Chapter 5. Coastal Systems and Low-Lying Areas

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Contents

Executive Summary

Coasts are increasingly exposed to varying extreme weather and climate events and impacts from more gradual climate change and increased sea-level rise. The main climate drivers include changing storm regimes, temperature increases, precipitation changes, changes in runoff and sediment transport from watersheds into coastal waters, and increased salinization. It is very likely the mean sea-level rise will contribute to upward trends in extreme coastal high water levels. Locations currently experiencing coastal erosion and inundation will continue to do so due to increasing sea level, in the absence of changes in other contributing factors (*very high confidence*). [5.2.2.1]

Vulnerability and exposure to climate change at the coast is exacerbated by population growth, socio-economic growth and urbanization. More than 200 million people are already exposed to flooding by extreme water levels worldwide and this population could be increased by a factor of 4 due to rising population and coastward migration, especially in Asia. Assuming a sea-level rise of 0.5 to 2.0 m and no upgrade in coastal defences, 72 to 187 million people could be displaced due to submergence and erosion by 2100 and about 70% of these affected are from East, Southeast and South Asia (*very high confidence*). [5.3.2, 5.5.3]

Impacts of climate change vary globally with different burdens for both developed and developing countries More assets of developed countries are increasingly affected. In developing countries, the poorer sectors are most vulnerable (5.4.2.1). Developing countries and small island states within the tropics relying on coastal tourism, are impacted not only by weather and climate extremes, future sea-level rise but also the added impacts of coral bleaching and ocean acidification and reduction in tourist flows from mid-latitudes (*very high confidence*). [5.3.2.4]

Various approaches in coastal management have made possible for coastal regions to achieve their diverse goals in their adaptation to climate change. Overall, these approaches achieve greater integration, smoother governance, improved social, ecological and economic outcomes, the minimization of risks and impacts from coastal hazards, economic development and use of coastal resources, and protection of coastal environmental resources, natural assets, and ecosystems (*very high confidence*). [Table 5-6, 5.6.1, 5.6.2]

While cost of adaptation to sea-level rise is high, the costs of inaction are larger than the sum of adaptation and residual damage costs for the 21st century and the global scale. Even with mean sea-level rise of 2 m by 2100, protection is considered economically rational for most countries. Under medium socio-economic development assumption, the expected direct cost of coastal flooding may reach US$300 billion per year in 2100 without adaptation and US$90 billion per year with adaptation under a 1.26 m sea-level rise scenario (*high confidence*). [5.5.4]

An extensive set of information is available on global and regional costs of adaptation. New studies have emerged using a wider range of scenarios, expanded on the impacts considered, and integrating other adaptation options. A wide range of adaptation measures is available, and specific on protection measures and beach nourishment. With additional accessible information available for assessment, e.g. LIDAR (Light Detection And Ranging) data, and knowledge sharing platforms, policymakers should be in a better position to assess local areas for adaptation to climate change (*high confidence*). [5.5.1, 5.5.4, 5.7]

5.1. Introduction

This chapter presents an updated picture of the impacts of climate change and sea-level rise on the coasts. Unlike the coastal chapter in the previous assessment (AR4), some materials pertinent to the oceans are not covered in this chapter but in two new ocean chapters (Chapters 6 and 30).

The topics to be covered in this chapter are developed along the outline for sectoral chapters approved by the IPCC. Preceding the various sections is an Executive Summary summarizing the key messages with a line of sight to the various sections in the chapter.

This chapter is organized around eight sections with this first section dealing with the scope, summary and conclusion of the AR4 and key issues. Section 2 provides the necessary definitions that include the coastal systems and climate and non-climate drivers. The coastal systems include both coastal ecosystems and human systems and this division is generally followed for the rest of the sections in the chapter. The observed impacts of climate change on coastal systems and human systems are assessed in section 3 followed by the projected impacts on both systems in section 4. Section 5 assesses the vulnerabilities, risks and costs. Section 6 deals with adaptation and managing risks. There are four case studies distributed within the chapter. Uncertainties and data gaps are assessed in section 7 followed by the conclusion in section 8.

The coasts chapter in AR4 assessed the impact of climate change and global sea-level rise of 0.6 m up to 2100.

The coastal ecosystems are affected mainly by higher sea level, increasing temperature, changes in precipitation, increased extreme events and reduction in ocean pH. Human activities continued to increase their pressure on the coasts with rapid urbanization in coastal areas and growth of megacities with consequences on the coastal resources. Regionwise, South, Southeast and East Asia, Africa and small islands are most vulnerable. The AR4 chapter offers a range of adaptation measures, many under the ICZM framework that can be carried out in the developed and developing countries, recognizing that the latter would face more challenges. Various issues on increasing the adaptive capacity or increasing the resilience of coastal communities were discussed.

A number of key issues related to the coasts have arisen since the AR4.

Coastal systems and their functions and services and how they can be affected by climate change are now better understood. Their linkages landward to the watersheds and seaward to the seas and oceans have to be considered for an integrated assessment of climate change impacts. Semi-empirical models on sea level project higher estimates of sea-level rise by 2100 than that reported in the AR4 but there are still uncertainties (Rahmstorf, 2010; Lowe and Gregory, 2010). This may have serious implications for coastal cities, deltas and low-lying states. While erosion from a higher sea-level rise is expected in future, its relationships with coastal systems such as beaches, barriers, mangroves and coral reefs have to be better established at regional and even local scales and not just at global scale.

Another concern is ocean acidification and implications of reduced calcification in shellfish impacting worldwide commercial aquaculture (Barton *et al*., 2012). It also causes coral reefs to lose their structural stability with negative implications for reef communities and shore protection (Kapos *et al*., 2009; Manzello et al., 2008; see also Box 5-3). An important amount of new findings regarding the impacts of climate change on human settlements, key coastal habitats and ecosystems such as rocky shores, beaches, estuaries deltas, mangroves, coral reefs or submerged vegetation is currently available and reviewed. Unfortunately, it will be shown that uncertainties regarding projections of potential impacts on coastal systems are still high and that further work is required.

This chapter also provides a more updated assessment of vulnerability, risks and costs to the coasts since the AR4. Assessments of vulnerability have progressed beyond assessment of potential impacts in that they include information on adaptation. A larger number of studies now include estimates of inaction and adaptation.

The human drivers continue to put heavy pressure on the coasts resulting in increased degradation. Adaptation has been accepted and a wider range of approaches and frameworks such as integrated coastal management, ecosystem-based adaptation, community-based adaptation and disaster risk reduction and management are being used. However, the relative costs of adaptation have to be worked out as well as more information on the constraints and limitations and where to apply. Future land-use in the coastal areas will be dominated by climate change effects and these would be quite profound over the next 50 years (Hadley, 2009).

On future coasts of developed countries the major effects of climate change will interact with a variety of human activities and drivers of change. For example over the next 50 years on SE England, climate change impacts arising from weather and climate extremes and sea-level rise would occurred with demand for housing and recreational facilities and construction of renewable energy infrastructure at the coast (Hadley, 2009). On coasts of developing countries, the weather and climate extremes put an additional risk to many of the fastest-growing coastal urban areas, such as in Bangladesh and China (McGranahan *et al.,* 2007; Smith 2011)

5.2. Coastal Systems

5.2.1. Definitions

Coastal systems include estuaries, coastal plains dominated by mangrove forests and salt marshes, coastal seas and human-built systems. Located at the coastal zone, an interface between purely terrestrial systems and purely marine ones, coastal systems are subject to very large environmental gradients, which, combined with numerous types of geomorphological features, leads to a generally high spatial heterogeneity and high number of habitats. The coastal zone is home to a large variety of important ecosystems whose functions provide goods and services that satisfy human needs, directly or indirectly (De Groot *et al.*, 2002). Ecosystem functions and services can be affected by the variability or long-term change of climatic drivers as well as by non-climatic drivers.

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Box 5-1. Definitions Central for this Chapter

Coastal systems: Include estuaries, coastal plains dominated by mangrove forests and salt marshes, coastal seas and human-built systems.

Coastal zone: Area between purely terrestrial systems and purely marine ones. It is subject to very large environmental gradients, which, combined with numerous types of geomorphological features, leads to a generally high spatial heterogeneity and high number of habitats. Hence, the coastal zone is characterized by strong physical, chemical, biological and biogeochemical interactions and hosts a large variety of ecosystems (Crossland *et al.*, 2005). It is also one of the most perturbed areas in the world where non-climate-related drivers are generally greatly affected by human activities and combine with changes in climate-related drivers to affect natural systems and in turn human activities. For the purpose of this assessment, coastal systems and low-lying areas include estuaries, coastal plains dominated by mangrove forests and salt marshes, and coastal seas. Its boundary towards the open ocean is at the continental shelf break, which lies between 110 and 146 m depth (Shepard, 1939 in Sverdrup *et al.* 1942), making the marine part of the coastal zone a narrow band with an average width of 34 km (Smith, 2005).

[INSERT FIGURE 5-1 HERE
Figure 5-1: Coastal zone.]

Coasts: Used for convenience to refer to coastal systems and low-lying areas.

Ecosystem: an assemblage of organisms of different types (species, life forms) together with their abiotic environment in space and time (Jax, 2006). The main coastal environments are beaches and intertidal flats, rocky shores, coral reefs, coastal lagoon and lakes, ice shelf (Whitfield and Elliott, 2012).

Ecosystem functions: capacity of natural processes and components to provide goods and services that satisfy human needs, directly or indirectly (De Groot *et al.*, 2002). They are grouped in four categories:

- *Regulation functions*: relate to the capacity of natural and semi-natural ecosystems to regulate essential ecological processes and life support systems through biogeochemical cycles and other biospheric processes. They provide services that have direct and indirect benefits to humans (e.g., clean air, water and soil, and biological control services).
- *Habitat functions*: natural ecosystems provide refuge and reproduction habitat to wild plants and animals and thereby contribute to the conservation of biological and genetic diversity and evolutionary processes.
- *Production functions*: photosynthesis and nutrient uptake by autotrophs converts energy, carbon dioxide, water and nutrients into organic matter which is then used by secondary producers to create an even larger variety of living biomass. This broad diversity in organic matter provides ecosystem goods for human consumption, ranging from food and raw materials to energy resources and genetic material.
- *Information functions*: Because most of human evolution took place within the context of undomesticated habitat, natural ecosystems provide an essential ‘reference function’ and contribute to the maintenance of human health by providing opportunities for reflection, spiritual enrichment, cognitive development, recreation and aesthetic experience.

Ecosystem services: the benefits, in the form of goods and services, people obtain from ecosystems (Millennium Ecosystem Assessment, 2005). They include goods obtained from ecosystems such as food, fiber, fuel, fresh water and genetic resources, regulating services such as air quality maintenance, climate regulation and water regulation, as well as non-material cultural services such as spiritual enrichment, recreation, and aesthetic experiences (Groot *et al.*, 2002). Ecosystem services are provided by ecosystem functions (see ‘Ecosystem functions’).

Habitats: Physical environment in which a species, or assemblage of species, lives.

Low-lying areas: Area or range where coastal and marine processes operate in addition to climate change-related drivers.

Drivers: Any environmental or biotic factor that exceeds natural levels of variation (Breitburg *et al.*, 1999). Climate-related drivers exhibit a wide range of variation at all spatial and temporal scales. This range includes the global or regional annual mean and extreme values, such as sea-level and temperature increases and changes in storm events projected for the next decades. As a result of their location at the interface between atmosphere, land and ocean, coastal systems are subject to a large range of climate-related and non-climate-related drivers.

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5.2.2. Climatic and Non-Climatic Drivers and Variability

5.2.2.1. Climatic Drivers

Any environmental or biotic factor that exceeds natural levels of variation (Breitburg *et al.*, 1999) is defined as a driver. Climate-related drivers exhibit a wide range of variation at all spatial and temporal scales. This range sometimes includes the global or regional annual mean values projected for the next decades. As a result of their location at the interface between atmosphere, land and ocean, coastal systems are subject to large range of climate-related and non-climate-related drivers.

Climate indices or modes of variability combine complex temporal and spatial changes in several drivers including some considered in the present section, into a simple metric. Since climate does not affect organisms and communities through a single driver but through a blend of multiple drivers, climate indices such as the North Atlantic Oscillation (NAO) and the El Niño Southern Oscillation (ENSO) have been useful to investigate the ecological effects of climate change (Stenseth *et al.*, 2002).

5.2.2.1.1. Sea-level including extremes

Since human-induced global warming emerged, sea-level rise has been pointed out as a major threat to coastal systems and low-lying areas around the globe (Nicholls, 2010). There is also major concern about higher extreme sea levels due to more intense storms surges and waves superimposed on these mean rises.

It is virtually certain that global mean sea level (MSL) has been rising since 1900 at a rate of 1.7 mm yr^{-1} and 3.2 mm yr^{-1} since 1993 (AR5, Chap 13). Current observations show large regional variability around the global mean trend on interdecadal periods.

It is considered likely that extreme sea levels have increased at most locations around the world, largely due to the change in Mean Sea Level (Menendez and Woodworth, 2010) and very likely that mean sea level rise will contribute to upward trends in extreme coastal high water levels Seneviratne *et al.* (2012).

Consequently, there is *very high confidence* that locations currently experiencing coastal erosion and inundation will continue to do so due to increasing sea level, in the absence of changes in other contributing factors.

5.2.2.1.2. Wind, tropical and extratropical storms

Extreme wind speeds pose a direct threat to coastal population, the integrity of offshore and coastal infrastructures or to navigation. They also contribute to storm surge and associated flooding events (McInnes *et al.*, 2011). Longer-term changes in prevailing winds can cause changes in the stability of sand dunes, or in the wave climate mean energy flux resulting in changes in coastline stability (Reguero *et al.*, 2012).

A number of recent studies report trends in mean and extreme wind speeds in different areas of the world based on the analysis of instrumental wind observations and numerical reanalysis. Most of them report declining or increasing trends but mostly on continental areas. Only limited studies consider wind stress fields in the ocean, essentially due to the limited long-term, high quality wind measurements in the marine environment.

Based on reanalysis information, Yang *et al.* (2007) and Xue *et al.* (2010) reported increasing evidence for strengthening of the zonal wind stress field in the Southern Ocean. Using a 23-year database satellite altimeter measurements global changes in oceanic wind speed have shown that the mean and 90th percentile, wind speeds over the majority of the world's oceans have increased by at least 0.25 to 0.5% per year (a 5 to 10% net increase over the past 20 years). The trend is stronger in the Southern Hemisphere than in the Northern Hemisphere. The only significant exception to this positive trend is the central north Pacific, where there are smaller localized increases in wind speed of approximately 0.25%. Extreme wind speeds show a more positive trend increasing over the majority of the world's oceans by at least 0.75% per year (Young *et al.* 2011).

Due to the shortcomings associated to the length and quality of the observations we have low confidence in wind trends and their causes at this stage (McInnes, et al., 2011; Seneviratne, *et al.*, 2012).

Consideration of extreme winds requires the analysis of extreme phenomena such as tropical and extratropical cyclones. Tropical cyclones pose a significant threat to coastal population, mostly not due to extreme winds but for the associated storm surge most often combined with fresh water flooding due to extreme rainfall (Rappaport, 2000). 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). Still, since around the mid-seventies, each year, about 90 tropical cyclones occur globally, resulting in a major threat for coastal systems.

Extratropical cyclones exist throughout the mid latitudes in both hemispheres mainly developing over the oceanic basins. From recent studies it can be concluded that it is likely that there has been a poleward shift in the main northern and southern storm tracks during the last 50 years. There is low confidence in the amplitude, and in some regions, in the sign of regional changes in extratropical storms, (Seneviratne, *et al.*, 2012). Thus the role of changes in the intensity and shift in the geographical location of extratropical cyclones on ocean waves and storm surges requires further studies.

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Box 5-2. Case Study – Tropical Cyclones

Tropical cyclones, called also typhoons and hurricanes, cause powerful strong winds, torrential rains and high waves and storm surge, all of which have major impacts on people, human systems and ecosystems. Though the strongest storms (Categories 3, 4, and 5) are comparatively rare, they are generally responsible for the majority of damage. For example, Bangladesh and India account for 86% of mortality from tropical cyclones (Murray *et al.*, 2012). Coastal systems and low-lying areas suffer from these impacts.

Densely populated deltas, particularly in Asia, are recognized as one of the most vulnerable areas to tropical cyclones (Nicholls *et al.*, 2007). The estimated population density is 1,000 people/km^2 for nine megadeltas in Asia in 2015 (Woodroffe *et al.*, 2006) compared to the average population density of 500 people/km^2 for 40 deltas globally (Ericson *et al.*, 2006), which is ten times larger than the global average population density.

Extreme cyclones in Asia since 1970 caused over 0.5 million fatalities (Murray *et al.*, 2012) e.g., cyclones Bhola in 1970, Gorky in 1991, Thelma in 1998, Gujarat in 1998, Orissa in 1999, Sidr in 2007, and Nargis in 2008. Tropical cyclone Nargis hit Myanmar on 2 May 2008 and caused over 138,000 fatalities. Several-meter high storm surges widely flooded densely populated coastal areas of the Ayeyarwady Delta and surrounding areas (Revenga *et al.*, 2003; Brakenridge *et al*., 2012). The flooded areas were captured by a NASA MODIS image on 5 May 2008 (Figure 5-2).

[INSERT FIGURE 5-2 HERE
Figure 5-2: The intersection of inland and storm surge flooding. Red shows May 5, 2008 MODIS mapping of the tropical cyclone Nargis storm surge along the Ayeyarwady Delta and to the east, Myanmar. The blue areas to the north were flooded by the river in prior years. (From Brakenridge *et al*., 2012, submitted in 2011).]

Murray *et al*. (2012) compared the response to Indian Ocean cyclones in Bangladesh (Sidr in 2007) and in Myanmar (Nargis in 2008) in the context of the developments in preparedness and response in Bangladesh through the experiences with previous cyclones Bhola and Gorky and other events. They demonstrated that climate change adaptation efforts could be effective in limiting the impacts from extreme tropical cyclone events by the use of disaster risk reduction methods. These include the construction of multi-storied cyclone shelters, improvement of forecasting and warning capacity, establishing coastal volunteer network, and coastal reforestation of mangroves. Although cyclone Sidr was both slightly more powerful and affected more people than cyclone Nargis, it caused much fewer human losses as a result of the combined disaster risk reduction methods.

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5.2.2.1.3. Wave climate

Since AR4 a series of new studies with detailed quantification and regionalization have confirmed the connection between significant wave height (SWH) and extreme wave heights with climate variability. It is likely that SWH has been increasing over much of the North Pacific since 1900 and the North Atlantic from the 1950s (AR5, chap 3, page 3.17). Several authors reported rates of increase in the SWH, from the 1950s varying from 8 cm per decade to 20 cm in winter months in the North Atlantic with smaller values in the North Pacific (Gulev and Gregorieva, 2006; Wang et al. 2009; Sendo et al. 2010). Dodet et al., 2010 and Wang et al., 2009 report also evidence of increasing peak period during 1953-2009 in the Northeast Atlantic of up to 0.1 s per decade.

Changes in extreme wave heights have been detected in several areas around the globe. In particular, an increase in the frequency and intensity of the most severe storms has been found in the northeast Pacific (Menendez *et al*., 2008) or North American Atlantic Coast (Komar and Allan, 2008). Significant wave height data sets from 26 buoys over the period 1985–2007 reveals significant positive long-term trends in extreme wave height between 30–45ºN near the western coast of the US averaging 2.35 cm yr^{-1} (Izaguirre *et al*., 2011). These changes at high latitudes in extreme conditions have been confirmed by Young *et al*. (2011) based on a 23-year database of satellite altimeter measurements. More neutral conditions are found in equatorial regions and no clear statistically significant trends for mean monthly values. Conclusions regarding long-term trends on extreme waves should be taken with care considering the relatively short length of available data sets.

Very limited information of reliable long-term trends in SWH is available in the Southern Hemisphere. Hemer (2010) and Hemer *et al*. (2010) reported the existence of areas with statistically significant increases in SWH. Dragani *et al*. (2010) reported a 7% increase in SWH during 1990 and early 2000s in the area of the South American shelf.

The mean annual significant wave height is an indicator of how wave climate is evolving under mean conditions, influencing port activities among others. Hs_{12}, the significant wave height exceeded on average every 12 hours every year, is intimately linked to the depth of closure of the beach profile (Birkemeier, 1985) and so to potential erosion, as well as the mean energy flow direction, which is related to the transport of sediments and pocket beach planform rotation (González and Medina, 2001).

Reguero *et al*. (2012), considering numerical reanalysis over the 1948-2010 period, indicated that the largest trends in SWH variation can be found at the Pacific coast of Mexico with about 0.6 cm yr^{-1} representing almost a 30% increase over 6 decades and also in southern Chile, reaching 1 cm^{-1}. In the range of high percentiles of wave heights,

Hs_{12} seems also to have increased at a rate of about 2 cm yr^{-1} on the Pacific coast of Mexico and 3 cm yr^{-1} on the south-eastern margin of the continent, implying about a 45% and 35-45 % of change respectively for the last 6 decades. Mean energy flux direction shows sustained changes in the eastern coast from 0.2 (clockwise) to 0.4 deg yr^{-1} (counterclockwise), with lower changes in the western coast of the continent.

In order to evaluate impacts in coastal areas, it has to be said that trends in SWH in deep water are not necessarily the same as those affecting the beaches and coastal infrastructures, because wave propagation involves several processes, which modify the characteristics of the waves nearshore, (Reguero *et al.*, 2012.)

5.2.2.1.4. Temperature changes

More than 70% of the world's coastlines have significantly warmed during the past 30 years, with rates of change highly heterogeneous both spatially and seasonally (Lima and Wethey, 2012). The average rate is 0.18 ± 0.16°C per decade and the average change in seasonal timing was -3.3 ± 4.4 days per decade. These values are significantly larger than in the global ocean where the average of change is about 0.1°C per decade in the upper 75 m during the period 1970-2009 (Rhein *et al.*, WGI AR5) and the seasonal shift -2.3 days per decade (Lima and Whethey, 2012). During the period 1985-2005, the annual, night-time, warming of coastal waters along the coasts of the Iberian Peninsula and France exhibited a north-south gradient from 0.12 to 0.35°C per decade (Gómez *et al.*, 2008). Importantly with respect to impacts, the warming also differs seasonally. Gómez *et al.* (2008) have shown that most of the warming occurred in spring and summer, with values as high as 0.5°C per decade. Temperature controls the rate of fundamental biochemical processes such as enzyme reactions and membrane transport (Hochachka and Somero, 2002) with wide-ranging consequences on life history traits (e.g., development rate and survival), population growth and biogeochemical processes in coastal organisms and ecosystems (Hoegh-Guldberg and Bruno, 2010; see Table 5-1).

[INSERT TABLE 5-1 HERE
Table 5-1: Survey of literature on the impacts of anthropogenic climate change on marine ecosystems (adapted and updated from Hoegh-Guldberg and Bruno, 2010). [To be revised and confined to coastal ecosystems.]]

5.2.2.1.5. Ocean acidification

The oceans absorb about 25% of anthropogenic CO_2 emissions, leading to changes in the carbonate chemistry of seawater, including an increase in the concentration of inorganic carbon and ocean acidity (decreased pH) and a decrease in the concentration of carbonate ion (Box 3.2 in Rhein *et al.,* WGI report). These changes are collectively referred to as anthropogenic ocean acidification and are detectable. The decrease of surface ocean pH ranges between -0.0010 and -0.0018 pH unit yr^{-1}. In contrast with the open ocean where changes in the carbonate chemistry are generally moderate at timescales shorter than 1 year, coastal waters exhibit much larger changes due to changes in upwelling intensity (Feely *et al.*, 2008), deposition of atmospheric nitrogen and sulphur (Doney *et al.*, 2007), carbonate chemistry of the freshwater supply (Salisbury *et al.*, 2008), as well as inputs of nutrients and organic matter (Borges, 2011; Cai *et al.*, 2011) which control primary production (counteracting ocean acidification) and respiration (promoting ocean acidification).

Short-term (hours to weeks) changes of up to 0.5 pH unit are not unusual in coastal ecosystems (Hofmann *et al.*, 2011). There are few time series with a timespan of 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. For example, the surface pH of a southern North Sea station increased as a result of increased availability of nutrients from 1976 to 1987 (Figure 5-3; Provoost *et al.*, 2010). A phosphorus removal policy has limited primary production and led to a decrease in pH much larger than would be expected from the invasion of atmospheric CO_2 alone (-0.016 pH unit yr^{-1}). The spatial and vertical variability is also considerably larger than in the open ocean. For example, pH_{NBS} ranges from 6 to 9 in 24 estuaries (Borges and Abril, 2012).

[INSERT FIGURE 5-3 HERE
Figure 5-3: Time series of modelled gross primary production (A; Gypens *et al.*, 2009) and measured pH_T (B) at a fixed station in the southern North Sea (Borges, 2011). pH is expressed on the total scale. Shown is the regression before and after 1987 (solid lines) and the change in pH expected from increased atmospheric CO_2 alone (broken line).]

Lerman *et al.* (2011) projected that, under the IS92a scenario, pHT will decrease from about 8.16 in the year 1850 to 7.83 in 2100 but the considerable temporal and spatial variability of coastal pH illustrate the fact that ocean acidification generated by the uptake of anthropogenic CO_2 can be greatly lessened or enhanced by coastal biogeochemical processes (Borges and Gypens, 2010; Feely et al., 2010). Cai *et al.* (2011) have shown that atmospheric CO_2 invasion is a significant but minor (24%) component of the 0.45 unit decline in pH in the Northern Gulf of Mexico since pre-industrial time. Using the IS92a CO_2 emission scenario, they also projected that the overall decline in pH by 2100 will reach 0.74, a value that is much greater than that projected in the open ocean.

5.2.2.1.6. Coastal upwelling

The hypothesis that the intensity of coastal upwelling has increased because stronger warming on land compared to the sea leads to the enhancement of upwelling-favourable winds (Bakun, 1990) has recently gained support (Narayan *et al.*, 2010). Upwelled waters are rich in CO_2 and nutrients; they are also cold, leading to a decrease in temperature of 0.3 to 0.4°C per decade since the mid 20th century off Peru (Gutiérrez *et al.*, 2011).

5.2.2.1.7. Changes in freshwater input

Land-use change and climate change have modified river runoff and thus freshwater, sediment and nutrient delivery to coastal systems (Piao *et al.,* 2007). Clearing of land for agricultural use increases erosion, sediment yield and runoff. Although clearing of land for agriculture has started thousands to hundreds years ago depending on the continent (Ruddiman, 2007; Stinchcomb *et al.*, 2011), land-use change has intensified due to human population growth and has increased global runoff on average 0.08 mm y-1 over the last century (Piao *et al.,* 2007). River runoff is generally higher and more variable because of lowered retention due to land clearing (link to other chapters).

