Chapter 5. Coastal Systems and Low-Lying Areas

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Executive Summary

[Need to develop stronger messages]

Based on 2000 estimates, the land of less than 10 m in elevation along the world's coasts constitutes 2% of the world's land area but contains 10% of world's population (600 million) and 13% of world's urban population (360 million). Within this narrow low-lying belt and its nearshore waters are distinct coastal ecosystems producing unique goods and services, but are increasingly impacted by climate change and accelerated sea-level rise.

Of 136 port cities around the world each with >1 m inhabitants in 2005, 40 million inhabitants are exposed to a 1 in 100 year coastal flood event. By 2070 this would trebled to 150 m. Of the top 10 exposed cities in terms of exposed population, the majority are in Asia. Many of the Asian cities are also located near to the Pacific Ring of Fire and several are severely affected by subsidence.

The coasts are increasingly exacerbated by human activities where population growth, socio-economic growth and urbanization are most important drivers. They are now 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 as well as human activities.

Within the near future, the 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. Non-climatic stressors include population and development increases in vulnerable areas, pollution from land use and industrial activities, and threats from infectious diseases.

Sea-level rise of more than one metre by the end of this century poses the single major threat to the coastal areas. More than 200 million people are already vulnerable to flooding by extreme sea levels worldwide and this population could be increased by a factor of 4 due to rising population and coastward migration, especially in Asia.

New information is available on the likelihood of increased rates of ocean acidification. Although acidification is being addressed through international mitigation efforts, coastal policies need to address ocean acidification at the local and regional levels. More detailed and useful information would be required for the implementation of such policies**.**

Of various approaches to adaptation, coastal zone management has developed to the point where it is the major framework for adaptation to climate change. Its integrated framework has made possible the achievement of the various 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.

An extensive information is available on regional and global costs of adaptation; new studies have emerged using a wider range of scenarios, expanded on the impacts considered, and integrated 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 data, and knowledge sharing platforms, policymakers should be able in a better position to assess local areas.

5.1. Introduction: Scope, Summary, and Conclusion of AR4 and Key Issues

This chapter presents an updated picture of the impacts of climate change and sea-level rise on the coasts and low-lying areas (henceforth coasts) since the AR4. With a new chapter on oceans in the AR5 the physical boundaries between coasts and oceans are sometimes not clear even if one wishes as there is no one acceptable definition of the coastal area. Some countries have legislated boundaries for the seaward boundary of their coasts whereas the boundary of the catchment area is often considered the landward limit. In Netherlands, the ‘coast’ is interpreted in broad terms to include the entire low-lying area of the country (Delta Commission, 2008). The MEA (2005) considers the coast to be between the middle of the continental shelf at depths <50 m below MSL and the 50 m high tide level or 100 km from shore.

Globally, the coasts consists of 4.1% of the terrestrial earth’s surface (MEA, 2005) and are an significant zone of interaction between human and natural environment. The coasts contain a variety of coastal ecosystems such cliffs, beaches and barriers, deltas and estuaries, mangroves, salt marshes, corals, and sea grasses. The interacting important and distinctive economic activities in the coastal area include ports and harbours, beach and island tourism, and inshore fisheries to name a few.

In terms of elevation, the Low Elevation Coastal zone (LECZ) of less than 10 m of the Earth above sea level consists of 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. 65% of cities more than 5 million each are in this zone including disproportionate numbers of small island states and densely populated megadeltas (McGranahan *et al*., 2007).

The coasts chapter in AR4 gave very clear statements on the population and economic activities in the coastal zone exposed to climate and sea-level rise of 0.6 m during this century. Physically, the coastal ecosystems are mainly affected by higher sea level, increasing temperatures, increased extreme events and ocean acidification. Human pressures continued to increase their stress on the coasts with rapid urbanization in coastal areas and growth of megacities with consequences on the coastal resources. The AR4 chapter offered a range of adaptation measures both carried in the developed and developing countries, many under the CZM framework. Various issues were discussed to increase the adaptive capacity of coastal communities or increase the resilience.

A number of key issues related to the coasts have arose since the AR4. There is scope for a more integrated perspective with the coastal systems and their functions and services linked landward to the watersheds and seaward to the seas and oceans. With a much higher sea-level rise exceeding one metre in this century, there are new and increased concerns especially for coastal cities, deltas and low-lying states. While erosion from a higher sea-level rise is expected the relationships have to be better established with beaches, barriers, mangroves and reefs not globally and regionally but also at local scales. More is known about ocean acidification and its impacts on coasts but not definite to quantify the consequences in future. In general, the main concerns would be ocean acidification, sea surface temperature, sea ice, sea level rise and coastal systems, and coral reefs (Campbell *et al*., 2009).

The human drivers continue relentlessly to put pressure on the coasts resulting in increased degradation and the issue of coastal squeeze becoming more critical. While adaptation has been accepted the relative costs of adaptation have to be worked out and more information on the constraints and limitations and where to apply. A wider range of approaches and frameworks such as integrated, ecosystem-based, stakeholder-based, are bottom-up are being used in adaptation. Future land-use in the coastal area will be dominated by climate change effects and these would be quite profound over the next 50 years. Sea level, storm surges and flooding, erosion, coastal habitats, managed realignment are likely to be the key drivers of coastal land-use (Hadley, 2009).

This chapter hopes also to provide a more updated assessment of risks to the coasts since the AR4. Recent studies and knowledge of ice-sheet dynamics and glacier melt have indicated a larger sea-level rise. Most studies suggest the frequency of strong tropical cyclones in recent decades to increase globally in association with increases in SST. While the attribution of warming to anthropogenic GHG emissions is robust the detection and attribution of changes in other meteorological quantities are emerging. Of particular interest is the attribution of changes in non-meteorological quantities such as hydrological and ecological measures and changes in risk of extreme weather events to anthropogenic emissions (Stone *et al.,* 2009).

5.2. Coastal Systems Functions, Goods, and Services

The world's total 1,634,701 km of coastline (Burke *et al.,* 2001) includes a large variety of geomorphological features, weather regimes and biomes. The coasts include soft-shores (beaches and dunes), rocky shores and cliffs, hilly or flat coastal plains, narrow or wide coastal shelves and a wide variety of wetlands (estuaries, saltmarshes) and deltas (Schwartz, 2005). The heterogeneity in terms of weather and geomorphological characteristics results in an equally large variety of biomes found along the coasts. On the terrestrial part there are different kinds of forests (tropical and temperate, evergreen and deciduous), shrubs, and savannas, while the aquatic ecosystems comprise mangroves, saltmarshes, estuaries, coral reefs, sea grasses and the coastal shelf (Burke *et al.,* 2001).

Ecosystem services are the benefits people obtain from ecosystems. These include provisioning; regulating; cultural services that directly affect people and supporting services needed to maintain the other services. Provisioning services are the products obtained from ecosystems; regulating services are the benefits people obtain from the regulation of ecosystem processes while cultural services are nonmaterial benefits people obtain through spiritual enrichment, recreation and aesthetic experiences, among others. These categories of services have relatively direct and short-term impact on people. However, supporting services have indirect impacts on people and are either indirect or occur over a very long time. They are necessary for the production of all other ecosystem services (MA, 2005; de Groot et al. 2002).

