 2011).
15

16 For European coastlines facing coastal erosion, flooding and landslide events, more specific practices are given in a
17 good practice guide (McInnes, 2006). In the California adaptation study that includes coasts, the lessons learnt
18 include using best available science, decision on goals and early actions, locating relevant partners, identification
19 and elimination of regulatory barriers and encouragement of introduction of new state mandates and guidelines
20 (Bedsworth and Hanak, 2010). Boateng (2010) presented 15 case studies from 12 countries of best practice in
21 coastal adaptation for surveyors. Bangladesh provides good examples in areas of raising awareness, disaster warning
22 and control, and protective building measures (Martinez *et al.*, 2011). In general, documentation on good adaptation
23 practices for coasts is improving.
24

25 The issues for coastal adaptation are not radically different from issues encountered with integrated coastal zone
26 management (ICZM) which offers an enabling environment for adaptation practice (Celliers *et al.*, 2013) (Box 5-4).
27 A guidebook by USAID (2009) indicates the transfer of successful experience in ICZM to coastal adaptation.
28 Detailed descriptions of adaptation measures are available in a number of guides or manuals (Linham and Nicholls,
29 2010; NOAA, 2010; Engineers Australia, 2012). Eleven types of structural projects have been identified for coastal
30 protection and restoration for Louisiana (CPRA, 2012). The major difference of coastal adaptation from ICZM is
31 coping with the dynamic nature of coastal areas, greater uncertainty, longer time frames in planning (beyond 30
32 years), and long-term commitments inherent in climate change.
33

34 Adaptation practice *is likely* to move forward as climate change adaptation (CCA) converges with disaster risk
35 reduction (DRR) (ISDR, 2009; Setiadi *et al.*, 2010; Tran and Nitivattananon, 2011; Hay, 2012). Adaptation practice
36 *is likely* to expand with two emerging approaches to adaptation in recent years – community-based adaptation
37 (CBA) and ecosystem-based adaptation (EBA). CBA involves all relevant stakeholders especially local communities
38 and is a bottom-up approach instead of the usual top-down (Ayers and Huq, 2009; UNDP, 2010; Riadh *et al.*, 2012)
39 (Table 5-7). EBA includes innovative measures (Clark and Jupiter 2010; Crooks *et al.*, 2011; Girot *et al.*, 2012;
40 Jones *et al.*, 2012; Mercer *et al.*, 2012) especially using mangroves for both CCA and DRR (Lacambra *et al.*, 2008;
41 Spalding *et al.*, 2012).
42

43 In summary, adaptation practice in the coastal zone continues to meet challenges of climate change and sea-level
44 rise (*very high confidence*). While more traditional adaptation practices may be revealed there is a myriad of
45 adaptation practices depending on technology, policy, financial and institutional support, supported by
46 documentation on good practices. ICZM with its emphasis on integration *is likely* to remain a major process for
47 coastal adaptation. With a better understanding of coasts as a complex socio-ecological system, the future *is likely* to
48 see a wider net and application of adaptation practices (*very high confidence*).
49

50 _____ START BOX 5-3 HERE _____
51
52

Box 5-3. Paradigm Shift in Adaptation to Rising Sea Levels in The Netherlands

Inhabitants in the low-lying coastal area of the Netherlands have been facing coastal and river flooding for centuries. Extreme sea levels together with long-term delta subsidence have been responsible for major catastrophic events causing thousands of fatalities over the last ten centuries. The expansion of habitable land and the increase in the population exposed to catastrophic events have co-existed with technological improvements for coastal protection and large investments resulting in a dramatic decrease in mortality rate (Van Baars and Van Kempen, 2009). Most of the coastal protection has been implemented during the second half of the twentieth century, resulting in the construction of large and numerous structures altering the appearance of an important part of the Dutch coastal area (Kabat *et al.*, 2009).

At present, nine million residents live in coastal areas at an elevation below sea level, where roughly 65% of gross national product is generated (Stive *et al.*, 2011). The anticipation of a changing climate, including sea-level rise, during the twenty-first century, together with an audit carried out in 2007 giving evidence of an aging flood protection system and an increasing vulnerability has renewed the demand for new plans for water and coastal management.

In this context the Dutch Government has set out far-reaching recommendations on how to keep the country flood-proof over the 21st century by considering a paradigm shift, namely addressing coastal protection ‘working with nature’ and providing ‘room for river’ instead of only ‘fighting’ the forces of nature with engineered structures (Figure 5-7). This takes into account a sea-level rise of as high as 0.65-1.3 by 2100. Some of the recommendations include soft and environmentally friendly solutions such as preserving land from development to accommodate increased river inundation; raising the level of lakes to ensure a continuous supply of fresh water; removing existing protection structures to restore natural estuary and tidal regimes; improving the standards of flood protection by a factor of 10 until 2050; maintaining coastal protection by beach nourishment, expanding the coast seaward in the next century and putting in place the necessary political-administrative, legal and financial resources. The estimated total cost of implementing this ambitious plan is €2.5-3.1 billion a year to 2050, representing a 0.5% of the current Dutch annual gross national product (Stive *et al.*, 2011).

[INSERT FIGURE 5-7 HERE

Figure 5-7: Overview of the Delta Committee National Recommendations. Source: Stive *et al.*, 2011.]

Aerts *et al.* (2008) estimated today’s economic damage from flooding based on differentiation according to water depth of all 53 dyke rings as approximately €190 billion covering both direct and indirect damage. The estimated future potential damage would be €400-€800 billion in 2040 and €3700 billion in 2100 in the absence of any measures, given a sea-level rise of 24-60 cm in 2040 and 150 cm in 2100. The factors that govern calculations of estimated future potential damage are economic growth combined with indirect damage. The Delta Committee suggested that, under the umbrella of this paradigm shift in the approach to water and coastal management, climate change offers key challenges that can result in societal and economic growth and evolution, moving the Netherlands into a sustainable country (Kabat *et al.*, 2009).

_____ END BOX 5-3 HERE _____

_____ START BOX 5-4 HERE _____

Box 5-4. Climate Change Adaptation and Integrated Coastal Zone Management in Developing Countries

Integrated Coastal Zone Management (ICZM) promotes sectoral and spatial integration of various activities in the coastal zone by establishing coordination across various sectors and government institutions with a view to sustainably developing coastal resources and protecting the environment. This makes it feasible for combining climate change adaptation with ICZM as a part of an integrative effort in coastal management.

ICZM in developing countries fostered by international organizations, in particular, struggle to meet the goals of ICZM (Isager, 2008). The drawbacks in the implementation of their ICZM act as constraints in climate change

1 adaptation within ICZM. For example, when initial funding by the external organizations disappears national
2 governments have to step up to finance the cost of ICZM (Ibrahim and Shaw, 2012). Ineffective coastal governance
3 is more visible in cases where the capacity of actors is low, the operation of single agency is dysfunctional, and
4 subsequently, the integration of multiple coastal agencies is beyond the reach of many developing countries
5 (Ibrahim and Shaw, 2012; Martinez *et al.*, 2011). Politics are also a strong force because of the involvement of
6 various stakeholders, the hierarchy of government agencies and ministries, and the power of the majority political
7 party or political leaders (Tabet and Fanning, 2012; Isager, 2008). Furthermore, the nature of public participation in
8 developing countries differs from that in developed countries, and different norms and cultures need to be taken into
9 account to assess public participation central to ICZM (Barale and Özhan, 2010). In some cases, there is lack of
10 knowledge regarding the coastal systems (González-Riancho *et al.*, 2010).

11
12 As legal and institutional capabilities critical to the implementation of ICZM are often not available in developing
13 countries, governments generate climate change adaptation strategies that are part of shoreline management plan,
14 regional development, disaster management, and coastal resource management. Cases of adaptation strategies
15 specific to climate change in practice are few as most are at the planning stage equipped with scenarios. Existing
16 strategies derive from responses to coastal disasters and economic and social change affecting coastal livelihoods,
17 for example, readily accessible and trained volunteers respond well by disseminating cyclone warnings and
18 evacuating and rescuing people (WRI, 2007) and this could be translated into a strategy for climate change
19 adaptation. Other strategies in progress or at the trial stage include forested buffer zones such as wetlands and
20 mangroves (Mustelin *et al.*, 2011) and incremental migration. The long-term results and their replicability need to be
21 further assessed.

22
23 To anticipate climate change and adapt, a variety of strategies could be used in the future. No or low-regret options
24 provide co-benefits to the goals of sustainable development, livelihood improvement, and human well-being (IPCC,
25 2012). Combining different strategies are also increasingly under consideration (Cheong, 2011; Cheong *et al.*, 2013;
26 Cartwright, 2009) including the blend of ecology and engineering such as mangrove planting, buffer zones and land
27 use, and insurance and structural coastal defence (Yohe *et al.*, 2011). Adaptation planning on different geographic
28 scales ranging from international, national, and regional in addition to local is at work. Regional adaptation
29 strategies (Martinez *et al.*, 2011) and community-based adaptation (Cutter *et al.*, 2012) are both on the rise.
30 Although ICZM can be a valuable policy framework to integrate climate change adaptation and coastal
31 management, no studies of the effectiveness of ICZM combined with climate change adaptation in developing
32 countries exist yet to assess its utility. Furthermore, there is a need for more detailed understanding of the science of
33 coastal change at the local level that can be coupled with existing adaptation strategies of coastal communities.

34
35 _____ END BOX 5-4 HERE _____
36
37

38 5.5.5. *Adaptation Opportunities, Constraints, and Limits*

39
40 During the last years the attention on adaptation opportunities, constraints and limits has grown considerably aiming
41 at a better assessment of our knowledge on adaptation strategies. In order to avoid the existing confusion on the
42 contents of these terms, definitions provided in Chapter 16, Box 16-1 are used here.

43
44 There is a growing recognition of the potential co-benefits and new opportunities that can be achieved by
45 mainstreaming adaptation with existing local to national goals and priorities (Chapter 14). Disaster Risk Reduction
46 (DRR) and adaptation share the common goals of reducing vulnerability against impacts of extreme events while
47 creating strategies that limit risk from hazards (IPCC, 2012). This is especially true in coastal areas where extreme
48 flooding events due to severe storm surges are one of the main sources of hazard (Box 5-5). Besides, integrating
49 adaptation with national and local planning can also contribute to build resilience in coastal areas. There is a *very*
50 *high agreement high confidence* that Integrated Coastal Zone Management (IZCM) can make it possible for coastal
51 regions to achieve their diverse goals in their adaptation to climate change (*limited evidence*) (5.5.1.4).

52
53 Ecosystems-Based Adaptation (EBA) is considered to be an emerging adaptation opportunity for adaptation
54 (Munroe *et al.* 2011). In coastal area the conservation or restoration of habitats (e.g. mangroves, wetlands and

1 deltas) can provide effective measure against storm surge, saline intrusion and coastal erosion by using biodiversity
2 and the ecosystem services they provide as a mean for adaptation (Jones *et al.*, 2012; Duarte *et al.* 2013, van
3 Wesenbeeck, B.K., 2013, Borsje, *et al.*, 2011).

4
5 Since AR4 a variety of studies have been published producing a better understanding of the nature of the constraints
6 and limits to adaptation, both generally (Chapter 16) and more specifically in the coastal sector (e.g., Lata and Nunn,
7 2011; Mozumber *et al.*, 2011; Storbjörk and Hedrén, 2011; Bedsworth and Hannak, 2010; Frazier *et al.*, 2010;
8 Saroar *et al.*, 2010; Moser *et al.*, 2008; Tribbia and Moser, 2008; Ledoux *et al.*, 2005).

9
10 Researchers have categorized constraints in different ways (Chapter 16). The common link among all constraints is
11 that they make adaptation less effective or they can lead to missed opportunities, difficult trade-offs, or higher costs.
12 Several examples of constraints for specific for coastal adaptation can be found in the literature. Among others:
13 polarized views in the community regarding the risk of sea level rise and concerns about fairness about retreat
14 schemes in Australia (Ryan *et al.*, 2011); lack of awareness of sea level rise risks and spiritual beliefs in Fiji (Lata
15 and Nunn 2011); insufficient budget for the development of adaptation policies and other currently pressing issues
16 in the US (Mozumber *et al.*, 2011; Tribbia and Moser, 2007 and 2008); distinct preferences for retreat options
17 depending on several social and exposure conditions in Bangladesh (Saroar and Routray, 2010); need to provide
18 compensatory habitats under the Habitats Regulations and lack of local public support in the UK (Ledoux *et al.*
19 2005).

20
21 The wide range of constraints identified in this assessment reflects different coastal management contexts, different
22 foci on levels of governance and actors/decision-makers, as well as different methods used in identifying them.
23 The commonly heard claim that lack of information is the main constraint to coastal adaptation is refuted by the
24 wide range of constraints identified, and many of them are empirically shown to be more important than lack of
25 locally relevant, credible information. (*high agreement, robust evidence*). Different constraints typically do not act
26 in isolation, but come in interacting bundles (*high agreement, robust evidence*). Therefore it is difficult to predict
27 which constraints matter most in any specific context but instead multiple constraints need to be addressed if
28 adaptation is to move successfully through the different stages of the management process (*high agreement,*
29 *moderate evidence*) (Moser and Ekstrom, 2010; Storbjörk, 2010; Lonsdale *et al.*, 2010). Besides, some factors can
30 act as enablers and add capacity to adapt, while acting as constraints at others (*high agreement, moderate evidence*)
31 (Burch, 2010; Storbjörk, 2010).