The hydrological cycle is intensified with global warming (Huntington, 2006; link to other chapters), because specific humidity increases approximately exponentially with temperature. Global warming via changes in hydrological cycling is thought to account for about 50% of runoff increase (Piao *et al.,* 2007; cross link required). However, changes are regionally variable. For instance, a detailed 500-yr reconstruction for the Baltic Sea revealed enhanced runoff in the northern Baltic and reduced runoff in the southern Baltic (Hansson *et al.,* 2011). A thorough attribution study revealed that the frequencies of floods have increased significantly in UK and Wales due to increasing greenhouse gas concentrations (Pall *et al.,* 2011).

Changes in river runoff have multiple effects on coastal systems. Relevant are not only changes in the quantity and quality of runoff but also in the temporal distribution. Freshets or sudden overflow and other pulsed discharges of freshwater into marine systems may impact coastal communities not able to deal with low-salinity water and has consequence for the efficiency of estuaries to retain or filter material delivered by the rivers. Freshwater pulses may cause delivery of riverine nutrients to open sea systems that would otherwise have been processed during transit.

5.2.2.2. Non-Climate Drivers

Coastal systems are subject to a wide range of non climate-related drivers (e.g., Crain *et al.*, 2009) the impacts of which can interact with those climate-related drivers. Some of the major drivers are briefly reviewed below.

5.2.2.2.1. Hypoxia

The excessive input of nutrients generates coastal eutrophication and the subsequent decomposition of organic matter leads to a decrease in the oxygen concentration (hypoxia) that is reinforced by ocean warming which decreases the solubility of oxygen in seawater. Upwelling of low oxygen waters (e.g., Grantham *et al.*, 2004) and ocean warming (Shaffer *et al.*, 2009) are secondary drivers. Cultural eutrophication induced hypoxia interacts with climate-change induced de-oxygenation. Attribution of low oxygen conditions to natural variability, climate change and cultural eutrophication is therefore difficult (Zhang *et al.,* 2010). Hypoxia poses a serious threat to marine life, which is exacerbated when combined with elevated temperature (Vaquer-Sunyer and Duarte, 2010). The number of so-called "dead zones" has approximately doubled each decade since 1960 (Diaz and Rosenberg, 2008). Fisheries catches from these areas are generally lower than what would be predicted from nutrient loading (Breitburg *et al.*, 2009).

5.2.2.2.2. Water diversion in watersheds

Human engineering can affect the runoff of individual river basins to the coastal ocean much more than climate change (Wisser *et al.*, 2010). The main drivers are expansion of irrigation and the construction of structures for water diversion, flood control, power generation and recreation that retains 15% of the global water discharge, hence altering the delivery of sediment and nutrients to coastal systems. An estimated 25% of the world's river basins run dry before reaching the oceans, due to use of freshwater resources in the basins (Molden *et al.* 2007).

However, the direct human influence on annual stream flow is small compared with climatic changes during 1948–2004 for most of the world's major rivers (Dai *et al.*, 2009) and at the global scale (Wisser *et al.*, 2010).

5.2.2.2.3. Sediment delivery

The reduction in sediment delivery to the coast due to trapping behind dams, irrigation (water diversion), sand and gravel mining in river channels causes the sinking of world river deltas, shoreline erosion, threatened mangroves swamps and wetlands, and increased salinization of cultivated land and ground water (Syvitski, 2008). Riverine sediment discharge globally is estimated to be ~20 Gt yr^{-1} before dam construction in 1950s (e.g., Syvitski *et al.*, 2005; Milliman and Farnsworth, 2011), however present sediment discharge has decreased down to 12–13 Gt yr^{-1} (Syvitski and Kettner, 2011). On the other hand soil erosion due to land–use change causes the increase in sediment discharge (e.g., Restropo and Syvitski, 2006), and also impacts coastal ecosystem, particularly coral reefs (McCulloch *et al.*, 2003).

5.2.2.2.4. Subsidence: relative sea-level rise

Subsidence is a common feature of coastal plains and leads to amplified hazards from relative sea-level rise and flooding in the coastal cities built on plains (Mazzotti *et al.*, 2009). Accelerated compaction associated with subsurface resources extraction (gas, petroleum and groundwater) can exceed rates of natural subsidence and global sea-level rise by an order of magnitude (Syvitski, 2008). Increased sediment consolidation due to artificial loads and buildings can lead to significant augmentation of subsidence and relative sea-level rise (Mazzottii *et al.*, 2009).

5.2.2.2.5. Habitat loss

The conversion of wetlands, intertidal and shallow subtidal habitats to make way for coastal development including land reclamation, harbors or ponds for fish farming is a major factor leading to loss of coastal habitats such as salt marshes, seagrass beds, mangrove forests, beaches and mudflats (Crain *et al.*, 2009).

5.3. Observed Impacts

5.3.1 Impacts on Coastal Habitats and Ecosystems

Coastal habitats and ecosystems have been changed with impacts from both climatic and non-climatic drivers. Halpern *et al*. (2008) have shown that coastal ecosystems, which are subject to both land- and ocean-based anthropogenic stressors, are those experiencing the greater cumulative impact of human activities. Anthropogenic drivers associated with global climate change are distributed widely and are an important component of global cumulative impacts. There are few coral reefs, seagrass beds, mangroves, rocky reefs and shelves with limited impact, and it is hard to discriminate climatic and non-climatic drivers from all ecosystems. However some ecosystems indicate the changes impacted by climate drivers. Coral bleaching impacted by climate change shows detection (D) with very high confidence and attribution (A) with high confidence. Decreased calcification is regarded as D with medium confidence and A with low confidence, and polar-ward expansion of coral species over recent decades is D with high confidence and A with low confidence. However overexploitation and habitat destruction have been responsible for most of the historical changes that occurred in coastal systems (Lotze *et al*., 2006).

[INSERT FIGURE 5-4 HERE
Figure 5-4: Confidence in Detection and Attribution of observed impacts for coastal systems. Values will be inserted at right positions post FOD, and iterated across chapters to ensure consistency. [Combined one for all coasts still to be developed.]]

The following sections assess the impacts of climatic and non-climatic drivers observed in coastal habitats and ecoystems. The summary of these impacts leads to the recognition of key vulnerable systems and hotspots.

5.3.1.1. Rocky Shores

Rocky shores occur at the margins of the oceans throughout the world and can be natural or man-made (e.g., docks, dykes, breakwaters). They are characterized by very steep environmental gradients, especially in the intertidal area where environmental challenges are posed by both aquatic and aerial climatic regimes (e.g., temperature and desiccation). Changes in abundance and distribution of rocky shore species have long been recognized, for example as early as the late 1940s in the North East Atlantic (Hawkins *et al*., 2008) and perturbation experiments provided information of environmental limits, acclimation and adaptation, particularly to changes in temperature (e.g., Peck *et al*., 2009a). The challenge is to distinguish the response to changes from climatic drivers, hydrology or from natural temporal and spatial fluctuations.

Species can be eliminated from intertidal habitats by increases in air and water temperature, changes in upwelling regimes, and changes in oxygen levels that can lead to lethal and sublethal effects, which in turn affect population size, species interactions and species persistence. Antarctic ectotherms have very poor abilities to acclimate to elevated temperature and are at least as sensitive as tropical marine ectotherms (Peck *et al*., 2009a) and an Antarctic brittle star is incapable of acclimating to a temperature of 2°C, only 0.5°C above currently experienced summer maximum temperatures (Peck *et al*., 2009b). Helmuth *et al*. (2006) reported shifts of range limits of many intertidal species of up to 50 km per decade, much faster than most recorded shifts of terrestrial species. However, the geographical distribution of some species did not change in the past decades. The lack of ranges shifts could be due to weak local warming (Rivadeneira and Fernández, 2005) or overriding effects of variables such as timing of low tide, hydrographic features, lack of suitable bottom types, larval dispersal, food supply, predation and competition (Poloczanska *et al*., 2011; Helmuth *et al*., 2002, 2006).

Changes in current patterns and increased storminess can dislodge benthic invertebrates affect the distribution of propagules and recruitment. For example, changes in hurricane activity could subject mussels to more frequent and more severe disturbances compared to those that occurred during 1971-1994 (Carrington, 2002).

Rocky shores are one of the few ecosystems for which field evidence of effects of ocean acidification is available. Wootton *et al*. (2008) provided observational and modeling analysis of rocky shore community dynamics in relation to pH and associated physical factors over nine years (2000–2008). The community structure shifted from a mussel to an algal-barnacle-dominated community but attribution to a specific driver or set of drivers is difficult. Observations near natural CO_2 vents in the Mediterranean Sea showed profound changes of the community structure of shallow rocky shores at an average pH value around the one expected in 2100. Subtidal calcifiers are absent below mean pHT 7.8 (Hall-Spencer *et al*., 2008) while calcareous and turf algae are significantly reduced and other macroalgae are tolerant (Porzio *et al*., 2011). The negative effects of ocean acidification on several Mediterranean rocky shore invertebrates are mostly due to increased calcium carbonate dissolution in organisms that have no organic protective layer or have lost it, and are exacerbated at higher temperatures (Rodolfo-Metalpa *et al*., 2011). Similar tolerance to low pH is found in calcifying invertebrates of the Baltic Sea (Thomsen *et al*., 2010), probably at the cost of increased energy expenditure (Thomsen and Melzner, 2010). Increased acidity increases the rate of dissolution of the calcium carbonate framework.

5.3.1.2. Beaches and Sand Dunes

Throughout the world, beaches and dunes, as well as bluffs and cliffs, have in general been undergoing net erosion over the past century or longer (e.g. Bird, 2000, estimated at least 70% of the world's sandy beaches were eroding). This erosion is due to a variety of processes only some of which are climate related, like rising mean sea levels (Ranasignhe and Stive, 2009); changes in the frequency and severity of transient storm associated erosion events (Tebaldi *et al*., 2012); wave propagation caused by sea-level changes realigning shorelines (Tamura *et al*. 2010); sustained changes in the direction of mean wave energy (Reguero *et al*. 2012); changes in the loss of natural protective structures such as coral reefs (Grevelle and Mimura, 2008) or mangrove forests due to increased ocean temperatures or ocean acidification (Bongaerts *et al*. 2010); permafrost degradations and sea ice retreat, which exposes soft shores to waves and storms (Manson and Solomon, 2007). These processes may act at different time scales. For example, there is high confidence that erosion on the beaches of Southeast Australia is intimately related to interannual changes in swell direction (Harley *et al*. 2010).

Non-climate related processes include reductions of sand supply, through trapping by river dams or coastal protection structures. Reasonably accurate maps have been available since about the mid-19th century to compare to more recent maps and imagery to quantify combined climate and non-climate changes. For example, the long-term rate of erosion along the U.S. Mid-Atlantic and New England coasts is 0.5 ± 0.09 m yr^{-1} (Hapke *et al*., 2011). This is based on over 21,000 measurement locations equally spaced along the more than 1,000 km of coast, 68% of which indicated net erosion. Arctic coasts have experienced some of the greatest magnitudes of erosion in the world, for example in parts of Alaska as much as 0.9 km of retreat in 50 years (Mars and Houseknecht, 2007) and in parts of Siberia a range of 434 m of retreat to 92 m of deposition in 56 years (Lantuit *et al*., 2011). However, in a survey of 27 atoll islands in the central Pacific, 43% of islands were found to have remained stable and 43% were found to have increased in area (Webb and Kench, 2010). Where an eroding shoreline approaches hard, immobile, structures like seawalls or resistant natural cliffs, the beaches will narrow due to coastal squeeze that removes the sands and associated habitats, and steepens the beach slope, impacting the survivability of a variety of organisms (e.g. in northern Scotland, see Jackson and McIlvenny, 2011). With coastal squeeze, sand dunes will ultimately be removed as the beach erodes and narrows. Extreme storms can erode and completely remove dunes, degrading land elevations and exposing them to inundation and further change (e.g. Plant *et al*., 2010).

Unfortunately, due to the scarcity and fragmentary nature of the information available and to the multiple natural and anthropogenic drivers contributing to coastal erosion, attributing shoreline changes to climate change is still difficult. In the absence of adaptation measures there is a high confidence that beaches and sand dunes currently affected by erosion, will continue to do so under increasing sea levels or changing wave heights and mean energy flux direction.

5.3.1.3. Estuaries, Tidal Flats, and Lagoons

Estuaries connect rivers with adjacent coastal systems and are the primary conduit for water, nutrients and particulates from the continent to the sea. Depending on the hydrology, oceanographic, climatic and geological settings estuaries can be well-mixed or stratified, shallow or deep, river or tidally dominated, but a common characteristic is the presence of fresh and marine water within the system and consequently salinity gradients (Heip *et al*., 1995; Breitburg *et al*., 2009).

Riverine transport of particles and delivery of suspended matter from the sea supports high rates of sediment deposition in estuarine systems. Sediment accumulation in estuaries is heterogeneous and habitat specific (generally little in the main channels and more accumulates in marginal systems such as marshes) and affected directly by dredging activities for shipping and indirectly via habitat loss, sea-level, storminess and land-use changes related changes in sediment supply by rivers (Syvitski *et al*., 2005). Climate and non-climate induced changes in estuarine sediment budgets have consequences for carbon, nutrients and contaminants budgets.

Estuarine systems, with low tidal ranges, are strongly affected by run-off since the water residence time is primarily governed by runoff. Water residence time is a key predictor and governing factor for many ecosystem and biogeochemical processes including nutrient processing, the metabolic balance, carbon dioxide exchange rates and hypoxia (Howarth *et al*., 2009). Floods, freshets and other runoff events may diminish estuarine communities and in that way the processing of organic matter and nutrients in these systems.

Estuaries are known to be sites with high-intensity water-air and sediment-air carbon dioxide exchange. Most estuaries are a source of carbon dioxide to the atmosphere (Borges, 2005), the global carbon dioxide emission rate is about 0.25 Pg y-1 (Cai, 2011; Laruelle *et al*., 2010). Although most researchers agree that estuaries emit carbon dioxide there is debate on whether the carbon dioxide originates from riverine carbon, i.e. input of carbon dioxide rich rivers and respiration fuelled by riverine particulate and dissolved organic matter, or from within mangroves and tidal marshes within the estuary (Borges, 2005; Hofmann *et al*., 2008; Cai, 2011).

Increasing atmospheric carbon dioxide levels would theoretically impede these effluxes (lower gradient from water to air), but this is difficult to detect because of the high heterogeneity and large temporal variability of estuarine carbon dioxide pressures (Borges, 2005; Chen and Borges, 2009). Increasing atmospheric carbon dioxide may also lead to acidification of estuarine waters and if waters become undersaturated with respect to calcium carbonate, this may have major consequences for some calcifiers, including ecological key species such as ecosystem engineers and commercially important species (e.g., oysters, mussels, Gazeau *et al*., 2007). However, acidification of estuarine waters is not only due to atmospheric carbon dioxide uptake as in the open ocean and on the continental shelf, but also due to mixing of fresh and marine waters, input of riverine waters rich in carbon dioxide and nitrification supported by high ammonium concentrations (Salisbury *et al*., 2008; Hofmann *et al*. 2009). Changes in eutrophication and the balance between production and respiration have been identified to overrule atmospheric carbon dioxide induced acidification processes in coastal waters (Borges and Gypens, 2010). A detailed analysis of long-term time series for estuarine waters in the Dutch coastal zone revealed large changes, both increases and decreases (Provoost *et al*., 2010).

Riverine delivery of nutrients has increased significantly the last century and is projected to increase further (Bouwman *et al*., 2011). The elevated nutrient loadings to estuaries have resulted in major changes in biogeochemical processes, community structure and ecosystem functions (Howarth *et al*. 2009). Eutrophication has modified food-web structure, has led to more intense and longer lasting hypoxia and to more frequent occurrence of harmful algal blooms (Breitburg *et al*., 2009; Howarth *et al*., 2009). These nutrient-induced environmental issues have affected estuarine fishery yield and sustainance.

Coastal lagoons are shallow bodies of seawater or brackish water separated from the ocean by a barrier, connected at least intermittently to the ocean. Coral reef lagoons are considered elsewhere in this chapter. Temperate coastal lagoons are formed and maintained through sediment transport and are therefore highly susceptible to alterations of sediment input from land and erosional processes driven by changes in sea level, precipitation, and storminess.

Temperate coastal lagoons often host salt marshes, seagrasses and macroalgae (see sections 5.3.1.5, 5.3.1.7) and aquaculture. Due to their restricted exchange with the adjacent ocean, they are particularly vulnerable to eutrophication.

On average, the fisheries yield is higher in coastal lagoons than in other ecosystems (Kapesky, 1984 in Pauly and Yáñez-Arancibia, 1994) and there appears to be an empirical correlation between primary production and fisheries yields (Nixon, 1982). Hence, any change in primary production generated by climatic or non-climatic drivers could impact fisheries. For example, it has been shown that changes in water temperature and reduction in plankton productivity caused by the modification of seasonal precipitation patterns will negatively affect clam aquaculture in the lagoon of Venice (Canu *et al*., 2010). Small changes in salinity were also shown to generate major changes in food webs (Jeppesen *et al*., 2007) but the global impact on lagoon fisheries remains uncertain.

5.3.1.4. Deltas

Coastal zones receive substantial amounts of nutrient and sediment from rivers, and deltas are formed at river-mouth areas influenced by a combination of river, tide and wave processes. Deltas are one of the most important ecosystems and habitats, and also areas for socio-economic human activities. Deltas consist of a compound coastal system of natural systems, e.g., tidal flats, salt marshes, mangroves, beaches, estuaries, low-lying wetlands, and also human systems, e.g., houses, agriculture, aquaculture, industry, transport, with a high population density of more than 10 times the world average (Ericson *et al*., 2006; Foufoula-Georgiou *et al*., 2011). However deltas are among the highly vulnerable and stressed coastal systems and are subjected to human and climate impacts from both drainage basins of rivers and oceans, and also within delta itself: e.g., changes in runoff, sea-level rise, as well as human activities as land-use changes, dam construction, irrigation, mining, extraction of subsurface resources, urbanization. In particular, Asian megadeltas and low-lying coastal urban areas including megacities are identified as one of vulnerable areas (Nicholls *et al*., 2007).

Decreased sediment discharge due to construction of dams and irrigation makes imbalance of sediment in coastal zones, resulting in loss of beaches, mangroves and tidal flats by coastal erosion (e.g., Nile and Ebro, Sanchez-Arcilla *et al.,* 1998; Po, Simeoni and Corbau, 2009; Krishna-Godavari, Nageswara Rao *et al*., 2010; Changjiang, Yang and Milliman, 2011; Huanghe, Chu *et al.,* 1996). In particular, 25% of the wetlands of the Mississippi Delta have been lost over the last few centuries (Blum and Roberts, 2009). Fluctuations in sea-level rise rate and sediment supply mainly dominate the formation and evolution of coastal wetlands. The wetlands with high sediment input, mainly riverine are only ones for surviving accelerated sea-level rise, based on a comparative study of the wetlands of Mediterranean deltas and lagoons (Day *et al*., 2011). High sediment input and high capture efficiency of sediments including inundation frequency by tides are necessary for sediment accumulation (Day *et al*., 2011; Andersen *et al*., 2011). The dominant species in the marsh, together with nutrient availability, also control the rate of organic peat production. The highest rates of marsh vertical accretion are found in fluvially dominated systems due to high inorganic sediment influx (FitzGerald *et al*., 2008). On the other hand, land-use change from natural delta plains to agricultural and industrial use is a major cause of wetlands loss more than natural causes. Globally, 42 deltas show wetland loss with an average annual rate of 26,000 km^2 for the last 14 years (Coleman *et al*., 2008).

Major sea-level rise impacts are coastal wetland change, increased coastal flooding, increased coastal erosion, and saltwater intrusion into estuaries and deltas (Mcleod *et al*., 2010b). Subsidence due to natural and anthropogenic compaction of underlying sediments is a common feature of river deltas and leads to amplified hazards from relative sea-level rise in the coastal cities built on deltaic plains (Day and Giosan, 2008; Mazzotti *et al*., 2011). The most dramatic subsidence effects have been caused by drainage and groundwater fluid withdrawal. Over the 20th century, coasts have subsided by up to 5 m in Tokyo, 3 m in Shanghai, and 2 m in Bangkok. To avoid submergence and/or frequent flooding, these cities now all depend on a substantial flood defence and water management infrastructure (Nicholls *et al*., 2010). In Thailand the extreme Chao Phraya flood of 2011 in the delta plain caused a loss of human life and impacted the global economy. Increased sediment consolidation due to artificial loads can also lead to significant augmentation of subsidence and relative sea-level rise. For the Fraser River delta, areas with recent large structures may undergo relative sea-level rise of as much as ~1–2 m (Mazzotti *et al*., 2011). Relative sea-level rise also impacts the decrease in sediment delivery from rivers to the coastal zone by deposition in river channels in deltas in the Po river delta (Syvitski *et al*., 2005).

Thirty-three deltas in the world show that 85% of the deltas experienced severe flooding in the past decade, resulting in the temporary submergence of 260,000 km^2 (Syvitski *et al*., 2009). Deltas have received substantial impacts by river floods and from oceans by storm surges and tsunamis. Tropical storms also have impacted ecosystems and human systems in deltas, e.g., the city of New Orleans and the Mississippi Delta by Hurricane Katrina in 2005 (Dixon *et al*., 2006), Ayeyarwady (Irrawaddy) Delta by Cyclone Nargis in 2008, Ganges-Brahmaptra Delta by Cyclone Gorky in 1991 and Cyclone Sidr in 2007 (Murray *et al*., 2012). The tropical cyclones in the North Indian Ocean account for 86% of the world mortalities (ISDR, 2009), which occur mostly in highly populated deltas in this region.

5.3.1.5. Mangroves and Salt Marshes

Mangrove forests occur along the coast of more than hundred countries. These ecosystems provide many functions including coastal defence, nursery grounds for fishes and carbon storage (Bouillon *et al*., 2008, Feller *et al*., 2010). Mangrove trees are found in the intertidal zone along subtropical and tropical coasts. These forests are essential in protecting shorelines (Gedan *et al*., 2011). They stabilize sediments and enhance settling and retention of fine-grained sedimentary materials. Mangrove forests act as sediment sinks and as consequence of this also as organic carbon sinks (Duarte *et al*., 2005).

The area of mangrove forests has declined by 30 to 50% during the last 50 years due to coastal development, over-harvesting and increasing use for aquaculture (Duarte *et al*., 2005; Donato *et al*., 2011; Irving *et al.,* 2011). Clear-felling to generate space for commercial pond aquaculture for fish and crustacean is in particular important. Annual rate of areal decrease for the period 1970 to 2000 were about 2% yr^{-1} (Duarte *et al*., 2005; Irving *et al*., 2011), implying that without further protection they will disappear in as little as 100 years. This will have consequences for coastal protection and carbon burial. Mangrove forests are the most carbon dense forest on earth with about 1 Gg carbon stored per ha, primarily below ground (Donato *et al*., 2011). Reclamation of mangrove forest results in 112 to 392 Mg C loss per ha, depending on the depth to which soil carbon is oxidized. This represents 0.02-0.12 Pg yr^{-1}, as much as around 10% of emissions from deforestation globally, despite mangroves accounting for just 0.7% of tropical forest area (Donato *et al*., 2011). This carbon loss should be combined with the loss of long-term carbon sequestration because of loss of organic carbon burial that would otherwise occur (Duarte *et al*., 2005; Irving *et al*., 2011).

Coastal wetlands are prominent features and important habitats along the coastline. Mangroves dominate subtropical and tropical coastlines while tidal marshes (saline, brackish and fresh-water tidal) dominate temperate systems. Saltmarshes provide many ecosystem functions and services including coastal defence against storms and waves, nutrient removal and transformation, nursery for fish and shrimp, fishing, carbon burial and tourism (Bromberg Gedan *et al*., 2009; Irving *et al*., 2011). Coastal marshes play a major role in protecting shorelines via multiple mechanisms including wave attenuation and shoreline stabilization (Bromberg Gedan *et al*. 2011). Saltmarshes have been used and shaped by humans since Medieval Times. Human impacts include use as pasturelands for livestock, use of marsh plants for construction, conversion of marshes into agricultural, urban and industrial use (Bromberg Gedan *et al*. 2009). Moreover, deliberate introduction of species and invasive species have modified marsh communities and functioning (Neira *et al*., 2006). Intertidal Spartina and phragmites have been introduced deliberately for coastal protection or were favoured by nutrient enrichments. Changes in marsh hydrology due to ditching or tidal restriction have significantly affected coastal marsh distribution patterns and functioning (Bromberg Gedan *et al*., 2009; 2011).

Saltmarshes represent a major sink for sediment and thus organic carbon (Duarte *et al*., 2005). Any loss of saltmarsh area (climate change, habitat destruction) thus lowers natural CO_2 sequestration potential (Irving *et al*., 2011). Decline in saltmarsh area, therefore, exacerbates climate change and also implies that shorelines become more vulnerable to erosion due increased sea level rise and increased wave action.

The distribution of tidal marshes is closely linked with sea level and thus sea level rise. Historical records show that saltmarshes have generally adapted accretion rates to match sea-level rise (Redfield, 1972). The response of saltmarsh to sea-level rise involves landward migration of salt marsh vegetation zones and submergence at lower elevations and drowning of interior marshes. Marsh can increase accretion rates by either accumulating more external mineral particles or by accumulation of peat, the relative importance of these two modes of accretion depending on geological setting and ecosystem production (Allen, 1995; Middelburg *et al.*, 1997)

5.3.1.6. Coral Reefs

Coral reefs are shallow-water structures made of calcium carbonate mostly secreted by scleractinian corals and algae. They harbour a biodiversity that is disproportionately high compared to their surface area and are sources of key services to humans. Coral reefs are susceptible to several climatic (sea-level rise, warming and ocean acidification) and non climatic (e.g., coastal development, pollution, nutrient over-enrichment and overfishing). Most human-induced disturbances until the early 1980s were local but climate-related disturbances have become more obvious in recent decades.

Coral reef growth is intimately linked to sea level. Within the uncertainties of both the estimates of past sea level rise and coral reef growth, most reef ecosystems seem to have kept pace with sea-level rise during the past 100 years (Buddemeier and Smith, 1988).

Increased temperature triggers bleaching of corals, which are key reef ecosystem engineers (Wild *et al.*, 2011). Bleaching involves the loss of endosymbiotic algae, which live in the coral tissues and play a key role in their physiology, especially nutrition (Baker *et al.*, 2008) (see chapter 6 for physiological details and chapter 30 for a regional analysis). Mass coral bleaching has occurred in association with episodes of elevated sea temperatures over the past 30 years (e.g., Hoegh-Guldberg, 1999; Kleypas *et al.*, 2008). For example, the level of thermal stress at most of the 47 reef sites where bleaching occurred during 1997-98 was unmatched in the period 1903 to 1999 (Lough, 2000). The intensity of bleaching events is very variable on yearly timescale: the percentage of reef cells which exhibited at least one bleaching event was 7% in 1985-1994 and 38% in the subsequent decade due to intense El Niño events. Bleaching is not always fatal for coral colonies; recovery depends on (1) the magnitude and duration of the elevated temperature event, (2) the species that have been lost, (3) the acclimation potential of the species remaining, and (4) the interaction with other drivers. Reef recovery from the 1998 global bleaching event was significant but slow in the Indian Ocean (median rate of recovery of about 1% yr^{-1}, absent in the western Atlantic and locally variable elsewhere (Baker *et al.*, 2008). It has also been limited in the southern Arabian Gulf although the community is among the most tolerant to environmental extremes (Burt *et al.,* 2011).