Coastal ecosystems provide an ample range of services highly valuable to human society including food, resources, construction materials, biodiversity, protection against extreme events, water and others. They also offer a highly valued habitat for recreation and tourism.

[INSERT TABLE 5-1 HERE
Table 5-1: Ecosystems goods and services offered by coastal ecosystems.
[Note: Last column is to be removed and table to be revised]

Existing assessments of economic value of goods and services provided by coastal ecosystems of the world, including natural (terrestrial and aquatic) and human-transformed ecosystems, estimate values between 63% and 77% of the world global ecosystem services value (Costanza *et al.,* 1997; Martinez *et al.,* 2007).

5.3. Climate and Non-Climate Impacts on Coastal Ecosystems

There is an ample range of natural and human-induced drivers that directly or indirectly cause changes in ecosystems and their services including climate change. Moreover, increasing human pressure exacerbates the impact of climate change on coasts. Therefore, understanding the factors causing changes in coastal ecosystems and ecosystem services and their multiple interactions, and obtaining a quantitative assessment of their impacts is crucial to the design of interventions that may enhance positive and minimize negative impacts. Preliminary assessments IPCC (2007) have already pointed out that coasts are experiencing the adverse consequences of hazards raleted climate chage. This new assessment builds on and develops these insights in the AR4 by considering new knowledge on how coastal systems may respond to climate change, the effects on coastal ecosystem services and the implications to the human system.

5.3.1. 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 steep environmental gradients, especially in the intertidal area where environmental challenges are posed by both aquatic and aerial climatic regimes (e.g., temperature desiccation). Species can be eliminated from intertidal habitats by increases in water temperature, changes in upwelling regimes, oxygen levels or when the upper limit of a prey species is squeezed down to the upper limit of its predator. Helmuth et al. (2006) has reported shifts of range edges of many intertidal species of up to 50 km per decade, much faster than most recorded shifts of terrestrial species. However, some species to not exhibit any change in their geographical distribution (e.g., Rivadeneira & Fernández, 2005; Poloczanska *et al.,* 2011) in the past decades. Variables other than stressors, such as local or basing scale hydrographic features or the lack of suitable bottom types, could explain the lack of ranges shifts (Helmuth *et al.,* 2006).

Changes in current patterns and increased storminess can dislodge benthic invertebrates affect the distribution of propagules and recruitment. For example, Carrington (2002) suggested that, with increased hurricane activity in the North Atlantic, it is likely that mussels will suffer more frequent and more severe disturbances compared to those that occurred during 1971–1994.

Sea cliffs are ubiquitous, occurring along about 80% of the ocean coasts (Emery & Khun, 1982). Where shores with a shallow slope occur beneath cliffs or where the natural sea shore has been covered by an artificial sea wall, sea level rise will squeeze the tidal range into a smaller horizontal extent, reducing intertidal area, steepening the shore profile, and increasing the proportion of vertical substrata at the expense of horizontal surfaces (Jackson & McIlvenny, 2011). It will lead to the expansion of assemblages dominated by encrusting coralline algae and grazing gastropods, and the reduction of abundance of filamentous forms and barnacles (Vaselli *et al.,* 2008)
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). Associated with the declining pH is a shift in ecosystem structure from a mussel to an algal-barnacle-dominated community. Model projections also suggest an interaction between temperature and lower pH to control the distribution of the barnacle *S. balanoides* causing a local population to die out 10 years earlier than would occur if there was only global warming and no concomitant decrease in pH (Findlay *et al.,* 2010). Data collected in rocky shore stations near CO_2 vents showed a 30% reduction in species numbers (notably calcifiers) at pH levels close to those expected in 2100 (pH_T of 7.8-7.9), with the caveat that 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.

5.3.2. Beaches and Sand Dunes

Sandy beaches and sand dunes are valuable ecosystems under threat (Defeo *et al.,* 2009). These threats come from human development and sprawl on their landward edge and climate change from the marine side (Schlache *et al.,* 2008). Climate change impacts on beaches and sand dunes through sea level rise, changes in storm and wave regimes and altered sediment budgets (Jones *et al.,* 2008; Defeo *et al.,* 2009). These impacts lead to beach erosion and recession (Slott *et al.,*2006), which is already affecting 70% of beaches globally (Bird, 2000). Reduced coastal calcification rates with ocean acidification may also reduce the supply of biogenic materials to beach and dune ecosystems and further exacerbate the impacts of sea level rise on beach erosion (Defeo *et al.,* 2009).

Warming of sandy beaches can also affect organisms that use them as habitat. In particular, records show a warming trend of turtle nesting sites that may affect hatching success and sex determination in turtles (e.g. Hays *et al.,* 2003). Many turtle populations are already affected by warming of their nesting sites in sandy beaches. Populations of turtles in southern parts of the United States are likely to become ultra-sex biased with as little as 1°C of warming and experience extreme levels of mortality if warming exceeds 3°C (Hawkes *et al.,* 2007).

5.3.3. Estuaries

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.

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 is a natural process, but long-term global warming, climate-related precipitation changes and altered riverine 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).

Estuarine systems 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 will have major consequences for 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 contintal 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 are 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.

5.3.4. Temperate Lagoons

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 (see Box 5-1). 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. Anthony et al. (2010) projected that climate change will generate sediment redistribution as well as increased erosion and shoreward migration of barriers. The flushing rate, which is a key parameter controlling biogeochemical processes such as primary production (Smith *et al.,* 2005b; Webster & 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).

Temperate coastal lagoons often host salt marshes, seagrasses and macroalgae (see sections 5.3.5, 5.3.8 and 5.3.9) and aquaculture. Due to their restricted exchange with the adjacent ocean, they are particularly vulnerable to eutrophication. 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 & Chauvaud, 2002), their demise could increase the occurrence and magnitude of eutrophication (Lloret *et al.,* 2008).

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 stressors could impact fisheries. For example, it was 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 was also shown to generate major changes in food webs (Jeppesen *et al.,* 2007) but the global impact on lagoon fisheries remains uncertain.

5.3.5. Salt Marshes

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 defense 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 are 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 sealevel 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) 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). 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 sealevel rise (Kirwan and Blum, 2011).

5.3.6. Mangroves

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 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). Accelerated 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. 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% y^{-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 forest 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 y^{-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).

5.3.7. Coral Reefs

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Box 5-1. Case Study: Coral Reefs – Bleaching and Acidification (to be revised)

Coral reefs harbour a very high biodiversity and are sources of key services to humans. Almost half of all coral reefs experience medium high to very high impact of human activities (Halpern *et al.,* 2008). Many coral reefs have been subject to widespread degradation since the 1970. For example, in Jamaica, coral abundance 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). Most of the human-induced disturbances until the early 1980s were at the local scale (e.g., coastal development, pollution, nutrient over-enrichment and overfishing) but climate-related disturbances have become more obvious in the past decades and will be increasingly prominent in the future.