32
33 Finally, a common concern emerging from the literature reviews (Biesbroek *et al.*, 2011; Ekstrom *et al.*, 2011) is
34 that some critical constraints arise from the interactions across policy domains, existing laws and regulations, and
35 long-term impacts of past decisions and policies (*high agreement, low evidence*). A limit is reached when adaptation
36 efforts are unable to provide an acceptable level of security from risks to existing objectives and values and prevent
37 the loss of the key attributes, components or services of ecosystem (Chapter 16, Box 16-1; 16.2, 16.5) and may arise
38 due to most of the constraints described above.

39
40 As with regards coastal areas, it is widely recognized that biophysical limitations arise, for example, in small
41 developing island states where adaptation through retreat to increasing impact of sea level rise in conjunction with
42 storm surges and flooding is not an option due to limited high land availability, creating a temporary and eventually
43 permanent human displacement from low-lying areas (Green *et al.* 2009; Pelling and Uitto, 2001), (*high agreement,*
44 *moderate evidence*). Nicholls *et al.* 2011, show that only a limited number of adaptation options are available for
45 specific coastal areas if sea level exceeds a certain threshold (1 m) at the end of the century.

46
47 As with regards to natural (unassisted) adaptation, several researchers have examined particularly biophysical limits,
48 e.g., of coastal marshes (Kirwan *et al.*, 2010a, b; Craft *et al.*, 2009; Langley *et al.*, 2009; Mudd *et al.*, 2009). Kirwan
49 *et al.* (2010a) found that coastal marshes can adapt to conservative rates of sea-level rise (A1B), as long as there is
50 sufficient sediment supply. By contrast, even coastal marshes with high sediment supplies, will *likely* submerge near
51 the end of the 21st century under scenarios of more rapid sea-level rise (e.g., those that include ice sheet melting).

52
53 _____ START BOX 5-5 HERE _____
54

Box 5-5. Adaptation to Climate Change in the Framework of Coastal Disaster Management in Japan

Coastal disaster management in Japan is implemented through the Seacoast Law which was established in 1956 after the frequent severe natural disasters such as the Tonankai Earthquake Tsunami in 1944, Nankai Earthquake Tsunami in 1946 and Typhoon No. 13 in 1953. The aim of the law was to “protect the country’s seacoast from damage due to sea or ground movement including, but not limited to, tsunami, storm surges and high waves”. Later, in 1999, the law was amended to include “conservation of the coastal environment” and “promotion of proper use of the coast by public” in view of various functions of the coast. Under these laws the prefectural governors of each of 71 coastal zones covering the whole coastline in Japan shall established a master plan for coastal conservation. If deemed necessary to take management measures against damages the prefectural governor may designate seacoast conservation areas within the coastal zone. By 2010, about 14,200 km out of the total 35,300 km coastline have been designated and about 9,600 km was protected by coastal structures (River Bureau, 2011).

The crown height of coastal protection structures is determined from the height necessary of storm surges and tsunamis with an additional allowance. The sea-level rise at the time of design is taken into consideration by using the latest tide record. After the 2011 Tohoku Earthquake Tsunami, the Central Disaster Management Council (2011) decided to reconstruct protective coastal structures against the relatively frequent tsunamis (with a return period of several tens to one hundred and some years) and to save human lives by evacuation and all other means for the tsunami of the largest class based on scientific knowledge.

On this basis, the Committee on Adaptation Strategy for Global Warming in the Coastal Zone (2011) developed a manual for adaptation. According to the report, the land area below the mean sea level increases by about 50% in the three major bay areas (Tokyo, Nagoya and Osaka) if the sea level rises by 59 cm which is the highest projection in the IPCC (2007) Fourth Assessment Report. In the Tokyo Bay, the inundation area with a sea-level rise of 60 cm was predicted for Typhoon Muroto which landed on the western part of Japan in 1934 and is stronger than the present design typhoon by 40%. The results showed that 265 km² of the Tokyo metropolitan area would be inundated.

In order to develop an adaptation strategy, a case study on the criterion for priority was done. Two indicators were selected and calculated for each section of the land area. One indicator is evaluated from the age and earthquake resistance of the coastal structures in the section, reflecting the soundness of the structures and the urgency for improvement. The other reflects the effectiveness of the structural protection which is evaluated from the damage based on the assets in the predicted inundation area. Figure 5-8 shows the diagram for judging priority of adaptation to global warming. In Tokyo Bay, the allowance in the design crown height has absorbed the sea-level rise up to the present. However, adaptation to the future climate change needs to be implemented according to the diagram in parallel to improvement to aging coastal structures and earthquake resistance.

[INSERT FIGURE 5-8 HERE

Figure 5-8: Priority in investment for adaptation to global warming.]

_____ END BOX 5-5 HERE _____

5.5.6. Synergies and Tradeoffs 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. Bunce *et al.*, 2010b; Barbier *et al.*, 2008; Tol 2007; Brown *et al.*, 2002).

A range of studies suggest that adaptation will be the predominant approach to reducing climate risks to coastal communities, populations, resources and activities over the 21st because large increases in sea-level rise cannot be

1 ruled out (WG1, Chapter 13, 13.5.2.) and because of the time lag between emission reductions, temperature changes
2 and impacts on global sea levels (Nicholls *et al.*, 2011; Nicholls *et al.*, 2007). Systematic assessment of potential
3 synergies and trade-offs between mitigation, adaptation, and other, non-climatic policy goals and efforts to maintain
4 or increase flexibility to enable policy adjustments in the future have been proposed as strategies to recognize, avoid
5 and minimize the risk of negative policy interactions (e.g., Vermaat *et al.* 2005; Nicholls *et al.*, 2011; Chapter 20,
6 20.3.3.).

7
8 Positive synergies and complementarities between mitigation and adaptation in the coastal sector exist. Marine
9 vegetated habitats (seagrasses, saltmarshes, macroalgae or mangroves) contribute to 50% of the total carbon burial
10 in ocean sediments and provide additional functions including the buffering of impacts against storm surges and
11 waves, soil preservation, raising the seafloor and shelter for fish nursery or habitat protection (Duarte *et al.* 2013,
12 Alongi, 2002, Kennedy and Björk, 2009). Consequently, restoration or ecosystem engineering of marine vegetated
13 areas can be considered as a good example of positive synergies between adaptation and mitigation in coastal areas
14 (Duarte *et al.* 2013, Jones, *et al.* 2012, Borsje *et al.* 2011).

15
16 Many coastal zone-based activities and various coastal management activities involve emissions of greenhouse
17 gases, the reduction or cessation of some of the may have positive implications for both mitigation and adaptation.
18 The reduction/cessation of offshore oil production will imply a reduction in liquid fuel-related GHG emissions but
19 would also imply a reduced risk of oil spills, a reduction of stresses on the marine/coastal eco-systems and variable
20 socio-economic impacts on human communities and public health (O'Rourke and Connolly, 2003). This may result
21 in reduced vulnerability or increased resilience and consequently a positive for adaptation.

22
23 However, some of the coastal adaptation options may have potential negative implications on mitigation. Relocation
24 of infrastructure and development out of the coastal floodplains (retreat) will imply increase in one-time GHG
25 emissions due to rebuilding of structures and possible increase in sprawl and ongoing transportation-related
26 emissions (Biesbroek *et al.* 2009). The building or upgrading of coastal protection structures or ports will also imply
27 an increased energy use and GHG emissions related to construction (cement production) (Boden *et al.* 2011).

28
29 Similarly, actions beneficial for mitigation in coastal areas may result in potential negative impacts for adaptation. A
30 more compact coastal urban design, increasing development in floodplains (Giridharan *et al.* 2007) or the
31 development of offshore renewable energy introducing additional drivers on near- and offshore coastal and marine
32 ecosystems and species, are some examples.

33 34 35 **5.5.7. Commitment to Adaptation**

36
37 Recent results (Meehl *et al.* 2012) from global coupled climate model simulations with the new RCPs scenarios to
38 2300 confirm AR4 (Meehl *et al.* 2007) and indicate that there is a commitment to further sea level rise even if
39 temperatures stabilize due to different levels of mitigation measures. This is mostly due to thermal expansion of
40 seawater and the melting of ice-sheets and glaciers (WG1, Chapter 13).

41
42 Table 5-2 summarizes projections from (WG1, Chapter 13) for different extended RCPs for time horizons ranging to
43 2500 and considering GHG concentrations > 700 ppm. Results show that with aggressive mitigation measures in
44 RCP2.6 limiting global warming, sea level continues to rise after 2100. With more moderate (RCP4.5.) and little
45 (RCP8.5) mitigation, larger ongoing increases in sea level are expected lasting for several centuries.

46
47 It can be concluded that since AR4, there is *high agreement* that benefits from mitigation are most immediate for
48 ocean acidification and least immediate for impacts related to sea level rise. A detailed discussion on adaptation
49 efforts mitigation efforts and residual impacts can be found in Chapter 19.

50
51 A limited number of studies have estimated impacts due to sea level rise under low or high emission scenarios.
52 Pardaens et al (2011), using projections from two coupled climate models considered the effects on 21st century sea-
53 level rise of mitigation policies, under which the global-mean air temperature stabilizes close to a 2°C increase,
54 relative to a scenario of business-as-usual (a variant of the A1B scenario). The model-averaged projected sea level

1 rise for 2090–2099 relative to 1980–1999 is 0.29 m–0.51 m and a reduced range under mitigation of 0.17 m–0.34 m,
2 primarily due to reduced thermal expansion. To estimate impacts on coastal populations of the sea level rise
3 projections, the Dynamic Interactive Vulnerability Assessment (DIVA) model was used. Results suggest that by the
4 end of the 21st century and without adaptation around 55% of the 84 million additional people flooded from sea
5 level rise per year globally, under the business-as-usual scenario, could be avoided under such mitigation.
6

7 On the other end Nicholls *et al.* (2011) considering an estimate of sea-level rise by 2100, between 0.5 m and 2 m, for
8 a temperature rise of 4°C or more over the same time frame and no mitigation, showed that a real risk of the forced
9 displacement of up to 187 million people over the century (up to 2.4% of global population) exists. By introducing
10 upgrade of protection structures as an adaptation option, it is estimated that the likelihood of protection being
11 successfully implemented varies between regions, and is lowest in small islands, Africa and parts of Asia.
12

13 In summary, mitigation plays a role in reducing climate change risk in coastal areas. The intensity and time scale
14 varies depending on the impact considered. Even with aggressive mitigation options future sea-level rise will
15 continue for centuries, but model results show that it can be slowed down, providing more time for long-term
16 strategic adaptation measures to be adopted.
17

18 5.6. Information Gaps, Data Gaps, and Research Needs

19 This chapter has updated knowledge about the impacts of climate change on the coastal systems not in isolation but
20 also from the perspective of overexploitation and degradation that have been responsible for most of the historical
21 changes. There is a better understanding of the varying impacts of weather and climate extremes and long-term sea-
22 level rise on human systems.
23

24 That sea levels will rise is a confident projection of climate science but uncertainties around the magnitude of future
25 sea level rise remain large. It is very likely that GMSL rise during the 21st century will exceed the observed rate for
26 the period 1971–2100 (Chapter 13, WGI) and that sea level rise will continue to rise for several hundred years even
27 if temperature is stabilized at 2–3°C above pre-industrial values (Meehl *et al.*, 2012). However, many sea level rise
28 assessments are not at spatial or temporal scales most relevant for decision makers who require information on
29 baseline conditions and projections of change (Kettle, 2012) of relative sea level rise (i.e. including local
30 subsidence) for vulnerability assessment and adaptation planning.
31

32 Quantitative predictions of future coastal change remain difficult despite the application of improvements in
33 technology, e.g., aerial photographs, satellite imagery, LiDAR (Sesil *et al.*, 2009; Revell *et al.*, 2011; Pe’eri and
34 Long, 2012) to investigate and characterize large-scale changes in shoreline. There is incomplete understanding of
35 coastal changes over the decade and century timescales (Woodroffe and Murray-Wallace, 2012). Shoreline response
36 is more complex than simple submergence because of factors such as sediment supply, offshore geology,
37 engineering structures, and wave forcing (Ashton *et al.*, 2008).
38

39 The projection of the future impacts of climate change on natural systems is hampered by the lack of sufficiently
40 detailed data at the required levels of space and time. Observed impacts on beaches, rocky coasts, wetlands, coastal
41 aquifers or deltas area due to the joint effect of multi-drivers of climate and human-induced origin. There is still
42 incomplete understanding of the relative role played by each of these drivers and, especially on their combined
43 effect. Uncertainties are even higher when it comes to the evaluation of projected impacts. For coastal ecosystems
44 virtually all data used to parametrize predictive models have been gathered during perturbation experiments
45 involving only one driver, performed on isolated organisms in the laboratory, and on short periods of time (typically
46 days to weeks). Reliable predictions require information on multifactorial experiments performed on communities
47 (preferably in the field), and on time scale of months to years in order to take into consideration the processes of
48 biological acclimation and adaptation.
49

50 Although sea level is projected to rise in future, there are significant gaps in vulnerability assessment of other
51 specific coastal impacts. For example, climate modeling of diseases that could affect coastal areas is based mainly
52
53

1 on the mean values of climate. Also, despite tourism as one of most important industries in the coastal areas, not
2 enough is known about tourists' behavioural reactions to projected climatic changes (Moreno and Amelung, 2009).
3