The increase in temperature is also suspected to have caused a poleward range expansion of corals (e.g., Precht and Aronson, 2004). The northward speed along the coasts of Japan is to up to 14 km y-1 since the year 1930, with no evidence of southward range shrinkage or local extinction (Yamano *et al.*, 2011). Some of the new sightings could be due to a recent increase in monitoring and the introduction of larvae or adults by humans can contribute to range expansion. Nevertheless, increased temperature favours range shifts.

The decline of seawater pH has become a recent source of concern for the future of coral reefs. The geological record indicates that four of five global metazoan reef crises in the last 500 Myr were probably at least partially governed by ocean acidification and rapid increase in temperature (Kiessling and Simpson, 2011). Experimental evidence shows that lower pH decreases the rate of calcification of most, but not all, reef-building corals and coralline algae (reviewed in Andersson et al., 2011; Pandolfi *et al.*, 2011) and enhances the competitiveness of seaweeds over corals (Diaz-Pulido *et al.*, 2011).

Retrospective studies have provided clear outcomes but attribution to drivers has proven difficult. Although perturbation experiments suggest that coral calcification may have decreased since the beginning of the industrial revolution, clear evidence is not available in all field samples. Most (e.g., De'ath *et al.*, 2009, Manzello, 2010), but not all (Bessat and Buigues, 2001; Helmle *et al.*, 2011) retrospective studies show decreasing trends in calcification for the past several decades but whether the decrease is due to ocean acidification, other environmental drivers (e.g., ocean warming), or a combination of drivers remains unclear. Despite a few shortcomings (Riebesell, 2008), observations near CO_2 vents (Fabricius *et al.*, 2011) have shown that ocean acidification has dramatic impacts on the biodiversity of natural communities even though reef-building corals are not completely eliminated at lower pH (pHT 7.73 to 8.00) compared to control (pHT 7.97–8.14) and the rate of calcification of the one of the resistant species exhibits small changes relative to pH. At lower pH, the community composition tips in favour of seagrasses and fleshy non-calcareous macroalgae and against hard corals.

Published evidence supports the hypothesis that coral infectious diseases are emerging in response to drivers such as ocean warming, altered rainfall, increased storm frequency, sea level rise, altered circulation, and ocean acidification (Sokolow, 2009). Based on population reduction in the recent past, it is estimated that one third of all coral species exhibit a high risk of extinction (Carpenter et al., 2008). Although less well documented, non-coral benthic invertebrates are also at risk (Przeslawski *et al.*, 2008). Reef fish are also vulnerable, less from climatic drivers than from overfishing (Graham *et al.*, 2011).

Almost half of all coral reefs experience medium high to very high impact of human activities (30-50% to 50-70% degraded; Halpern *et al.*, 2008). Many coral reefs have been subject to widespread degradation since the 1970. In the Indo-Pacific, the estimated yearly coral cover loss was approximately 1% over the last twenty years (Bruno and Selig, 2007). For example, in Jamaica, coral cover has declined from more than 50% in the late 1970s to less than 5% in the early 1990s. A dramatic phase shift has occurred producing a system dominated by fleshy macroalgae (more than 90% cover).

_____ START BOX 5-3 HERE _____

Box 5-3. Case Study – Coral Reefs

[cross chapter (5, 6, 25, and 30) box]

Coral reef ecosystems are mostly distributed in the tropics and play multiple key roles despite their relatively small surface area. Almost 500 million people live within 100 kilometers of a coral reef (Burke *et al.*, 2011), deriving benefits such as provisioning functions (e.g. food, construction material, medicine), regulating functions (e.g. shoreline protection, maintenance of good water quality), cultural functions (e.g., tourism) and supporting functions (e.g. oxygen supply) (Hoegh-Guldberg, 2011). A wide range of climatic and non-climatic drivers affect coral reefs and negative impacts are already observed (section 5.3.1.6). Coral bleaching, largely triggered by positive temperature anomalies, is the most widespread and conspicuous impact (Figures 5-4 and 5-5) (Chapter 6, section 6.2.2.4; Chapter 25, section 25.6.3; Chapter 30, section 30.5.3-6 and 30.10.2). Increased seawater acidity limits the calcification rate of many coral reef builders, increases reef dissolution, and reduces biodiversity (Figure 5-5c,d).

[INSERT FIGURE 5-5 HERE
Figure 5-5: 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% almost all of which was severely bleached, resulting in mortality of 20.9% (Elvidge *et al.* 2004). C and D: three CO_2 seeps in Milne Bay Province, Papua New Guinea show that prolonged exposure to high CO_2 is related to fundamental changes in coral reef structures (Fabricius *et al.*, 2011). Coral communities at three high CO_2 (median pH_T 7.7, 7.7 and 8.0), compared with three control sites (median pH_T 8.02), are characterised 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 pH values below 7.7. Photo credit: R. Berkelmans (A and B) and K. Fabricius (C and D).]

There is robust evidence and high agreement that coral reefs are one of the most vulnerable marine ecosystems (Chapters 5, 6, 25 and 30). Globally, more than half of the world's reefs are under medium or high risk (Burke *et al.*, 2011) even in the absence of climatic factors. Future impacts of climate drivers (warming, sea level rise and increased acidity) will considerably exacerbate the impacts of non-climatic drivers (high agreement, robust evidence).

Damages to coral reefs have implications for several key regional services:

- Resources: Coral reefs produce 10-12% of the fish caught in tropical countries, and 20-25% of the fish caught by developing nations (Garcia and Moreno, 2003). Over half (55%) of the 49 island countries considered by Newton *et al.* (2012) are already exploiting their coral reef fisheries in an unsustainable way.
- Tourism: More than 100 countries benefit from the recreational value provided by their coral reefs (Burke *et al*., 2011). For example, the Great Barrier Reef Marine Park attracts about 1.9 million visits each year and generates A$ 5.4 billion to the Australian economy and 54,000 jobs (90% in the tourism sector; Biggs, 2011).
- Coastal protection: Coral reefs protect the shoreline from the destructive action of storm surges and cyclones, providing the only habitable land for several island nations and habitats suitable for the establishment and maintenance of productive mangroves and wetlands, as well as areas for recreational activities. This role is threatened by sea-level rise as well as the decrease in coral cover, lower rate of calcification, and higher rate of dissolution of the reef framework due to ocean warming and acidification.

Marine protected areas (MPAs) may be useful to increase ecosystem resilience and moderate the impacts of climate change (McLeod *et al*., 2009). Although MPAs are a key conservation and management tool, they have generally no effect on the resilience of coral reefs to thermal stress (Selig *et al*., 2012) and hence alternative strategies need consideration (Rau *et al*., 2012). Controlling the input of nutrients and sediment from land is an important complementary management strategy. However, there is *high confidence* that, in the long term, limiting the amount of warming and acidity are the most important tools to maintain viability of current coral reef systems and communities.

_____ END BOX 5-3 HERE _____

5.3.1.7. Submerged Vegetation

Seagrass meadows are ecosystems composed by marine angiosperms, a group of about 60 species of clonal angiosperms, distributed in shallow coastal areas of all continents, except Antarctica (Hemminga and Duarte, 2000). Seagrass meadows rank amongst the most valuable ecosystems, in terms of the services and benefits they support, in the biosphere, but are also highly vulnerable and about one third of the area they occupied has been lost since World War II, declining globally at rates of 7% y-1 since 1990 (Orth *et al*., 2006; Waycott *et al*., 2009). Whereas eutrophication is recognised as the primary force accounting for the global seagrass decline (Duarte 2000, Orth *et al*. 2006; Waycott *et al*., 2009), seagrass meadows are vulnerable to climate change (Short and Neckles, 1999, Duarte, 2000). Climate change affects seagrass meadows in multiple ways, as seagrass meadows are affected by warming, sea-level rise, and changes in wave energy and storminess (Short and Neckles, 1999; Duarte, 2000).

Seagrass meadows are particularly vulnerable to temperature extremes, as many seagrass meadows occur in areas where maximum temperatures are close to their physiological maxima. In these situations increased maximum temperature by a few degrees Celsius triggers seagrass mortality (e.g. Massa *et al*., 2009; Marbà and Duarte, 2010). Evidence for negative effects of high temperature on seagrass biomass has been reported for seagrass meadows in the Atlantic Ocean (Reusch *et al*., 2005), Mediterranean Sea (Marbà and Duarte, 2010) and Australia (Rasheed and Unsworth, 2011). Heat waves lead to widespread seagrass mortality as documented for *Zostera* species, the dominant seagrass genus in the Atlantic (Reusch *et al*., 2005), and *Posidonia oceanica*, the dominant species in the Mediterranean Sea (Marbà and Duarte, 2010). In particular, Marbà and Duarte (2010) demonstrated that *P. oceanica* meadows are highly vulnerable to warming, as demonstrated by a direct functional relationship between maximum seawater temperature and mortality rates of *P. oceanica* shoots, with shoot mortality rates increasing by 0.022 yr-1 for each additional degree of annual maximum temperature. Warming also triggers flowering of *P. oceanica* (Díaz-Almela *et al*., 2007), but the increased recruitment rate is insufficient to compensate for the losses resulting from elevated temperature (Díaz-Almela *et al*., 2009). Current observations indicate that seagrass meadows are already under stress due to realised climate (e.g. Marbà and Duarte, 2010, Rasheed and Unsworth, 2011).

Seagrasses, particularly those in shallow waters, are often carbon-limited (Hemminga and Duarte, 2000), and may benefit from increased CO_2. Due to the realised increased in CO_2 concentration in surface waters (Duarte, 2002), seagrass photosynthetic rates may have already increased by 20% (Hemminga and Duarte, 2000; Hendriks *et al.*, 2010).

Sea-level rise may result in the upslope migration of seagrass meadows, with both their shallow and depth limit migrating upwards to maintain their depth range (Duarte, 2002). However, sea-level rise often results in submarine erosion and the loss of seagrass meadows, particularly where shorelines have been occupied by infrastructure (Marbá and Duarte, 1997; Duarte, 2002). Extreme events, such as droughts, can also impact on estuarine seagrasses. Cardoso *et al.* (2008) concluded that extreme weather events contributed to the overall degradation of seagrass meadows in a Portuguese estuary.

Loss of seagrass meadows with climate change erodes natural CO_2 sequestration potential, as seagrass meadows act as CO_2 sinks, ranking among the most intense CO_2 sinks in the biosphere (Duarte *et al.,* 2010; Kennedy *et al.* 2010). Loss of seagrass meadows, therefore, aggravates climate change and also renders shorelines more vulnerable to erosion due increased sea level rise and increased wave action.

Macroalgal beds grow in shallow coastal areas worldwide, including rocky and sandy shores, and form highly productive communities with rapid turnover. Temperature affects growth and biogeographic ranges of macroalgae, especially in polar and cold-temperate regions. Macroalgae are also affected by increased CO_2, which is expected to lead to enhanced photosynthetic rates (Wu *et al.*, 2008).

Contrasting response of macroalgae and corals to climate change has lead to the prediction of a tendency for phase shifts from corals to macroalgae. However, a recent global assessment concluded that coral reef ecosystems appear to be more resistant to macroalgal blooms than assumed (Bruno *et al.*, 2009).

5.3.2. Impacts on Human Systems

Coasts are complex, linked social-ecological systems where anthropogenic alteration has modified the natural processes to the extent that the system dynamics are difficult to separate in terms of human effects and natural processes (Kittinger and Ayers, 2010). The following sections assess understanding of observed weather and climate impacts on human systems on the coasts, with the severity depending on their exposure and vulnerability.

5.3.2.1. Human Settlements

Aspects of weather and climate, such as storms, heat waves, riverine and flash flooding, storm surge inundation and erosion pose a range of hazards for coastal settlements (Handmer *et al.*, 2012). Settlements can amplify the impacts of weather and climate extremes. The urban heat island effect caused by the large amounts of heat absorbing materials used in settlements, and heat emitted from energy and vehicle usage increases daytime maximum and reduces nighttime minimum temperatures. Heat waves can also reduce air quality and increase the number of days in which pollution levels are elevated (Wilby, 2007; Handmer *et al.*, 2012). Most significant for coastal settlements is the potential from flooding from extreme sea levels, which in recent decades have increased at rates similar to mean sea levels rise (Menendez and Woodworth, 2010). Excessive hard paving associated with settlements increases runoff concentration while increased occupation of flood plains for settlements reduces floodplain storage. These can amplify the impacts of flooding as well as increase the risks for those settled in vulnerable areas. Problems of coastal flooding are further enhanced in areas experiencing subsidence due to compaction and groundwater extraction. Settled areas adjacent to the shore are also vulnerable to loss of land through erosion.

Globally, the Low Elevation Coastal zone (LECZ) of less than 10 m above sea level constitutes 2% of world's land area but contains 10% of world's population (600 million) and 13% of world's urban population (360 million) based on 2000 estimates. About 65% of the worlds cities with populations of over 5 million are in this zone including a disproportionate number of small island states and densely populated megadeltas (McGranahan *et al.*, 2007). Urban poor in informal settlements, of whom there are about 1 billion worldwide, are particularly vulnerable to weather and climate impacts (Handmer *et al.*, 2012). Of the top ten nations classified by population and proportion of population in coastal low-lying areas the majority are developing countries (Table 5-2).

[INSERT TABLE 5-2 HERE
Table 5-2: 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.]

Since the AR4, a large number of coastal assessments have been undertaken that consider exposure to submergence from increasing sea levels or flooding from extreme sea level events ranging from global to local scale (see Table 5-4). In general these studies find current exposure to be largest in the populous Asian cities. Population growth, socio-economic growth and urbanization are the most important drivers of increased exposure of these cities, although climate change and subsidence exacerbate the effect in Asia, particularly in the megadeltas. In Bangkok subsidence has trebled flood damage costs. The Pearl River and Mekong deltas are particularly vulnerable to subsidence as result of land compaction or extraction of groundwater. As urban population represents increasing proportion of world populations, urban floods will account for an increasing percentage of total flood impact as seen in Pakistan, Australia and Brazil (Jha *et al.*, 2011).

To summarise, there is *very high confidence* that coastal settlements currently exhibit high exposure to weather and climate particularly through sea level extremes (high agreement, robust evidence). The increasing trend of urbanisation over recent years is contributing to this exposure.

5.3.2.2. Industry, Transport, and Infrastructures

Coastal industries, their supporting infrastructure including transport (ports, roads, rail, airports), power and water supply, storm water and sewerage are sensitive to a range of extreme weather and climate events, many of which are projected to change over coming decades (Seneviratne *et al.*, 2012). Severe storms with associated winds, rain, lightning and storm surges are particularly disruptive to transport and power and water supplies. Heat extremes affect asphalt road surfaces and cause movement of materials used in infrastructure (e.g., buckling of rail tracks). Droughts affects water quality and supply as does increasing salinisation of coastal aquifers due to rising sea levels or extreme sea level events (Handmer *et al.*, 2012).

Sea transport accounts for more than 80% of global goods trade (by volume) and so disruption to port activities in one location can disrupt supply chains, which can have far reaching consequences (Handmer *et al.*, 2012). Increased sediment mobility and changes in sedimentation/erosion patterns restrict operations of harbours and access channels (UNCTAD, 2008). Coastal industries in high latitudes are affected by permafrost thaw causing ground stability and erosion thereby affecting transport safety and the industries that rely on such travel in these regions (e.g., Pearce *et al.*, 2010).

For certain coastal environments such as barriers, climate-related modification of roads brings significant changes including coastal squeeze. To summarise, climate impacts on coastal industries vary considerably depending on geographical location, associated weather and climate and specific composition of industries within particular coastal regions.

5.3.2.3. Fisheries, Aquaculture, and Agriculture

Fisheries constitute one of the most important economic sectors in the coastal region. Fisheries and acquaculture industries are estimated to employ 43.5 million people globally with the majority in developing countries (Daw *et al.*, 2009). Nearly 1.5 billion people worldwide rely on fish for more than 20% of their dietary animal protein (Badjeck *et al.*, 2010) and many small island states rely on fisheries and aquaculture for 50% of their animal protein (Barange and Perry, 2009). The coastal zone also supports significant agricultural food production. For example, rice production is a major crop grown in the low-lying deltaic regions of Asia; 54% and 17% of Vietnam's rice production occurs in the Mekong and Red River deltas respectively; 68% and 34% of Mynamar's and Bangladesh's rice production occurs in the Irrawaddy and Ganges-Brahmaputra deltas (Wassman *et al*., 2009).

Recent studies have investigated the changes in the regional abundance of fish species. In the North Sea, Hiddink and Hofstede (2008) found that ocean warming over the period 1977-2002 led to 8 times more fish species exhibiting increased distribution than decreased distribution. The species showing increase were of southerly origin while those showing decrease were the larger northerly species. In southeastern Australia, Last *et al.* (2011) also found an increasing abundance of 45 fish species of warm temperate origin, which they linked to the observed strengthening of the East Australian Current (EAC) bringing warm waters further south (Ridgeway, 2007). Long term declines in abundance were found in only 9 species, which were attributed to fishing pressure. They noted however the potential for longer term detrimental effects for cool temperate species endemic to the region whose southward migration would be constrained by the southern limits of the continental shelf.

Warming ocean temperatures can also lead to the migration of more pest species. For example, in southeastern Australia, the sea urchin, problematic because it can overgraze seaweed beds, has also migrated south under the influence of the warmer EAC (Ling *et al*., 2009). In coastal Louisiana, saltwater intrusion was found to reduce the population size of the freshwater western mosquitofish (*Gambusia affinis*) although populations from more brackish sites were less affected suggesting some degree of localised adaptation (Purcell *et al*., 2010). Eutrophication and hypoxia give rise to harmful algal blooms (HABs) and episodes of HABs have increased in frequency and intensity, harming fisheries and human health (MEA, 2005).

In coastal Bangladesh salinity has become a major problem for traditional agriculture, displacing production of vegetables, fruit and animals and increasing shrimp farming. Once established, shrimp farming further increases the salinity of the local environment rendering it unsuitable for a return to traditional farming and necessitating the cultivation of high yielding, salt-tolerant rice varieties (Rahman *et al*., 2011). Saltwater inundation events and droughts have reduced the yield or destroyed crops such as taro and breadfruit, particularly in low-lying island nations (e.g. Keener *et al*., 2012).

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

5.3.2.4. Coastal Tourism and Recreation

Coastal tourism is considered the most important and fastest growing tourism sector (UNEP, 2009). Yet, coastal zones and islands as tourism destinations are among the most vulnerable to climate change. For example, the island nations of the Caribbean, Mediterranean, Indian Ocean and Pacific Ocean and Australia/New Zealand comprise five of eleven most at-risk tourism destinations (WTO, 2007). Significant impacts are occurring from changes in extreme events (e.g. flooding, tropical storms, storm surges, heat waves) and climate variability (e.g. drought and prevailing winds accelerating coastal erosion) (Scott *et al*., 2008).

Impacts are particularly relevant for tropical island coasts that depend on coral reefs for tourism where coral bleaching events observed since 1980 due to SST increase are a major concern. Globally, tourism and recreation accounted for $9.6 billion net benefits of coral reefs. In the Caribbean alone, the net benefits from dive tourism are estimated to be $2.1 billion. Australia's Great Barrier Reefs has a recreational use value of $700 million to $1.6 billion per year (Conservation International, 2008).

In summary, coastal tourism is highly vulnerable to weather and climate extremes and rising sea-levels (*high confidence*) with the additional sensitivity to ocean temperature and chemistry changes for the sectors that rely on reef tourism.

5.3.2.5. Water Resources

Coastal aquifers are sensitive to a range of climate-related factors such as temperature and evaporation rise, rainfall decline and/or changes in rainfall intensity that affect aquifer recharge, and rising sea levels and storm surges that cause salt water intrusion into aquifers. Combined with this excessive groundwater extraction for coastal settlements and agriculture causes intrusion of saline water laterally from the ocean or from deeper, more saline layers below the acquifer (the pathway depends on the particular hydrogeological characteristics). Intrusion can also occur as a result of poorly constructed or abandoned wells, open boreholes and dredged channels (Barlow and Reichard, 2011). However, Werner (2010) noted that there are fundamental knowledge gaps that impede assessment of changes in seawater intrusion due to land and water resource management changes. This will impede the assessment of climate change impacts that may arise from changes in ground water recharge and sea level rise.

Many parts of the world where groundwater is used for human consumption or agriculture are experiencing changes in water quality such as salinisation (e.g., Custodio, 2010; Werner, 2010; Steyl and Dennis, 2010; Bocanegra *et al.*, 2010; Barlow and Reichard, 2010; Essink *et al.*, 2010). For example, coastal aquifers on the east and west coasts of the US have experienced increased levels of salinity largely due to excessive anthropogenic water extraction (Barlow and Reichard, 2011). In the semi-arid Chaouia Coast region of Morocco, about half of the wells that commenced pumping in the 1960s have ceased to be operational because of water shortage (84%) or salinity (16%). Modelling indicates that despite rainfall declines since 1977, the reduction in water resources is less sensitive to the drought conditions than it is to the intensive and uncontrolled water pumping for agriculture over this time (Moustadraf *et al.*, 2008). In rainfall intensive Taiwan, about 34% of annual water is sourced from groundwater, but over exploitation has lead to a lowering of groundwater levels, seawater intrusion, salinization of soil and reduced well yields (Hsu *et al.*, 2007).

Around 8,000 inhabited small tropical islands in the Pacific, Indian and Atlantic Oceans face water supply problems. Many rely on extraction of groundwater from thin freshwater lenses in highly permeable aquifers (Terry and Falkland, 2010). Droughts, storm surges and sea level variations, which are strongly linked to natural modes of variability such as ENSO strongly influence the groundwater supply. For example, saline intrusion into freshwater aquifers following cyclone-induced overwashes can take many months to resolve (Terry and Falkland, 2010). The combination of natural with anthropogenic drivers of over-extraction, pollution from human, animal and industrial sources, mining of sand and gravel for building and erosion due to shoreline works compound groundwater supply problems in these locations (White *et al.*, 2007; White and Falkland, 2010).

In summary, there is *very high confidence* that increased usage of groundwater resources for agriculture and coastal settlements globally has led to a reduction in groundwater quality, including increased salinization (high agreement, much evidence). There is *high confidence* that climate change through changing patterns of precipitation and sea level rise will exacerbate these problems.

5.3.2.6. Health

In coastal regions, climate may impact human health directly through the occurrence of events such as floods, droughts, storm surges and extreme temperatures and indirectly through changes in the transmission of vector, food and water borne infectious diseases. Diseases associated with air pollutants and aeroallergens can also be affected by climate (Ebi *et al.*, 2008). Understanding the relationship between climate and health is often confounded by socio-economic factors that influence coastal settlement patterns and the level and organisation of the response of authorities to health related issues (Baulcomb, 2011).

Flood mortality risk has fallen since 1980 in all regions apart from South Asia and cyclone mortality risk has fallen in all regions since 2000 and is now lower than in 1980. Since exposure has increased over the same period, this result is significant and reflects how development has reduced vulnerability and strengthened countries capacity to respond to disasters. However, mortality is still rising in the countries with the weakest risk governance capacities (UNISDR, 2011). Heat extremes can also directly affect health outcomes in coastal cities, even those of tropical countries that are acclimatised to high temperatures (McMichael *et al.*, 2008). Health impacts affect low income groups and countries more severely than high income countries (Handmer *et al.*, 2012)

Vector-borne diseases such as malaria, dengue and leishmaniasis are sensitive to increasing temperature, humidity and rainfall, which can increase suitable mosquito habitats, shorten the breeding cycles and reduce the time to infection (Stratten *et al.*, 2008; van Kleef *et al.*, 2010). For example, dengue risk in Hawaii contracts under El Nino-induced droughts and increases with increased precipitation during La Nina (Kolivras, 2010). Although dengue has been reported a few new locations, its distribution generally contracted over the past century, which probably relates to changes in housing conditions and methods of water supply (Van Kleef *et al.*, 2010). On the other hand, despite efforts to eradicate malaria from the 1950's to 1980's the death rate from malaria is higher today than 40 years ago (Stratten *et al.*, 2008). Jackson *et al.* (2010) found minimal correlation reported malaria rates and climate in west Africa and suggested that climate linkages may be more complex than those they considered. In Bangladesh, more visceral leishmaniasis cases are found near flood control embankments, implying that building more embankments in response to sea-level rise may increase the vectors and incidence of this disease (Shahid, 2009).

Food and water borne infectious diseases include viral, bacterial or parasitic pathogens that are transmitted to humans through ingestion or inhalation of contaminated food and water. A link between infectious diseases and temperature has been reported in several recent studies including diarrhea in Taiwan (Chou *et al.*, 2011), non-cholera diarrhoea in Bangladesh (Hashizume *et al.*, 2007), salmonella infection in tropical and temperate coastal cities in Australia (Zhang *et al.*, 2010), bacillary dysentery in China (Zhang *et al.*, 2007), infectious gastrointestinal disease in Japan (Onozuka *et al.*, 2010) and rotovirus in Bangladesh (Hashizume *et al.*, 2008). Precipitation, humidity and, in the rotovirus case, river levels also affected incidence with relationships that differed across studies. Schistosomiasis, a parasitic disease in which free swimming larvae of a parasitic worm penetrate human flesh for reproduction, represents a significant health burden to the 76 countries in which it is endemic (Yang, 2006). Mangal *et al.* (2008) found that human infections increase linearly with temperature to 30°C but beyond 35°C, the infection rate drops off because of increased mortality in the snail intermediate host.

Climate variations potentially provide a strong link to outbreaks of disease due to aquatic bacteria such as cholera (Costello *et al.*, 2010) and toxins generated by Harmful Algal Blooms (HABs) such as ciguatera. An increase in both the extent and the frequency of HABs has been reported in the eastern North Sea due to increases in sea surface temperature and decreased salinity (Jaykus *et al.*, 2008). An indirect link through increased sea levels, increased precipitation and flash floods may also contribute to the occurrence of HABs by increasing nutrient rich water release to coastal and marine waters (Jaykus *et al.*, 2008; Erdner *et al.*, 2011). Nontoxic blooms that grow to high biomass also can have detrimental effects on biodiversity through oxygen depletion and physical shading of the benthos (Erdner *et al.*, 2011) with flow on effects to ecosystem health, human nutrition and health.

In summary, there is clear evidence of relationships between climate and many diseases that affect human health mainly through increases in temperature, rainfall and humidity. However, the relationships are complex and vary between diseases and even regionally for the same disease (high agreement, robust evidence).