Increased temperature triggers bleaching of scleractinian corals which are key reef ecosystem engineers. Bleaching is essentially caused by the loss of endosymbiotic algae which live in the coral tissues and play a key role in their physiology, especially feeding (Baker *et al.,* 2008). Mass coral bleaching has occurred in association with episodes of elevated sea temperatures over the past 30 years and 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). Coral bleaching is not always fatal. 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 stressors. Recovery from the 1998 global bleaching event was significant in the Indian Ocean, absent in the western Atlantic and locally variable elsewhere (Baker *et al.,* 2008). Dramatic mass-mortalities occur when recovery is limited.

The increase in temperature is also suspected to have caused a poleward range expansions of corals since the 1930s at a speed of up to up to 14 km y^{-1} along the coasts of Japan, with no evidence of southward range shrinkage or local extinction (Yamano *et al.,* 2011). Although continued poleward shift will be limited by light availability at some point (Hoegh-Guldberg, 1999), small range shifts may aid in developing new refugia against future extreme temperature events.

Ocean acidification 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 global warming (Kiessling, 2011). Experimental evidence shows that lower pH decreases the rate of calcification of most reef-building corals and coralline algae (Anderson *et al.,* in press) and enhances the competitiveness of seaweeds over corals (Diaz-Pulido *et al.,* in press).

Retrospective studies have not provided clear outcomes, partly because attribution to stressors has proven difficult. Although perturbation experiments suggest that coral calcification may have decreased since the beginning of the industrial revolution, clear evidence has not been found yet in field samples. Some (e.g., De'ath et al. 2009, Manzello, 2010), but not all (e.g., Bessat & Buigues, 2001; Helmle *et al.,* 2011), retrospective studies show decreasing trends in calcification for the past several decades but whether the decreases are due to ocean acidification, some other environmental stressors (e.g., warming), or a combination of stressors remains unclear. Observations near CO_2 vents (Fabricius *et al.,* 2011) have shown that ocean acidification has dramatic impacts in the field even though reef-building corals are not completely eliminated at the pH level expected at the end of the century and the rate of calcification of the one of the resistant species exhibits small changes relative to pH. The taxonomic richness of hard corals was reduced by 39%, the cover of fleshy non-calcareous macroalgae doubled and seagrass increased eight fold, the cover of crustose coralline algae was reduced seven fold, and the density and taxonomic richness of hard coral juveniles were reduced more than 2-fold.

Future impacts of increasing temperature and decreasing pH will be regionally variable but a large decline of coral cover is highly likely (for example in the Hawaiian Archipelago; Hoeke *et al.,* 2011). A global model that takes in consideration both the loss of coral cover due to bleaching and the effect of ocean acidification on coral calcification has shown that by the time atmospheric partial pressure of CO_2 will reach 560 ppm all coral reefs will stop growing and start to dissolve (Silverman *et al.,* 2009). Veron et al. (2009) have argued that atmospheric CO_2 should be stabilized at 350 ppm to prevent catastrophic decline in coral reefs due to warming and acidification.

Current rates of coral growth and reef accretion appear to be able to keep up with present rate of sea level rise but this may be compromised with a decreased rate of accretion driven by climatic and non-climatic stressors, especially if the rate of sea level rise increases. There is geological evidence that coral reefs have problems keeping pace with sea level rise exceeding 30 mm y^{-1} (Blanchon *et al.,* 2009). Published evidence supports the hypothesis that coral infectious diseases are emerging in response to stressors such as ocean warming, altered rainfall, increased storm frequency, sea level rise, altered circulation, and ocean acidification (Sokolow, 2009).

Recent analyses suggest that one third of all coral species may be at risk of extinction (Carpenter et al. 2008) and reef fish are also vulnerable although less from climatic stressors than from overfishing (Graham et al. 2011).

However, although less well documented, noncoral benthic invertebrates are also at risk (Przeslawski *et al.,* 2008). Hoegh-Guldberg (2011) has listed the benefits of corals reefs for human societies. They include provisioning functions (food, construction material, medicine), regulating functions (shoreline protection, maintenance of good water quality), cultural functions (e. g., tourism) and supporting functions (oxygen supply). The combined effects of climatic and non-climatic factors paint a grim picture for the future of coral reefs and the benefits that they provide if the magnitude of these stressors continues to increase at the present rate.

_____ END BOX 5-1 HERE _____

5.3.8. Seagrass Meadows

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 & 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% $year^{-1}$ 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 & 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 & 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 & 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 & 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 & 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 *Posidonia oceanica* shoots, with shoot mortality rates increasing by 0.022 $year^{-1}$ 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). These observations indicate that seagrass meadows are already under stress due to realised climate change and predict that seagrass meadows will experience a decline with further warming (e.g. Marbà & Duarte, 2010, Rasheed & 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. Yet, a lack of reports on the dynamics of seagrass meadows at high latitudes preclude the assessment of whether the expected poleward expansion is already occurring (Duarte, 2000).

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

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 & 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 render shorelines more vulnerable to erosion due increased sea level rise and increased wave action.

5.3.9. Macroalgal Beds

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 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 are been documented for warm-water species 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).

Ice scouring often limits macroalgal biomass in polar coastal areas (Gutt, 2001). A reduction in sea ice may, therefore, allow the growth of macroalgae in some of these areas. However, foliose macroalgae often grow under sea ice, particularly in Antarctica, and loss of sea ice cover leads, therefore, to loss of this component.

Macroalgae are also affected by increased CO_2, which is expected to lead to enhanced photosynthetic rates (Wu *et al.,* 2008). Hence, 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 CO_2 enriched reefs near volcanic areas suggests that macroalgal cover increases at high CO_2 (Fabricius *et al.,* 2011).

Contrasting response of macroalgae and corals to climate change have 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).

5.4. Sensitivity to Climate Change

The most general definition of the coastal zone is the 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, lead 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 as well as 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).

“Stressor” is used here to describe any environmental or biotic factor that exceeds natural levels of variation (Breitburg *et al.,* 1999). Climate-related stressors 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. For example, global mean-surface pH_T (on the total scale) is expected to decrease from 8.18 to 7.82 (Orr, in press) whereas the range of variation is much larger in coastal systems (e.g., Feely *et al.,* 2010). 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 stressors.

5.4.1. Marine, Terrestrial, and Atmospheric Stressors

5.4.1.1. Sea-Level Rise

Sea level change impacts are due to relative changes as a result of large-scale basin-wide, and global-scale changes in sea levels and land levels, as well as regional and local changes (Woodwarth *et al.,* 2010). 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).

Current global sea level rise is x.x ± x.x mm yr-1 based on the 17-year satellite altimeter record, and tide gauge measurements give a consistent result over the same period. The overall pattern of sea level change from 1993 to 2010 is similar to the pattern from 1993 to 2003 in AR4. [WGI AR5 related to WGII]. There is also major concern about higher extreme sea levels due to more intense storms surges and waves superimposed on these mean rises. So far, it is found that increases in mean sea level are likely responsible for the observed increase in extreme sea level events and storm surges. [WGI AR5 related to WGII].