4 A wide range of coastal management framework and measures is available and used in coastal adaptation to climate
5 change, and their scope for their integration has increased by combining scenarios of climate change and socio-
6 economic conditions and risk assessment (Kirshen *et al.*, 2012). While various adaptation measures are available, at
7 the local level, there remains insufficient information on assessment of adaptation options. Data and knowledge gaps
8 exist or their reliability is insufficient. Despite the availability of potential useful climate information, a gap exists
9 between what is useful information for scientists and for users in decision-making. The proposed actions to improve
10 usability include varying levels of interaction, customization, value-adding, retailing and wholesaling (Lemos *et al.*,
11 2012) so that data and methods can be more openly-accessable to fellow scientists and public (Kleiner, 2011).
12

13 Coastal systems are affected by human and climate drivers and there are also complex interactions between the two.
14 In general, where components of coastal systems are sensitive to temperature change, there is a greater degree of
15 confidence that climate change has played a role. Data are available on the range shift in coastal plant and animal
16 species and the role of higher temperatures on coral bleaching. However, in many cases in the human systems, the
17 detected changes can be largely attributed to human drivers. Reducing our knowledge gaps on the understanding of
18 the processes inducing changes would help to respond to them in an efficient way.
19

20 The economics of coastal adaptation is under researched. More comprehensive assessments of adaptation costs and
21 benefits that simultaneously consider both the gradual impact of land loss due to sea level rise and the stochastic
22 impacts of extreme water levels (storm surges, cyclones) are needed, as well as other impacts such as salt water
23 intrusion, wetland loss and change and backwater effects. Assessments should also consider a more comprehensive
24 range of adaptation options and strategies, including "soft" protection, accommodation and retreat options as well as
25 the trade-offs between these.
26

27 Governance of coastal adaptation and the role of institutions in the transition towards sustainable coasts are under-
28 researched. While institutional factors are recognized to be decisive in constraining and enabling coastal adaptation,
29 there is little dedicated social science research aiming at understanding which institutional arrangement are effective
30 in which socio-economic and biophysical contexts.
31

32 Developing a coastal adaptation knowledge network between scientists, policy makers, stakeholders and the general
33 public could be considered as a priority area for coastal areas of large or regional areas affected by climate change
34 and sea-level rise. This is well developed in the European Union, the Mediterranean and Australia but less so in the
35 developing countries, except in certain regions, e.g. Caribbean islands, Pacific Islands.
36

37 Future research needs for coastal adaptation are identified by several developments in climate science. Based on Li
38 *et al.* (2011) survey of the foci of climate research in the 21st century, the implications for coasts would be on
39 biodiversity and flooding. Future technological advances may be significant, e.g., new forms of energy and food
40 production, information and communication technology (ICT) for risk monitoring (Delta Commission, 2008) and
41 these would be useful for flood risks and food production in deltas and coastal systems (aquaculture). With recent
42 adverse climatic and environmental events on coasts, adaptation demands different decision regimes (Kiker *et al.*,
43 2010) but adaptation, mitigation and avoidance measures still require integrating research that includes natural and
44 social sciences (CCSP, 2009). Although many gaps still remain, there is nevertheless a greater foundation of climate
45 change research on coasts across a wide range of fields (Grieneisen and Zhang, 2011) upon which scientists,
46 policymakers and public may find improved solutions for coastal adaptation.
47
48

49 **Frequently Asked Questions**

51 ***FAQ 5.1: How does climate change affect coastal ecosystems?***

52 The major climate-related drivers affecting coastal ecosystems are sea-level rise, ocean warming and ocean
53 acidification. The impact of sea level is mostly related to the capacity by animals (e.g. corals) and plants (e.g.
54 mangroves) to keep up with the vertical rise of the sea. Ocean warming affects all organisms, increasing their

1 metabolism, causing mass mortality events of those living close their upper thermal limit, and/or affecting their
2 geographical distribution. Ocean acidification negatively impacts many organisms that build shells and skeletons but
3 its effects are poorly known at the ecosystem level.
4

5 ***FAQ 5.2: How is climate change influencing coastal erosion?***

6 Coastal erosion can be caused by winds, waves and currents, especially during storms, as well as sea-level rise and
7 for deltas, river sediment transport and deposition are important factors. Based on the simplest model, a rise in mean
8 sea level usually results in a landward and upward displacement of the cross-shore seabed profile and a retreat of the
9 shoreline. Increasing waves heights can cause the sand bars to move seawards and high storm surges (sea levels)
10 also produce an offshore movement of sand due to non-equilibrium in the profile. Higher waves and surges may
11 increase the probability of sand barrier and dune overwash or breaching. Changes in wave direction may result in
12 increased sediment transport and subsequent erosion.
13

14 ***FAQ 5.3: How can coastal communities adapt to climate change impacts?***

15 Various adaptation strategies are available which range from (managed) retreat, accommodation and protection.
16 Adaptation through structural measures includes hard (e.g. sea walls) and soft (e.g. coastal revegetation)
17 management options. Non-structural measures include land-use planning (e.g. rolling easements that require
18 relocation of vulnerable infrastructure as critical risk thresholds are crossed) and climate-aware policies and plans,
19 including EIA and building codes. Monitoring and compliance are required to ensure implementation of plans.
20 Education is also important for building community resilience. Risk transfer mechanisms (e.g. insurance) address
21 residual risk although where risks are too high, retreat from coastal areas may be the only viable response. A
22 combination of strategies, tailored to suit the particular coastal community, may be required and will need to be
23 reviewed and adjusted as circumstances change in the future.
24

25 ***FAQ 5.4: Does adequate planning for coastal uses contribute to a reduction in climate change risks?***

26 Yes, adequate planning of coastal uses contributes to reduced climate change risks and lessens the chances of
27 reactive responses to the impacts of extreme events. Such planning is normally supported by national legislation and
28 considers both the problems of both climate change and coastal hazards, especially coastal flooding. Regional
29 coastal strategies and plans are established with guidelines for local governments to implement. For measures to be
30 taken, the focus is on precautionary measures irrespective of future climate change. An important paradigm change
31 of planning land uses to reduce climate change is to use the buffer zone as a response to coastal inundation. The
32 strategy is to work with nature rather than against nature, e.g. in the Netherlands. It should be noted that for many
33 developing countries planning at the grass-root level either does not exist or is not yet workable requiring re-
34 evaluation of how to make adaptation more sustainable..
35

36 ***FAQ 5.5: How does ocean acidification affect marine and coastal areas and islands?***

37 PH, a measure of seawater acidity, has numerous implications on biological and geological systems. For example, in
38 coastal systems, it plays a role in primary production which constitutes the base of the food chain, in the deposition
39 of calcium carbonate in shells and skeletons, in the degradation of limestone, as well as in the abundance of certain
40 forms of chemical elements and on their toxicity. Ocean acidification has therefore a lot of ramifications on the
41 biology, ecology, biogeochemistry, and socio-economy of coastal systems. Some of these ramifications are well
42 understood while others such as changes in coastal food-webs and fisheries are poorly known.
43
44

45 **Cross-Chapter Boxes**

46
47 **Box CC-CR. Coral Reefs**

48 [Jean-Pierre Gattuso (France), Ove Hoegh-Guldberg (Australia), Hans-Otto Pörtner (Germany)]
49

50 Coral reefs are shallow-water structures made of calcium carbonate mostly secreted by reef-building (scleractinian)
51 corals and encrusting macroalgae. They occupy less than 0.1% of the ocean floor yet play multiple important roles
52 throughout the tropics. About 275 million people live within 30 km of a coral reef (Burke et al., 2011) and are likely
53 to derive some benefits from the ecosystem services that coral reefs provide (Hoegh-Guldberg, 2011) including
54 those from provisioning (food, construction material, medicine), regulating (shoreline protection, water quality),

1 supporting services (oxygen supply) and cultural (religion, tourism). This is especially true in small islands
2 (29.3.3.1).

3
4 Most human-induced disturbances to coral reefs were local (e.g., coastal development, pollution, nutrient
5 enrichment and overfishing) until the early 1980s when global and climate-related disturbances (ocean warming and
6 acidification) began to occur. Temperature and seawater acidity are two of the most important environmental
7 variables determining the distribution of coral reefs (Kleypas et al., 2001). As corals are centrally important as
8 ecosystem engineers (Wild et al., 2011), the impacts on corals have led to widespread degradation of coral reefs.

9
10 A wide range of climatic and non-climatic stressors affect corals and coral reefs and negative impacts are already
11 observed (5.4.2.4, 30.5.3, 30.5.6). Bleaching involves the breakdown and loss of endosymbiotic algae (genus
12 *Symbiodinium*), which live in the coral tissues and play a key role in supplying the coral host with energy and
13 nutrients (Baker et al., 2008) (see 6.2.5 for physiological details and 30.5 for a regional analysis). Mass coral
14 bleaching and mortality, triggered by positive temperature anomalies, is the most widespread and conspicuous
15 impact (Fig. 5X; see Sections, 5.4.2.4, 6.2.5, 25.6.2, 30.5 and 30.8.2). For example, the level of thermal stress at
16 most of the 47 reef sites where bleaching occurred during 1997-98 was unmatched in the period 1903 to 1999
17 (Lough, 2000). Elevated temperature along with ocean acidification reduces the calcification rate of corals (*high*
18 *confidence*; 5.4.2.4), and may tip the calcium carbonate balance of reef frameworks towards dissolution (*medium*
19 *evidence and agreement*; 5.4.2.4). These changes will erode fish habitats with cascading effects reaching fish
20 community structure and associated fisheries (*robust evidence, high agreement*, 30.5).

21
22 Around 50% of all coral reefs have experienced medium-high to very high impact of human activities (30-50% to
23 50-70% degraded; Halpern et al., 2008), which has been a significant stressor for over 50 years in many cases. As a
24 result, the abundance of reef building corals is in rapid decline (1 to 2% per year, 1997-2003) in many Pacific and
25 SE Asian regions (Bruno and Selig, 2007). Similarly, the abundance of reef-building corals has decreased by over
26 80% on many Caribbean reefs (1977 to 2001; Gardner et al., 2003), with a dramatic phase shift from corals to
27 seaweeds occurring on Jamaican reefs (Hughes, 1994). Tropical cyclones, coral predators and coral bleaching have
28 led to a decline in coral cover on the Great Barrier Reef (about 51% between 1985 and 2012; De'ath et al., 2012).

29
30 One third of all coral species exhibit a high risk of extinction, based on recent patterns of decline and other factors
31 such as reproductive strategy (Carpenter et al., 2008). Although less well documented, non-coral benthic
32 invertebrates are also at risk (Przeslawski et al., 2008). Fish biodiversity is threatened by the permanent degradation
33 coral reefs, including in a marine reserve (Jones et al., 2004). While many factors, such as overfishing and local
34 pollution, are involved in the decline of coral reefs, climate change through its pervasive influence on sea
35 temperature, ocean acidity, and storm strength plays a very significant role.

36
37 There is *robust evidence* and *high agreement* that coral reefs are one of the most vulnerable marine ecosystems
38 (Chapters 5, 6, 25, and 30). Globally, more than half of the world's reefs are under medium or high risk of
39 degradation (Burke et al., 2011) even in the absence of climatic factors. Future impacts of climate stressors (ocean
40 warming, acidification and sea level rise) will exacerbate the impacts of non-climatic stressors (*high agreement*,
41 *robust evidence*). Even under optimistic assumptions regarding corals being able to rapidly adapt to thermal stress,
42 one-third (9–60%, 68% uncertainty range) of the world's coral reefs are projected to be subject to long-term
43 degradation under the RCP3-PD scenario (Frieler et al., 2013). Under the RCP4.5 scenario, this fraction increases to
44 two-thirds (30–88%, 68% uncertainty range). If present day corals have residual capacity to acclimatize and/or
45 adapt, half of the coral reefs may avoid high frequency bleaching through 2100 (*limited evidence, limited*
46 *agreement*; Logan et al., sbm). Evidence of corals adapting rapidly, however, to climate change is missing or
47 equivocal (Hoegh-Guldberg, 2012).

48
49 Damage to coral reefs has implications for several key regional services:

- 50 • *Resources*: Coral reefs produce 10-12% of the fish caught in tropical countries, and 20-25% of the fish
51 caught by developing nations (Garcia & Moreno, 2003). Over half (55%) of the 49 island countries
52 considered by Newton et al. (2012) are already exploiting their coral reef fisheries in an unsustainable way
53 (13.X.X).

- 1 • *Tourism*: More than 100 countries benefit from the recreational value provided by their coral reefs (Burke
2 et al., 2011). For example, the Great Barrier Reef Marine Park attracts about 1.9 million visits each year
3 and generates A\$ 5.4 billion to the Australian economy and 54,000 jobs (90% in the tourism sector; Biggs,
4 2011).
- 5 • *Coastal protection*: Coral reefs contribute to protecting the shoreline from the destructive action of storm
6 surges and cyclones (Sheppard et al., 2005), sheltering the only habitable land for several island nations,
7 habitats suitable for the establishment and maintenance of mangroves and wetlands, as well as areas for
8 recreational activities. This role is threatened by future sea level rise, the decrease in coral cover, reduced
9 rates of calcification and higher rates of dissolution and bioerosion due to ocean warming and acidification
10 (5.4.2.4, 6.4, 30.5).