5.4. Projected Impacts

5.4.1. Impacts on Habitats and Ecosystems

Coastal ecosystems are subject to both land- and ocean-based anthropogenic drivers and are experiencing some of the greatest cumulative impact of human activities (Halpern *et al.*, 2008). Anthropogenic drivers associated with global climate change are distributed widely and are an important component of global cumulative impacts. There are few coral reefs, seagrass beds, mangroves, rocky reefs and shelves with limited impact. Lotze *et al.* (2006) argued that overexploitation and habitat destruction have been responsible for most of the historical changes that occurred in coastal systems and that eutrophication, although severe in the last phase of estuarine history, largely followed rather than drove observed declines in diversity, structure, and functioning. Further, extreme climate events produce simultaneous changes to the mean and to the variance of climatic variables over ecological time scales. Here we discuss projected physical and biological impacts to specific coastal habitats and ecosystems.

5.4.1.1. Rocky Shores

Rocky shores composed of both soft (readily-erodible) and hard (relatively resistant) material will likely erode more rapidly with rising sea level (Trenhaile, 2011). For shores composed of resistant materials, the rates will be relatively low. Beaches that lie seaward of rocky shores will be squeezed, particularly on resistant rocky coasts, and lost, leaving the rocky habitats exposed to ocean forces. In a feedback, eroding soft rocks in bluffs composed of loosely-consolidated sand deposits will release sand that may naturally nourish the ocean fronting beach and help maintain the beach and protect the cliff.

The abundance and distribution of rocky-shore species have long been recognized to vary, and will continue to do so in a warming world. The number of species, notably calcifiers, found in rocky shore stations located near natural CO_2 vents at Ischia (Mediterranean Sea) is 30% lower at pH levels close to those expected in 2100 under the IS92a CO_2 emissions scenario (Barry *et al.*, 2011). However, the temporal variability in pH may have contributed to the pronounced biodiversity shifts observed, as these stations experienced short periods of pH_T as low as 7.4-7.5. Model projections that assume a linear increase in temperature and ocean acidity, and include the interactive effects of temperature and pH suggests that a local population of the barnacle *S. balanoides* will become extinct in the Channel ten years earlier than would occur if there was only global warming and no concomitant decrease in pH (Findlay *et al.*, 2010).

5.4.1.2. Beaches and Sand Dunes

Climate change has undoubtedly contributed to the observed erosion impacts found along the world's beaches and dunes (See 5.3), but there are other processes, unrelated to climate change, that contribute as well, such as dams capturing fluvial sand (e.g., in Morocco, Chaibi and Sedrati, 2009). Definitively linking sea-level rise to observed magnitudes of beach erosion has been challenging (e.g. see Sallenger *et al.*, 2000), although recent results using a Bayesian network has been successful in hindcasting sea-level rise induced shoreline change (Gutierrez *et al.*, 2011). With projected sea-level rise approaching 1 m or more over the next century, the resulting inundation and erosion should become readily detectable and progressively important. The impacts will be first apparent by sea-level rise adding to storm surge, making wave runup higher, and more frequent on beaches and dunes. For example, Tebaldi *et al.* (2012) showed how projected sea level rise shortens return periods of extreme storm surges, potentially reducing their return periods from centuries to decades. Sea-level rise will not only inundate low-lying land, like filling a bath tub, but can contribute to dynamic changes in sandy beaches, through shifting the beach position landward and higher. How to calculate the amount of retreat is controversial (e.g., see recent attempt by Ranasinghe *et al.*, 2012 and the Bayesian network forecast approach by Gutierrez *et al.*, 2011). Scientists disagree on whether tropical cyclones will become more intense and/or frequent in the future, although recent, as of yet non-conclusive, evidence suggests extra-tropical storm tracks may change in a warmer future extending Atlantic winter storms eastward impacting Europe to a greater degree than present (Schwierz *et al.*, 2010; Woolings *et al.*, 2012.). Such increase in storminess could accelerate erosion of beaches and dunes. Coastal squeeze will accelerate with rising sea level. Finding, and funding, sufficient sand to artificially rebuild beaches and dunes will likely become increasingly difficult.

5.4.1.3. Estuaries, Tidal Flats, and Lagoons

Sea-level rise will have consequences for the partitioning of habitats within estuaries and for the landward extension of estuaries. Global warming has consequences for the physics, chemistry and biology of estuaries. Most of the time stratification, dominated by sality, is a natural process, but long-term global warming, climate-related precipitation changes and altered riverine discharge may increase the extent, duration and frequency of estuarine stratification with consequences for ecosystem metabolism, biogeochemical processes and organism distribution patterns. For instance increasing persistence of stratification in the estuarine plume of the Mississippi river will lead to more increasing hypoxia (Rabalais *et al.*, 2009).

Anthony *et al*. (2010) projected that climate change will generate sediment redistribution as well as increased erosion and shoreward migration of barriers in coastal lagoons. The flushing rate, which is a key parameter controlling biogeochemical processes such as primary production (Smith *et al*., 2005b; Webster and Harris, 2004), could either increase due to barrier breaching or lower freshwater supply or decrease if the input of freshwater decreases (Anthony *et al*., 2010).

The loss of benthic macrophytes is projected in some lagoons due to increased mortality and decreased net primary production driven by increased temperature and lower light availability resulting from sea level rise and increased inputs of nutrients and suspended solids (Lloret et al., 2008). Since benthic macrophytes play a key role to intercept and store nutrients (Grall and Chauvaud, 2002), their demise could increase the occurrence and magnitude of eutrophication (Lloret *et al*., 2008).

5.4.1.4. Deltas

Deltas are influenced by climatic drivers from drainage basins, e.g., changes of precipitation, and from oceans, e.g., sea-level rise and changes of waves and storm surges, and also non-climatic drivers, e.g., changes of water and sediment discharges, subsidence, land-use change. Projected impacts on deltas are caused mainly by fluvial floods, future sea-level rise, changes of waves and storm surges, resulting in increased coastal flooding, wetland decrease, increased coastal erosion and increased salinization of cultivated land and ground water (McLeod *et al.,* 2010; Day *et al.,* 2011). As non-climatic drivers, e.g., reduction in sediment delivery, subsidence, and land-use changes, have impacted deltas for the last 50 years more than climatic drivers (Syvitski, 2008), combined impacts of both drivers on deltas will be projected. Flooding of surface areas of 33 deltas chosen to represent global delta variability will increase by 50 % for the future sea-level rise projected for 2100 using the IPCC AR4 scenario (Syvitski *et al.,* 2009). Future sea-level rise and storm surges by potentially stronger tropical cyclones will present a threat to deltas, particularly densely populated megadeltas in Asia (Murray *et al*., 2012).

5.4.1.5. Mangroves and Salt Marshes

Sea-level rise may be problematic for mangrove systems in case mangrove-derived peat accumulation and/or sediment supply and thus accumulation cannot keep pace with sea-level rise and drowning will occur. Geological record shows that these systems migrate landwards during transgressions.

Global warming will have effect on the geographical distribution patterns of salt marshes, with likely increases at high latitudes and decreases at lower latitudes, but this is rather uncertain at the moment (Bromberg Gedan *et al*., 2009). Salt marsh plant may become more productive at temperature rises but respiration losses also increase by about 20% (Kirwan and Blum, 2011). The balance between increase in production due to temperature and carbon dioxide increases and increase in respiration due to elevated temperature appears to be in favour of mineralization processes, suggesting that coastal marshes in a high carbon dioxide, high temperature world would be less resilient to sea-level rise (Kirwan and Blum, 2011).

Submergence-accretion and productivity-submergence feedbacks couple rates of accretion to sea-level rise and may limit drowning of marshes due to accelerated sea-level rise (Kirwan and Temmerman, 2009; Bromberg Gedan *et al*., 2011).

The direct effect of atmospheric carbon dioxide increase on saltmarshes will be differential depending on whether C3 (Phragmites) or C4 (e.g. Spartina) plants dominate, because the latter are usually rather insensitive to direct CO_2 effects (Rozema *et al.,* 1991).

5.4.1.6. Coral Reefs

Considering the maximum rate of vertical accretion recorded during the last deglaciation (about 20 mm y-1; Dullo, 2005; Montaggioni *et al.*, 2005), modern reefs appear to be able to keep up with the present rate of sea level rise but this may be compromised with a decreased rate of accretion driven by climatic and non-climatic drivers. A 0.5 to 1.0 m rise in sea level would increase coastal erosion, sediment resuspension, and the duration of high turbidity events on exposed reef flats of Molokai, Hawaii, leading to decreased light availability for photosynthesis and increased sediment-induced stress (Storlazzi *et al.*, 2011). Model results suggest that the thermal tolerance of reef-building corals are likely to be exceeded every year within the next few decades (Hoegh-Guldberg, 1999). The combination of ocean acidification and temperature being synergistic in several reef-builders (Reynaud *et al.*, 2003; Anthony *et al.*, 2008), it is very likely that the impacts will be more dramatic in the next decades than observed today near CO_2 vents, which do not simulate future warming (Fabricius *et al.*, 2011). Under the A1B CO_2 emission scenario, frequency and intensity of bleaching events will increase considerably during the period 2000-2100, with 99% of the reef cells experiencing at least one severe bleaching event in 2090-2099 (Figure 5-6; Teneva *et al.*, 2011; see also Meissner *et al.*, 2012). There is a high level of confidence that a large decline of coral cover will occur in the Hawaiian Archipelago during the 21st century (A1B CO_2 emission scenario; Hoeke *et al.*, 2011). A global model suggests that all coral reefs will stop growing and start dissolving when atmospheric CO_2 reach 560 ppm (Silverman *et al.*, 2009).

[INSERT FIGURE 5-6 HERE
Figure 5-6: Percent of reef locations (1°x1° latitude/longitude 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 standard degree heating month formula (Teneva *et al.*, 2011). The labels of values ≤ 1% are not shown.]

5.4.1.7. Seagrasses and Algae

Based on current observations indicating that seagrass meadows are already under stress due to realised climate change, it is projected that seagrass meadows will experience a decline with further warming (e.g., Marbà and Duarte, 2010, Rasheed and Unsworth, 2011).

Seagrass meadows may, however, expand their poleward ranges with warming, particularly towards the Arctic, along the coasts of Greenland, Norway, Siberia and North America. However, a lack of reports on the dynamics of seagrass meadows at high latitudes precludes the assessment of whether the expected poleward expansion is already occurring (Duarte, 2000).

Increased CO_2 is expected to increase seagrass photosynthetic rates (Hemminga and Duarte, 2000; Hendriks *et al.*, 2010).

Macroalgae in the north temperate zone are expected to extend their distribution into the High Arctic towards the end of the 21st century, but retreat along the northeastern Atlantic coastline (Müller *et al.*, 2009), whereas Antarctic seaweeds are not expected to alter their distribution substantially (Müller *et al.*, 2009). However, range shifts of macroalgae may be slow (Hinz *et al.*, 2011) and poleward shifts have been documented for warm-water species rather than for cold-water ones (Lima *et al.*, 2007). Hence, the expectation of poleward range shifts of macroalgae due to increasing temperature should be considered with caution as it does not seem to be a universal process (Lima *et al.*, 2007).

Macroalgae are, in general, not expected to be negatively affected by ocean acidification (Hendriks *et al.*, 2010). However, calcifying macroalgal species may be affected by ocean acidification, as macroalgae calcification rates have been shown to be inhibited by elevated CO_2 concentrations (Gao *et al.,* 1993; Kuffner *et al.,* 2008). Examination of community structure along volcanic areas, naturally enhanced in CO_2 suggests that turf algae may be impacted by the acidification levels expected by 2100 (Porzio *et al.*, 2011), and research on coral reefs along naturally CO2 enriched reefs near volcanic areas suggests that macroalgal cover increases at high CO_2 (Fabricius *et al.*, 2011).

5.4.2. *Impacts on Human Systems*

5.4.2.1. Human Settlements

The most important effects of climate change on the coastal cities include the effects of sea-level rise, effects of extreme events on built infrastructure (such as wind storms, storm surges, floods, heat extremes and droughts), effects on health, food and water-borne disease, effects on energy use, and effects on water availability and resources (Hunt and Watkiss, 2010). Considering that projected changes up to 2100 indicate that it is very likely that mean sea level rise will contribute to upward trends in extreme coastal high water levels, there is a high confidence that human settlements currently experiencing coastal inundation and erosion, will continue to do so in the absence of changes in other contributing factors.

An assessment of coastal flooding on 136 port cities around the world each with >1 m inhabitants in 2005 indicated 40 million inhabitants to be exposed to a 1 in 100 year coastal flood event. By 2070 this would trebled to 150 million. The top 10 exposed cities in terms of exposed population are Mumbai, Guangzhou, Shanghai, Miami, Ho Chi Minh City, Kolkata, Greater New York, Osaka-Kobe, Alexandria and New Orleans, almost equally split between the developed and developing countries. In terms of assets exposed, 60% are from the USA, Japan and the Netherlands. The total assets exposed in 2005 across all cities are estimated to be US$3,000 billion, which would increase to US$35,000 billion by 2070s (Nicholls *et al.*, 2008; Hanson et al., 2011).

Land subsidence is greater than the effect of sea-level rise in a number of Asian coastal cities. For example, parts of Jakarta are subjected to regular flooding on a near-monthly basis. Under current conditions, the estimated damage by extreme coastal flood events with return periods of 100 and 1000 years is €4 billion and €5.2 billion respectively. Under a scenario for 2100, damage is increased by a factor of 4-5 (Ward *et al.*, 2011). Semarang, 400 km east of Jakarta, is already subject to coastal hazards due to tidal inundation and land subsidence. With a scenario of 1.2 m inundation, nearly 4600 ha would be affected at a cost of €1.8 billion (Marfai and King, 2008).

Based on the assumption that projected increase in extreme sea levels is largely due to an increase in MSL, Hunter (2010) described a method of combining observations of present sea level extremes with the projections of sea level rise to obtain a "sea level allowance." This allowance is calculated so that the expected frequency of flooding events is preserved. It is based on the projected rise in mean sea level and its uncertainty, and on the variability of tides and storm surges (which are parameterised by the scale parameter of their Gumbel distribution). The method was applied to 198 tide gauge stations over the globe, yielding estimates of the scale parameter (a measure of the variability of high sea levels), which varied between 0.05 and 0.20 m for 90% of the stations considered (Hunter, 2010).

5.4.2.2. Industry, Transport, and Infrastructures

Climate change and especially sea-level rise may impact critical infrastructures located at the coastal area.

Transportation facilities serve as the lifeline to communities. Sea-level rise poses a risk to transportation in ensuring reliable and sustained transportation services since due to the network configuration, inundation of even the smallest component of an intermodal system can result in a much larger system disruption. For instance, even though a transportation terminal may not be affected, the access roads to it could be, thus forcing the terminal to cease or reduce operation (CCSP, 2008). Some low-lying railroads, tunnels, ports and roads are already vulnerable to flooding and a rising sea level will only exacerbate the situation by causing more frequent and more serious disruption of transportation services. Furthermore, sea-level rise will reduce the extreme flood return periods and will lower the design critical elevations of infrastructure such as airports, tunnels, and ship terminals (Jacob *et al.,* 2007). For example, it is estimated that a hypothetical 1 m rise in relative sea level projected for the Gulf Coast region between Alabama and Houston over the next 50-100 years would permanently flood a third of the region's roads as well as putting more than 70% of the regions ports at risk (CCSP, 2008).

Although not completely coastal, the estimated costs of climate change to Alaska's public infrastructure could add 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 12%) from now to 2080 (Larsen *et al*., 2008). Higher costs of climate change for coastal infrastructure are expected due to its proximity to the marine environment.

Other projected impacts are beneficial for the transportation system. For example, decline of Arctic sea-ice coverage could extend seasonal accessibility to high-latitude shipping routes such as the northwest shipping route that connects the Atlantic to the North Pacific (MCCIP, 2008).

Coastal infrastructural instability may result from natural hazards triggered by groundwater-level (GWL) variations resulting from rising sea level. For earthquake-prone coasts, this could be exacerbated by earthquake liquefaction if GWL increases with sea-level rise (Yasuhara *et al*., 2007).

Transportation infrastructure is not the only sector affected. There are several lifeline, infrastructures and industry facilities traditionally located at or close to the shoreline that play a very relevant role to the human system. A number of these existing facilities are located at lower elevations and if extreme climate events (storm surges, extreme winds and waves) become more frequent and intense, there will be increased stress on all of these infrastructure systems (Zimmerman and Faris 2010). Table 5-3 summarizes potential impacts of sea level rise, coastal floods and storms on critical coastal infrastructure in the communications, energy, transportation and water waste sectors.

[INSERT TABLE 5-3 HERE
Table 5-3: Impacts of sea level rise, coastal floods, and storms on critical coastal infrastructure by sector.]

5.4.2.3. Fisheries, Aquaculture, and Agriculture

The potential for climate change to affect food security in the coastal zone may arise through one or more climate drivers such as sea-level rise, increases in ocean temperature, acidity and changes in rainfall patterns. The impact of such drivers will be enhanced where other non-climate drivers such as pollution and poor management practices occur. For aquaculture, it is anticipated that negative impacts of rising ocean temperatures will be felt in the temperate regions due to exceedance of the optimal temperature range of organisms currently cultured in this region whereas positive impacts will be felt in the tropical and subtropical regions (De Silva and Soto, 2009).

5.4.2.4. Coastal Tourism and Recreation

Globally, coastal tourist destinations are affected by sea-level rise (coastal erosion), sea surface temperature and acidification (coral reefs), and increased frequency and intensity of tropical storms (damage to infrastructure and tourist attractions). Future sea-level rise aggravates coastal erosion leading to the loss of beaches. Even small rises in sea level could result in significant erosion and submergence of land, increased floods, contamination of freshwater aquifers, loss of protective coral reefs, mangroves and beaches which will increase exposure to extreme weather events including tourism destinations which will reduce amenity (Scott *et al*., 2008).

The Caribbean with many high-dependency tourism islands would be impacted by climate change and sea-level rise. St. Kitts and Nevis, Antigua and Barbuda, Barbados, St. Vincent and the Grenadines and Grenada are particularly affected with high annual costs due to degrading beach assets and inundation. The estimated capital costs to rebuild tourist resorts are US$10-23 billion in 2050 and US$24.5-73.9 billion in 2080. A hypothetical 1-m sea-level rise would result in the loss or damage of 21 CARICOM airports, inundation of land surrounding 35 ports, and at least

307 multi-million dollar tourism resorts damaged or lost from erosion to the coastal beach areas (Simpson *et al.*, 2011).

For tropical islands and coasts dependent on corals for tourism, there has been a concern about coral bleaching and, in recent years, about the impacts of acidification. While large communities of coral reefs may persist under scenarios of atmospheric carbon dioxide at 375 ppm (+1°C) and 450-500 ppm (+2°C), will degrade carbonate reef structures under a scenario of >500 ppm (+3°C) with serious consequences for tourism destinations in Australia, Caribbean and other small island nations (Hoegh-Gulberg *et al.*, 2007).

Another result of climate change on coastal tourism would be the coastal squeeze exacerbated by coastal construction and tourist hotels built within the zone at risk to flooding and erosion (Schleupner, 2008). Dykes, as an adaptation measure for sea-level rise have a negative impacts on tourist coasts as shown in the coastal districts of Schleswig-Holstein, Germany, where an increase in the length of dikes resulted in the reduction in the average price of accommodation.

5.4.2.5. Water Resources

Salinization is often considered the major impact on coastal aquifers as a result of sea-level rise. A typical situation is where coastal geological conditions favoured saltwater intrusion into the recharge zone. For example, Guyana with more than 90% of its ¾ million population in a narrow coastal strip less than 10 km from the coast is protected by a system of dikes constructed mainly of concrete and clay. The flat coastal plains extend more than 40 km inland and, under a hypothetic 1 m sea level rise, saltwater is estimated to intrude into the recharge zones for a distance of 1-12.5 km. Water extraction will exacerbate the intrusion (Narayan, 2006).

5.4.2.6. Health

The expansion of brackish and saline water bodies in the coastal areas associated with rising sea levels is now recognized as a potential health hazard to coastal communities (Ramasamy and Surendran, 2011). In Bangladesh increased salinity in drinking water will increase the risk of diarrhea and skin diseases. Inland intrusion of saltwater may turn former freshwater habitats into saltmarsh areas acting as breeding ground of saltmarsh mosquitoes and increase vector-borne diseases in the coastal areas of the country. The construction of embankments as a response to sea-level rise, may favour visceral leishmaniasis vectors and result in increased cases of visceral leishmaniasis (Sahid, 2009).

Kolstad and Johansson (2011) contend that sparsity of empirical climate–health data is a major contributing factor to uncertainties in projections of future climate change on health.

5.5. Assessing Vulnerabilities, Risks, and Costs

5.5.1. Approaches

Vulnerability and risk are ambiguously defined concepts and a wide variety of methods are applied for assessing these (e.g., Adger, 2006; Hinkel, 2011). When following the IPCC definition of vulnerability, assessments of vulnerability ought to go beyond assessments of potential impacts in that they also include information on adaptation. This can either be done explicitly by including adaptation within an impact model or implicitly by using generic indicators of adaptive capacity. Roughly two interpretations of risk can be distinguished in the literature. The first one refers to risks of gradual changes of mean climate variables (e.g., global mean sea-level rise). Under this interpretation, approaches applied for assessing risks are identical to those applied for assessing vulnerability. The second interpretation refers to extreme events and interprets risk as a measure of the probability of occurrence of extreme events and their consequences (i.e., damages). Under this second interpretation, coastal assessments focus on flood risk. In summary, the following seven types of approaches for assessing coastal vulnerability and risk can be distinguished in the literature:

- *Submergence exposure approaches* that use GIS to assess the exposure (in terms of people, assets, ecosystems) to permanent inundation under a given level of global mean sea-level rise (e.g., Dasgupta *et al*., 2008; Boateng, 2012).
- *Flood exposure approaches* that use GIS to assess the exposure to temporary inundation during a coastal flood event, either assuming present sea-levels or future ones by combining the extreme water level of the flood event with a given level of global mean sea-level rise (e.g., Dasgupta *et al*., 2009; Kebede and Nicholls, 2012).
- *Indicator-based approaches* that aggregate data on the current state of the coastal systems into vulnerability indices. The indicating variables used can either be biophysical (e.g., Yin *et al*., 2012; Bosom and Jimenez, 2011), socioeconomic (Cinner *et al*., 2012) or both (e.g., Bjarnadottir *et al*., 2011; Yoo *et al*., 2012; Li and Li, 2012). The socioeconomic variables used refer to the social system's current and usually generic (i.e., not impact specific) capacity to adapt.
- *Impact model-based approaches* that include adaptation explicitly in computational models and simulate impacts attained over time under various socio-economic and climate scenarios as well as adaptation strategies. Examples of this approach are the applications of the DIVA and FUND models discussed in Section 5.5.3 and 5.5.4.
- *Hydrodynamic flood damage approaches* that use hydrodynamic models to simulate the consequences of particular extreme water level events (e.g., Xia *et al*., 2011; Lewis *et al*., 2011). The probabilities used for calculating risks are either the ones of extreme-water levels or, in the case of existing defences, those of defence failure (e.g., Reeve, 1998; Dawson *et al*., 2009; Dutta, 2011).
- *Expected flood damage approaches* that assess current and future flood risks as mathematical expectation using the full distribution of extreme water levels (e.g., the flood component of the DIVA model as done by Hinkel *et al*., 2010; Hinkel *et al*., 2011; Hinkel *et al*., 2012).
- *Qualitative approaches* that assess coastal vulnerability and risk using a range of methods including literature review, expert interviews and participatory methods.

In terms of cost assessment, most studies use the direct cost method, in which exogenous prices are multiplied with quantities and aggregated. For instance, the amount of land lost to sea level rise is multiplied by the value of land. Estimates of land values are based on data from the respective markets. For wetland loss, direct costs are used too but the “prices” are taken from monetary valuation studies for non-market goods and services (Woodward and Wui, 2001; Brander et al., 2006; Barbier, 2012). Some studies use computable general equilibrium models and growth models to study the indirect and dynamic impacts of climate change, including sea level rise. These studies are reviewed in Chapter 10.

5.5.2. Coastal Systems

[Section 5.3 and 5.4 overlaps to be resolved in this section]

Since AR4, no new global study of the vulnerability of coastal wetlands to sea-level rise has been conducted. Dasgupta *et al*. (2009) estimated that 88,224 – 347,400 km^2 of wetland area are exposed to sea-level rises of 1-5 m across 84 developing nations, but it is unknown how much of this area will be lost, as wetlands are able to keep pace with rising sea-levels if sufficient sediment supply and migration space is available (McFadden *et al*., 2007). The DIVA model considered this process (Hinkel and Klein, 2009) but has not been applied globally for this impact. McLeod *et al*. (2010a) applied DIVA to the Coral Triangle Nations and find that under 0.54m of SLR by 2100, the Solomon Islands may loose 68%, the Philippines 51% and East Timor 50% of their total coastal wetland area. This study also found that the composition of wetland area changed toward a greater percentage of mangroves and smaller percentage of unvegetated wetlands. The majority of work on the vulnerability of coastal habitats and ecosystems is carried out at local scales. The remainder of this chapter summarizes results of these studies for various types of coastal ecosystems.

5.5.2.1. Rocky Shores

The FAR identified differences in the vulnerability of rocky shores to erosion due to various climate factors, primarily in terms of cliff retreat patterns and rates, and concluded that cliffs formed in softer lithologies are likely to retreat more rapidly in the future. Since then research has confirmed the large spatial and temporal variability of these processes in different parts of the world and has examined the control of various factors on the rates of retreat. Findings show that the main risks for this type of coastal systems appear to arise from sea-level rise.

Jackson and MacIlvenny (2011) estimated potential changes for the coasts of northern Scotland due to sea-level rise. They found rising sea levels to lead to a significant decrease and steepening of the intertidal area in rocky shores, which could have further impacts on the ecology of intertidal areas. In a modelling study, Trenhaile (2011) found sea-level rise to trigger faster rates of cliff recession, especially in coasts that are already retreating fast. However, results further suggested that coasts currently retreating slowly would experience the largest proportional increases in retreat rates. Increases in storminess appear to have smaller effects on rocky shores (Trenhaile, 2011; Dawson *et al.*, 2009). Importantly, the study of Dawson et al. (2009) in the East Anglian coast of England demonstrated the potential of cliff erosion in reducing flood risk, thus highlighting the tradeoffs that exist between cliff erosion and flood impacts.

Other factors may also affect the response of rocky shores to changes in climate. However, the study of Dornbusch *et al.* (2008) who examined cliff retreat rates in East Sussex, England for a period of 130 years concluded that climate factors, such as precipitation and frost, appear to have a limited role in cliff retreat. Currently, our understanding of the response of rocky coastlines to changes in climate is limited, partly due to its large spatial and temporal variability. Research also suggests that the response of these systems to larger changes, particularly in the rates of sea-level rise, may lead to increased sensitivity (Dawson *et al.*, 2009; Jackson and McIlveny, 2011), which needs to be further explored.