More than 200 million people are already vulnerable to flooding by extreme sea levels worldwide and this population could be increased by a factor of 4 due to rising population and coastward migration (Nicholls, 2010), especially in Asia.

5.4.1.2. Wind

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). This may have important consequences on wave generation.

5.4.1.3. Storm Surges and Wave Climate

Long-term 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). 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 (Izaguirre *et al.,* 2011). This trend in extreme conditions of increasing wave height at high latitudes have been confirmed by Young *et al.* (2011) based on a 23-year database satellite altimeter. More neutral conditions are found in equatorial regions and no clear statistically significant trends for mean monthly values.

5.4.1.4. Temperature Rise

The global rate of ocean warming is around X.X °C per decade during the period 1967-2009 (Rhein *et al.,* WGI AR5) but there is a lot of spatial differences at the regional level, especially in coastal areas. For example, 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 & 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 & Bruno, 2010).

5.4.1.5. Ocean Acidification

The oceans absorbs 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.,* in prep.). These changes are collectively referred to anthropogenic ocean acidification (see also the glossary) and are detectable. Rhein et al. (in prep.; Table 3.1 and Fig. 3.16) provide evidence of pH changes of -0.0010 to -0.0018 pH unit y^{-1} in the open ocean. 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 a more active control of circulation (Feely *et al.,* 2008), deposition of atmospheric nitrogen and sulphur (Doney *et al.,* 2007), carbonate chemistry of the freshwater supply (Gypens *et al*., 2011), as well as inputs of nutrients and organic matter which control primary production (counteracting ocean acidification) and respiration (promoting ocean acidification). There are few time series data available in the coastal ocean (Wootton *et al.,* 2008; Provoost *et al.,* 2010). North Sea surface pH increased until 1987 and decreased since then at a rate larger than in the open ocean (Provoost *et al.,* 2010), illustrating the fact that ocean acidification generated by the uptake of anthropogenic CO_2 can be mitigated or enhanced by coastal biogeochemical processes (Borges and Gypens, 2010; Feely *et al.,* 2010).

5.4.1.6. 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).

5.4.1.7. Runoff

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 the last decade due to human population growth and has increased global runoff 0.08 mm y^{-1}(Piao *et al.,* 2007). River runoff is generally higher and more variable because of lowered retention due to land clearing (link to other chapters).

Elevated carbon dioxide levels have been suggested to increase runoff via the direct effect of carbon dioxide on evapotranspiration by terrestrial plants (Gedney *et al.,* 2006), but another modeling study including the effect of carbon dioxide fertilization on plant growth predicted a decrease in runoff instead (Piao *et al.,* 2007).

The hydrological cycle is intensified with global warming (Huntington, 2006; link to other chapter), 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 and other pulsed discharges of freshwater into marine systems may cause wiping out of 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.

Eutrophication problems may thus occur more offshore due to pulsed freshwater delivery. Changes in runoff have also consequences for the hydrology and hydrodynamics of coastal systems including increased vertical salinity gradients and thus less efficient vertical mixing. This may have consequence for many biogeochemical processes and ecosystem functions: e.g. hypoxic areas may increase.

5.4.2. Non-Climate Stressors

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

5.4.2.1. Hypoxia

The excessive input of nutrients generates coastal eutrophication and the subsequent decomposition of organic matter lead to a decrease in the oxygen concentration (hypoxia). 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 and 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 in so-called “dead zones”, the number of which has approximately doubled each decade since 1960 (Diaz and Rosenberg, 2008), but does not generally reduce fisheries landings below what would be predicted from nitrogen loadings (Breitburg *et al.,* 2009).

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

5.4.2.3. Habitat Loss

The conversion of wetlands, intertidal and shallow subtidal habitats to make way for coastal development such as 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).

5.4.2.4. Overexploitation

Seafood as the primary protein source for many human population and marine-derived compounds are key products for various industries. Overexploitation is a major threat to marine species and ecosystems.

[Notes for subsequent revisions]

- UV is not covered in this draft. Although it is likely not a major stressor, it could at least be mentioned.
    - Conde D., Aubriot L. & Sommaruga R., 2000. Changes in UV penetration associated with marine intrusions and freshwater discharge in a shallow coastal lagoon of the Southern Atlantic Ocean. Marine Ecology Progress Series 207:19-31.
    - Häder D. P., Kumar H. D., Smith R. C. & Worrest R. C., 2007. Effects of solar UV radiation on aquatic ecosystems and interactions with climate change. Photochemical Photobiological Sciences 6:267-285.
- Relatively little use was made of Harley C. D. G., Hughes A. R., Hultgren K. M., Miner B. G., Sorte C. J. B., Thornber C. S., Rodriguez L. F., Tomanek L. & Williams S. L., 2006. The impacts of climate change in coastal marine systems. Ecology Letters 9:228-241.

[To be considered:]

- River plumes show different behavior, depending on the carbonate chemistry of the freshwater end-member. Rivers with low total alkalinity can be undersaturated with respect to calcium carbonate (Salisbury *et al.,* 2008; Chierici and Fransson, 2009) whereas plumes generated by rivers from the souuthern Bight of the North Sea exhibit high total alkalinity and are supersaturated with respect to $CaCO_3$ (Gypens et al, 2011).
- Many marine organisms, including economically-important ones spend part of their life cycle in coastal ecosystems. Their alteration together with changes in ocean currents could influence the distribution of fish and shellfish between coastal waters and open sea with unknown consequences for species recruitment (Philippart *et al.,* in press).
- Coral reefs (Box 5-1): For example, they produce 10-12% of the fish caught in tropical countries, and 20-25% of the fish caught by developing nations (Garcia & Moreno, 2003).]

5.4.3. Sensitivity of Coastal Ecosystems

Halpern *et al.* (2008) have shown that coastal ecosystems, which are subject to both land- and ocean-based anthropogenic drivers, are those experiencing the greater cumulative impact of human activities. Perhaps not surprisingly, 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.

Extreme climate events produce simultaneous changes to the mean and to the variance of climatic variables over ecological time scales. A relatively large number of studies have investigated how ecological systems respond to changes in mean values of climate-related but the combined effects of mean and variance are poorly understood. For example, there is evidence that the mean intensity and temporal variance of aerial exposure, a type of disturbance projected to occur with changing climate conditions, interactively affect assemblages of algae and invertebrates of rocky shores and that high temporal variance may mitigate the ecological impacts of projected climate changes (Benedetti-Cecchi *et al.,* 2006).

Although the following sections will show ample evidence of the impacts of climatic and non-climatic stressors on coastal systems, a precise understanding of their sensitivity on decadal timescales is hampered by several impediments.

- While numerous studies have reported the effects of individual stressors on coastal organisms, the physiological and ecological responses of different stages of their life history and effects at the community level are generally much less understood.
- The cumulative effects of multiple stressors can be synergistic (additive or multiplicative) or antagonistic (the effect of one driver being mitigated by the change of another driver). Yet, they are poorly known, especially at the community level (Crain *et al.,* 2008), mostly due to experimental and logistic challenges.
- The understanding of the indirect effects of climate change, for example along the food web, is still limited. The complexity of many coastal food web and the nonlinear nature of diverse interactions between stressors make predictions based on short-term studies of a small number of species are likely to be misleading.
- Conclusions based on purposeful perturbation experiments are plagued by the short duration which does not account for evolutionary processes to project the patterns and rates of response to climate change. Yet such changes, although poorly documented, have been reported in some coastal organisms such as mollusks (Hellberg *et al.,* 2001).