11
12 Coral reefs make a modest contribution to the global domestic product but their economic importance can be high at
13 the country and regional scales (Pratchett et al., 2008). For example, tourism and fisheries represent on average 5%
14 of the GDP of South Pacific islands (Laurans et al., 2013). At the local scale, these two services provide at least 25%
15 of the annual income of villages in Vanuatu and Fiji (Pascal, 2011; Laurans et al., 2013).

16
17 Marine protected areas (MPAs) and fisheries management have the potential to increase ecosystem resilience and
18 increase the recovery of coral reefs after climate change impacts such as mass coral bleaching (McLeod et al., 2009).
19 Although they are key conservation and management tools, they are less effective in reducing coral loss from
20 thermal stress (Selig et al., 2012) suggesting that they need to be complemented with additional and alternative
21 strategies (Rau et al., 2012). Controlling the input of nutrients and sediment from land is an important
22 complementary management strategy because nutrient enrichment can increase the susceptibility of corals to
23 bleaching (Wiedenmann et al., 2012). There is also high confidence that, in the long term, limiting the amount of
24 warming and acidity is central to ensuring the viability of coral reef systems and dependent communities (5.X.X and
25 30.5).

26
27 [INSERT FIGURE CR-1 HERE

28 Figure CR-1: A and B: the same coral community before and after a bleaching event in February 2002 at 5 m depth,
29 Halfway Island, Great Barrier Reef. Coral cover at the time of bleaching was 95% bleached almost all of it severely
30 bleached, resulting in mortality of 20.9% (Elvidge et al., 2004). Mortality was comparatively low due in part
31 because these communities were able shuffle symbiont types to more thermo-tolerant types (Berkelmans and van
32 Oppen, 2006; Jones et al., 2008). C and D: three CO₂ seeps in Milne Bay Province, Papua New Guinea show that
33 prolonged exposure to high CO₂ is related to fundamental changes in coral reef structures (Fabricius et al., 2011).
34 Coral communities at three high CO₂ (Fig. XB; median pHT 7.7, 7.7 and 8.0), compared with three control sites
35 (Fig. XA; median pHT 8.02), are characterized by significantly reduced coral diversity (-39%), severely reduced
36 structural complexity (-67%), low densities of young corals (-66%) and few crustose coralline algae (-85%). Reef
37 development ceases at pHT values below 7.7. Photo credit: R. Berkelmans (A and B) and K. Fabricius (C and D).]

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37

38 **Box CC-OA. Ocean Acidification**

39 [Jean-Pierre Gattuso (France), Peter Brewer (USA), Ove Hoegh-Guldberg (Australia), Joan A. Kleypas (USA), Hans-Otto Pörtner (Germany),
40 Daniela Schmidt (UK)]

42 **Introduction**

43 Anthropogenic ocean acidification and climate change share the same primary cause at the global level, the increase
44 of atmospheric carbon dioxide (WGI, 2.2.1). Eutrophication and upwelling contribute to local ocean acidification
45 (5.3.3.6, 30.5.4). Past and futures changes in chemistry are well known in the surface open ocean (WGI, 3.8.2 and
46 6.4.4) but are more difficult to project in the more complex coastal systems (5.3.3.6 and 30.5.2).

48 **Chemistry and Projections**

49 The fundamental chemistry of ocean acidification has long been understood: the uptake of CO₂ into mildly alkaline
50 ocean results in an increase in dissolved CO₂ and reductions in pH, dissolved carbonate ion, and the capacity of
51 seawater to buffer changes in its chemistry (*very high confidence*). The changing chemistry of surface seawater can
52 be projected at the global scale with high accuracy from projections of atmospheric CO₂ levels. Time series
53 observations of changing upper ocean CO₂ chemistry support this linkage (WGI Table 3.2 and Figure 3.17; WGII
54 Figure 30.5). Projections of regional changes, especially in coastal waters (5.3.3.6), and at depth are more difficult;

1 observations and models show with high certainty that fossil fuel CO₂ has penetrated at depths of 1 km and more.
2 Importantly, the natural buffering of increased CO₂ is less in deep than in surface water and thus a greater chemical
3 impact is projected. Additional significant CO₂ increases and pH decreases at mid-depths are expected to result from
4 increases in microbial respiration induced by warming. Projected changes in open ocean, surface water chemistry for
5 year 2100 based on representative concentration pathways (WGII, Figure 6.28) compared to preindustrial values
6 range from a pH change of -0.14 unit with RCP 2.6 (421 ppm CO₂, +1 °C, 22% reduction of carbonate ion
7 concentration) to a pH change of -0.43 unit with RCP 8.5 (936 ppm CO₂, +3.7 °C, 56% reduction of carbonate ion
8 concentration).
9

10 ***Biological, Ecological, and Biogeochemical Impacts***

11 The effects of ocean acidification on marine organisms and ecosystems have only recently been investigated. A wide
12 range of sensitivities to projected rates of ocean acidification exists within and across organism groups and phyla
13 with a trend for higher sensitivity in early life stages (*high confidence*; Kroeker et al., in press; 6.2.3-5, 6.3.4). A
14 pattern of impacts, some positive, others negative, emerges for some processes and organisms (*high confidence*; Fig.
15 X.C) but key uncertainties remain from organismal to ecosystem levels (Chap. 5, 6, 30). Responses to ocean
16 acidification are exacerbated at high temperature extremes (*medium confidence*) and can be influenced by other
17 drivers, such as oxygen concentration, nutrients, and light availability (*medium confidence*).

18 Experimental evidence shows that lower pH decreases the rate of calcification of most, but not all, sea-floor
19 calcifiers such as reef-building corals (Box CC-CR, coralline algae (Raven, in press), bivalves and snails (Gazeau et
20 al., in press) reducing their competitiveness compared to, e.g. seaweeds (Chap. 5, 6, 30). A reduced performance of
21 these ecosystem builders would affect the other components of the ecosystem dependent on the habitats they create.

22 Growth and primary production are stimulated in seagrass and some phytoplankton (*high confidence*) and
23 harmful algal blooms could become more frequent (*limited evidence, medium agreement*). Ocean acidification may
24 significantly stimulate nitrogen fixation in the oceans (*limited evidence, low agreement*; 6.2.3, 6.3.4). There are few
25 known direct effects on early stages of fish and adult fish remain relatively undisturbed by elevated CO₂. Serious
26 behavioral disturbances were reported, mostly on larval and juvenile coral reef fishes (6.2.4).

27 Projections of ocean acidification effects at the ecosystem level are limited by the diversity of species-level
28 responses. Natural analogues at CO₂ vents indicate decreased species diversity, biomass and trophic complexity of
29 communities living on the sea-floor. Shifts in community structure have been documented in rocky shore
30 environments (e.g., Wootton et al., 2008), in relation with rapidly declining pH (Wootton and Pfister, 2012).
31 Differential sensitivities and associated shifts in performance and distribution will change predator-prey
32 relationships and competitive interactions (6.2-3), which could impact food webs and higher trophic levels (*limited
33 evidence, high agreement*).

34 There is *limited evidence* and *medium agreement* that some phytoplankton and mollusks can adapt to ocean
35 acidification, indicating that the long-term responses of these organisms to ocean acidification could be less than
36 responses obtained in short-term experiments. However, mass extinctions during much slower rates of ocean
37 acidification in Earth history (6.1.2) suggest that evolutionary rates are not fast enough for sensitive animals and
38 plants to adapt to the projected rate of change (*high confidence*).

39 The effect of ocean acidification on global biogeochemical cycles is difficult to predict due to the species-
40 specific responses to ocean acidification, lack of understanding of the effects on trophic interactions, and largely
41 unexplored combined responses to ocean acidification and other climatic and non-climatic drivers, such as
42 temperature, concentrations of oxygen and nutrients, and light availability.
43

44 ***Risks***

45 Climate risk is defined as the probability that climate change will cause specific physical hazards and that those
46 hazards will cause impacts (19.5.2). The risks of ocean acidification to marine organisms, ecosystems, and
47 ultimately to human societies, includes both the probability that ocean acidification will affect key processes, and
48 the magnitude of the resulting impacts. The changes in key processes mentioned above present significant
49 ramifications on ecosystems and ecosystem services (Fig. 19.3). For example, ocean acidification will cause a
50 decrease of calcification of corals, which will cause not only a reduction in the coral's ability to grow its skeleton,
51 but also in its contribution to reef building (*high confidence*; 5.4.2.4). These changes will have consequences for the
52 entire coral reef community and on the ecosystem services that coral reefs provide such as fisheries habitat (*medium
53 confidence*; 19.5.2) and coastal protection (*medium confidence*; Box CC-CR). Ocean acidification poses many other

1 potential risks, but these cannot yet be quantitatively assessed due to the small number of studies available,
2 particularly on the magnitude of the ecological and socioeconomic impacts (19.5.2).

4 ***Socioeconomic Impacts and Costs***

5 The biological, ecological and biogeochemical changes driven by ocean acidification will affect several key
6 ecosystem services. The oceans will become less efficient at absorbing CO₂, hence less efficient at moderating
7 climate change, as their CO₂ content will increase (*very high confidence*). The impacts of ocean acidification on
8 coral reefs, together with those of bleaching and sea level rise, will in turn diminish their role of shoreline protection
9 in atolls and small island nations as well as their direct and indirect benefits on the tourism industry (*limited*
10 *evidence, high agreement*; Box CC-CR).

11 There is no global estimate of the observed or projected economic costs of ocean acidification. The production
12 of commercially-exploited shelled mollusks may decrease (Barton et al., 2012) resulting in an up to 13% reduction
13 of US production (limited evidence, low agreement; Cooley and Doney, 2009). The global cost of production loss of
14 mollusks could be over 100 billion USD by 2100 (Narita et al., 2012). The largest uncertainty is how the impacts on
15 prey will propagate through the marine food webs and to top predators. Models suggest that ocean acidification will
16 generally reduce fish biomass and catch (*limited evidence, high agreement*) and that complex additive, antagonistic
17 and/or synergistic interactions will occur with other environmental (warming) and human (fisheries management)
18 factors (Branch et al., 2012; Griffith et al., 2012). The annual economic damage of ocean-acidification-induced coral
19 reef loss by 2100 has been estimated, in 2009, to be 870 and 500 billion USD, respectively for A1 and B2 SRES
20 emission scenarios (Brander et al. 2012). Although this number is small compared to global GDP, it represents a
21 large proportion of the GDP of some regions or small island states which rely economically on coral reefs.

23 ***Adaptation and Mitigation***

24 The management of ocean acidification comes down to mitigation of the source of the problem and adaptation to the
25 consequences (Rau et al., 2012; Billé et al., sbm). Mitigation of ocean acidification through reduction of atmospheric
26 CO₂ is the most effective and the least risky method to limit ocean acidification and its impacts. Climate
27 geoengineering techniques based on solar radiation management would have no direct effect on ocean acidification
28 because atmospheric CO₂ would continue to rise (6.4.2). Techniques based on carbon dioxide removal could directly
29 address the problem but their effectiveness at the scale required to ameliorate ocean acidification has yet to be
30 demonstrated. Additionally, some ocean-based approaches, such as iron fertilization, would only re-locate ocean
31 acidification from the upper ocean to the ocean interior, with potential ramifications on deep water oxygen levels
32 (Williamson and Turley, 2012; 6.4.2; 30.3.2.3 and 30.5.7). Mitigation of ocean acidification at the local level could
33 involve the reduction of anthropogenic inputs of nutrients and organic matter in the coastal ocean (5.3.4.2). Specific
34 activities, such as aquaculture, could adapt to ocean acidification within limits, for example by altering the
35 production process, selecting less sensitive species or strains, or relocating elsewhere. A low-regret approach is to
36 limit the number and the magnitude of drivers other than CO₂. There is evidence, for example, that reducing a
37 locally determined driver (i.e. nutrient pollution) may substantially reduce its synergistic effects with a globally
38 determined driver such as ocean acidification (Falkenberg et al., 2013).

39
40 [INSERT FIGURE OA-1 HERE

41 Figure OA-1: A: Overview of the chemical, biological, socio-economic impacts of ocean acidification and of policy
42 options (adapted from Turley & Gattuso, 2012). B: Multi-model simulated time series of global mean ocean surface
43 pH (on the total scale) from CMIP5 climate model simulations from 1850 to 2100. Projections are shown for
44 emission scenarios RCP2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the
45 distribution of individual model simulations (shading). Black (grey shading) is the modelled historical evolution
46 using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global
47 carbon cycle while being driven by prescribed atmospheric CO₂ concentrations. The number of CMIP5 models to
48 calculate the multi-model mean is indicated for each time period/scenario (IPCC AR5 WG1 report, Figure 6.28). C:
49 Effect of near future acidification on major response variables estimated using weighted random effects meta-
50 analyses, with the exception of survival which is not weighted (Kroeker et al., in press). The effect size indicates
51 which process is most uniformly affected by ocean acidification but large variability exists between species.
52 Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of
53 experiments used in the analyses is shown in parentheses. * denotes a significant effect.]

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Box CC-TC. Case Study Building Long Term Resilience from Tropical Cyclone Disasters

[Yoshiki Saito (Japan), Kathleen McInnes (Australia)]

Tropical cyclones (also referred to as hurricanes and typhoons in some regions) cause powerful winds, torrential rains, high waves and storm surge, all of which can have major impacts on society and ecosystems. For example, Bangladesh and India account for 86% of mortality from tropical cyclones (Murray *et al.*, 2012), which is mainly due to the rarest and most severe storm categories (i.e. Categories 3, 4, and 5).