5.5.2.2. Beaches and Sand Dunes

Beaches and sand dunes are particularly vulnerable to increased erosion under sea-level rise. Vulnerability of beaches to sea-level rise is assessed qualitatively (Abuodha and Woodroffe, 2010; Sheik Mujabar and Chandrasekar, 2011) or quantitatively (Snoussi *et al.*, 2009). However, the widely employed Bruun rule has been under criticism (Cooper and Pilkey, 2004; Ranasinghe and Stive, 2009), particularly when used for national to local assessments, and alternative models are proposed (Ranasinghe *et al.*, 2012). Also, advanced numerical models, such as the Long-Term Configuration (LTC) model (Coelho *et al.*, 2007) have been applied for evaluating the effects of wave climate and sea-level rise on beach erosion.

Further to erosion, beach and dune recession and inundation will lead to loss of coastal biodiversity. Defeo *et al.* (2009) discussed the impacts of climate change on sandy beach ecosystems, with particular reference to erosion and rising temperatures and how those factors can affect habitats and food supply. Some studies that assess impacts of sea-level rise on beach ecosystems exist. For example, Fuentes *et al.* (2010) discussed the impacts of sea-level rise on green turtle population in the northern Great Barrier Reef, Australia. Nevertheless, the links between climate change and coastal biodiversity in beach ecosystems have not so far been adequately studied.

5.5.2.3. Estuaries

Estuaries are vulnerable to a range of climate drivers including sea-level rise, changes in runoff and storminess. The vulnerability of estuaries varies geographically and is determined by both direct changes in environmental variables as well as changes in the geomorphology of estuaries (e.g. build-up of sand bars across estuary entrances) resulting from factors sensitive to climate (e.g. runoff, erosion, salinization) (Gillanders *et al.*, 2011).

Some studies found that estuaries are particularly vulnerable to fluctuations in salinity which may result from changes in precipitation extremes and freshwater supply. Pollack *et al.* (2011) assessed long-term trends in the response of benthic macrofauna to climate variability in Lavada-Colorado estuary, Texas and found the abundance of benthic macrofauna to be significantly correlated with salinity but not with temperature. Levinton *et al.* (2011) simulated salinities for a period of 100 years for the Hudson estuary and found it vulnerable to changes in precipitation and discharge with respect to oyster mortality. Fujii and Raffaelli (2008) examined the spatial patterns of benthic macrofaunal biomass in the Humber estuary, UK, and related them to variables such as salinity, sediment characteristics and morphological factors. Using model simulations they estimated that sea-level rise and associated changes in these variables could have significant implications for the intertidal habitats of the estuary.

Changes in estuaries will also affect fisheries. Changes in salinity have led to reduced species abundance (Zampatti *et al.*, 2010) but the response of the ecosystem is complex as species have been found to react to these changes by moving in other areas of the estuary (Sakabe and Lyle, 2010).

5.5.2.4. Temperate Lagoons

Climate-induced changes in coastal lagoons can include, among others, the redistribution of sediments and altered sedimentation patterns as well as changes in turbidity, salinity and temperature (Anthony *et al.*, 2009). The response of lagoon systems to these changes will vary greatly, both spatially and temporally, between lagoons and will depend on the physical characteristics of the lagoons and on the processes that control these characteristics.

Vulnerability of coastal lagoons to different types of stresses, such as sea-level rise, storminess or increased water temperature, has been studied for several lagoons around the world (Bruneau *et al.,* 2011; Brito *et al.*, 2010; Nixon et al., 2009) and some characteristics of individual responses of specific lagoon systems can be extrapolated for other lagoon systems (Canu *et al.*, 2010). Further work is required to understand the response of lagoons to different drivers. At the same time, uncertainties exist as to how human and climate induced pressures will affect vulnerable lagoon systems and how the implications of potential management schemes for maintaining lagoon ecosystem services (Chapman, 2010) will impact coastal lagoons.

5.5.2.5. Salt Marshes

The future development of coastal salt marshes is subject to a variety of natural and anthropogenic risks. As the vertical growth of salt marshes tends towards an equilibrium with sea-level rise (Redfield, 1972) salt-marsh accretion rates lag behind accelerated sea-level rise rate by about 20-30 years (Kirwan and Temmerman, 2009). Accelerating sea-level rise rates may therefore result in marsh submergence, retrogressive vegetation succession, or complete drowning of the marsh (Craft *et al.*, 2009). Salt marshes appear to be more resilient to sea-level rise in macro-tidal environments than in micro-tidal environments (Kirwan *et al.*, 2010).

Subsidence of salt marshes is also triggered by human activities, such as the extraction of underground natural resources (Day Jr. *et al.*, 1999; Dijkema, 1997), or the use of salt marshes as pasturelands for livestock, inducing sediment compaction and shallow subsidence of the salt marsh surface. Natural shallow subsidence within the salt marsh layer is observed as a consequence of autocompaction of the marsh sediments and is especially large on highly organic marshes (Allen, 2000; Cahoon *et al.*, 1995).

Besides relative sea-level rise, potential changes in storminess can play a role in the survival of marshes. The natural development of salt marshes, continuously migrating inland as sea level rises and eroding at the seaward edge, is inhibited at many coastlines since salt marshes have been embanked in historic times or coastlines were fixed in place for coastal protection reasons (Doody, 2004). This effect, often referred to as coastal squeeze, is amplified through lateral erosion of the salt marshes, if storminess and associated wave heights are increasing (van der Wal and Pye, 2004). However, increasing storminess can also increase the resilience of salt marshes towards drowning as vertical accretion is enhanced through increasing inundation heights and inundation frequencies (Schuerch *et al.*, 2012).

5.5.2.6. Mangroves

Sea-level rise poses the greatest challenge to mangroves (Gilman *et al*., 2008). Various studies indicate an increased vulnerability of mangrove forests to rises in sea-level. Lovelock *et al*. (2011) found subsidence due to organic sediment compaction in western Moreton Bay to negate surface accretion processes, rendering the mangrove forest vulnerable to sea-level rise. At the same time, mangroves in the eastern part of the bay appeared to be stable with current rates of sea level rise, mostly due to sufficient sediment supply. In Micronesia, Krauss *et al*. (2010) also reported differential susceptibilities of mangrove forests to sea-level rise and found fringe mangrove forests to be most vulnerable. However, due to the importance of subsurface root accumulation for mangrove elevation (McKee *et al*., 2007; McKee, 2011) and therefore in mangroves keeping up with rising sea level, further work is needed for understanding the response of mangrove forests to changes in different climate factors. Langley *et al*. (2009) suggested that increased CO_2 can stimulate elevation gain for wetlands and can counterbalance sea-level rise. Furthermore, changes in precipitation patterns may also affect the spatial distribution and growth of mangroves by influencing salinity and fluvial supply of sediment and nutrients. However the response of mangroves to variability in precipitation remains largely unexplored (Gilman *et al*., 2008).

5.5.2.7. Seagrass Meadows

Currently, a worldwide decline of seagrass beds is being observed (Lotze *et al*., 2006; Waycott *et al*., 2009; Short *et al*., 2011). In most cases the decline is caused by direct human impact such as eutrophication, increased sedimentation as well as habitat and ecological degradation, but other drivers are expected to be also relevant (Orth *et al*., 2006).

Increased sea surface temperatures are suggested as an important seagrass driver and shifts in seagrass distribution, alteration of growth rates, physiological functions and sexual reproduction are expected, even though the extent of impacts depends on the thermal tolerance of individual species (Orth et al., 2006; Short *et al*., 2011). Elevated temperatures may also increase growth of algae and epiphytes which are in competition to seagrass, especially for sunlight (Short and Neckles, 1999; Holmer *et al*., 2011). This situation will have further implications as seagrasses (*Zostera marina*) show increased light requirements with higher temperatures as their photosynthetic capacities decrease (Zimmerman *et al*., 1989; Moore *et al*., 1997).

Rising sea levels are also expected to have multiple effects on seagrasses. Increases in water depths above present meadows will lead to reduced light conditions, while increased hydrodynamics (wave and currents), often associated with a higher sea level, can aggravate this effect by increasing the amount of suspended matter in the water. As studies in the U.S. and the Wadden Sea have shown, seagrass is particularly sensitive to increased hydrodynamics (Fonseca and Bell, 1998; Schanz and Asmus, 2003) and to their indirect effects (Cabaço and Santos, 2007; Dolch and Reise, 2010). Such conditions can be exacerbated by changes in storminess, leading to a significant threat for seagrass communities (Dolch and Reise, 2010). Further risks for seagrass from storms can be caused by heavy rainfall. Assessing the vulnerability of seagrasses to hurricanes, Carlson Jr. *et al*. (2010) showed that increased runoff following the 1997-98 El Nino event resulted in large declines in seagrass in Florida. These impacts were possibly due to light stress caused by increased turbidity, dissolved organic matter and phytoplankton blooms and were more damaging than the physical impacts of moderate tropical cyclones (Carlson Jr. *et al*., 2010).

5.5.3. Human Activities

Since the publication of AR4 progress has been made in quantifying risks and vulnerabilities of coastal human systems to climate change and sea-level rise. A large number of regional, national and sub-national scale studies has been conducted using the range of methodologies presented in 5.5.1. Table 5-5 highlights some of these studies. A comprehensive account of vulnerabilities of specific regions is given in the regional chapters.

At the global scale, a number of studies have been conducted since AR4. Generally, these studies confirm, as also highlighted in AR4, that coastal vulnerability and risks are strongly influenced by non climatic drivers, in particular socio-economic development, which influences vulnerability in two ways: It determines the level of future exposure and it determines the level of future capacity to adapt (Nicholls *et al*., 2007).

For densely populated coastal areas, socio-economic development is expected to be the major driver of exposure and hence impacts during the 21st century (Nicholls and Cazenave, 2010). Under the UN medium population projections, the population of 126 major port cities exposed to a 1-in-100 year flood event is expected to increase by 50% in 2070 through sea-level rise alone and by 150% if socio-economic development is considered on top of this (Hanson *et al*., 2011). Comparatively, Asia contains the greatest exposure in terms of population, assets and productivity and the largest increases in exposure through socio-economic development are expected in Asia and Africa (Dasgupta, 2009; Hanson, 2011; Kebede and Nicholls, 2012).

Two recent global studies using the DIVA model indicate that the potential impacts on human activities in the 21st century are substantial, but also that impacts can be reduced substantially through adaptation. Nicholls *et al*. (2011) estimated that without adaptation 72-187 million people would be displaced due to submergence and erosion by 2100 assuming sea level increases of 0.5-2.0 m by 2100. About 70% of these people are from East, Southeast and South Asia. Adaptation reduces these impacts roughly by three orders of magnitude, with annual incremental adaptation costs between US$25 and $270 billion. Hinkel *et al*. (2012) estimated the expected number of people flooded annually in 2100 to reach 170-260 million per year in 2100 without adaptation and two orders of magnitude smaller with adaptation assuming global mean sea-level rises of 0.6-1.3m by 2100.

Few studies have assessed the effects of mitigation on coastal risks. Nicholls and Lowe (2004) estimated that stabilizing emission at 550 ppm reduces the number of people flooded annually by factor 50% in 2110 compared to a scenario of unmitigated emissions. Tol (2007) found that stabilizing emissions at 550 ppm reduces global impacts on wetlands and drylands by about 10% in 2100 compared to scenario of unmitigated emissions. Hinkel *et al*. (2012) reported that stabilizing emissions at 450 ppm-CO_2-eq reduces flood risks by 23-29%. These numbers need to be taken with caution, as all three studies assume that the effects of lower levels of global warming due to mitigation on global mean sea-level rise are assumed to be small (about 10-20cm). This many not be the case as unmitigated global warming increases the risk of an accelerated melting of the ice sheets of Greenland and West Antarctica leading to higher rates of sea-level rise, which were not considered in the studies listed above.

Recent studies also underpin the AR4 conclusions that there are significant regional differences in coastal vulnerability (Nicholls *et al*., 2007). Most countries in South, South East and East Asia are particularly vulnerable to sea-level rise due to rapid economic growth and coast-ward migration of people into urban coastal areas together with high rates of anthropogenic subsidence in deltas where many of the densely populated areas are located (Nicholls and Cazenave, 2010). At the same time, economic growth also increases the capacity to adapt and the benefits of adaptation are also highest in these regions (Nicholls *et al*., 2010). On the contrary, while many African countries experience a similar trend in rapid urban coastal growth, the level of economic development is generally lower and hence the capacity to adapt is smaller (Hinkel *et al*., 2011; Kebede and Nicholls, 2012).

[INSERT TABLE 5-4 HERE
Table 5-4: 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.]

5.5.4. Costs

A comprehensive picture on coastal vulnerability needs to take into account costs, in particular the costs of inaction in relation to the costs of adaptation and residual damages. Since the AR4, a large number of studies have assessed costs of sea-level rise to regions and countries. These will be discussed comprehensively in the Regional Chapters. There are only a few studies that systematically compare costs across the countries of the world and provide a comprehensive and internally consistent estimate of the costs at global scales (Table 5-5). These studies are difficult to compare due to differences in scenarios used, impacts considered, methodologies applied and impact indicators used. Nevertheless, some robust findings emerge.

[INSERT TABLE 5-5 HERE
Table 5-5: Global assessments of costs of sea-level rise.]

Recent global modeling studies indicate that while the cost of sea-level rise in the 21st are substantial, the cost of inaction are larger than the sum of adaptation and residual damages costs for large parts of the world. Nicholls and Tol (2006) applied FUND to estimate the direct costs of dry land loss due to submergence and wetland loss under a global sea-level rise of 0.35m by 2080 for all countries in the world for 4 of the SRES scenarios. Direct costs are the costs of coastal protection, plus residual land loss, plus wetland loss due to both sea level rise and coastal protection. They found that coastal protection is cheap relative to the value of the land protected and, using the cost-benefit model of Fankhauser (1995), concluded that it would be economically justified to protect the bulk of low-lying, populated coastline. They assumed that the value of land increases with economic growth but the costs of coastal protection do not. Thus, more than 80% of the exposed coast is protected in all but 15 countries in all scenarios, and coastal protection is stronger in the scenarios that assume more rapid economic growth. The annual cost of coastal protection is below 0.1% of GDP in over 180 countries. Land loss nowhere exceeds more than 3% of the country's total area. As the most valuable areas are protected first, the economic impact would be smaller than that (but is unreported by Nicholls and Tol, 2006). Using the same methodology, Anthoff *et al.* (2010) confirmed that applying protection is economically rational for most countries even for a global mean sea-level rise of 2m by 2100. Studies using DIVA come to similar conclusions. Hinkel *et al.* (2012) estimated that the direct cost of coastal flooding (comprising dike upgrade, dike maintenance and residual damage cost) reaches US$ 300 billion per year in 2100 without adaptation and US$90 billion per year with adaptation under a 1.26 m sea-level rise scenario.

Even though the risks of sea-level rise seem manageable for human activities in large parts of the developed world through enhancing coastal protection, the risk of low probability high impact events will increase with protection and rising sea-levels. This holds particularly true for many coastal cities such as London, Tokyo, Shanghai, Hamburg and Rotterdam that already rely heavily on coastal defences (Nicholls *et al.*, 2007) and defence failure could have severe consequences.

From the perspective of less-wealthier and small island countries, annual costs of sea-level rise can amount to several percentage points of national GDP. Nicholls and Tol (2006) reported the highest coastal protection costs for Palau, Tuvalu and the Federated States of Micronesia. For the later country, protection costs reach 14% of GDP in the 2080s in the B2 scenario. Hinkel *et al.* (2012) reported that the direct annual cost of coastal flooding (including adaptation and residual damages) in 2100 lies between 5% and 9% of GDP for Kiribati, the Solomon Islands, Vanuatu and Tuvalu under 0.64m of sea-level rise.

These regional differences in vulnerability are also highlighted in continental scale studies. For the European Union, Hinkel *et al.* (2010) estimated that without adaptation the total monetary damage caused by flooding, salinity intrusion, erosion and migration is estimated to US$17 billion per year under global mean sea-level rise scenarios of 0.35m-0.45m. Adaptation reduces these damages by one order of magnitude and costs 2.6-3.5 billion US$ per year in 2100. For Africa, Hinkel *et al.* (2011) estimated the expected annual damage costs due to flooding, erosion and salinity intrusion to US$5-9 billion under scenarios of global mean sea-level rises from 0.64-1.26 m by 2100, if no adaptation takes place. Adaptation cuts damage costs in half by 2100, but requires substantial investments of US$2-US$6 billion per year. The adaption costs reported are incremental costs that do not take into account the current adaptation deficit, which is expected to be substantial for developing countries but has not been assessed in detail (Parry *et al.* 2009). Hinkel *et al.* (2011) estimated that overcoming Africa's current adaptation deficit with respect to coastal flooding would require an initial investment of US$300 billion for building dikes and an additional US$3 billion per year for future maintenance.

5.5.5. Uncertainties and the Long-Term Commitment to Sea-Level Rise

The three major sources of uncertainty in the assessment of coastal vulnerability, risk and costs are (i) sea-level rise including local subsidence, (ii) socioeconomic development including coastward migration and urbanization patterns, and (iii) the level of adaptation that will take place. The available studies have only explored a small fraction of this uncertainty. Only few assessments consider global mean sea-level rise scenarios beyond the range given in the AR4, thus excluding the impacts of a possible large contribution of the melting of the ice sheets of Greenland and Antarctica to global mean sea-level rise. Studies considering regional patterns of climate-induced sea-level rise are missing. Many studies rely on few or only a single socio-economic scenario.

Only few studies consider adaptation in the estimation of vulnerabilities and risks, which gives an incomplete picture as the question to what extent society can handle the potential impacts that is omitted (Hinkel, 2012). In the case where adaptation is considered, most studies focus on protection via hard structures, because protection via ‘soft’ options such as dune or mangrove rehabilitation is difficult to simulate at broad scales and cost estimates are less developed (e.g., Linham and Nicholls, 2010; Hinkel *et al.*, 2011). Many more adaptation options are, however, available including retreat and accommodation (See Section 5.6) and future work needs to consider these. With future socio-economic development being often the major risk factor, steering development away from low-lying areas seems to be a potentially effective adaptation strategy (Kebede and Nicholls, 2012) which, however, has not been explored in studies.

For deltas, another major source of uncertainty is human-induced subsidence due to anthropogenic sediment compaction as a result of the withdrawal of ground fluids such as oil, water and gas. Human-induced subsidence may lead to rates of local sea-level rise that are an order of magnitude higher than current rates of climate-induced global-mean sea level rise (Syvitski *et al.*, 2009). Densely populated deltas are particularly vulnerable and many of the world's mega-cities are situated in deltas have subsided by several meters during the 20th century (Nicholls, 1995). It is difficult to predict how this trend will continue as information on annual rates of human-induced subsidence is extremely limited (Hanson *et al.*, 2011). Furthermore, while some cities such as Shanghai and Tokyo have managed to control subsidence rates through policy measures, other cities such as Bangkok, Manila and Jakarta continue to subside at high rates (Nicholls 1995; Hanson *et al.*, 2011).

The available studies also only cover a limited range of impacts. There is no recent global study on the long-term impacts on coastal wetlands and no global consistent study taking into account all major impacts including land loss due erosion, land loss due to submergence, wetland loss, flood damage and salinity intrusion. In particular, studies either focus on land loss due to submergence or on flood damage. The majority of research on coastal flood risks only assesses exposure and not damages (see Table 5-4). There is also a lack of intermediate scale methodologies for assessing coastal flood risk. Assessments are either carried out at local scales using hydrodynamic models or at global scales using damage functions. As there are so few studies of the costs of sea level rise at a global level, confidence is low. Uncertainties are largely unknown. The need for further research is large. Finally, there is insufficient knowledge on indirect impacts and costs of coastal flooding including health impacts and those related to the disruption of economic activities through a flood.

Most studies assess risks of single hazards. Integrated studies assessing multiple hazards and trade-offs between adaptation options are rare. Flood defences, for example, prevent the inland migration of coastal habitat when sea level is rising leading to a loss of intertidal habitat through coastal squeeze (Nicholls *et al.*, 2007; McFadden *et al.*, 2007). Furthermore, coastal armoring in one location may have negative consequences on other locations as reduced long-shore sediment transport through protection measures may increase both flooding and erosion risk at other locations (e.g., Dawson *et al.*, 2009). These trade-offs and processes need to be further explored.

Finally, few studies take into account that vulnerability and risk will increase beyond the 21st century as sea level will continue to rise for centuries due to global warming until reaching equilibrium conditions even if climate forcing is stabilized, which was termed commitment to sea-level rise in the AR4 (Meehl *et al.*, 2007; Nicholls *et al.*, 2007). Sea-level rise due to thermal expansion is estimated to reach equilibrium in the year 3000 at levels of about 0.5m per °C of warming if deep water-formation is sustained and higher values if not (Meehl *et al.*, 2007). The contribution of the melting of the ice-sheets to long-term sea-level rise is potentially much larger and while the timescales involved are unknown and subject to intense research, there is concern about a potential rapid melting due to self-amplification mechanisms involved (Levermann *et al.*, 2011).

5.6. Adaptation and Managing Risks

5.6.1. Approaches

Adaptation to coastal risks from climate variability and change occurs in the context of existing governance and socio-ecological systems, regardless of whether adaptation is proactive and planned or reactive and ad hoc. To discuss adaptation outside of these contextual factors is theoretical at best and misleading at worst. Governance involves the legal and institutional context of coastal management; ownership rules related to coastal land and resources; stakeholders typically involved in coastal management decisions, and the social norms, rules, and dynamics that guide their interactions.

The socio-ecological system within which governments and individuals act is intricately connected to the governance system, but it helps to single it out as its own co-determinant of adaptation. The socio-economic context of adaptation includes the general state of the (local) economy; prevalent urban and economic sectors dependent on or located in the coastal zone; past, present and planned development decisions; the degree of demographic concentration and the resulting build-up; the technologies employed; the state of human welfare; as well as any past or existing social conflict and social capital; access to power and relationships among power holders and affected stakeholders. Cultural factors play important roles, e.g., on world views, gender, class or caste relationships, concurrent pressures and trends of cultural transformation.

The physical and ecological contexts of relevance for adaptation is the geologic/geomorphologic type of coastline, the prevalent climate, the local ecosystems and existing biodiversity; the local rate of relative sea-level rise and interacting climate change impacts (temperature, precipitation, storm regime, sediment supply, and salinity changes); and concurrent non-climatic environmental or human pressures and trends on coastal geo-ecological systems. Together, the particular determinants of physical-ecological processes present a range of what adaptation options are physically feasible or environmentally appropriate.

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Box 5.4. Case Study – 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 defence 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 infrastructures altering the appearance of an important part of the Dutch coastal area (Kabat *et al.*, 2009).

[INSERT FIGURE 5-7 HERE
Figure 5-7: Case study: paradigm shift in adaptation to rising sea levels in the Netherlands. Source: Stive *et al.*, 2011.]

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' instead of only 'fighting' the forces of nature with engineered structures and providing 'room for river'. 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 flooding protecting structures to restore natural estuary and tidal regimes; improving the standards of flood protection by a factor of 10 until 2050; maintaining flood 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).

Aerts *et al.* (2008) estimated today's economic damage from flooding as approximately €190 billion covering both direct and indirect damage. The estimated future potential damage would increase to €400 to €800 billion in 2040 and €3700 billion in 2100 in the absence of any measures, given a sea-level rise of 24 to 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 into societal and economic growth and evolution, moving the Netherlands into a sustainable country (Kabat *et al.*, 2009).

_____END BOX 5-4 HERE _____

Coastal management typically needs to balance multiple goals that can and often do conflict, and frequently are adjudicated among in an unbalanced fashion. Among the most relevant coastal management goals for adaptation are the minimization of risks and impacts from coastal hazards to ensure public safety and welfare; economic development and use of coastal resources; and protection of coastal environmental resources, natural assets, and ecosystems.

Optimizing solutions taking into account the three goals is a common problem in coastal zones. Many approaches have been developed over time to achieve greater integration, better social, ecological, and economic outcomes when trade-offs are inevitable, and smoother governance, including Integrated Coastal Management (e.g., Sales, 2009; Christie *et al.*, 2005), Community-Based Adaptation (e.g., Dumaru, 2010; Huq and Reid, 2007; Reid *et al.*, 2009), Ecosystem-Based Adaptation (e.g., Zeitlin *et al.*, 2012; Vignola *et al.*, 2009; IUCN, 2008), and Disaster Risk Reduction and Management (Shaw *et al.*, 2010; IPCC, 2012).

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Box 5-5. Case Study – 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 varying sectors and government institutions with a view to sustainably develop coastal resources and protect the environment. This makes it feasible for combining climate change adaptation with ICZM as a part of integrative effort in coastal management. However, the difficulties of integration and coordination are present both in developed and developing economies and could arise if and when climate change adaptation is mainstreamed into ICZM.

ICZM in developing countries fostered by international organizations under the UN or (non)governmental units, in particular, struggle to meet the goals of ICZM (Isager, 2008). The drawbacks that are present in the implementation of ICZM in developing countries consequently act as constraints to enforcing climate change adaptation within ICZM. For example, inadequate financial commitment follows when initial funding by the external organizations disappears, and national governments have to step up to finance the cost of ICZM (Ibrahim and Shaw, 2012). Ineffective coastal governance is more visible in cases where the capacity of actors is low, the operation of single agency is dysfunctional, and subsequently, the integration of multiple coastal agencies is beyond the reach of many developing countries (Ibrahim and Shaw, 2012; Martinez *et al.*, 2011). Politics are also a strong force because of the involvement of various stakeholders, the hierarchy of government agencies and ministries, and the power of the majority political party or political leaders (Tabet and Fanning, 2012; Isager, 2008). Furthermore, the nature of public participation in developing countries differs from that in developed countries, and different norms and cultures need to be taken into account to assess public participation central to ICZM (Barale and Özhan, 2010).

As such, legal and institutional capabilities critical to the implementation of ICZM are often not available in developing countries. Instead, governments generate climate change adaptation strategies that are part of shoreline management plan, regional development, disaster management, and coastal resource management. In addition, cases of adaptation strategies specific to climate change in practice are few. Most are at the planning stage equipped with scenarios. Existing strategies derive from responses to coastal disasters and economic and social change affecting coastal livelihoods. For example, the Bangladesh case illustrates the benefits of trained volunteers readily accessible to affected population to disseminate cyclone warnings, evacuate people, and conduct rescue missions (WRI, 2007). This could be translated into a strategy for climate change adaptation. Other strategies in progress or at the trial stage include forested buffer zones (Mustelin *et al.*, 2011) and incremental migration. The long-term results and their replicability need to be further assessed.