When a population of organisms experiences an environmental challenge outside the normal range of phenotypic variability, they may respond in one of the three ways: migration, adaptation or extinction (Clarke, 1996). Range shifts provide key information on how species and communities have responded to past environmental change and how they might respond to future environmental change (Parmesan & Yohe, 2003). The geographic distribution can contract when climatic conditions exceed the species physiological threshold of tolerance or expand as environmental conditions at a site become physiologically tolerable for the first time, enabling new individuals to colonize (Helmuth *et al.,* 2006). Climate change can also promote the invasion of non-native species by making ecosystems less resistant to invasive species or more resilient to their impacts (Walther *et al.,* 2009).

Coastal marine habitats are key site for carbon storage. The total amount of carbon burial in the ocean amounts to 244 Tg C y^{-1}, of which 111 Tg C y^{-1} is buried in coastal vegetated habitats and 126 Tg C y^{-1} in unvegetated sediments (Duarte *et al.,* 2005). Even though vegetated carbon burial contributes about half of the total carbon burial in the ocean, burial represents a small fraction of the net production of these ecosystems, estimated at about 3388 Tg C y−1, suggesting that bulk of the benthic net ecosystem production must support excess respiration in other compartments, such as unvegetated sediments and the coastal pelagic compartment. The total excess or- ganic carbon available to be exported to the ocean is estimated at between 1126 to 3534 Tg C y−1, the bulk of which must be respired in the open ocean. The loss of vegetated coastal habitats through eutrophication, reclamation, engineering and urbanization (e.g., Valiela *et al.,* 2001; Duarte *et al.,* 2008; Waycott *et al.,* 2009) is eroding the capacity of the biosphere to remove anthropogenic CO_2. Duarte et al. (2005) estimated that this loss has already led to a decrease of carbon burial of about 30 Tg C y−1. The loss of vegetated habitats is also a significant source of CO_2. For example, approximately 39.3 Mmol C are released per ha of mangrove swamp cleared and excavated, and 31.3 Mmol C are released per 1000 t of dry peat combusted (De La Cruz, 1986). Local management of coastal ecosystems including efforts to avoid excessive nutrient and organic inputs from agricultural, aquaculture, and urban sources and to prevent sediment loading promotes favourable growing conditions that confer resistance and resilience against pressures that cannot be managed locally, such as those associated with climate change (e.g., Waycott *et al.,* 2009).

Greenhouse gas emissions that occur as results of the management of coastal ecosystems are not taken into consideration by international climate change mechanisms or in national inventory submissions (Laffoley & Grimsditch, 2009; Copertino, 2011). Countries could therefore underestimate their anthropogenic emissions and reductions in emissions resulting from the protection and restoration of coastal habitats does not count towards meeting international commitments.

[Most of the sensitivity of coastal systems to climate change will be based on recent existing summaries compiled in the tables included at the end of the chapter and part of the following references.]

[INSERT TABLE 5-2 HERE
Table 5-2: Sensitivity of natural systems to climate-related drivers (to be revised)

- table S2 in Hoegh-Guldberg & Bruno (2010)
- table 2 in Anthony et al. (2009)
- Table 4 in Bohensky et al. (in press)]

5.4.4. Sensitivity of Human Activities

[For possible integration with 5.5]

5.4.4.1. Industry, Transport, and Infrastructures

Climate change affects coastal human settlements and infrastructures in several ways. Especially the coupling of sea-level rise with storm surge is one of the most important considerations for assessing impacts of sea-level rise on infrastructures and coastal cities. In fact, many of world's megacities, cities with populations of many millions, are situated at the coast and new coastal infrastructure developments worth billions of dollars are being undertaken in many countries (Nicholls *et al*., 2008).

Especially remarkable is that Asia's urban population is increasing at the rate of 140,000 per day, with much of this growth occurring in low-lying coastal regions and on deltas characterized by land subsidence that is further contributing to flooding risks (Fuchs *et al*., 2011). This global coastal development, which demands has accelerated over the past decades, but it has taken with little consideration of sea level rise and increasing storm surge, flooding and erosion.

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 current minimum critical elevations of infrastructure such as airports, tunnels, and ship terminals (Jacob *et al.,* 2007).

It is estimated that a more than 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).

One other impact of sea-level rise not generally mentioned is the decreased clearance under bridges. Sea-level rise will affect the number of low water windows available for the large vessels now being built. Bridge clearance has already become an operational issue for major ports. Other potential effects on navigation system due to sea level rise may be the need to extend the estuarine navitagion channels landward from where they terminate now to provide access to a retreating shoreline.

But the 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 become more frequent and intense, there will be increased stress on all of these infrastructure systems (Zimmerman and Faris 2010). The following table summarizes 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.]

5.4.4.2. Tourism and Recreation

It is estimated that the global travel and tourism industry contributed 9.6 per cent of global Gross Domestic Product (GDP) and 7.9 per cent of worldwide employment in 2008 (UNWTO, 2009). From it an important part corresponds to coastal tourism which due to its close relationship to the environment and climate, is considered to be a highly climate-sensitive economic sector. Climate change will affect coastal tourism in different ways (UNWTO, 2009). Direct climate impacts may cause changes in the length and quality of tourism season; increased infrastructure damage due to flooding by extreme events; additional emergency preparedness requirements, higher operating expenses (insurance, backup water and power systems) and business operations. This aspect is especially relevant for coastal resorts. Indirect environmental change impacts: like changes in water availability due to increasing saltwater intrusion, biodiversity loss, increased natural hazards (hurricanes and typhoons), coastal erosion or increasing incidence of vector-borne diseases will all impact tourism to varying degrees. These indirect effects of climate induced environmental change are likely to be largely negative. (UNWTO, 2009).

Based on a beach tourism vulnerability index on a national level (Perch-Nielsen, S.L. 2010) carried out an analysis of climate change effects on beach tourism for 177 coastal countries worldwide presenting aggregate results for 51 countries in which tourism is most important. Results on an annual and national level indicate that large developing countries might be among the most vulnerable due to high exposure and low adaptive capacity. Beach tourism in small islands states is also vulnerable, especially due to their high sensitivity towards climate change. On the contrary, developed high latitude countries as well as the Mediterranean are amongst the least vulnerable countries.

5.5. Interactions between Coastal Systems and Human Activities

From the human perspective the most important impacts of climate change on the coasts are coastal flooding and inundation, coastal erosion, rising water tables, saltwater intrusion into surface and groundwater, and biological effects (Klein *et al.*, 2006). Sea-level rise is one of most apparent and widespread consequences of climate change and will have significant impacts on the coasts. The climate impacts are largely site specific due to the influence of local factors.

In general, the coasts can be viewed as 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 climate impacts in the more relevant human systems on the coasts.