About 90 tropical cyclones occur globally each year (Seneviratne *et al.*, 2012) although interannual variability is large. Changes in observing techniques particularly after the introduction of satellites in the late 1970s, confounds the assessment of trends in tropical cyclone frequencies and intensities. Therefore, SREX concluded that there is *low confidence* that any observed long-term (i.e. 40 years or more) increases in tropical cyclone activity are robust, after accounting for past changes in observing capability (Seneviratne, *et al.*, 2012; Chapter 2). There is also *low confidence* in the detection and attribution of century scale trends in tropical cyclones. Future changes to tropical cyclones arising from climate change are *likely* to vary by region. This is because there is *medium confidence* that for certain regions, shorter-term forcing by natural and anthropogenic aerosols has had a measurable effect on tropical cyclones. Tropical cyclone frequency is *likely* to decrease or remain unchanged over the 21st century, while intensity (i.e. maximum wind speed and rainfall rates) is *likely* to increase. Regionally specific projections have *lower confidence* (see WG1 Box 14.2).

1 Longer term impacts from tropical cyclones includes salinisation of coastal soils and water supplies and subsequent
2 food and water security issues from the associated storm surge and waves (Terry and Chui, 2012). However,
3 preparation for extreme tropical cyclone events through improved governance and development to reduce their
4 impacts provides an avenue for building resilience to longer term changes associated with climate change.
5

6 Densely populated Asian deltas are particularly vulnerable to tropical cyclones due to their large population density
7 in expanding urban areas (Nicholls *et al.*, 2007). Extreme cyclones in Asia since 1970 caused over 0.5 million
8 fatalities (Murray *et al.*, 2012) e.g., cyclones Bhola in 1970, Gorky in 1991, Thelma in 1998, Gujarat in 1998, Orissa
9 in 1999, Sidr in 2007, and Nargis in 2008. Tropical cyclone Nargis hit Myanmar on 2 May 2008 and caused over
10 138,000 fatalities. Several-meter high storm surges widely flooded densely populated coastal areas of the Irrawaddy
11 Delta and surrounding areas (Revenga *et al.*, 2003; Brakenridge *et al.*, 2012). The flooded areas were captured by a
12 NASA MODIS image on 5 May 2008 (Figure TC-1).
13

14 [INSERT FIGURE TC-1 HERE

15 Figure TC-1: The intersection of inland and storm surge flooding. Red shows May 5, 2008 MODIS mapping of the
16 tropical cyclone Nargis storm surge along the Irrawaddy Delta and to the east, Myanmar. The blue areas to the north
17 were flooded by the river in prior years. (From Brakenridge *et al.*, 2012).]
18

19 Murray *et al.* (2012) compared the response to cyclone Sidr in Bangladesh in 2007 and Nargs in Myanmar in 2008
20 and demonstrated how disaster risk reduction methods could be successfully applied to climate change adaptation
21 (Murray *et al.*, 2012). Sidr, despite being of similar strength to Nargis, caused far fewer fatalities (3,400 compared to
22 over 138000) and this was attributed to advancement in preparedness and response in Bangladesh through
23 experience in previous cyclones such as Bhola and Gorky. The responses included the construction of multi-storied
24 cyclone shelters, improvement of forecasting and warning capacity, establishing a coastal volunteer network, and
25 coastal reforestation of mangroves. Birkmann and Teichman, (2010) caution that while the combination of risk
26 reduction and climate change adaptation strategies may be desirable, different spatial and temporal scales, norm
27 systems, and knowledge types and sources between the two goals can confound their effective combination.
28

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7

Table 5-1: Projections of global mean sea level rise in metres relative to 1986–2005 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 is given whereas for projections from 2200 onwards, the range represents the model spread due to the small number of model projections available (source: WG1, Chapter 13).

	RCP	2080-2100	2100	2200	2300	2400	2500
Low	2.6	0.42 [0.29 to 0.55]	0.46 [0.32 to .61]	0.47–0.60	0.59–0.67	0.67–0.79	0.77–0.91
Medium	4.5	0.49 [0.36 to 0.63]	0.56 [0.41 to .71]	0.25–0.90	0.31–1.12	0.30–1.38	0.27–1.67
High	6.0	0.50 [0.37 to 0.64]	0.58 [0.42 to .74]	0.67–1.92	1.10–3.21	1.44–4.55	1.80–5.76
	8.5	0.64 [0.48 to 0.82]	0.76 [0.56 to .96]				

Table 5-2: Main climate-related drivers for coastal systems, their trends due to climate change, and their main physical and ecosystem effects (↑ increase; ↓ decrease; ↯ no change; ? uncertain; ↔ regional variability).

Climate Driver	Physical effects	Trends	Projections	Progress since AR4
Sea Level	Submergence, flood damage, erosion; saltwater intrusion; rising water tables/impeded drainage; wetland loss (and change).	GMSL <i>very likely</i> (5.3.2.2, WG1 Ch. 13)	GMSL <i>very likely</i> (see Table 5.1, WG1 Ch. 13) « (5.3.2.2, WG1 Ch. 13)	Improved confidence in contributions to observed sea level. More information on regional and local SLR.
Storms (Tropical cyclones (TC's), extratropical cyclones (ETC's))	Storm surges and storm waves, coastal flooding, erosion; saltwater intrusion; rising water tables/impeded drainage; wetland loss (and change). Coastal infrastructure damage and flood defence failure.	TC's (Box 5.1, WG1 2.6.3) <i>Low confidence</i> in trends in frequency and intensity due to limitations in observations « ETC's (5.3.3.1 WG1 2.6.4) <i>Likely</i> poleward movement of circulation features but <i>low confidence</i> in intensity changes.	TC's (Box 5.1) <i>Likely</i> ↓ in frequency; <i>Likely</i> ↑ in the most intense TC's ETC's (5.3.3.1) <i>High confidence</i> that reduction of ETC's will be small globally. <i>Low confidence</i> in changes in intensity.	Lowering of confidence of observed trends in TC's and ETC's since AR4. More basin-specific information on storm track changes.
Winds	Wind waves, storm surges, coastal currents, coastal infrastructure damage.	<i>Low confidence</i> in trends in mean and extreme wind speeds (5.3.3.2, SREX, WG1 Ch 2).	<i>Low confidence</i> in projected mean wind speeds. <i>Likely</i> increase in TC extreme wind speeds (5.3.3.2, SREX).	Winds not specifically addressed in AR4.

Waves	Coastal erosion, overtopping and coastal flooding.	<i>Likely</i> positive trends in high latitudes (5.3.3.2, WG1, Ch 3).	<i>Low confidence</i> for projections overall but <i>medium confidence</i> for southern ocean increases (5.3.3.2).	Large increase in number of wave projection studies since AR4.
Extreme Sea Levels	Coastal flooding erosion, saltwater intrusion	<i>High confidence</i> of increase due to GSLR (5.3.3.3, WG1 Chapter 13).	<i>High confidence</i> of increase due to GSLR, <i>low confidence</i> of changes due to storm changes (5.3.3.3, WG1 Chapter 13) «	Local subsidence is an important contribution to RSLR in many locations.
Sea Surface Temperature	Changes to stratification and circulation; reduced incidence of sea ice at higher latitudes; increased coral bleaching and mortality, poleward species migration; increased algal blooms.	<i>High confidence</i> that coastal SST increase is higher than global SST increase « (5.3.3.4, WG1 Ch. 3).	<i>High confidence</i> that coastal SSTs will increase with projected temperature increase (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.	<i>Medium confidence (limited evidence)</i> in a net declining trend in freshwater input.	<i>Medium confidence</i> for general increase in high latitudes and wet tropics and decrease in other tropical regions «.	Emerging information on freshwater input.
Ocean Acidity	Increased CO ₂ fertilisation; decreased seawater pH and carbonate ion concentration (or ‘ocean acidification’) [this is not a “Physical effect”]	<i>High confidence</i> of overall increase, with high local and regional variability (5.3.3.5).	<i>High confidence</i> of increase at unprecedented rates but with local and regional variability (Box CC-OA).	OA not specifically addressed in AR4. Considerable progress made in chemical projections and biological impacts.

Table 5-3: Top ten nations with the largest populations and the highest proportions of population in low-lying coastal areas (Countries with fewer than 100,000 inhabitants are not included; 15 SIDs (Small Island Developing States) with total of 423,000 inhabitants are also excluded). Source: Bollman *et al.*, 2010.

Top ten nations classified by population in low-lying coastal regions			Top ten nations classified by proportion of population in low-lying coastal regions		
Nation	Population in low-lying coastal regions (10 ³)	% of population in low-lying coastal regions	Nations	Population in low-lying coastal regions (10 ³)	% of population in low-lying coastal regions
1. China	127,038	10 %	1. Maldives	291	100 %
2. India	63,341	6 %	2. Bahamas	267	88 %
3. Bangladesh	53,111	39 %	3. Bahrain	501	78 %
4. Indonesia	41,807	20 %	4. Suriname	325	78 %
5. Vietnam	41,439	53 %	5. Netherlands	9590	60 %
6. Japan	30,827	24 %	6. Macao	264	59 %
7. Egypt	24,411	36 %	7. Guyana	419	55 %
8. USA	23,279	8 %	8. Vietnam	41,439	53 %
9. Thailand	15,689	25 %	9. Djibouti	250	40 %
10. Philippines	15,122	20 %	10. Bangladesh	53,111	39 %

Table 5-4: Main impacts of relative sea-level rise. Adapted from Nicholls 2002 and Nicholls *et al.* 2010.

Biophysical impacts of relative sea-level rise	Other climate drivers	Other human drivers
Dryland loss due to submergence	Wave and storm climate, morphological change, sediment supply	Sediment supply, flood management, morphological change, land claim
Flood damage (due to surges, tropical cyclones)	Wave and storm climate, morphological change, sediment supply	Sediment supply, flood management, morphological change, land claim
Backwater effect (river)	Runoff	Catchment management and land use
Wetland loss (and change)	Sediment supply, CO ₂ fertilization,	Sediment supply, migration space, direct destruction
Dryland loss due to erosion	Sediment supply, wave and storm climate	Sediment supply
Saltwater intrusion into surface waters	Runoff	Catchment management and land use
Saltwater intrusion into ground waters	Precipitation	Land use, aquifer use
Rising water tables/ impeded drainage	Precipitation	Land use, aquifer use

Table 5-5: Summary of Coastal Vulnerability Assessments conducted at national or regional scale. Studies that either costed (Adapt\$) or considered adaptation options (Adapt) are indicated. In studies that have considered adaptation: WOA=without adaptation; WA=with adaptation. CVI=Coastal Vulnerability Index; GIS=Geographic Information System, DIVA=Dynamic Interactive Vulnerability Assessment model. RSLR=relative sea level rise.

Location	Physical impacts considered	SLR scenario	Socio-economic scenario	Physical and ecosystem vulnerability	Human system vulnerability	Method and tools	Reference
Africa							
Africa	Erosion, flooding	0.64-1.26 m SLR by 2100, plus local subsidence/uplift	IMAGE model scenario		WOA: 16–27 million people flooded and US\$5-9 billion annual damage costs WA: Adaptation cuts people flooded by two orders of magnitude and damage costs by half, adaptation deficit US\$300 billion and annual costs US\$2-6 billion	DIVA (Adapt\$)	Hinkel <i>et al.</i> , 2011
Ghana (east coast)	Erosion, submergence	1-5m SLR		Possible erosion of existing coastal buffer zones that separate open coast from coastal lagoons and inundation of coastal plains		GIS	Boateng, 2012b
Tanzania (Dar-es-Salaam)	Flood exposure	0.13-0.66 m by 2070, plus local subsidence/uplift, plus to 1-in-100 event	A1 with rapid urbanization		210,000 people and US\$10 billion exposed to 100-year coastal flood by 2070	GIS	Kebede and Nicholls, 2012
Asia							
China				Sediment supply to major delta regions has reduced by 50% since early 1980's and is driving coastal erosion			Cai <i>et al.</i> , 2009
China	Flooding, erosion	Current rate of RSLR (average 6mm/yr)		Vulnerability to flooding and erosion of the 18,000 km coastline, is ranked very high-3%; high-29%; moderate- 58% and low-10%.		CVI	Yin <i>et al.</i> , 2012
East Timor	Flooding, erosion wetland loss, salt water intrusion	0.31-0.54 m by 2100, plus local subsidence / uplift	A2 and B1	Wetland area reduction under 0.54m SLR is greatest for the Solomon Islands (68%), the Philippines (51%) and East Timor (50%). Composition of wetland areas in 2100 change to include more mangroves and less unvegetated wetland areas in 2100 compared to 2010. Increased salinity intrusion up major rivers 14-27% under A2	Expected number of people flooded annually relative national population (pop): WOA 0.54% pop A2; WA 0.01% pop A2 WOA 1.19% pop A2; WA 0.00% pop A2 WOA 0.46% pop A2; WA 0.00% pop A2 WOA 0.07% pop A2; WA 0.01% pop A2 WOA 0.80% pop A2; WA 0.00% pop A2 WOA 0.27% pop A2; WA 0.00% pop A2	DIVA (Adapt\$)	McLeod <i>et al.</i> , 2010
Indonesia							
Malaysia							
Papua New Guinea							
Philippines							
Solomon Islands							