To anticipate climate change and adapt, scholars have considered a variety of strategies that could be of use in the future. No or low-regret options provide co-benefits to the goals of sustainable development, livelihood improvement, and human well-being (IPCC, 2012). Combining different strategies are also increasingly under consideration (Cheong, 2011; Cheong *et al.*, 2012; Cartwright, 2009). They include the blend of ecology and engineering such as mangrove planting, buffer zones and land use, and insurance and structural coastal defence (Yohe *et al.*, 2011). Adaptation planning by geographic scale is at work. Regional adaptation strategies (Martinez *et al.*, 2011) and community-based adaptation (Cutter *et al.*, 2012) are both on the rise as scale economies provided by adaptation at the regional level as well as the critical role of local physical and cultural attributes and local priorities are valuable in adaptation planning. Although ICZM can be a valuable policy framework to integrate climate change adaptation and coastal management, no studies of the effectiveness of ICZM combined with climate change adaptation in developing countries exist yet to assess its utility.

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Adaptation – as it becomes integral to what coastal managers do –will face the same multi-purpose challenges, as different interests, needs, and stakeholder viewpoints have to be addressed and as climate-driven and non-climatic pressures on coastal environments grow (Tobey *et al.*, 2010). Indeed, experience to date shows that the challenges with (integrative) adaptive coastal management is not radically different from those encountered with historical coastal management (Tobey *et al.*, 2010). However, climate change-conscious coastal management would adjust these approaches to the dynamic nature of coastal areas, long-term trends (as opposed to assuming static baselines) and thus greater uncertainty and longer time frames in planning (beyond 30 years), the long-term commitments inherent in climate change, the potential for physical and ecological thresholds or tipping points, and the long lead times often required for making changes in coastal management (see references in Table 5-6). Garmendia *et al.* (2010) suggested that improving the integration of various expertise and values can guide to the definition of appropriate policy options and adequate decisions when complexity, value conflict and uncertainty exist as is, generally, the case in coastal zones.

[INSERT TABLE 5-6 HERE
Table 5-6: Approaches to integrative, adaptive coastal management.]

To date, despite experimentation with these novel or adapted coastal management approaches, meeting the multiple goals, improving governance, accounting for the most vulnerable populations and sectors and fully integrating consideration of natural ecosystems is still largely aspirational. Meanwhile development in high risk areas grows, coastal ecosystems continue to degrade in many regions, coastal freshwater resources are being overdrawn in many highly populated areas, and vulnerability to coastal disasters grow (e.g., Jentoft, 2009; McFadden, 2008; Mercer, 2010; Shipman and Stojanovic, 2007).

5.6.2. Practices

Coping with the dynamics of physical processes and rapid population growth and investment in coastal areas has built a body of knowledge and tools applicable to many of the potential impacts associated with climate changes. These tools include the structural, planning and regulatory, hazard response planning, biological, and market-based tools as well as physical and integrated assessment modeling to assist in identifying possible impacts (Bedsworth and Hanak, 2010; Horstman *et al.,* 2009; Rosenzweig *et al.,* 2011). Climate change and related impacts raise new considerations, including greater degrees of uncertainty, and continue to confront long-standing analytical challenges.

Since the AR4, there has been further progress in impacts modeling and integrated assessment efforts. General adaptation tenants for climate change conservation strategies are advancing with more specific ecological and social conditions and context recommendations. The differences among coastal impact models as applied to environmental conservation goals result in important trade-offs of human and financial resources required for implementation, feedbacks and impacts represented and the degree of spatial resolution provided. The difficulty in obtaining critical information regarding appropriate uses, required data inputs and outputs, range of costs and expertise required have been identified as potential obstacles to their wider appropriate use (McLeod *et al.,* 2010a).

The scope of scale of integration is advancing. The development of successful coastal adaptation strategies needs combining scenarios of climate change and socio-economic conditions, and risk assessment (Kirshen *et al*., 2011). For example, Dawson *et al*. (2009) employed climate, coastal management, and socioeconomic scenarios in conjunction with physical models extended over larger spatial and temporal scales to evaluate probabilistic predictions of coastal behavior with an assessment of expected annual damages and illustrated trade-offs associated with different management approaches .

Inundation models benefit from the increased availability of more accurate lidar data of coastal elevations (Gesch, 2009), although these data are not widely available. Numerical modeling linking spectral wave transformation model with calculation of gradients in potential long shore sediment transport rate can be used to project magnitudes of potential coastal erosion and accretion, under proscribed deep water wave conditions (e.g. Adams *et al*., 2011).

Integrated assessment models continue to differ in their approaches to representing interactions among regions and sectors with the result that the ability to represent impacts and adaptation continues to involve significant limitations (UNFCCC, 2010a). For instance, these models do not consistently incorporate the interaction between impacts in one sector and human adaptation to impacts in another sector and other significant interactions (Warren, 2011). The majority of integrated assessment models address adaptation as an implicit rather than explicit process at an aggregated level with assumptions that may result in overly optimistic representations of the amount of adaptation and underrepresentation of costs (Patt *et al.,* 2010).

Efforts to develop improved vulnerability indices and to identify hotspots which serve to focus or prioritize management efforts continue to evolve although significant differences exist among them (e.g., McLaughlin and Cooper, 2010; Mustafa *et al.,* 2011; Ozyurt and Ergin, 2009). Diversity among coastal environments, local governments, institutions, economies, technologies, and cultures contribute to difficulty in generalization. Selection and availability of indicators as well as scale also contribute to differences in the sensitivity and applicability of these models across places and hazards. Consequently, tradeoffs occur between detailed locally actionable analyses and representation of broader patterns. Our ability to quantify vulnerability continues to be restricted by limits to our understanding of human adaptive capacity, broad social dynamics, and relationships between ecosystem and human well-being (Farhan and Lim, 2011; Raudsepp-Hearne *et al.,* 2010; Tol *et al.,* 2008).

Since the AR4, new information is available on the likelihood of increased rates of sea-level rise and ocean acidification. Policy recommendations for addressing ocean acidification at the local and regional levels, rather than through international mitigation efforts, are beginning to emerge. Application of existing water quality laws, land-use management to protect biological integrity, local mitigation efforts, and increased focus on data collection to inform future regulation have been proposed (Kelly *et al*., 2011).

As adaptation planning has begun in some places, there is an emerging body of literature to inform decision-making, public participation and communication efforts. Efforts to support decision-making recognize that information alone may not fully serve managers needs and could be supplemented by financial and technical assistance resources as well as organizations which serve as an interface between science and practice (Tribbia and Moser, 2008). Newly developed mapping and visualization approaches may contribute to these processes in several ways, however there is an important need for testing and evaluation of these technologies in public participation processes (Jude, 2008; Sheppard *et al.*, 2011). These participation processes carry with them the challenges or power relationships met in other public arenas and differences of opinion may be magnified by the uncertainty and longtime horizons associated with climate change making (Few *et al.,* 2007).

5.6.3. Adaptation Costs

Efforts to assess the costs and benefits of adaptation options are continuing to evolve, although significant further work is needed (Nicholls *et al.,* 2010, Yohe *et al.*, 2011). The cost of adaptation is only one part of the overall cost induced by climate change, which includes also the costs of mitigation and the costs of the residual impacts. Adaptation costs are defined as "the costs of planning, preparing for, facilitating, and implementing adaptation measures including transition costs" and adaptation benefits are "the avoided damage costs or the accrued benefits following the adoption and implementation of adaptation measures" (AR4 WG2). There are several potential assessment techniques; prominent among them is the cost-benefit analysis, although it has limitations with respect to the treatment of nonmarket values. All assessment types need to consider the distribution of burdens and benefits across groups, sectors, or other entities (UNFCCC, 2010b). A major review of methods and findings oriented towards national planning needs has also been produced under the Nairobi Work Plan (UNFCCC, 2010a). Coastal assessment also differ as some take an aggregate approach working at larger levels with generalizing assumptions while others take it disaggregated approach.

The coastal zone, along with water resources in agriculture, tends to have a deeper body of research on the costs and benefits of adaptation options than other sectors (Argawala and Fankhauser, 2008). Within the body of research, several methodological issues have been identified. These include the determination of baseline conditions; treatment of uncertainty and equity including distributional impacts, ancillary benefits and public-private efforts and economic valuation (UNFCC, 2010a).

Argawal and Fankhauser (2008) summarized key features of the large number of studies that focus on the costs of sea level rise impacts and adaptation. They identified three main themes: that there is extensive information available on regional and global costs of adaptation, although generally only for 1-m sea-level rise; the optimal percentage of coastline that should be protected in order to minimize costs (protection plus residual damage) is often quite high, however that is dependent on population density and land value; and, the annualized cost estimates for optimal protection are often less than 0.1% of national GDP, with the caveat that there is significant regional variation and higher costs particularly for small island states.

Newer studies have emerged using a wider range of scenarios, expanded on the impacts considered, and integrated other adaptation options (Anthoff *et al.,* 2010; Ciscar *et al.,* 2011; Nicholls *et al.,* 2011; Nicholls *et al.,* 2010). For example, cost-benefit analyses of 0.5, 1.0, and 2.0 m sea-level rise using the FUND model show significant benefits from protection, however authors caution that these findings might overestimate the extent of protection likely to be implemented (Anthoff *et al.,* 2010). The UNFCCC study estimated additional adaption costs of $4-11 billion/year in 2030 (Nicholls, 2007). However, those costs may be higher in the case of high-end sea level rise scenarios, and may also be underestimated because the analysis focuses mainly on the incremental adaptation costs with little attention to residual damages and no consideration of the adaptation deficit (Parry *et al.,* 2009). These authors go on to remark that it is quite possible that the cost of addressing the adaptation deficit for coastal protection will exceed the $11billion/year (Nicholls, 2007); however, that deficit is not well understood and requires further definition and quantitative analysis (Parry *et al.,* 2009).

Economic models and valuation studies are emphasizing the need to address ecosystem impacts and the value of ecosystem goods and services. Projected investments in coastal protection and beach nourishment would both entail environmental costs (Parry *et al.,* 2009). While there has been a rapid growth in research on ecosystem services, there is a substantial research agenda, including some longstanding challenges in valuation, to be addressed in both the ecological and economic dimensions (Anton *et al.,* 2010; Balmford *et al.,* 2011; Mendelsohn and Olmstead, 2009; Polasky and Segerson, 2009). The lack of understanding of the connections between ecosystem services and human well-being (Raudsepp-Hearne *et al.,* 2010) is also a barrier to valuation.

5.6.4. Constraints

The principal finding in the coastal chapter of the AR4 was that "there are limits to the extent to which natural and human coastal systems can adapt even to the more immediate changes in climate variability and extreme events, including in more developed countries" (Nicholls *et al*., 2007, p. 342). A variety of studies have been published in the interim, reinforcing this finding, and producing a better understanding of the nature of the barriers and limits to adaptation both generally (Biesbroek *et al*., 2011; Dupuis and Knoepfel, 2011; Gifford, 2011; Sietz *et al*., 2011; Amudsen *et al*., 2010; Burch *et al*., 2010; Larson, 2010; Lonsdale *et al*., 2010; Moser and Ekstrom, 2010; Adger *et al*., 2009a,b; Mitchell *et al*., 2006; Huang *et al*., 2011); and more specifically in the coastal sector (e.g., Lata and Nunn, 2011; Mozumber *et al.,* 2011; Storbjörk and Hedrén, 2011; Bedsworth and Hannak, 2010; Frazier *et al*., 2010; Saroar *et al.,* 2010; Moser *et al*., 2008; Tribbia and Moser, 2008; Ledoux *et al*., 2005).

Since the AR4, a clearer definition of limits and barriers has emerged. Adaptation *limits* are defined as "obstacles that tend to be absolute in a real sense: they constitute thresholds beyond which existing activities, land uses, ecosystems, species, sustenance, or system states cannot be maintained, not even in a modified fashion" (Moser and Ekstrom, 2010, p. 22026). Coastal research since the AR4 has examined particularly physical limits to natural (unassisted) adaptation, e.g., of coastal marshes (Kirwan *et al*., 2010a, b; Craft *et al*., 2009; Langley *et al*., 2009; Mudd *et al*., 2009). In their experimental study, Kirwan *et al*. (2010a) found that coastal marshes – due to nonlinear feedbacks among inundation, tidal range, plant growth, organic matter accretion, and sediment deposition – can adapt to conservative rates of sea-level rise (A1B), so long as there is sufficient sediment supply. By contrast, even coastal marshes with high sediment supplies are hard-pressed to adapt to more aggressive rates of SLR (Rahmstorf, 2007). Marshes accustomed to large tidal ranges show greater capability to adapt than micro-tidal marshes (Kirwan *et al*., 2010b). Other studies show how different climate change impacts interact to reduce the viability of coastal ecosystems sooner than when only a single driver is considered (e.g., Desantis *et al*., 2007; Spalding and Hester, 2007).

By contrast, social, economic, institutional, informational and other *barriers* constitute mutable "obstacles that can be overcome with concerted effort, creative management, change of thinking, prioritization, and related shifts in resources, land uses, institutions, etc." (Moser and Ekstrom, 2010, p. 22027). As Adger *et al*. (2009b) argued, most social obstacles (even if they appear as limits to the involved), are barriers in that they "can be overcome with sufficient political will, social support, resources, and effort" (Moser and Ekstrom, 2010, p. 22027). The common thread among all barriers is that they make adaptation less efficient or less effective or may require significant changes that can lead to missed opportunities, difficult trade-offs, or higher costs.

Researchers have categorized barriers in different ways, and they have placed variable emphasis on certain barriers. For example, common barriers identified include negative environmental consequences, technological feasibility, costs, institutional settings, entitlements and entrenched habits, political calculus, deeply held cultural values, worldviews and beliefs, lack of awareness, knowledge or location-specific information, social justice concerns, or negative interactions between different policy goals. Table 5-7 provides some examples of barriers found in the literature specific to coastal adaptation.

[INSERT TABLE 5-7 HERE
Table 5-7: Common barriers to coastal adaptation.]

The wide range of barriers identified in Table 5-7 reflects different coastal management contexts, different foci on levels of governance and actors/decision-makers, as well as different methods used in identifying them. This diversity does not allow for a quantitative meta-analytical integration, and yet critical insights have emerged since the AR4. First, the commonly heard claim that lack of information is the main constraint to (coastal) adaptation is refuted by the wide range of barriers identified in the sampled literature listed in Table 5-7, and many of them are empirically shown to be more important than lack of locally relevant, credible information. While information is clearly important, it matters differently for certain actors, at certain times in the adaptation process. Second, different constraints typically do not act as barriers in isolation, but come in interacting bundles. For example, Moser and Tribbia (2006/2007) and Mozumber *et al.* (2011) showed that lack of staff time is related to and often correlated with overall lack of resources for planning and implementation; lack of awareness is often related to both lack of experience and lack of communication and education (Saroar and Routray, 2010); social resistance to certain adaptation options is related to attitudes, worldviews, (spiritual) beliefs, cultural norms, place attachment, and economic investment and options (Barnett and Campbell, 2010; Lata and Nunn, 2011). Third, it is therefore difficult to predict which barriers matter most in any specific context but instead multiple barriers need to be addressed if adaptation is to move successfully through the different stages of the management process (Moser and Ekstrom, 2010; Storbjörk, 2010; Londsdale *et al.,* 2010). Nonetheless, there are some non-surprising yet important commonalities: studies focused on government staff show the predominance of intra- and cross-institutional as well as budgetary constraints, with informational, communication, political, and public support barriers playing important additional roles (e.g., Storbjörk and Hedrén, 2011; Moser and Tribbia, 2006/2007; Ledoux *et al*., 2005). By contrast, studies focused on individuals and their views on potentially unplanned, reactive adaptation show a predominance of psychosocial (place attachment, social support, social norms, identity), cultural-cognitive (beliefs, worldviews, values, awareness, education) and economic barriers (e.g., Adger *et al*., 2011; Saroar and Routray*,* 2010). Fifth, some factors can act as enablers and added capacity to adapt, while acting in barriers at others (Burch, 2010; Storbjörk, 2010). For example, strong leadership in a government agency can help motivate and advance adaptation internally, while hindering cross-agency ownership of the challenges and responsibilities to plan and implement adaptation (Storbjörk, 2010). A complementary insight is that some capacities or factors can compensate for other present barriers, thus rendering them less severe (e.g., leadership can compensate to some extent for lack of information and economic resources).

Finally, as the Ledoux *et al.* (2005) study showed explicitly, and as emerges as a common concern from wide-ranging literature reviews (Biesbroek *et al*., 2011; Ekstrom *et al*., 2011), some critical barriers arise from the interactions across policy domains, existing laws and regulations, and historical legacies (long-term impacts of past decisions and policies). Dawson *et al.* (2009), for example, showed that – due to the interconnectivity of geomorphologic processes within a littoral cell – attempts to reduce one coastal climate risk (e.g., erosion) may well increase the exposure to another coastal climate risk (e.g., flooding). Such trade-offs can reduce the ultimate effectiveness of one or all of the interacting adaptation options.

5.6.5. Links between Adaptation and Mitigation

For the foreseeable future, coastal areas will be preoccupied with managing interacting stresses from sea-level rise, temperature increases, precipitation changes, changing storm regimes, runoff from coastal watersheds into near-coastal waters as well as non-climatic stressors such as population and development increases in vulnerable areas, pollution from land use and industrial activities, and threats from infectious diseases (e.g., Melbourne-Thomas *et al.,* 2011; Bunce *et al.* 2010a; Halpern *et al.,* 2008a). At the same time, 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 century due to the enormous momentum involved in sea-level rise and the time lag between emission reductions, temperature changes and impacts on global sea levels (Nicholls *et al*., 2011; Nicholls *et al*., 2007). Systematic assessment of potential synergies and tradeoffs between mitigation, adaptation, and other, non-climatic policy goals and efforts to maintain or increase flexibility to enable policy adjustments in the future have been proposed as strategies to recognize, avoid and minimize the risk of negative policy interactions (e.g., Vermaat *et al*. 2005; Nicholls *et al.,* 2011). Positive synergies and complementarities between mitigation and adaptation in the coastal sector exist because many coastal zone-based activities and various coastal management activities involve emissions of greenhouse gases and will be impacted to varying degrees by climate change (Section 5.3). The first few items in Table 5-8 show examples of such positive interactions. In addition to positive interactions, the possibility for negative interactions (or tradeoffs) exists as well.

[INSERT TABLE 5-8 HERE
Table 5-8: Positive synergies and tradeoffs between selected coastal adaptation and mitigation options.]

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)". This definition has been criticized as being too broad and potentially obscuring important differences between tradeoffs (Moser, 2011). A finer differentiation would distinguish various types of constraints that may prevent the full implementation of selected adaptation and mitigation measures either because of insufficient supporting means and conditions or due to concerns over unwanted outcomes. Such undesirable outcomes may include, but not be constrained to, negative environmental consequences, undesirable social implications, political repercussions, equity concerns such as distributional or intergenerational impacts, and so on (see references in Table 5-8). The second and third sections of Table 5-8 list a range of adaptation and mitigation options and show their respective potential negative implications for the complementary goal.

5.7. Uncertainties and Data Gaps

This chapter has updated knowledge about the impacts of climate change on the coastal ecosystems including a better understanding of the coastal ecosystems not on their own right but also from the impacts of overexploitation and habitat destruction that have been responsible for most of the historical changes. There is a better understanding of the varying impacts of weather and climate extremes and long-term sea-level rise on human systems. For example, the projected increase in both tropical storm intensity and population in the next 20 years can expect to greatly increase the number of people exposed and exacerbate disaster risk (Knutson *et al*., 2010). While knowledge has increased it has yet to provide a complete understanding of new issues, e.g., ocean acidification impacts, or old issues, e.g., adaptation costs and options. The complexity of adaptation issues, especially involving interacting with human systems has been discussed. Adaptation has widened in scope to cover areas where policymakers would like to have more information to act in future, e.g., vulnerability assessment, costs of adaptation and more adaptation options.

Although a better understanding of shoreline response to future sea-level rise has been made by recent improvements in technology (e.g., satellite imagery) to investigate and characterize large-scale changes in shoreline, quantitative predictions of future coastal change remains difficult. This is due to the complexity of coastal systems, influence of infrequent storm events and insufficient understanding of coastal systems over decadal timescales. Shoreline response is more complicated than simple drowning alone because of factors such as sediment supply, offshore geology, engineering structures, and wave forcing (Ashton *et al*., 2008). For example, for many sedimentary coasts, one fundamental question is the sediments and rate of sedimentation in response to sea-level rise. In the long-term, we "need to eventually develop the capability to predict at least a regionally averaged shoreline response to a given change in the rate of sea-level rise" (Ashton *et al*., 2008: 737).

Although sea level is predicted to rise in future, there are uncertainties in evaluating the historical changes, modeling future climatic change and estimating site-specific impacts. Many SLR assessments are not at spatial or temporal scales most relevant for decision makers who required information on baseline conditions and projections of change (Kettle, 2012). The local data required for SLR assessment are also not easily available. For example, LIDAR data are only easily available for the USA coasts (NOAA Digital Coast Data Access Viewer website) but not for the rest of the world yet. Only when such data become available in future, many developing countries, especially low-lying countries, the deltaic areas of Asia and small island states could better assess the impact of sea-level rise.

There are significant gaps in vulnerability assessment of other specific coastal aspects. For example, climate modeling of diseases that could affect the coastal areas is based mainly on the mean values of climate. There is a need to incorporate effects of daily temperature variation into predictive models and show how that variation is altered by climate change (Paaijmans *et al*., 2010). Also, despite tourism as one of most important industries in the coastal areas, not enough is known about tourists' likely behavioural reactions to projected climatic changes (Moreno and Amelung, 2009).

The available vulnerability studies only explore a small fraction of the uncertainty. Generally, studies do not consider the full range of possible relative sea-level changes and often exclude a potential large contribution of ice sheet melting to sea-level rise, regional variations in climate-induced sea-level change and local factors such as human-induced subsidence. Many studies rely on few or only a single socio-economic scenario and exclude adaption or consider only a few stylized options. The available studies also only cover a limited range of impacts. Integrated studies considering various impacts and their interdependence are rare. In particular, studies either focus on land loss due to submergence or on flood damage. Generally, few studies explore indirect impacts and indirect costs.

A wide range of coastal management framework and measures is available and used in coastal adaptation to climate change, and their scope of integration has increased by combining scenarios of climate change and socio-economic conditions and risk assessment (Kirshen *et al.,* 2011). While various adaptation measures are available, at the local level, apart from adaptation options such as dykes and beach nourishment, there is not enough information on assessment of adaptation options. Knowledge gaps exist, data are missing or their reliability is insufficient. In some cases, alternatives are clear, e.g., giant floodgates or floating houses and amphibious housing (e.g., UK, Netherlands). For many developing countries with narrow coastal areas and small island nations, the issue of coastal squeeze becomes an increasing pertinent issue as the coastal ecosystems are drowned and cannot migrate inland because of coastal protection measures or coastal communities cannot move inland.

Of various adaptation approaches to climate change, the integrated coastal management (ICM) has developed as an effective framework and been able achieve a number of goals : the minimization of risks and impacts from coastal hazards, economic development and use of coastal resources, and protection of coastal environmental resources, natural assets, and ecosystems. However, the ICM still faces the limitation and uncertainty of the longer time frames for sea-level rise and ocean acidification, the potential for physical and ecological thresholds or tipping points, and the long lead times often required for making changes in coastal management, due to system lags in socioeconomic systems.

There is an increasing trend to merge the practice of DRR (disaster risk reduction) and CCA (climate change adaptation) particularly in developing countries (Berse *et al*., 2011; CCD 2009). However, DRR differs from CCA in spatial and temporal scales, knowledge and norms and DRR goals, strategies and measures need to be revised or modified to meet the goals of CCA more effectively (Birkman and von Teichman, 2010).

The coastal zone has developed a body of research on the costs and benefits of adaptation options (Argawala and Fankhauser, 2008). There is a continued evolution on the assessment of costs and benefits of adaptation options with a wider range of scenarios, expanded impacts considered and integrated adaptation options. However, several key issues in methodological development still exist: these include the determination of baseline conditions; treatment of uncertainty and equity including distributional impacts, ancillary benefits and public-private efforts and economic valuation (UNFCCC, 2010a).

Developing a knowledge platform for adaptation with communication between scientists, policy makers, stakeholders and the general public could be considered as a priority area for coastal areas of a large or regional area affected by climate change and sea-level rise. This is well developed in European Union (European Commission Climate Action website), the Mediterranean (PAP website) and Australia (OzCoasts website), and but less so in the developing countries, except in certain regions, e.g. Caribbean islands (CCCCC website), Pacific Islands (SPREP website). An Adaptation Knowledge Platform has been developed for Asia-Pacific (Adaptation Knowledge Platform website) but no coastal portal is available for Southeast Asia and East Asia.

Lastly, coastal research relating to climate change needs to be positioned in a proper context and in line of what has been noted in the 21st century. Based on Science Citation Index, Li *et al*. (2011) concluded that temperature, environment, precipitation, greenhouse gas, risk and biodiversity will be the foci of climate research in the 21st century. The implications for coasts would be on biodiversity and flooding which is more coast-bound. Future technological advances can be significant, e.g., new forms of energy and food production, information and communication technology (ICT) for risk monitoring (Delta Commission, 2008). This would be useful for flood risks and food production in deltas and coastal systems (aquaculture).

5.8. Conclusion

Since the AR4, there has been much research on the impacts of climate change on the coasts. While the observed and future increase in weather and climate extremes can be variable, the rate of sea-level rise would seem to be critical to many issues related to the response of both coastal ecoystems and human systems.

In some way, the human systems in the coastal areas are critical than the coastal ecosystems considering the fact that they exacerbate the impacts of climate change on the coastal ecosystems. At the same time, it is evident that increased vulnerability and exposure to climate change and sea-level rise would be exacerbated by rapid population growth and increased urbanization in the LECZ. Such hotspots would be in the developing world, particularly, the megadeltas in Asia and small island states.

Some assessments of vulnerabilities and costs for coasts at the global, regional and the national level are available. But these assessments have uncertainties and limitations and not suitable for local areas to take appropriate action. While some local areas have relied on traditional practices or use current adaptation measures, many have difficulties in deciding what appropriate or effective options can be made for the future.

Despite various problems, issues and limits to which natural and human coastal systems can adapt, adaptation will remain the predominant approach to reduce climate risks to coastal communities. While costs assessments have yet to be fully developed for easy application, adaptation has to be taken now. As coastal areas are also affected by non-climate related disasters, e.g., earthquakes, tsunamis, there is increasing options for climate change adaptation (CCA) to incorporate disaster risk reduction (DRR) to maintain sustainable coastal communities.

Frequently Asked Questions

FAQ 5.1: How does climate change affect coastal ecosystems?

The major global stressors, mostly caused by increased concentration of CO2 in the atmosphere, affecting coastal ecosystems are extreme weather and climate events, sea-level rise, ocean warming and ocean acidification. The impact of sea level is mostly related to the capacity by animals (e.g. corals) and plants (e.g. mangroves) to keep up with the vertical rise of the sea. Warming affects all organisms, increasing their metabolism and causing mass mortality events of those living close their upper thermal limit. Ocean acidification negatively impacts many organisms that build shells and skeletons but its effects are poorly known at the ecosystem level.