5.5.1. Human Settlements

The coast remains a magnet for housing, industry and asset creation over the 21st century unless planning measures are enforced. 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 cities more than 5 million each are in this zone including a disproportionate number of small island states and densely populated megadeltas (McGranahan *et al.*, 2007).

Of the top ten nations classified by population and proportion of population in coastal low-lying areas the majority are developing countries (Table 5.1). For the majority of the developing countries, the population in the coastal low-lying areas face issues of flooding, erosion, storm surges and other coastal hazards and have little opportunities to move inland. In developed and wealthy countries, for example, in Australia, the coastal areas are highly favoured areas of settlement as people move to be closer to amenity and lifestyle opportunities (Gurran *et al.*, 2008).

[INSERT TABLE 5-4 HERE
Table 5-4: 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 with total of 423,000 inhabitants are also excluded).]

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).

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. The top 10 cities in terms of assets exposed are Miami, Greater New York, New Orleans, Osaka-Kobe, Tokyo, Amsterdam, Rotterdam, Nagoya, Tampa-St Petersburg and Virginia Beach. 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).

Population growth, socio-economic growth and urbanization are the most important drivers of increased exposure of port cities, with climate change and subsidence exacerbating the effect in Asia, particularly in the megadeltas. Of 136 port cities in the world, 52 (or 38%) are in Asia. China has 14 ports (10%) and the USA has 17 ports (13%). Globally, 37 port cities are entirely or partially in deltaic locations. The top 20 cities for population exposed are disproportionately located in deltas, 13 currently and 17 in 2070s. A high proportion (>65%) of the top 20 rankings, especially in 2070s, are in Asia because of urbanization and population growth (Hanson *et al.*, 2011).

Many of the Asian coastal cities are also located near to the Pacific Ring of Fire which is home to 75% of the world's volcanoes and source of 90% of earthquakes. In the coastal areas, storm surges historically killed hundreds of thousands of people. In 2007-2009, Asia accounted for 95% of more than ¼ million deaths attributed to natural catastrophes (Jha and Brecht, 2011).

The issue of land subsidence is greater than the effect of sea-level rise in a number of Asian coastal cities. In Bangkok the subsidence has resulted in trebling flood damage increases. The Pearl River and Mekong deltas are particularly vulnerable to subsidence as result of land compaction or extraction of groundwater (Jha *et al.*, 2011). 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, 4567.5 ha would be affected at a cost of €1812.8 million (Marfai and King, 2008).

In the USA available fine-scale data of coastal population estimated 19 million within 1 km from the shoreline in conterminous USA and 11.6 million live below the 3-m elevation (Lam *et al*., 2009). New geospatial dataset showed 20 municipalities with populations greater than 300,000 and 160 municipalities with populations between 50,000 and 300,000 are at 6 m or below. Approximately 9% of the land is at 1 m or below (Weiss *et al*., 2011).

As urban population represents increasing proportion of world populations, urban floods account for an increasing percentage of total flood impact as seen in Pakistan, Australia and Brazil. Urban expansion contributes to excessive discharge of water to flood conditions, particularly development in flood prone areas (Jha *et al*., 2011).

5.5.2. Coastal Industries and Infrastructures

The industries, coastal infrastructures and essential services of coastal cities and towns are exposed to three major climate impacts: rising temperature, rising sea level, and extreme weather conditions. For example, higher temperatures affect maritime transport infrastructure, vehicles and operating equipment. Rising sea levels, floods and inundations may damage terminals, storage facilities, containers and cargo. Extreme weather disrupts port operation. Increased sediment mobility and changes in sedimentation/erosion patterns restrict operations of harbours and access channels (UNCTAD, 2008). Modelling showed that field installations and even offshore operations could be severely affected by inundation and erosion caused by storm surges and sea-level rise (Singh *et al*., 2008).

Ports by virtue of their long-lived, fixed assets and infrastructure face a range of climate hazards, including sea-level rise, storm surge, extreme wind and waves and river flooding. Although extreme weather events are projected globally the climate impacts on ports vary considerably. For many ports, the compound effects of mean sea-level rise, high tides and increased storm surges would be most significant. Ports in low-lying coasts are threatened by rising sea levels and storm surges; those in the high latitudes are affected by permafrost thaw causing ground stability and erosion (Stenek *et al*., 2011). Ports in developing countries would have large increases in total value of assets exposed to climate change risks between 2005 and 2070s (Nicholls *et al*., 2008).

The transport systems in coastal areas would be affected by sea-level rise, increased intensity of storm surges and flooding. Empirical data showed the effects on transport are substantial on the US East Coast and Gulf area (Koetse and Rietveld, 2009). 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.

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). For certain coastal environments such as barriers, climate-related modification of roads brings significant changes including coastal squeeze. Also further coast hardening changes the morpho-sedimentary equilibrium of barriers (Jolicoeur and O'Carroll, 2007).

5.5.3. Fisheries, Aquaculture, and Agriculture

Fisheries constitute one of the most important economic sectors in the coastal areas. It is the livelihood for 36 million fisherfolk worldwide and nearly 1.5 billion people rely on fish for more than 20% of their dietary animal protein (Badjeck *et al*., 2010). It provides direct employment for 43.5 million with the great majority in developing countries. Many small island states depend on fisheries and aquaculture for 50% of their animal protein (Barange and Perry, 2009). Regionally, North-East Asia has the biggest yield, consumption and international trade in fisheries products in the world.

The main fisheries products are small pelagic fish whose biomass fluctuations are sensitive to climate changes where the impacts come from gradual warming and the frequency, intensity and location of extreme events (Barange and Perry, 2009). Climate change adds uncertainty about fish stock productivity, migratory patterns, trophic interactions and vulnerability of fish populations to fishing pressure. Where governance (fishery management regimes, schemes for capacity adjustment, catch limitation and alternative fishing livelihoods) is less developed, the fisheries are less able to adapt to climate change impacts (McIlgorm *et al.*, 2010).

Sea-level rise results in saltwater intrusion and may affect fish. In coastal Louisiana, this seems to reduce population size for most fish populations. In more saline sites, some may develop localized adaptations (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).

Coastal fisheries thus face cumulative impacts from multiple threats associated with climate change (sea-temperature rise, sea-level rise, ocean acidification), invasive species, bottom fishing destroying habitat, and coastal habitat destruction (from shoreline hardening and coastal development) (Crain *et al.*, 2009).

The coast is a significant zone for aquaculture but the climate impacts are very variable, depending on geographical location. The more negative impacts are in the temperate regions and more positive are in the tropical and subtropical regions (De Silva and Soto, 2009)

The major rice growing regions in Asia are particularly vulnerable to climate impacts. The megadeltas in Vietnam, Myanmar and Bangladesh are impacted by sea-level rise and storm surge. The Mekong Delta and Red River Delta provide 54% and 17% of Vietnam's rice production respectively; the Irrawaddy Delta and Ganges-Brahmaputra Delta provide 68% and 34% of Mynamar and Bangladesh rice production respectively. In Myanmar, saltwater intrusion attributed to sea-level rise could affect 85% of national rice production; 55% of the Bangladesh national rice production could be affected by higher flood risk. The tropical cyclone in May 2008 with a storm surge of 4 m high devastated an entire rice crop in Myanmar. Higher resilience to flooding and salinity are crucial to maintain or even increase yields (Wassmann *et al.*, 2009)

Variable climate effects on coastal farming are evident. In coastal Bangladesh salinity has become one of major problems for traditional agricultural practices and threatens the farmers' ability to continue crop cultivation and thus their livelihood. However, salinity benefits only the expansion of shrimp ponds and cultivation of high yielding, salt-tolerant rice varieties (Rahman *et al.*, 2011).