				Increased salinity intrusion into land areas 7-12% under A2			
India (Udupi coast)	Erosion, submergence	1-10m SLR		Erosion risk: of the 95 km of coastline, 59% assessed as very high; 7% high, 4% moderate, 30% low erosion risk. 372-42 km ² exposed to submergence from 1m SLR	Qualitative assessment of affected areas include residential and recreational areas, agricultural land and the natural ecosystem	CVI	Dwarakish <i>et al.</i> , 2009
Vietnam	Submergence exposure	1-5m			Exposure is largest in Red River and Mekong deltas. Options identified to prolong the use of these areas into the future	GIS	Boateng, 2012a
Australasia							
Australia	Flood exposure, Erosion	1.1 m, combined with either 1-in-100 year flood event or mean high tide level		Exposure to tropical cyclone related hazards across northern half of continent, health of Great Barrier Reef will affect coastal resilience in NE. Southern coastline with extensive cliffs, large bays, estuaries, gulfs and flats vulnerable to SLR inundation and cliff instability if wave climate changes. Greater erosion along populous eastern coast due to SLR and storm changes.	Potential inundation of, 157,000–247,600 of the 711,000 existing residential buildings close to water. Nearly 39,000 buildings at risk from erosion due to SLR. Indigenous communities, including island based deemed particularly vulnerable due to their remoteness and location on low elevation land.	GIS coastal geomorphology model and Bruun Rule GIS DEM infrastructure database	Department of Climate Change, 2009
Australia (Victoria)	Flood exposure	0.8-1.4 m SLR by 2100, plus 1-in-100 year flood event		Across 9 coastal settlements considered, area exposed to 1-in-100 flood ranges from 153 to 408 km ² for 0-1.4 m SLR	Across 9 coastal settlements considered, land parcels exposed to 1-in-100 flood ranges from 2,362 to 47,102 for 0 to 1.4 m SLR	Hydrodynamic modelling, GIS	McInnes <i>et al.</i> , 2011
Europe							
Croatia	Submergence exposure	0.2-0.86 m SLR		A long narrow steep coastline with one major reclaimed alluvial plain will become increasingly vulnerable to inundation particularly for larger SLR projections. Erosion of pocket beaches will increase.	Sewage systems, agriculture and maritime transport and tourism affected by greater flood frequency of low-lying land and berths and piers.	Qualitative assessment	Baric <i>et al.</i> , 2008
Denmark-Copenhagen	Flood exposure	0.0-1.25 m SLR			Copenhagen not highly vulnerable to coastal flooding due to existing flood protection. WOA: direct costs of 1-in-100 year event increase from €3-4.8 billion with 0.5m SLR	GIS (Adapt)	Hallegatte <i>et al.</i> , 2011
Estonia	Submergence exposure	1 m SLR adjusted for regional uplift (i.e.		Observed beach erosion has resulted from increased storminess in the eastern Baltic Sea, combined with decline in winter sea-ice cover. Future	Possible productivity benefit from longer growing season. Major towns are not threatened due to location inland and mitigating effects of uplift. Sandy beaches and emerging coastal	Qualitative assessment	Kont <i>et al.</i> , 2008

		69–73 cm RSLR)		land loss will impact major bird breeding grounds	tourism at risk.	t	
France	Flood exposure, erosion	0.88 m SLR + 5.8m surge (Atlantic) and 2.7 m surge (Mediterranean)		Atlantic coast with extensive dune systems is assessed as more resilient to rising sea levels over the coming century compared with Mediterranean coast where narrow dune systems are highly urbanized		GIS	Vinchon <i>et al.</i> , 2009
Germany	Submergence exposure	1 m SLR		There is a high level of reliance on hard coastal protection against extreme sea level hazards which will increase ecological vulnerability over time	300,000 people exposed in the coastal cities and communities. Erosion and flooding risks US\$300 billion (based on 1995 values) of assets	GIS DEM, land-use, socioeconomic data	Sterr, 2008
Great Britain	Erosion, submergence	0.8 – 1m SLR		Large parts of the coasts are presently sediment starved and eroding and this will continue	At the national scale, economic losses due to erosion are expected to remain considerably smaller than flood losses	Qualitative assessment	de la Vega-Leinert and Nicholls, 2008
Norway	Submergence	0.5 - 1m SLR		Nationally, low susceptibility to accelerated sea-level rise due to mainly steep and resistant coastlines	Extensive infrastructure on northern and western coastlines likely to be negatively affected by sea-level rise, and adaptation costs could be significant	Qualitative assessment	Aunan and Romstad, 2008
Poland	Submergence	0.3 – 1m SLR		Lagoons, river deltas and estuaries in the far east and west were considered most vulnerable		Qualitative assessment	Pruszek and Zawadzka, 2008
Portugal	Submergence	0.14-0.57 m by 2100 SLR		Estuaries and coastal lagoons are assessed as most vulnerable and already sediment starved coastal beaches will continue to erode		Qualitative assessment	Ferreira <i>et al.</i> , 2008
Turkey	Submergence	1 m SLR			Without adaptation, impacts could cost 6% of current GNP. Adaptation/protection could cost 10% of current GNP.	Qualitative (Adapt)	Karaca and Nicholls, 2008
European Union	Erosion, flooding, salinity intrusion	0.35-0.45 m by 2100 SLR	A2 and B1		WOA: 0.2-0.8 million people flooded and US\$17 billion annual damage costs WA: adaptation cuts exposure by a factor of 100 and annual damage costs by a factor of 10.	DIVA (Adapt\$)	Hinkel <i>et al.</i> , 2010
N. America							
US	Submergence exposure	Land below 6 m above			20 municipalities with populations greater than 300,000 and 160 municipalities	GIS	Weiss <i>et al.</i> , 2011

		MHHW			with populations between 50,000 and 300,000 have land area with elevations at or below 6 m and connectivity to the sea,		
US	Land loss due to submergence	0.19-1.26 m SLR by 2100	2% annual GDP growth		WA: Total cost (adaptation plus residual damage) of US\$ 50-75 billion (discounted at 3%)	GIS, CBA of protection vs. retreat (Adapt\$)	Neumann <i>et al.</i> , 2010
US South Florida	Land loss due to submergence	0.5, 1.0, 1.5 m SLR by 2100 combined with MHHW		Submergence affects areas of ~1300 km ² , ~1700km ² , ~ 3000 km ² respectively for SLR scenarios considered	~68000, ~210000, ~750000 population exposed to SLR scenarios respectively \$8 billion, \$47 billion, \$144 billion exposed to SLR scenarios respectively	GIS	Zhang, 2011
US Florida Keys	Land loss due to submergence	0.3, 0.6, 0.9, 1.2, 1.5, 1.8m SLR by 2100 combined with MHHW		Submergence affects areas of ~82 km ² , ~95km ² , ~ 107 km ² , ~119 km ² , ~127km ² , ~ 133 km ² respectively for SLR scenarios	2663, 6403, 11,026, 15933, 19802, 21768 population exposed to SLR scenarios respectively ~\$56 million, ~\$367 million, ~\$2 billion, ~\$6 billion, ~\$9 billion, ~\$12 billion exposed to SLR scenarios respectively	GIS	Zhang <i>et al.</i> , 2011
US	Land loss due to submergence	0.67 m by 2100			Under the mid-SLR scenario (), approximately 1,630,000 people are potentially affected by SLR. Of these, 332,000 (~20%) are among the most socially vulnerable.	GIS & Social Vulnerability Index (SoVI)	Martinich <i>et al.</i> , 2012
NW territories (Canada)	Shoreline stability and population exposure	Temperature, wind patterns		Loss of sea ice and shorter winter season and more variable weather patterns lead to changes in coastal sea ice coverage. Effects on species health and numbers.	More hazardous travel conditions for traditional hunting practices. Loss of traditional knowledge, skills and values.	Qualitative (Adapt)	Pearce <i>et al.</i> , 2010

Table 5-6: Impacts of sea level rise, coastal floods, and storms on critical coastal infrastructure by sector. Sources: Horton and Rosenzweig (2010), Zimmerman and Faris (2010).

Communications	Energy	Transportation	Water and waste
Higher average sea level			
<ul style="list-style-type: none"> Increased salt water encroachment and damage to low-lying communications infrastructure not built to withstand saltwater exposure Increased rates of coastal erosion and/or permanent inundation of low-lying areas, causing increased maintenance cost and shortened replacement cycles Tower destruction or loss of function 	<ul style="list-style-type: none"> Increased rates of coastal erosion and/or permanent inundation of low-lying areas, threatening coastal power plants and refineries Increased equipment damage from corrosive effects of salt water encroachment resulting in higher maintenance costs and shorter replacement cycles 	<ul style="list-style-type: none"> Increased salt water encroachment and damage to infrastructure not built to withstand saltwater exposure Increased rates of coastal erosion and/or permanent inundation of low-lying areas, resulting in increased maintenance cost and shorter replacement cycles Decreased clearance levels under bridges 	<ul style="list-style-type: none"> Increased salt water encroachment and damage to water and waste infrastructure not built to withstand saltwater exposure Increased release of pollution and contaminant runoff from sewer systems, treatment plants, brownfields and waste-storage facilities Permanent inundation of low-lying areas, wetlands, piers, and marine transfer stations Increased salt water infiltration into distribution systems transfer stations
More frequent and intense coastal flooding			
<ul style="list-style-type: none"> Increased need for emergency management actions with high demand on communications infrastructure Increase damage to communications equipment and infrastructure in low-lying areas 	<ul style="list-style-type: none"> Increased need for emergency management actions Exacerbated flooding of low-lying power plants and equipment, as well as structural damage to infrastructure due to wave action Increased use of energy to control floodwaters Increased number and duration of local outages due to flooded and corroded equipment 	<ul style="list-style-type: none"> Increased need for emergency management actions Exacerbated flooding of streets, subways, tunnel and bridge entrances, as well as structural damage to Decreased levels of service from infrastructure due to wave action flooded roadways; increased hours of delay from congestion during street-flooding episodes Increased energy use for pumping 	<ul style="list-style-type: none"> Increased need for emergency management actions Exacerbated street, basemend and sewer flooding, leading to structural damage to infraescture Episodic inundation of low-lying areas, wetlands, piers, and marine transfer stations

Table 5-7: Community-based adaptation options.

Impact	Type of option	Option	Brief description	References	
Salinity	New and diversified livelihoods	Saline-tolerant crop cultivation	Farmer production of saline-tolerant multi-vegetable varieties and non-rice crops.	Rabbani <i>et al.</i> 2013; Ahmed 2010	
	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 <i>et al.</i> 2009	
	Structural	Homestead protection	Houses constructed on raised foundations to mitigate salinity ingress.	Ayers and Forsyth 2009	
Flooding /Waterlogging	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.	Pouliotte <i>et al.</i> 2009; Khan <i>et al.</i> 2012; Pomeroy <i>et al.</i> 2006	
	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.	Dev 2013; Ahmed 2010; Ayers and Forsyth 2009	
	Cyclones / storm surges	Structural/hard	Homestead reinforcement	Low-cost retrofitting to strengthen existing household structures especially roofs; strict implementation of building codes.	Ahmed 2010; Sales 2009
		Structural/soft	Homestead ecosystem protection	Plantation of specific fruit trees around homestead area.	Haq <i>et al.</i> 2012
Structural/hard		Underground bunker construction	Underground bunker established providing protected storage space for valuable community assets.	Raihan <i>et al.</i> 2010	
Sea-level rise (SLR)	Institutional	Risk insurance mechanisms	Farmers educated on comprehensive risk insurance focusing on sea-level rise and coastal agriculture.	Khan <i>et al.</i> 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 plan (ICZM)	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.	Sovacool <i>et al.</i> 2012; Rawlani <i>et al.</i> 2011	

	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 centres; community-based monitoring of changes in coastal areas.	Rawlani <i>et al.</i> 2011; Sales 2009

Table 5-8: Global assessments of costs of sea-level rise.

Reference	Physical impacts	SLR scenario	Socio-economic scenario	Impact indicators	Without adaptation	With adaptation
Anthoff <i>et al.</i> , 2010	Submergence, wetland loss	0.5-2.0m SLR by 2100	A1, A2, B1, B2	Net present value of total cost for 2005-2100 (pure rate of time preference 1%)	US\$ 800-3300 billion in 2100	US\$200-2200 billion in 2100
Nicholls <i>et al.</i> , 2011	Submergence, erosion	0.5-2.0 m SLR by 2100	A1FI	Cumulative number of people displaced due to land loss to submergence and erosion	72-187 million people during 21 st century	0.04-0.3 million people during 21 st century
				Annual adaptation cost	N/a	US\$ 25-270 billion/yr
Hinkel <i>et al.</i> , 2012	Flooding	0.6-1.3m by 2100	UN medium fertility	Annual expected number of people flooded	170-260 million people/yr in 2100	Two orders of magnitude smaller than w/o adaptation
				Annual total cost (including dike upgrade, dike maintenance and residual damage cost)	US\$ 160-300 billion/yr in 2100	US\$ 30-90 billion/yr in 2100
				Annual total cost relative to GDP	0.05% -0.09% of global GDP in 2100	0.01%-0.03% of global GDP in 2100

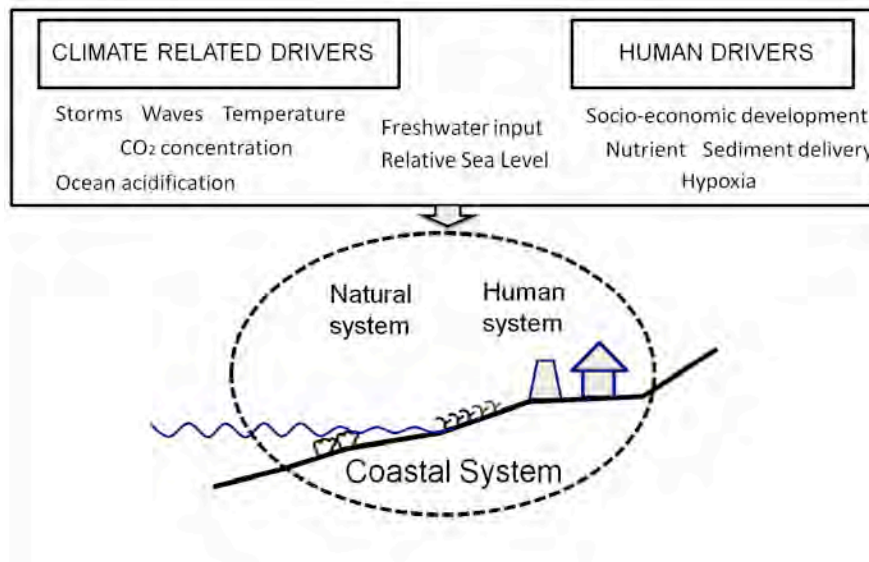


Figure 5-1: Schematic diagram indicating the elements of the coastal zone that are considered in this chapter.