FAQ 5.2: How is climate change contributing to coastal erosion?

Erosion is the process of wearing away material from the coastal profile due to imbalance in the supply and export of material from a certain section: dunes, beaches, cliffs, etc. It is mainly caused by winds, waves and sea level. Any rise in mean sea level will result in a landward and upward displacement of the cross-shore seabed profile and a retreat of the shoreline. Increasing waves heights can cause the sand bars to move seawards and high storm surges (sea levels) also produce an offshore movement of sand due to non-equilibrium in the profile. Higher waves and surges may increase the probability of sand barriers and dunes overwash or breaching. Changes in wave direction or propagation due to changing wave heights or sea levels may result in increasing gradient in the sediment transport rate and consequently erosion.

FAQ 5.3: Does adequate planning of the coastal uses contributes to reduce climate change impacts?

Yes, adequate planning of the coastal uses contributes to reduce climate change impacts. Such planning is normally supported by national legislation and considers both the problems of both climate change and coastal hazards, especially coastal flooding. Regional coastal strategies and plans are established with guidelines for local governments to implement. For measures to be taken, the focus is on precautionary measures irrespective of future climate change. An important paradigm change of planning land uses to reduce climate change is to use the buffer zone as a response to coastal inundation. The strategy is to work with nature rather than against nature, e.g. in the Netherlands.

FAQ 5.4: Is the sea level rising equally in all regions?

No, there are spatial variations in sea-level changes that can add to or subtract from the global average rise. The spatial variations can result from a variety of processes such as ocean circulation, where sloping sea level balances the Coriolis force; changes in seawater temperature, where warming of seawater causes it to expand and raise sea level in a thermal expansion; and changes in gravity, where the loss of mass from ice sheet melting changes the local gravity field and seawater moves away, raising sea level at distant locales.

FAQ 5.5: What climate change impacts are getting more severe for the coasts?

The primary coastal impact becoming more severe is elevated water levels due to sea-level rise (SLR). SLR not only inundates low-lying land, like filling a bath tub, but can contribute to dynamic changes in sandy beaches, through shifting the beach location landward and higher, and in wetlands, by drowning marsh vegetation. Scientists disagree on whether tropical cyclones will become more intense and/or frequent in the future. However, for some coasts, where beaches cannot shift landward and upward, storm surges will increasingly impact coastal development due to their superposition on top of a rising sea.

FAQ 5.6: How can coastal communities adapt to climate change impacts?

Various adaptation options are available which range from accommodation to retreat. Adaptation through structural measures include hard (e.g. sea walls) and soft (e.g. coastal revegetation) management options. Non-structural measures include land-use planning (e.g. rolling easements that require relocation of vulnerable infrastructure as critical risk thresholds are crossed). Education is also important for building community resilience. Risk transfer mechanisms (e.g. insurance) address residual risk although where risks are too high, retreat from coastal areas may be the only viable response. A combination of strategies, tailored to suit the particular coastal community, may be required and will need to be reviewed and adjusted as circumstances change in the future.

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Table 5-1: Survey of literature on the impacts of anthropogenic climate change on marine ecosystems (adapted and updated from Hoegh-Guldberg and Bruno, 2010). [To be revised and confined to coastal ecosystems.]

Climate system change	Organism/ ecosystem	Expected impact	Observed change	References
Increasing temperature	Seagrass	Seasonal and permanent loss of seagrass biomass with increased frequency and intensity of extreme temperatures	Increased temperatures results in a reduction in the above-ground biomass of seagrass and the disruption of the photosystem. Mass die-offs and ecosystem loss in areas exposed to prolonged extreme temperatures	Borum et al., 2005; Campbell et al 2006; Greve et al, 2003; Mayot et al, 2005; Moore and Jarvis, 2008; Najjar et al, 2010; Orth et al, 2006; Seddon and Cheshire; 2001; Seddon et al, 2000; Short and Neckles, 1999.
		Shift in community structure	Warm-water species proliferate, dominating communities in areas of low-level warming	Boudouresque et al, 2009; Ehlers et al, 2008; Francour et al, 1994; McMillan, 1984; Peirano et al, 2005; Walker, 1991
	Mangroves	Changes in species distribution and loss of habitat	Increased salinity due to higher evaporation leads to mortality and redistribution of species and reduced species richness due to variable salinity tolerance levels. Prolonged periods of extreme salinity may result in theformation of salt pan systems	Ball, 1998; Ball and Pidsley, 1995; Bertness and Pennings, 2000
	Rocky shores	Poleward shift in species ranges	The range and abundance of warm-water species are increasing, whilst those of coldwater species are diminishing	Adey and Steneck, 2001; Harley et al, 2006; Hawkins et al, 2009; Helmuth et al 2006; Nieszkowska et al, 2006
		Zonation patterns influenced by both air and sea temperatures	Reduced recruitment of fucoids and intertidal invertebrates in the littoral zone due to rising temperatures causing desiccation of propagules and suppressing growth leaving new recruits more susceptible to grazers	Hawkins et al, 2009; Helmuth et al 2006; Findlay et al 2010; Kennedy 1976; Pearson et al, 2009; Yamane and Gilman, 2009
	Kelp communities	Decline of kelp ecosystems with rising sea surface	Range and distribution of kelps is diminishing with rising temperatures due to requirements of sporophytes. Species	Adey and Steneck, 2001; Harley et al, 2006; Dayton and Tegner, 1984;

	temperature	living close to their physiological limits will be likely to recede to higher latitudes and cooler waters.	Deysher and Dean, 1986; Steneck et al, 2002
Phyto-plankton	Changes in distribution and frequency of harmful algal blooms	Increased frequency of bloom events associated with increasing sea surface temperatures.	Peperzak, 2003; Peperzak, 2005
	Altered growth rates, species dependent	Some species growth rates increased with temperature	Fu et al, 2007; Fu et al, 2008
	Poleward shift in species ranges	Warm water species are increasing their distribution towards the poles as cold water warms	Beaugrand and Reid, 2008; Edwards, 2004;
	Altered abundance	A greater increase in abundance in cooler waters experiencing warming compared to warmer waters experiencing warming	Richardson and Schoeman, 2004
	Earlier appearance	Phytoplankton appearing earlier in summer in temperate regions	Edwards and Richardson, 2004
Zooplankton	Poleward shift in species ranges	A shift in community assemblages and biogeographical range, extending polewards with increasing sea surface temperatures	Beaugrand et al, 2002;Beaugrand et al, 2009; Parmesan and Yohe, 2003; Root et al, 2003.
	Alteration of phenology	Zooplankton communities appear earlier with warming sea surface temperatures	Edwards and Richardson, 2004; Parmesan and Yohe, 2003
	Altered abundance	Increase in abundance with warming water	Richardson and Schoeman, 2004; Aoyama et al, 2008
Coral reefs	Increased frequency and severity of coral bleaching with changing sea surface temperature	Severe bleaching events occurring globally with associated coral mortality	Hoegh-Guldberg, 1999; Knowlton, 2001; Miller et al, 2009; Mumby et al, 2001, Prada et al, 2010
	Increased occurrence of diseases	Frequency and severity of coral diseases increasing	Croquer and Weil, 2009; Mydlarz et al, 2009; Sokolow, 2009; Thinesh et al, 2009; Baker et al, 2008;

	Loss of coral reef species due to coral bleaching and mortality	Loss of coral reef fish, crustacea and other invertebrate diversity and abundance with loss of live coral habitat due to rising temperatures	Baker et al, 2008; Bruce and Biol, 1976; Castro, 1978; Castro, 1988; Feary et al, 2007
Seabirds	Poleward shift in species ranges and a shift in abundance toward species tolerant of warmer waters	Seabirds of Western Australia are becoming more abundant and extending their range polewards with changes in prey distribution with rising sea surface temperatures	Bancroft et al, 2004; Dunlop et al, 2001, Dunlop and Wooller, 1986; Smithers et al, 2003; Wynn et al, 2007
	Birds migrating earlier in temperate and subtropical regions	Alteration of breeding date with changing temperature, favouring early breeding and altered selection patterns	Moe et al, 2009; Moller et al, 2006
	Altered breeding seasons, affecting nesting and laying times	Extended breeding seasons in the temperate and tropical regions with earlier nesting and laying times	Dunlop and Wooller, 1986; Chambers, 2004, Nevoux et al, 2010
	Breeding success affected by climate change and prey Availability	Temperature and associated changes in prey availability and match-mismatch of breeding affect population success	Bustnes et al, 2010; Plestan et al, 2009; Watanuki et al, 2009
	Alteration of coastal habitats affect nesting bird populations	Penguin populations benefit from less snow and ice allowing better nesting and more abundant prey species improving breeding success	Huang et al, 2009
Marine turtles	Poleward shift in species foraging ranges	Temperature change has implications on migratory patterns, forcing a poleward shift in populations	Chaloupka et al, 2008; McMahon and Hays, 2006
	Change in the sex ratios	Changes in temperatures affect the sex ratio with rising temperatures favouring female populations	Booth and Freeman, 2006; Fuentes et al, 2010; Godley et al, 2001
	Changes in breeding	Warmer foraging and nesting grounds affect the timing of breeding, clutch number and nesting season length	Mazaris et al, 2009; Pike, 2009; Schofield et al, 2009; Weishampel et al, 2004
Marine mammals	Change in distribution range of Cetacea	Poleward migration of species causing a reduction in the range of cold water species and extension of warm water species resulting in changes in community structure	Azzellino et al, 2008; Gambaiani et al, 2009; MacLeod et al, 2005
Polar Ice	Ice thinning and loss results	Prolonged periods of ice loss, or thin ice affects the growth	Montes-Hugo et al, 2009; Zacker et

	Habitats	in greater UV penetration to the marine system	and distribution of benthic and pelagic microalgae and cyanobacteria altering productivity	al, 2009
		Changes to seasonal ice loss patterns	Changes to the seasonal ice break events alters the marine eukaryotic communities and system function	Piquet et al, 2008
		Loss of ice will change the distribution of ice-dependent macrofauna	Changes in migration patterns, adaptation to changing habitats and possible declining in population depending on level of dependency	Moore and Huntington, 2008
	Demersel and pelagic fish	Species range alters with warming	Poleward shift in species ranges and a shift in abundance toward species tolerant of warmer waters	Beare et al, 2004, Byrkjedal et al, 2004, Perry et al, 2005; Rose, 2005; Welsford and Lyle, 2003; Hiddink and Hofstede, 2008; Last et al, 2011; Ling et al, 2009
		Migration dates altered with warming	Earlier dates of mean migration and spawning in temperate and subtropical species	Sims et al, 2004
Wind strength change	Phyto-plankton and zooplankton	Alteration of productivity with wind-driven mixing of surface waters	Increased productivity where wind mixing is enhanced and a reduction where wind strength is declined	Montes-Hugo et al, 2009; Buranapratheprat et al, 2008; Harris et al, 1991; Polovina et al, 1994
		Changes in community structure with surface mixing	Alteration of the surface stratification with wind-driven upwelling can cause alterations in community structure and bloom formation	Nakane et al, 2008; Yin et al, 1996
	Coastal fish	Abundance of fish linked to wind strength	Increased wind-driven upwelling and mixing results in greater recruitment due to areas of higher productivity	Harris et al, 1991; Polovina et al, 1994; Criales et al, 2002; Thresher et al, 1989
	Seabirds	Alteration of breeding success with changing wind intensity and patterns	Prolonged periods of strong winds causes a reduction in the breeding success of seabirds	Devney et al, 2009; King et al, 1992

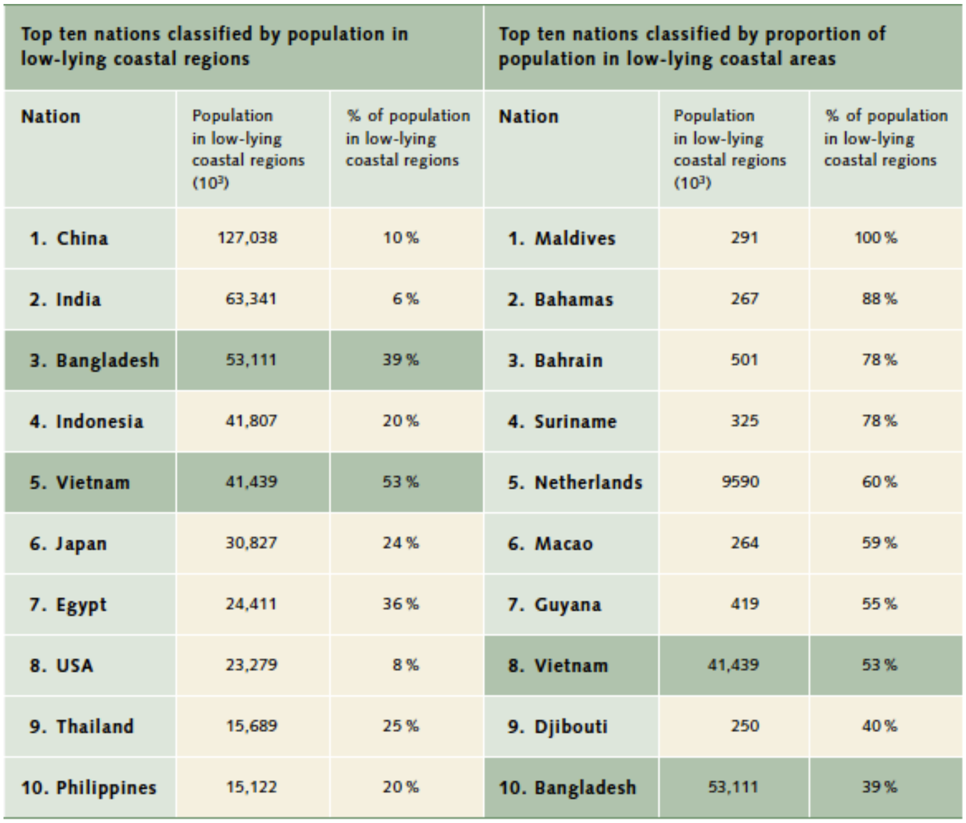
Alteration of currents	Seagrass	Changes in distribution of species with changing currents	Loss of cold-water species and appearance of topical species further poleward correlated with changes in warm water currents	Walker and Prince, 1987
	Mangroves	Breakdown in control of latitudinal distribution through propagule current translocation	Changes to currents responsible for propagule distribution results in the redistribution of mangroves	Delange and Delange, 1994
		Changes in local distribution patterns with changing sediment transport patterns	Changes in current-driven sediment distribution affects growth rates and success of plant	Ellison and Farnsworth, 1996
	Kelp communities	Local extinction of cold-water species with changes in currents and/or the appearance of warm-water species	Alteration of larval supply changes the distribution of species and success in altered thermal conditions	Johnson et al, 2005; Ling et al, 2009
	Rocky shores	Poleward shift of warm water species	Tropical species appearing in temperate latitudes due to changes in distribution of larvae	Griffiths, 2003
	Phyto-plankton and zooplankton	Change in distribution and occurrence of plankton communities with an extension polewards of warm-water species	Warm nutrient rich waters resulting form changes in current trajectories results in plankton bloom events	Blackburn and Cresswell, 1993; Oke and Middleton, 2001
Decline in mixed layer depth/ increasing stratify-ication	Seabirds	Increased mortality and reduced reproductive success	Reductions in surface water prey availability due to strengthened stratification and reduced mixed layer leads to mortality and reduced reproductive success	Richardson and Schoeman, 2004; Smithers et al, 2003; Wynn et al, 2007
	Pelagic fish	Abundance and distribution	Stratification and associated plankton community changes	Richardson and Schoeman, 2004;

		changes due to thermal stratification of upper ocean	alters food supply for fishes, altering community structure and distribution	Hsieh et al, 2009
	Phytoplankton and zooplankton	Changes in distribution and abundance due to altered stratification zones	Vertical stratification resulting from changes in sea surface temperatures strengthens existing thermoclines in warmer stratified waters and encourage the development of their formation in cooler turbulent waters creating suitable habitat for zooplankton	Richardson and Schoeman, 2004; Hsieh et al, 2009
		Decline in phytoplankton abundance	As the mixed surface layer diminishes phytoplankton productivity decreases	Polovina et al, 1994; Polovina et al, 1995; Venrick et al, 1987
Increasing intensity of storms/ greater inundation events from shifting rainfall	Seagrass	Physical destruction of seagrass beds	Storm-driven currents scour the benthos uprooting large areas of seagrass and removing from the site	Orth et al, 2006; Preen et al, 1995; Rodrigues et al, 1994; Thomas et al, 1961
		Changes in sedimentation regimes cause mortality	Sediment deposition caused my storm activity and increased rainfall runoff smothers seagrass	Preen et al, 1995; Rodrigues et al, 1994;
		Change in community composition as water clarity is changed	Alteration to light conditions due to reduced water quality resulting from increased sediment load results in a change of community shifting towards species adapted to low light levels	Rodrigues et al, 1994; Hale et al, 2004; Orth and Moore, 1983
	Mangroves	Change in community abundance associated with increased rainfall events	Mangrove community distribution increase due to altered salinity, nutrient and sediment loading	Gilman et al, 2008; Harty, 2004; Rogers et al, 2006; Saintilan and Williams, 1999
		Reproductive success and growth influenced by storm activity	Prolonged periods of flooding may cause the mortality and impeded propagation of juvenile plants	Gilman et al, 2008
	Rocky shore	Increased wave energy alters community structure	Storm-driven wave damage change in species zonation patterns	Helmuth et al 2006; Barry et al, 1995
		Increased storm frequency affects community structure and function group	Fucoid species will be lost and associated invertebrates, allowing those species that can withstand high energy environments, such as mussels and barnacles, to dominate	Kendall et al, 2004

	prevalence		
	Increased freshwater inputs alters zonation	Changes in species zonation driven by changes in salinity due to extreme rain events	Garza and Robles, 2010
Kelp communities	Change in community structure	Switch from canopy forming macroalgae to predominantly turf-algae due to physical wave damage and increased eutrophication from land run-off	Cole et al, 2001; Gorgula and Connell, 2004; Graham, 1997; Graham et al, 1997; Steneck et al, 2002
Coral reefs	Mass mortality due to physical damage	Extreme storm events cause physical destruction and mortality of corals with increased frequency preventing recovery leaving reef susceptible to less intense events	Gardner et al, 2005; Alvarez-Filip and Gil, 2006; Alvarez-Filip et al, 2009; Connell, 1997; Guillemot et al, 2010; Hughes and Connell, 1999; Knowlton et al, 1981; Porter and Meier, 1992
	Mass bleaching and mortality due to associated large freshwater flood events	Extended periods of extreme freshwater input from land run-off causes mass bleaching and potential mortality	Alongi and McKinnon, 2005; Alongi and Robertson, 1995; Goreau, 1964; Jokiel et al, 1993; VanWoesik et al, 1995
	Changes in reef community structure and composition	Differentiation in sensitivity to freshwater and mechanical stress, and differences in recover rates causes a shift in community composition and reduced diversity	Jokiel et al, 1993; VanWoesik et al, 1995; Adjeroud et al, 2009; Bythell et al, 2000; DeVantier et al, 2006
Phyto-plankton and zooplankton	Nutrient enrichment of surface waters due to terrestrial run-off	Increased nutrient state causes a change in community structure and dynamics causing a shift from heterotrophy to autotrophy	Carlsson et al, 1995; De Carlo et al, 2007; Goffart et al, 2002; Guadayol et al, 2009; Hoover et al, 2006
	Storm-forced upwelling of nutrient rich waters	Nutrient rich water promotes phytoplankton growth	Acker et al, 2009
Marine turtles and mammals	Increased mortality and reduced breeding success	Severe storm events cause mortality of terrestrial-obligate mammals and turtles including loss of turtle clutches	Dodd and Dreslik, 2008; Edmiston et al, 2008; Limpus and Reed, 1985; Pemberton and Gales, 2004; Pike and Stiner, 2007

	Seabirds	Increased feeding	Increased plankton abundance drives foraging success and breeding population dynamics	Devney et al, 2009
		Restriction and alteration of foraging and migration	Storm events prevent birds from travelling usual routes and cause changes in flight patterns	Blomqvist and Peterz, 1984
Rising sea levels	Seagrass	Loss of seagrass habitat	Rising sea levels results in increased light attenuation forcing seagrass migration landwards to areas of shallower water	Orth et al, 2006; Abal and Dennison, 1996
		Reduction in growth rate and changes in community structure due to lower light levels	Change in community structure with species with lower light demands dominating deeper zones	Short and Neckles, 1999
	Mangrove	Loss of mangrove habitat	Increased frequency and severity of extreme sea levels may results in mortality where migration is impeded	Blasco et al, 1996; Ellison, 1993; Ellison and Stoddart, 1991; Woodroffe, 1990
		Changes in habitat distribution	Landward migration in response to slow sea-level rise allowing the maintenance of relative height	Gilman et al, 2008; Ellison, 1993; Alongi, 2008; Gilman et al, 2006; Madsen et al, 2007; Parkinson, 1989 Parkinson et al, 1994
	Seabirds	Loss of nesting and breeding habitat	Inundation of nesting habitats in low lying habitat areas by water will cause a reduction the potential habitat for populations	Galbraith et al, 2005; Ratcliffe et al, 2008; Smart and Gill, 2003; Straw et al, 2006;
	Marine turtles and mammals	Loss of nesting and breeding habitat	Inundation of turtle nesting habitats in low lying areas by water will cause a reduction the potential habitat for populations	Fish et al, 2005; Limpus and Heidrun, 2006; Mazaris et al, 2009a, b; Whittock, 2009
	Coral reefs	Mortality and redistribution of communities	Distribution of corals will shift so as to maintain their relative sea-level while corals living at their physiological light limit will die if rate of sea-level change exceeds growth rate	Hoegh_Guldberg, 1999; Graus and Macintyre, 1998

Table 5-2: 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 areas		
Nation	Population in low-lying coastal regions (10^3)	% of population in low-lying coastal regions	**Nation**	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 5-3: Impacts of sea level rise, coastal floods, and storms on critical coastal infrastructure by sector.

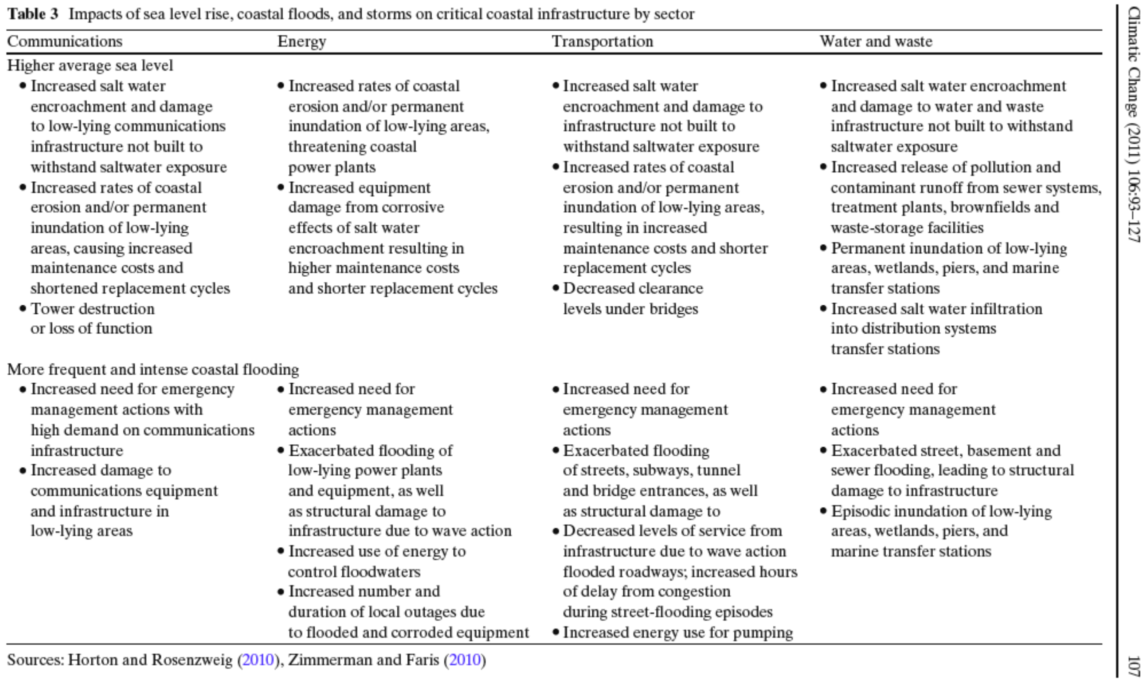


Table 3 Impacts of sea level rise, coastal floods, and storms on critical coastal infrastructure by sector

Communications	Energy	Transportation	Water and waste
Higher average sea level			
• 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 costs and shortened replacement cycles • Tower destruction or loss of function	• Increased rates of coastal erosion and/or permanent inundation of low-lying areas, threatening coastal power plants • Increased equipment damage from corrosive effects of salt water encroachment resulting in higher maintenance costs and shorter replacement cycles	• 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 costs and shorter replacement cycles • Decreased clearance levels under bridges	• 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			
• Increased need for emergency management actions with high demand on communications infrastructure • Increased damage to communications equipment and infrastructure in low-lying areas	• 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	• 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	• Increased need for emergency management actions • Exacerbated street, basement and sewer flooding, leading to structural damage to infrastructure • Episodic inundation of low-lying areas, wetlands, piers, and marine transfer stations

Sources: Horton and Rosenzweig (2010), Zimmerman and Faris (2010)

Table 5-4: 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 et al., 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 et al., 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 et al., 2012
East Timor	Flooding,	0.31-0.54	A2 and B1	Wetland area reduction under	Expected number of people flooded	DIVA	McLeod

	erosion wetland loss, salt water intrusion	m by 2100, plus local subsidence / uplift		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 Increased salinity intrusion into land areas 7-12% under A2	annually relative national population (pop): WOA 0.54% pop A2; WA 0.01% pop A2	(Adapt$)	et al., 2010
Indonesia					WOA 1.19% pop A2; WA 0.00% pop A2		
Malaysia					WOA 0.46% pop A2; WA 0.00% pop A2		
Papua New Guinea					WOA 0.07% pop A2; WA 0.01% pop A2		
Philippines					WOA 0.80% pop A2; WA 0.00% pop A2		
Solomon Islands					WOA 0.27% pop A2; WA 0.00% pop 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 et al., 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-		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 to1.4 m SLR	Hydrodynamic modelling, GIS	McInnes et al., 2011

		100 year flood event					
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 et al., 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 et al., 2011
Estonia	Submergence exposure	1 m SLR adjusted for regional uplift (i.e. 69–73 cm RSLR)		Observed beach erosion has resulted from increased storminess in the eastern Baltic Sea, combined with decline in winter sea-ice cover. Future land loss will impact major bird breeding grounds	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 tourism at risk.	Qualitative assessment	Kont et al., 2008
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 et al., 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, socio economic data	Sterr, 2008
Great	Erosion,	0.8 – 1m		Large parts of the coasts are	At the national scale, economic losses due	Qualitati	de la

Britain	submergence	SLR		presently sediment starved and eroding and this will continue	to erosion are expected to remain considerably smaller than flood losses	ve assessment	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	Pruszak 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 et al., 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 et al., 2010
N. America							
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 et al., 2010

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

Reference	Physical impacts	SLR scenario	Socio-economic scenario	Impact indicators	Without adaptation	With adaptation
Anthoff et al., 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$200-2200 billion in 2100
Nicholls et al., 2011	Submergence, erosion	0.5-2.0 m SLR by 2100	A1FI	Cumulative number of people displaced due to land loss to submergence and erosion	72-187 million people during 21st century	0.04-0.3 million people during 21st century
				Annual adaptation cost	N/a	US$ 25-270 billion/yr
Hinkel et al., 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

Table 5-6: Approaches to integrative, adaptive coastal management.