5.5.4. Coastal Tourism and Recreation

Coastal tourism is a highly climate-sensitive economic sector and affected in various ways : (1) Direct with climate as the principal resource affecting tourism seasons, e.g. sun-and-sea; (2) Indirect through environmental change impacts, such as water availability, coastal erosion and inundation, increased natural hazards and biodiversity loss; (3) Impacts of mitigation policies on tourist mobility such as transport costs affecting long-haul travel; (4) Indirect societal change impacts such as climate change associated with security risks (WTO, 2007; Shurland and de Jong, 2008)

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). Tourist beaches are under a significant threat from erosion (Phillips and Jones, 2006). On the demand-side for coastal tourist destinations there are impacts in reduced tourist flows, aviation mitigation measures (decreased flows) and natural disasters in some top tourist countries, such as China, India, Indonesia, and Thailand (Shurland and de Jong, 2008).

According to the WTO (2007) there are five tourism hotspots from mid- to late-21st century. Four are identified as coastal (Table 5.2) and the fifth is Australia/New Zealand. The Mediterranean continues to be the world's largest summer-time beach tourism and is likely to remain unaffected for another 50 years because heat waves are not critical (Moreno, 2010). Despite increasing temperature, the northern Europeans could acclimatize within the comfort level of the high temperature in the Mediterranean (Rutty and Scott, 2010). More critical issues are adaptation to sea-level rise, water availability, environmental quality, and the diversification of activities.

[INSERT TABLE 5-5 HERE
Table 5-5: Major coastal tourism hotspots and their major climate and non-climate impacts.]

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 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 only with 1 m SLR (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. The intensity and scale of observed bleaching events have increased since 1960s and major bleaching events in 1998, 2002 and 2005. Experimental studies suggest ocean acidification is likely to shift coral reefs from growing to dissolving structures by 2100. The tropical upper ocean, where coral reefs grow, has increased more than 0.01^{o}C per year over the past 50 years and the warming rate is increasing. Tropical storms can benefit coral reefs by alleviating thermal stress. But severe storms would relocate large coral colonies and reduce structures to rubble (WMO, 2010).

Often it is also important to distinguish between global stressors, for example, rising temperature and sea level, from local stressors and between non-climate stressors from climate stressors. For coral reefs the local stressors include coral diseases, overfishing, pollution and sedimentation. Bleaching could arise from local stressors lowering the thermal tolerance of reefs, fishing, and even management itself to reduce stressors (Carilli *et al.*, 2010; Darling *et al.*, 2010; Côté and Darling, 2010) whereas the topography and spatial arrangement of fringing reefs may influence the response to stresses (Crabbe, 2010).

For small islands in the tropics, another result of climate change on coastal tourism would be the coastal squeeze where beach reduction (erosion) and mangrove squeeze will be further exacerbated by coastal construction and tourist hotels built within the zone at risk to flooding and erosion (Schleupner *et al.*, 2008). Dikes, 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. Given the costs of dikes and reduced accommodation prices, beach nourishment is favoured in protecting the coast from erosion caused by sea-level rise (Hamilton, 2007).

Overall, it is generally anticipated that coastal tourism would be affected by weather conditions and sea-level rise has a significant impact on beaches. A study from East Anglia, UK, suggested that climate change will result in visitor increase outweighing the negative influences of reductions in beach width due to sea level rise for future climate change scenarios. The implications are for more targeted management strategies to minimize associated increases on beaches vulnerable to sea-level rise (Coombes *et al.*, 2009).

Policy proposals to reduce to reduce GHG emissions from domestic and international aviation have implications, especially for small island states depending on long-haul traffic. Significant decreases in tourist arrivals are expected in the post-2020 with more stringent mitigation policy scenarios. Arrivals from Europe and North America to Caribbean would be negatively impacted by new mitigation policies and fluctuating oil prices (Pentelow and Scott, 2011). Overall, the development of a serious global climate framework to reduce aviation emissions could lead to declining arrivals in some tourism-dependent SIDS (Gössling *et al.*, 2008).

Apart from climate change, a wide range of other factors could potentially cause changes on tourist flows, e.g. increasing fuel prices, water availability, potential changes in tourist preferences. Sea level rise impact may still be modest in most places in the next 50 years (Hein *et al.*, 2009).

Very often as shown in Australia, the tourism sector is not yet ready to invest in climate change adaptations because of perceived uncertainties. The perception is that measures should rest with the public sector, especially local authorities (Turton *et al.*, 2011). Also, not enough is known about the willingness of both tourism industry and tourists to significantly reduce global emissions (Scott and Becken, 2010).

5.5.5. 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 saltwater is estimated to intrude into the recharge zones for a distance of 1-12.5 km in the next century and water extraction will exacerbate the intrusion (Narayan, 2006).

A more severe situation exists where groundwater is being withdrawn in semi-arid coastal regions. In Morocco the aquifer of the Chaouia coast is subjected to intensive and uncontrollable withdrawals and the climate impact is exacerbated during droughts (Moustadraf *et al.*, 2008).

Even in wetter area, such as in the Pingtung Plain of southwestern Taiwan, where groundwater has been overexploited in the last two decades, this has led to the deterioration in quantity and quality of groundwater. The groundwater level in the proximal fan of Pingtung Plain will decrease most seriously under future climate change (Hsu *et al.*, 2007).

A total of 8,000 inhabited small tropical islands in the Pacific, Indian and Atlantic Oceans face water supply problems. Many have thin lenses of fresh groundwater which float above the seawater beneath and they are vulnerable to natural processes (storm surges and rising sea levels) and human activities (over-extraction, pollution) (White *et al.*, 2007). With a greater number of cyclones occurring during El Niño conditions, the Pacific atolls faced a greater threat from cyclone-induced overwashes and subsequent short-medium term contamination of their limited freshwater resources (Terry and Falkland, 2010).

Surprisingly, in Netherlands where much of the land is below the sea level, modelling showed that the impact of sea-level rise in the deltaic area is limited to within 10 km of the coastline and the main rivers because of the increasing head in the groundwater system within the highly permeable Holocene confining layer. In contrast, the deep polders more inland will have increased salinization (Essink *et al.*, 2010).

5.5.6. Human Health

The potential climate impacts on human health can be direct (through climatic factors) and indirect (mainly through infectious diseases). The health impacts on coastal areas arise from frequent floods and waterlogging, variable precipitation, increased temperature, impact of sea level rise, and a stressed environment. Increased risks to human health are exacerbated by the poor state of a country's public health infrastructure, as in Bangladesh (Shahid, 2009) or the geography of a large archipelago of low-lying islands and coasts, as in Indonesia (Wirawan, 2000).