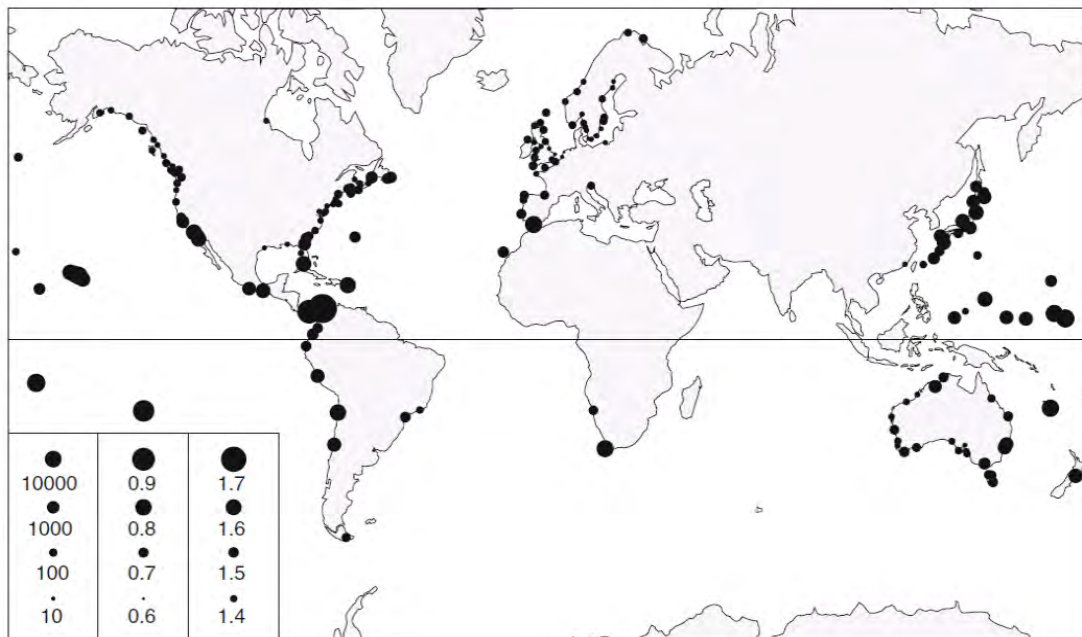


Figure 5-2: Results of global analysis, indicated by dot diameter. a Factor by which frequency of flooding events will increase with a rise in sea level of 0.5 metres (key is left-hand column of dots in the bottom left-hand corner). b Sea-level rise allowance (metres) for 1990–2100 which conserves frequency of flooding events for the IPCC A1FI Projection based on A1FI emission scenario and AR4-adjusted TAR projections (normal distribution with $\Delta z=0.542$ m and $\sigma=0.168$ m); key is central column of dots in the bottom left-hand corner. c Sea-level rise allowance (metres) for 21st century which conserves frequency of flooding events for the 1.0/1.0 m Projection, based on post-AR4 results (raised cosine distribution with $\Delta z=1.0$ m and $W/2=1.0$ m); key is right-hand column of dots in the bottom left-hand corner.

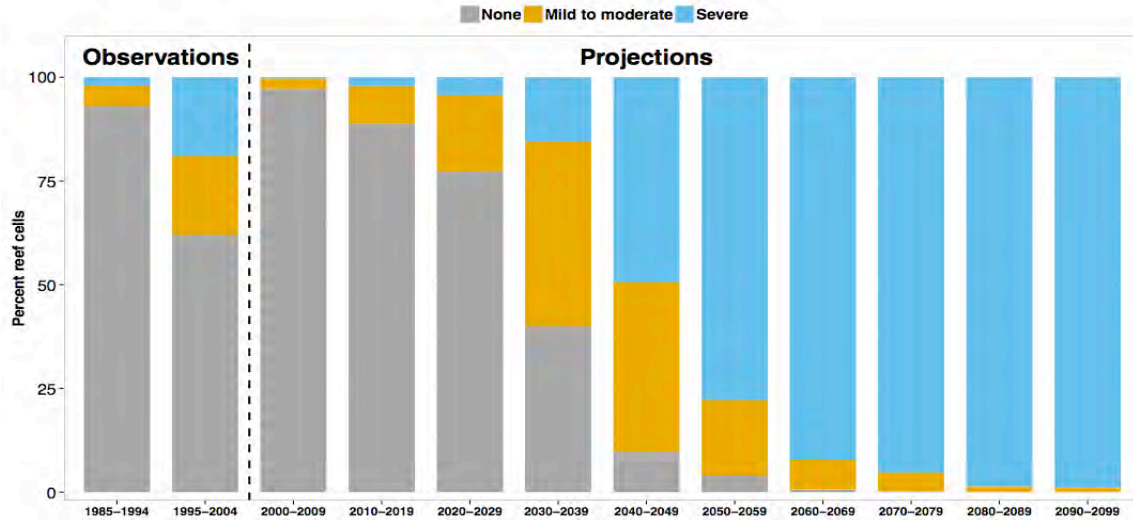


Figure 5-3: Percent of reef locations (1°x1° grid cells which have coral reefs) that experience no bleaching (green), at least one mild bleaching event (reddish-brown), or at least one severe bleaching event (purple) for each decade. Observed bleaching events are summarized from the ReefBase dataset (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 SRES A1B CO₂ scenario and the standard degree heating month formula (Teneva *et al.*, 2011). The labels of values ≤ 1% are not shown.]

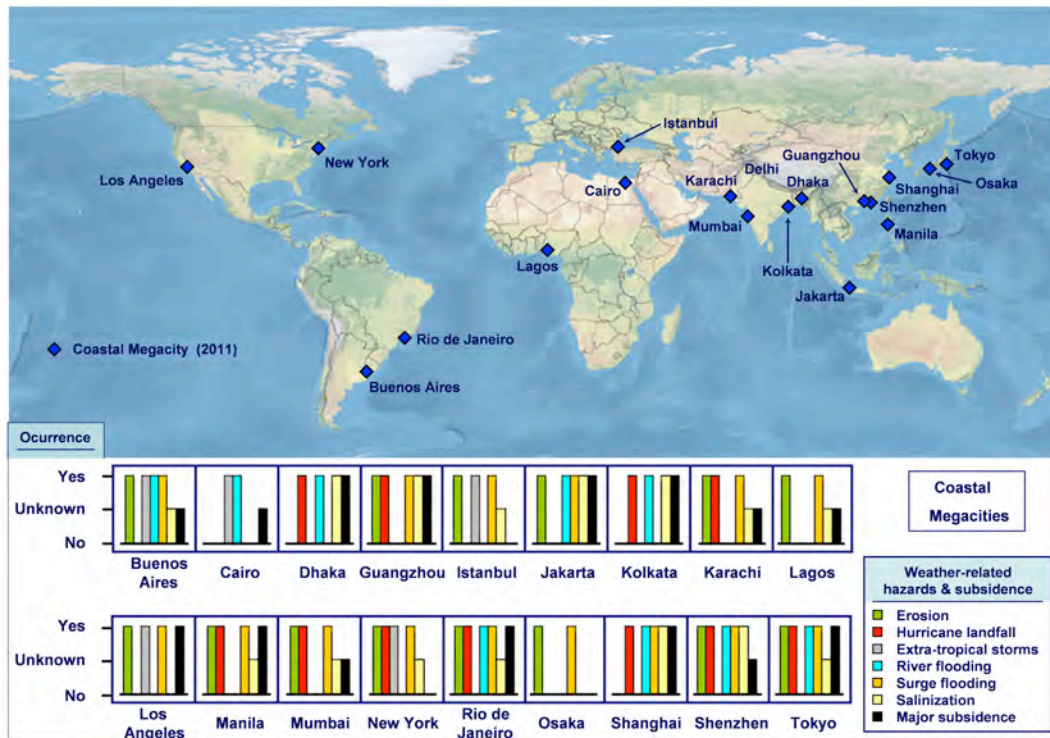


Figure 5-4: Mega-urbanisation on the coast. Source:Blackburn S and Marques da Silva C (2013) Mega-urbanisation on the coast: Global context and key trends in the twenty-first century, in Pelling M and Blackburn S (eds) Megacities and the Coast: Risk, Resilience and Transformation, Earthscan: London.

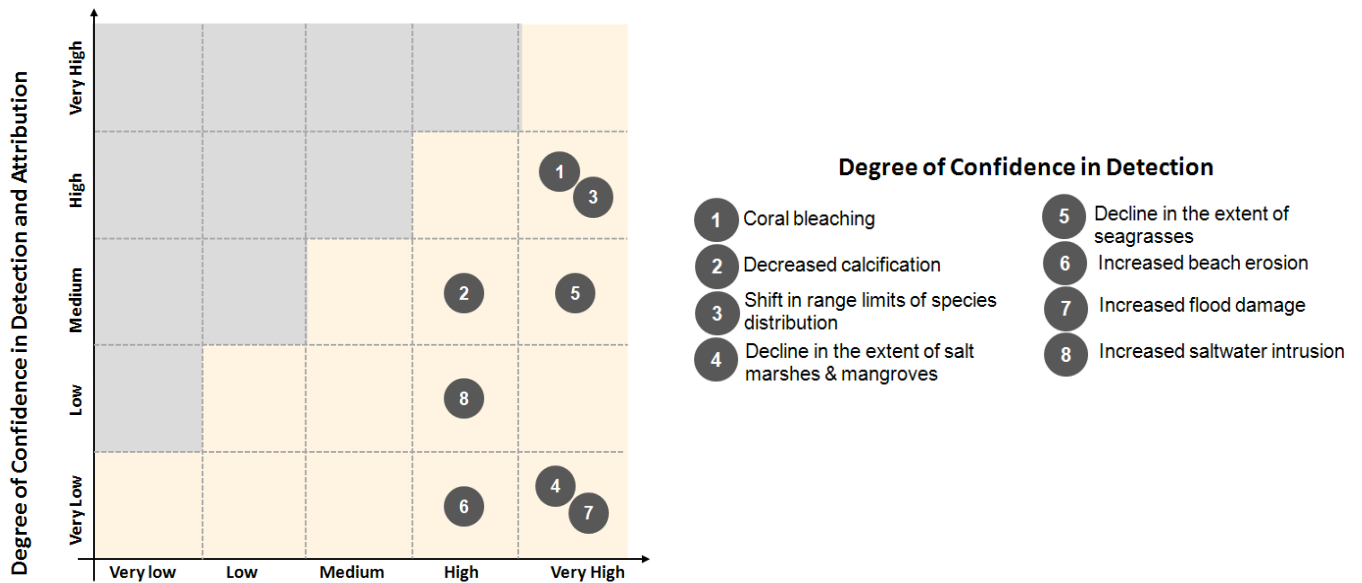


Figure 5-5: Summary on detection and attribution in this chapter.