Characteristics	Traditional Coastal Zone Management	Integrated Coastal Zone Management	Disaster Risk Reduction	Ecosystem-based Adaptation	Community Based Adaptation
Focus/purpose	Balancing multiple goals; economic development typically dominant	Sustainable multi-purpose, coastal development, accounting for synergies, trade-offs	Hazards, risks, disasters main focus; increasing attention to development	Ecosystem preservation/ restoration to protect against CC impacts; make ecosystems more resistant/resilient to CC	Integration of poverty reduction, development and other coastal goals (pro-poor adaptation)
Institutional arrangements	Multi-scalar, separate institutions	Multi-scalar; integration across "silos"	Multi-scalar (different levels emphasized)	Emphasis on local to regional level	Emphasis on local level
Stakeholder engagement	limited	central	varies, central at local level	varies	central
Other traits to compare??					
Other traits to compare??					
Sample applications and critical analyses of approaches (since AR4)	Hansen, 2011; Hallegatte, 2009; Tribbia and Moser, 2008; Van Koningsveld *et al.*, 2008	Nursey-Bray and Shaw, 2010; Jentoft, 2009; Dawson *et al.*, 2009; Sales, 2009; McFadden, 2008; Shipman and Stojanovic, 2007; Stojanovic and Ballinger, 2009; Falaleevaa *et al.*, 2011	Romieu *et al.*, 2010; Mercer, 2010; Mitchell *et al.*, 2010; Polack, 2010; Gero *et al.*, 2011; Kirshen *et al.*, 2011; Halpern *et al.*, 2008b	Espinosa-Romero *et al.*, 2011; McGinnis and McGinnis, 2011; Pérez *et al.*, 2010; Anthony *et al.*, 2009; Alongi, 2008	van Aalst *et al.*, 2008; Dumaru, 2010; Mustelin *et al.*, 2010; Raihan *et al.*, 2010; Milligan *et al.*, 2009

Table 5-7: Common barriers to coastal adaptation.

Location	Common Barriers to Coastal Adaptation Identified	Reference
Australia	• **Polarized views in the community regarding the risk of sea level rise** • **Among the vocal portion of population that does not recognize threat from sea-level rise, expectations** that o governments or insurance will compensate landholders for loss of property due to sea-level rise o governments will fund hard protection against rising seas o land owners will be allowed to build defences to protect their property o Private property rights should not be revoked under threat from sea-level rise • **Concerns about fairness about retreat scheme**	Ryan *et al.*, 2011
US, Alaska	• Currently no government agencies with the mandate or authority to address climate-induced relocation • Lack of financial resources locally or from federal sources to pay for relocation from eroding coastal locations • Assimilation into Western society undermines language, culture, and ties to the land and sea and seriously challenges the resilience of Inuit culture (loss of social institutions of support, traditional ecological knowledge etc.)	Adger *et al.*, 2011
Fiji, Rewa Delta	• Lack of awareness of climate change/sea-level rise risks • Lack of understanding of climate change (e.g., confusion with variability, natural cycles) • Short-term planning perspectives • Gap between official climate policy position and actual actions • Spiritual beliefs • Traditional governance structures (e.g., departmental divisions, top-down, consultative approach, non-democratic, hierarchical, exclusive)	Lata and Nunn, 2011
US, Florida Keys	• **Limited information resulting in lack of awareness** • **Lack a formal institutional framework** necessary to shape and execute adaptation measures (network for monitoring key indicators, coordination mechanism across scales of governance, interagency collaboration) • **Insufficient budget for the development of adaptation policies** • Lack of direction and leadership • Lack of perceived importance to public officials • Lack of assistance from state and federal agencies • Lack of public demand to take action • Lack of a legal mandate to account for climate change impacts • Lack of perceived solutions • Opposition from stakeholder groups	Mozumber *et al.*, 2011
Sweden	• Lack of clear institutional frameworks at the national and regional levels (lack of formal, coherent policy from higher level) • Disconnect between technical and strategic planning work related to coastal erosion • Weak vertical administrative interplay (local, regional national) • New proactive integrative policy approach not embraced by those outside the inner circle of erosion managers • Inability to reach general acceptability and organizational mainstreaming of climate concerns • "One-man show" (strong leader in one agency with cemented role and responsibilities) hinders cross-sectoral ownership, learning, and common frames of reference • Professional integrity and inter-departmental rivalry in the way of more	Storbjörk and Hedrén, 2011; Storbjörk, 2010

	integrated and learning-oriented approaches • Time and effort required to change departmental priorities • Differences in professional interests and priorities, administrative cultures and goals • Tensions between different interests, values and priorities (trade-offs) • Short-term planning perspective	
Bangladesh	• Lack of familiarity with the term "sea-level rise" (but clear familiarity with more immediate impacts of SLR) • Perception that SLR and its impacts are not an immediate threat to livelihood • **Preference for retreat option decreased with** o **greater length of attachment with coastal environment** o **lower wealth and social standing (lack of mobility)** o **lower climate familiarity and resiliency (lack of education, job mobility)** o stronger local social network o lower frequency of current coping and adaptive behavior (threshold of acceptability, fear) o higher exposure potential o greater tacit knowledge of SLR impacts (sense of manageability, less fatalism) o greater access to weather information through radio (increasing precautionary actions) o better access to shelters o age	Saroar and Routray, 2010
Pacific Atolls	• Limited adaptation options (due to small land area, high population densities, limited economic resources, economic marginalization due to isolation, and generally low levels of human resource development) • Climate change is still a foreign, unfamiliar concept for many • Language barriers (climate change information predominantly in English) • Climate change impacts perceived as occurring in distant places • Weakening of traditional cultural exchange mechanisms (based on reciprocity) • Loss of traditional ecological knowledge with modernization/ • Westernization of culture in some islands • International emigration is perceived as giving up	Barnett and Campbell, 2010; Adger, *et al.* 2011
US, Northeast	• Regulations restricting fishermen's ability to switch fisheries when stocks of one species are low • Traditional values and independence-mindedness of fishermen limit willingness to change jobs • Limited extent of higher education and professional training limit job mobility • Limited economic alternatives for fishermen in island communities • Past development and land use decisions in coastal areas restrict perceived and economical options • Expectations of protection and government assistance based on historical experience • Ingrained socioeconomic interests in the status quo	Moser *et al.* 2008
US, California	• **Monetary constraints locally and lack of funding from state and federal sources** • **Insufficient staff resources and time** • **Currently pressing issues all-consuming** • Lack of legal mandate • Lack of perceived importance • Lack of perceived solution options	Tribbia and Moser, 2008; Moser and Tribbia, 2006/2007

	• Lack of public awareness and demand • Lack of technical assistance from state or federal agencies • Limited social acceptability • Pressure to maintain status quo and stakeholder opposition • Lack of relevant information or science too uncertain • Lack of analytic capacity to use climate change information for decision-making • Lack of boundary organizations connecting climate change science with coastal management	
United Kingdom	• **Lack of adequate financial compensation to landowners** • **Need to provide compensatory habitats under the Habitats Regulations** • **Lack of public support (esp. locally)** • Lack of political acceptance for the loss of existing defence line and lack of support from public opinion • Insufficient consultation • Potential high cost of managed realignment • Potential loss of terrestrial and freshwater habitats • Managed realignment is ineffective if carried out on a piecemeal basis • Lack of access to or information about suitable funding • Insufficient robustness of flood and coastal defences • Difficulty of recreating an environmentally diverse habitat	Ledoux *et al.*, 2005
Netherlands	• The costs and benefits of the adaptation options can not be estimated with accuracy • For themajority of the options knowledge gaps exist, • data are missing or their reliability is insufficient • methodological difficulties and insufficient quantitative data to run social cost-benefice analysis	De Bruin *et al.*, 2009

Note: For studies that produced quantitative results the top three constraints are presented in **bold**.

Table 5-8: Positive synergies and tradeoffs between selected coastal adaptation and mitigation options.

Measure or Option	**Positive Implications for Mitigation**	**Positive Implications for Adaptation**	**References** *[REQUEST TO OTHER CHAPTER CO-AUTHORS AND REs FOR NEW REFS. ALSO: WE MAY BE ABLE TO ADD CONFIDENCE LANGUAGE TO THESE, IF DESIRED/ABLE TO DO SO.]*
Coastal seagrass and tidal marsh restoration	Increased carbon storage[a]	Storm buffer, species habitat, fish nursery	Whiting and Chanton, 2001; Turner *et al*., 2005; Chmura, 2011; Kennedy and Björk, 2011
Mangrove restoration species	Carbon storage[a]	Habitat and species protection, flood control, soil preservation	Alongi, 2002; Kristensen *et al*., 2008; Bouillon et al., 2011
Reduction/cessation of off-shore oil production	Reduction in liquid fuel-related GHG emissions	Reduced risk of oil spills, reduction of stresses on marine/coastal eco-systems; variable socio-economic impacts on human communities and public health (and thus on vulnerability)	O'Rourke and Connolly, 2003
Increased urban tree cover	Increased carbon storage, shading resulting in lower cooling energy demand	Increased shading, lesser urban heat island, better air quality	Nowak and Crane, 2002; Nowak *et al*., 2006; Pataki *et al*., 2006; Chen *et al*., 2011
Adaptation Measure or Option	**Potential Negative Implications for Mitigation**		
Desalinization, increased water reuse, groundwater banking and pumping, and inter-basin water transfers (if fossil fuel-based)	Higher ongoing energy consumption to fuel water pumping, storage and transfer processes, increase in GHG emissions		US DOE, 2006; Stokes and Horvath, 2006; Lofman *et al*., 2002
Relocation of infrastructure and development out of coastal floodplains	Increase in one-time GHG emissions due to rebuilding of structures; possible increase in sprawl and ongoing transportation-related emissions		Biesbroek *et al*., 2009
Building of large dams or massive coastal protection structures	Increased (one-time) energy use and GHG emissions related to construction (cement)		Boden *et al*., 2011
Mitigation Measure or Option	**Potential Negative Implications for Adaptation**		
Reforestation or forest conservation	Negative consequences for rural livelihoods (thus potentially increased vulnerability) if forest ownership and management are not held by local community		Chhatre and Agrawal, 2009
More compact coastal urban design	Potential increase in urban heat island, increased development in floodplains (if present)		Giridharan *et al*., 2007

Offshore renewable energy development	Potentially additional drivers on near- and offshore coastal and marine ecosystems and species	Gill, 2005; Boehlert and Gill, 2010
Rapid switch to low-or no-GHG energy sources	Higher energy prices may slow economic development and disproportionately affect low-income populations, increasing their vulnerability or reducing the resources available for adaptation	Tol, 2007

Source: Adapted from Moser (2011) and references cited in Table;
Notes: [a] – DeLaune *et al*. (2011) suggested this benefit may be smaller than previously thought given the losses of sequestered carbon in soils that erode during coastal storms.

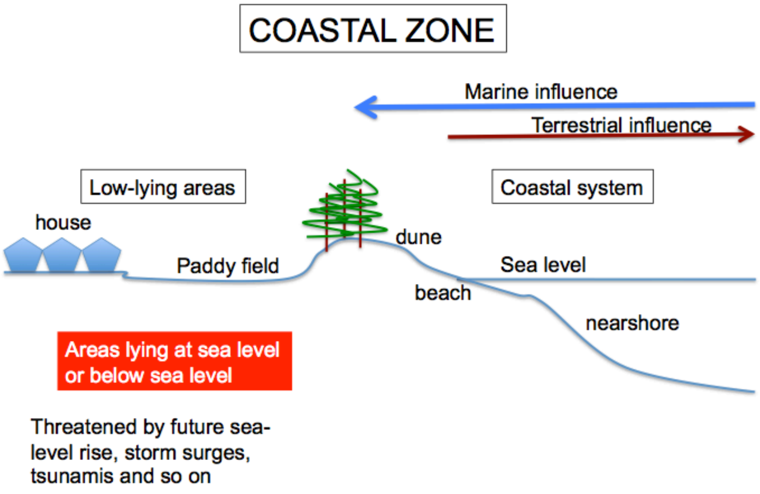


Figure 5-1: Coastal zone.

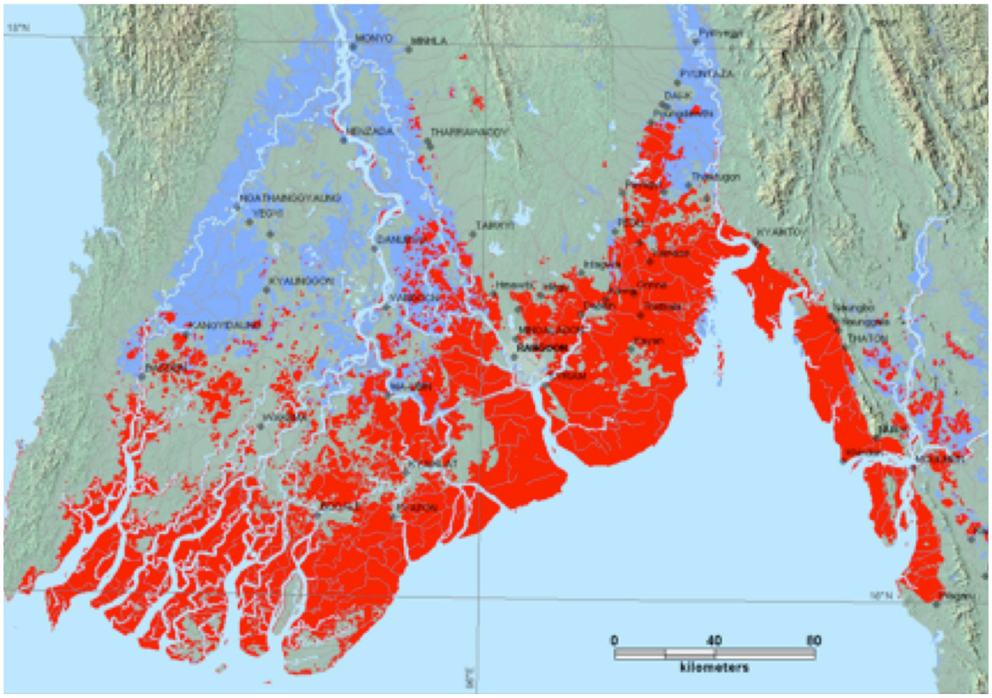


Figure 5-2: The intersection of inland and storm surge flooding. Red shows May 5, 2008 MODIS mapping of the tropical cyclone Nargis storm surge along the Ayeyarwady Delta and to the east, Myanmar. The blue areas to the north were flooded by the river in prior years. (From Brakenridge *et al.*, 2012, submitted in 2011).

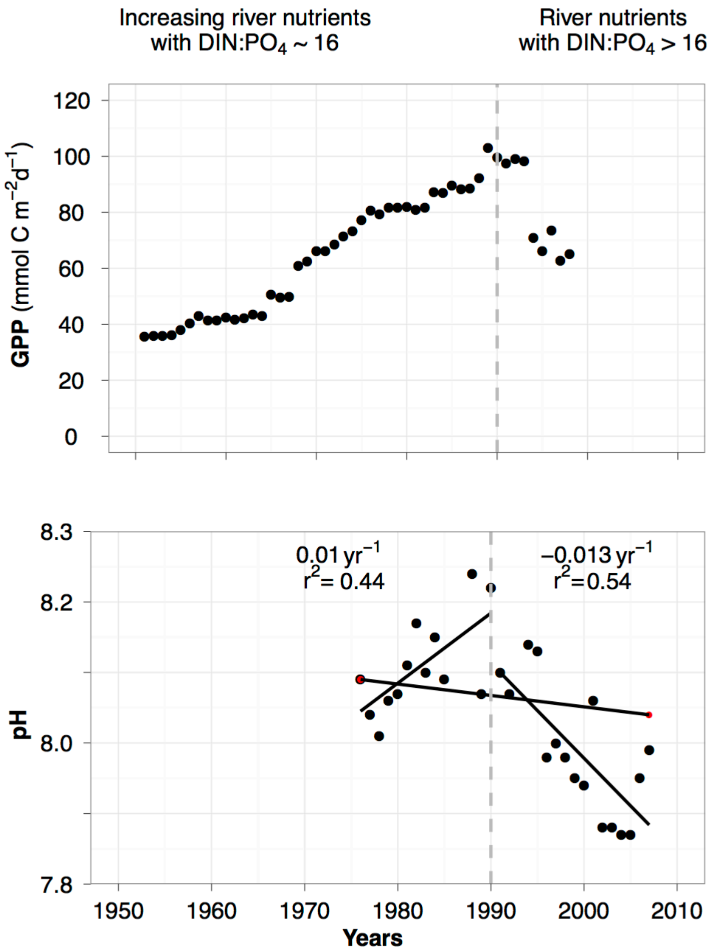


Figure 5-3: Time series of modelled gross primary production (A; Gypens *et al*., 2009) and measured pH_T (B) at a fixed station in the southern North Sea (Borges, 2011). PH is expressed on the total scale. Shown is the regression before and after 1987 (solid lines) and the change in pH expected from increased atmospheric CO_2 alone (broken line).

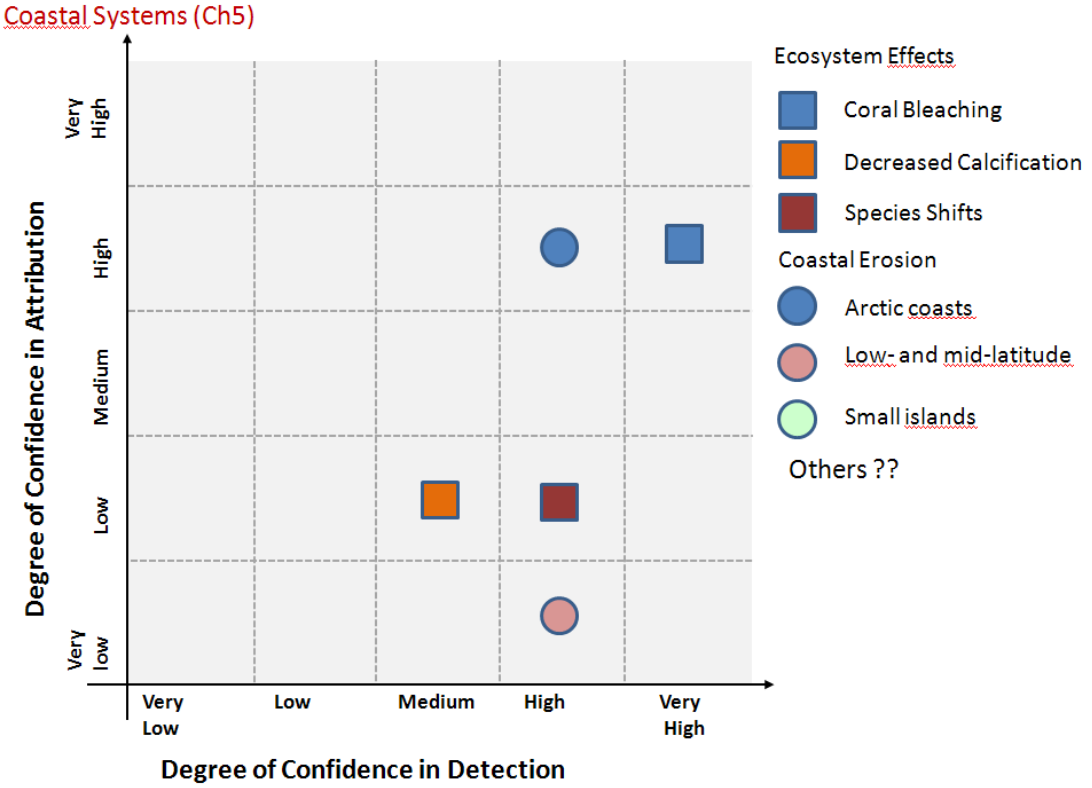


Figure 5-4: Confidence in Detection and Attribution of observed impacts for coastal systems. Values will be inserted at right positions post FOD, and iterated across chapters to ensure consistency. [Combined one for all coasts still to be developed.]

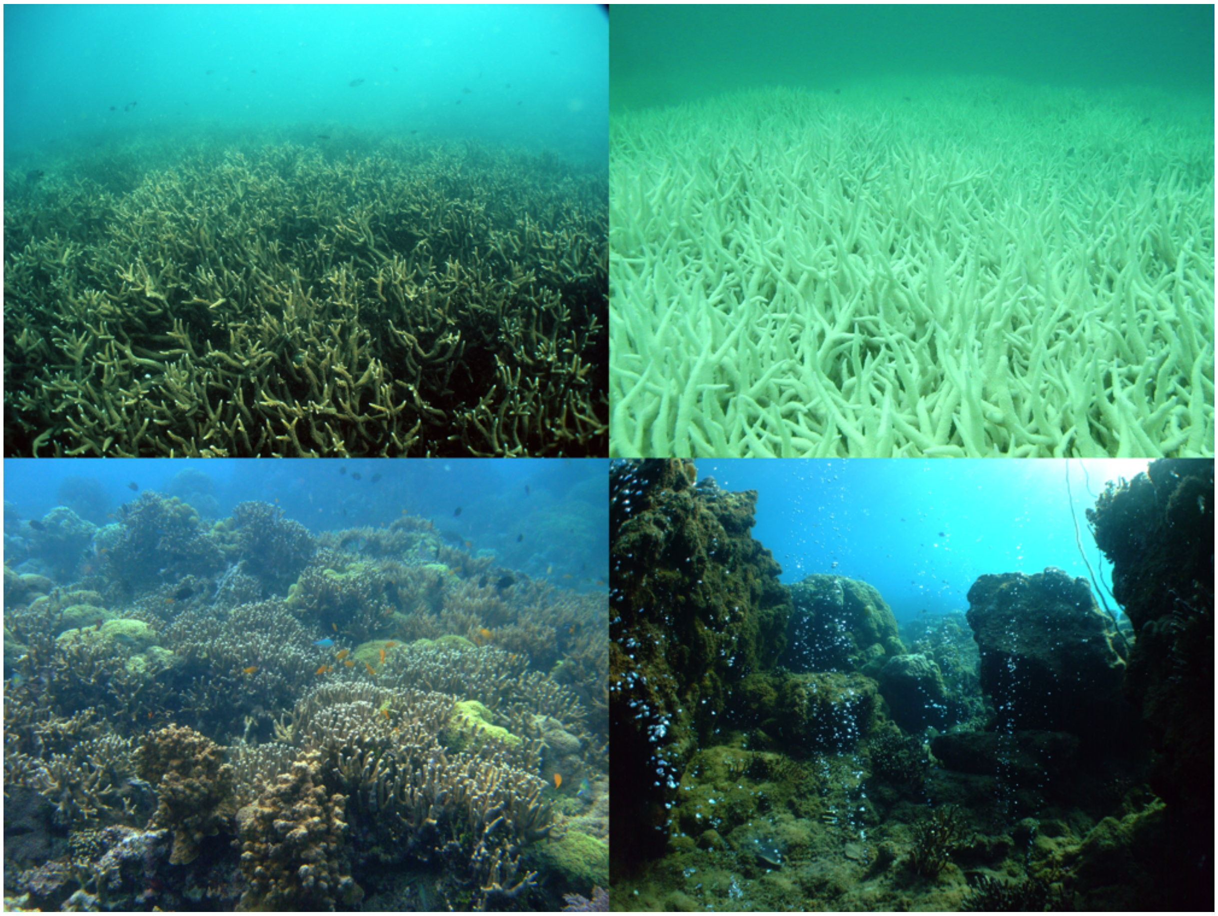


Figure 5-5: The same coral community before and after a bleaching event in February 2002 at 5 m depth, Halfway Island, Great Barrier Reef. Coral cover at the time of bleaching was 95% almost all of which was severely bleached, resulting in mortality of 20.9% (Elvidge *et al*. 2004). C and D: three CO_2 seeps in Milne Bay Province, Papua New Guinea show that prolonged exposure to high CO_2 is related to fundamental changes in coral reef structures (Fabricius *et al*., 2011). Coral communities at three high CO_2 (median pH_T 7.7, 7.7 and 8.0), compared with three control sites (median pH_T 8.02), are characterised 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 pH values below 7.7. Photo credit: R. Berkelmans (A and B) and K. Fabricius (C and D).

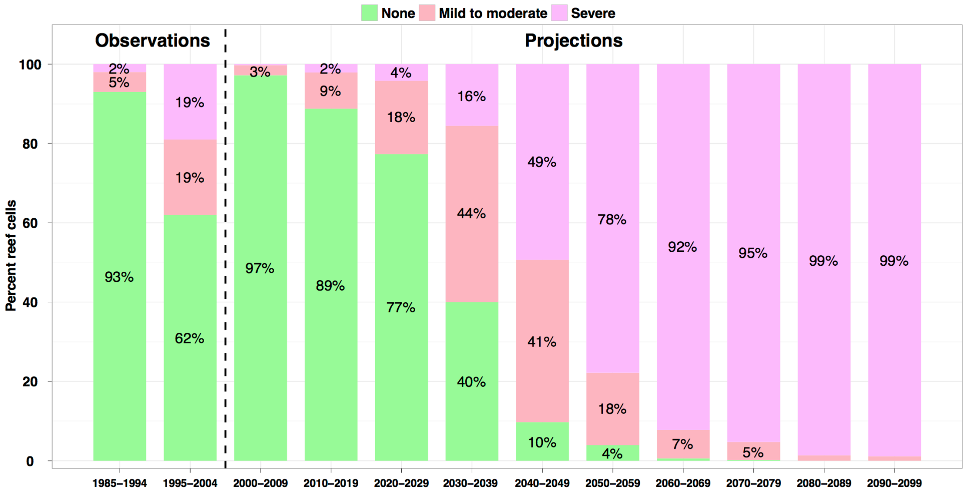


Figure 5-6: Percent of reef locations (1°x1° latitude/longitude cells which have coral reefs) that experience no bleaching (green), at least one mild bleaching event (reddish-brown), or at least one severe bleaching event (purple) for each decade. Observed bleaching events are summarized from the ReefBase 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 standard degree heating month formula (Teneva *et al*., 2011). The labels of values ≤ 1% are not shown.

Figure 5-7: Paradigm shift in adaptation to rising sea levels in the Netherlands: Source: Stive *et al*., 2011.