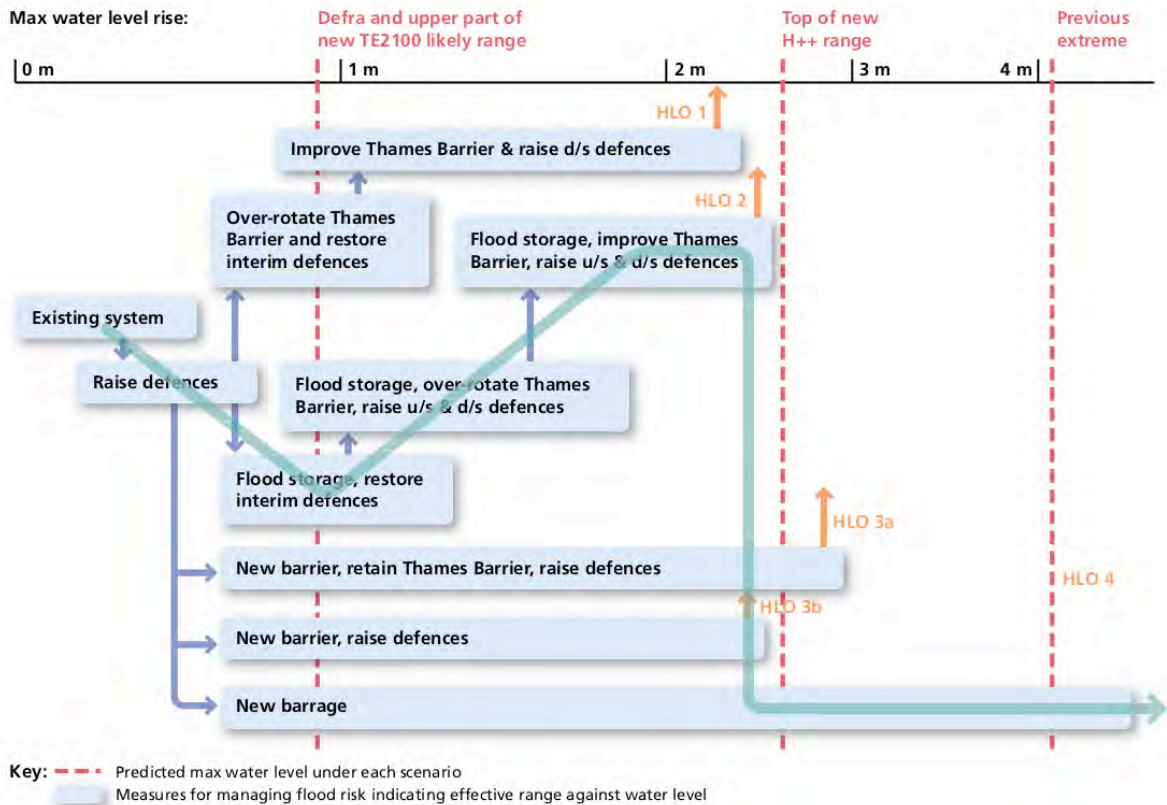


Figure 5-6: Adaptation measures and pathways considered in the TE2100 project. The boxed show the measures and extend over the range of sea level rise they are effective. The blue arrows link to alternative measures that may be applied once a measures is no longer effective. The red lines show the various sea-level rise scenarios used in the analysis. The fat green line shows a possible future adaptation pathway in the unlikely event of extreme change (>4 m rise).



Figure 5-7: Overview of the Delta Committee National Recommendations. Source: Stive *et al.*, 2011.

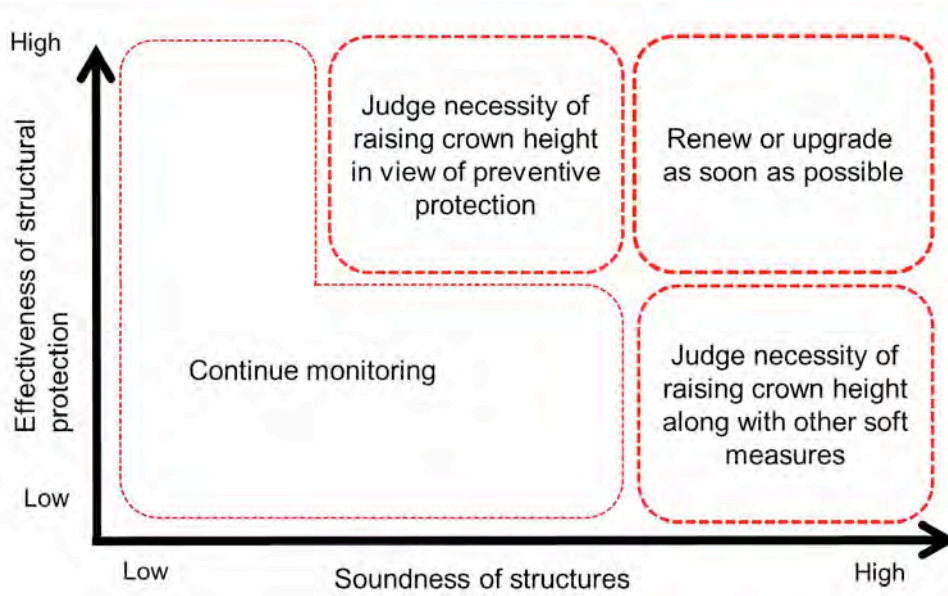


Figure 5-8: Priority in investment for adaptation to global warming.

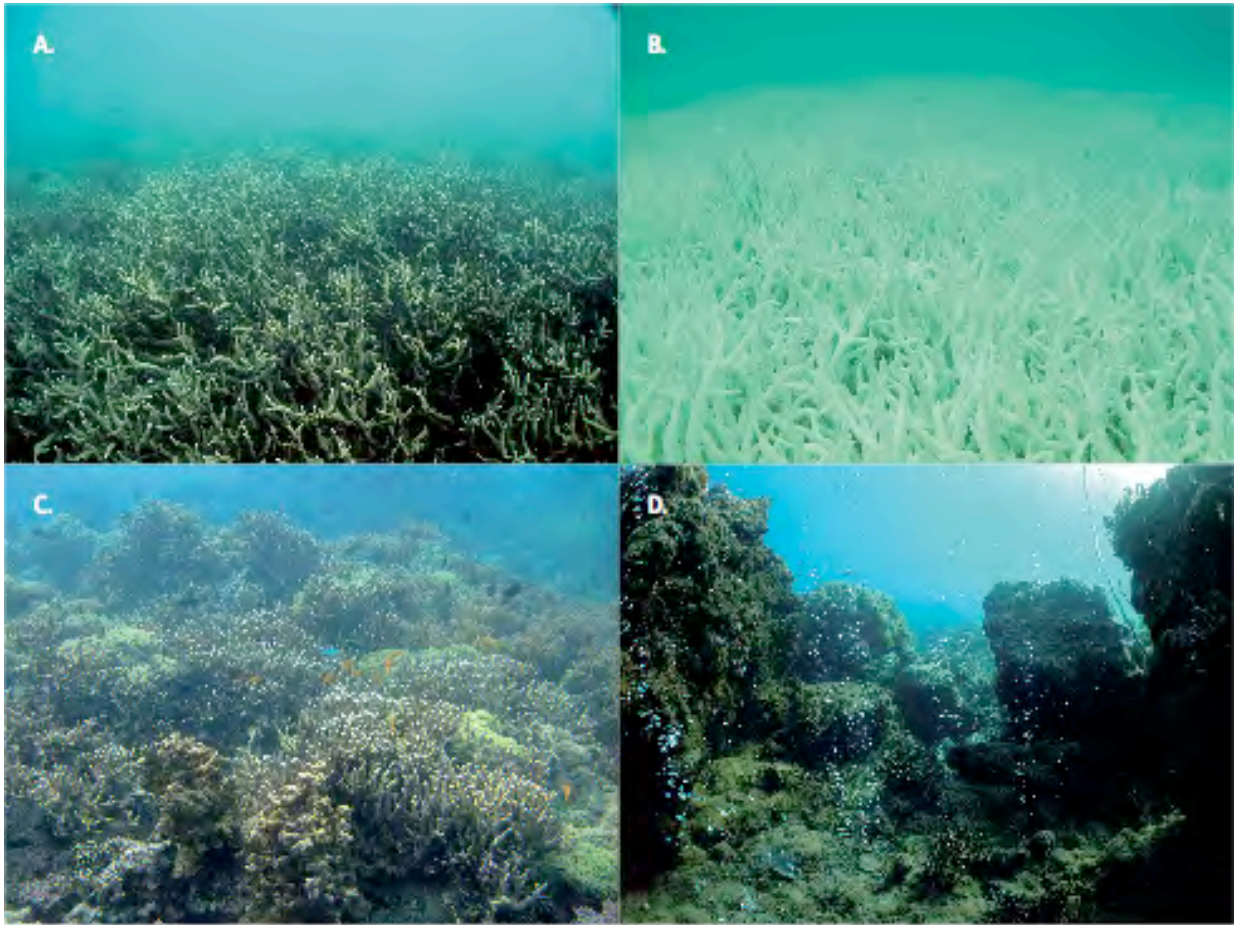


Figure CR-1: A and B: the same coral community before and after a bleaching event in February 2002 at 5 m depth, Halfway Island, Great Barrier Reef. Coral cover at the time of bleaching was 95% bleached almost all of it severely bleached, resulting in mortality of 20.9% (Elvidge et al., 2004). Mortality was comparatively low due in part because these communities were able shuffle symbiont types to more thermo-tolerant types (Berkelmans and van Oppen, 2006; Jones et al., 2008). C and D: three CO₂ seeps in Milne Bay Province, Papua New Guinea show that prolonged exposure to high CO₂ is related to fundamental changes in coral reef structures (Fabricius et al., 2011). Coral communities at three high CO₂ (Fig. XB; median pHT 7.7, 7.7 and 8.0), compared with three control sites (Fig. XA; median pHT 8.02), are characterized by significantly reduced coral diversity (-39%), severely reduced structural complexity (-67%), low densities of young corals (-66%) and few crustose coralline algae (-85%). Reef development ceases at pHT values below 7.7. Photo credit: R. Berkelmans (A and B) and K. Fabricius (C and D).

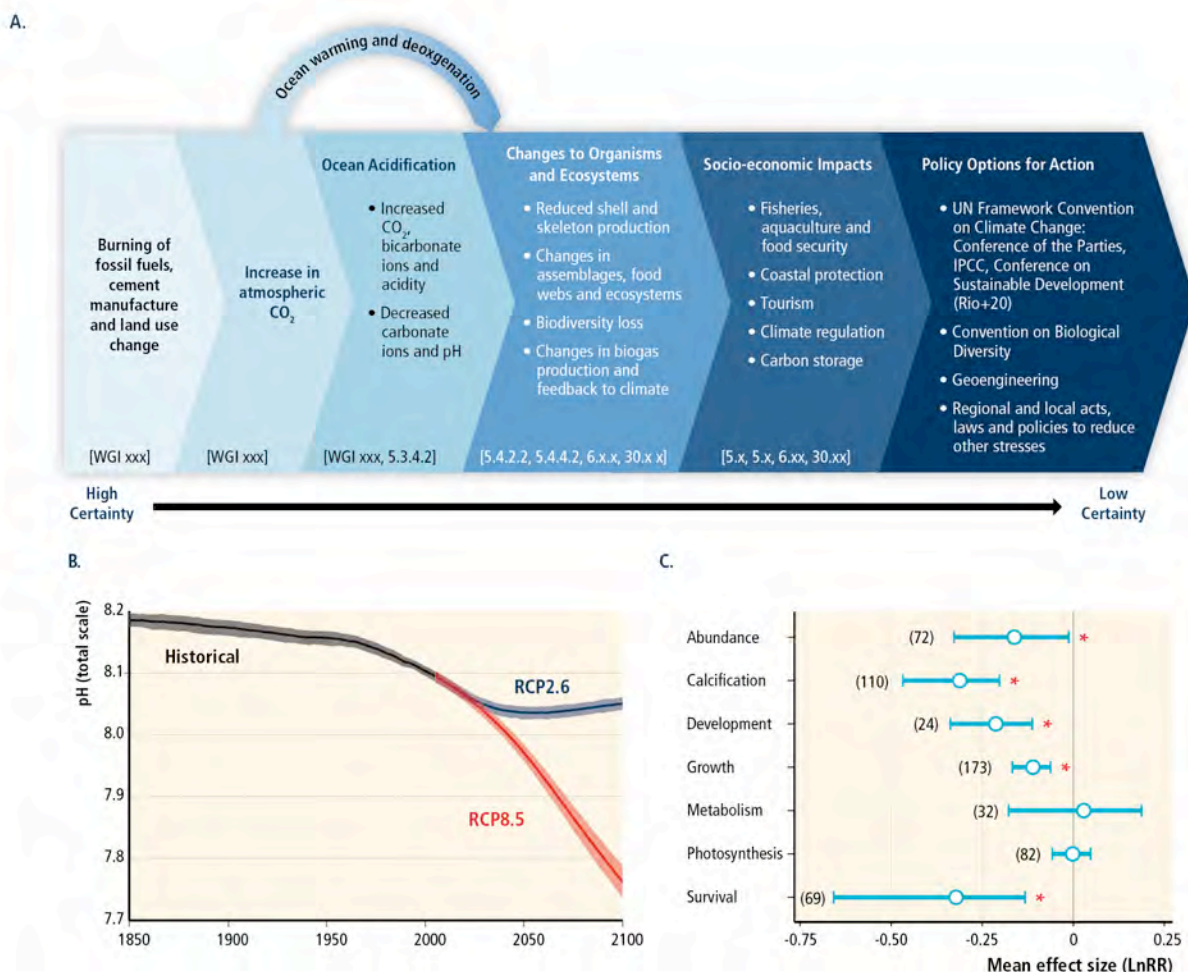


Figure OA-1: A: Overview of the chemical, biological, socio-economic impacts of ocean acidification and of policy options (adapted from Turley & Gattuso, 2012). B: Multi-model simulated time series of global mean ocean surface pH (on the total scale) from CMIP5 climate model simulations from 1850 to 2100. Projections are shown for emission scenarios RCP2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global carbon cycle while being driven by prescribed atmospheric CO₂ concentrations. The number of CMIP5 models to calculate the multi-model mean is indicated for each time period/scenario (IPCC AR5 WG1 report, Figure 6.28). C: Effect of near future acidification on major response variables estimated using weighted random effects meta-analyses, with the exception of survival which is not weighted (Kroeker et al., in press). The effect size indicates which process is most uniformly affected by ocean acidification but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. * denotes a significant effect.