Rising temperatures affect the spread and transmission rates of vector-borne and rodent-borne diseases. As ocean temperatures rise with global warming and El Niño events, cholera outbreaks might increase as a result of more harmful algal blooms (HABs) (Costello *et al.*, 2010). Along the coasts, the frequency and magnitude of some species of HABs are exacerbated by anthropogenic input of nutrients (eutrophication). The consequences of global change of HABs are poorly understood as they vary with tropical and temperature ecosystems and differing regional forcing environmental conditions (Erdner *et al.*, 2008).

In Bangladesh, frequent floods and cyclones cause waterlogging, destruction of freshwater resources and contamination of drinking water wells that often lead to increase in cholera, diarrhea, malnutrition and skin diseases.

The river level above the 4.8 m threshold is associated with an increase of rotavirus diarrhea by 5.5% per 10-cm river-level rise. In future, cholera could become a regular phenomenon in regions where it is now a seasonal disease (Hashizume *et al*., 2008).

Previous studies showed the role of extreme rainfall in the dynamics of diarrhea. Climatic variables may not directly affect the number of cases for diarrhea but provide an outbreak through various pathways. From different studies in tropical Taiwan and tropical Australia, the lag effects of temperature and rainfall on diarrhea morbidity vary 0 to 1 month for lag effects of temperature and up to 3 month for lag effects of rainfall (Chou *et al*., 2010). However, large uncertainties are still associated with future projections of diarrhea and climate change, attributed primarily to the sparsity of empirical climate-health data. Changes in the incidence of diarrhea are highly dependent on pathogens and on water and sanitation infrastructure in different regions and not only climatic variables (Kolstad and Johnsson, 2011).

Dengue is an emerging disease with almost half of the world's population at risk of infection including many coastal areas. So far theoretical and statistical models of dengue and climate show that relatively small increases in temperature (around 1ºC) can lead to substantial increases in the transmission potential (Van Kleef *et al*., 2010). A model study in Hawaii incorporating notions of climate variability and change showed dengue risk areas generally contract during El Niño-induced droughts and expand as a result of increased precipitation received during La Niña events (Kolivras, 2010).

Climate change is considered an important factor in malaria transmission with most studies on climate change and malaria risks based solely on mean temperatures. However malaria transmission intensity is influenced by daily fluctuations in temperature that influence the rate of parasite infection and development. A study from western Africa showed minimal correlation exists between reported malaria rates and climate and contradicts the prevailing theory that climate and malaria prevalence are closely linked (Jackson *et al*., 2010). In Bangladesh the malaria habitat may be reduced with temperature rise. However at same time the breeding period of mosquitoes may be shifted and prolonged leading to possible change in the malaria pattern in the country (Shahid, 2009).

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 (Ramakrishnan 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).

As yet climate modelling of diseases is based on 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).

5.6. Observed Impacts, with Detection and Attribution

[Comment: Overlaps with above subsections. Re-organization is required.]

5.6.1. Observed Impacts relating to Climate Change

[To be completed]

5.6.2. Interaction between Climate Change and Human Stressors

Human being has been impacted rivers, their drainage basins and coastal zones, resulting in changes of coastal systems and low-lying areas on millennial to centennial time scales. There are currently over 1.2 billion people living within 100 km of the coast and less than 100 m above sea level (Small and Nicholls, 2003).

Prehuman sediment flux of rivers globally, which is estimated to be 15 Gt/y for suspended material before 3000 years ago, increased up to ~20 Gt/y by soil erosion due to deforestation and agriculture until early to middle 20th century (Syvitski *et al.,* 2005; Milliman and Farnsworth, 2011). Increased sediment discharge from rivers has impacted coastal zones and formed rapidly-prograded deltas at coasts (e.g, Yellow, Po, Mississippi rivers). However numerous dams and other human activities (e.g., irrigation, mining) have reduced sediment discharges to the coastal zones, below the pristine (pre-human) level at present (Syvitski and Kettner, 2011). Relative sea-level rise (SLR) by eustatic sea-level rise since the Little Ice Age (natural and anthropogenical) and human-induced land subsidence also has been impacting the coastal zone. Particularly a delta subsidence began in the 1930s and is now dominant in terms of relative sea level for many coastal environments, overwhelming even the global warming imprint on sea level (Syvitski and Kettner, 2011). Coastal environment changes due to sea-level rise might be overwhelmed by excessive human impacts, on spatial and temporal scales and particularly local anthropogenic impact is the major threat to coastal and estuarine habitats, compared with natural erosive processes and global climate change driving forces over recent times (Chust *et al.,* 2009). SLR, sediment issues and other human-induced changes in coastal areas (such as coastal defenses, destruction of wetlands, port and harbor works) obscure the impacts of climate-induced SLR during the 20th century. Currently they are so widespread and amount to a global problem (Nicholls *et al.,* 2010).

5.6.2.1. Sediment Delivery to the Coastal Zones

Most of sediments to the coastal zones are supplied from rivers and coastal erosion. Riverine sediment discharge globally is estimated to be ~20 Gt/y. However it has been reducing by sediment retention in dam reservoirs and subsiding channels, irrigation, and mining. The major means to reduce the delivery of river sediment to the coast is through sediment retention in reservoirs (Vorosmarty *et al.,* 2003). Large reservoirs on average offer trapping efficiencies of 80 per cent (Syvitski and Millman, 2007). Globally, there are more than 48,000 large dams (heights greater than 15 m, average height 31 m, average reservoir area 23km2), with more than 2,000 large dams under construction (Syvitski and Kettner, 2011). Present sediment discharge has decreased down to 12-13 Gt/y, which is below the pre-human level (15 Gt/y) (Syvitski and Kettner, 2011). Asian region shows a typical example: total sediment discharge of five large rivers in Southeast to East Asia (Yellow, Yangtze, Pearl, Red, and Mekong rivers) delivered ~600 Mt/y before 3,000 years ago and increased up to ~2200 Mt/y in 1950s. It has been declining down to 600 Mt/y or less at present (Wang *et al.,* 2011). For many rivers, the history of sediment delivery to their deltas has been one of a slow developing rise in sediment conveyance followed by a rapid twentieth-century fall. Above-mentioned Asian deltas have a history of increase of sediment discharge for the last 1000-2000 years, followed by a rapid decline in late 20th century. However some river-delta systems where the sediment load is increasing include, for example: the Kolyma, in Siberia, attributed to mining activities (Bobrovitskaya *et al.,* 2003) and the Magdalena in the tropics, where the increase in flux is attributed to a combination of deforestation, agricultural practices including poor soil conservation and mining practices, and increasing rates of urbanization (Restropo and Syvitski, 2006). For these systems, the soil erosion increase has not been accompanied with damming of the various river branches. (Syvitski, 2008)

5.6.2.2. Impacts of Reduced River-Sediment Discharge on the Coasts

Appropriate sediment supply to the coast is essentially needed to keep the stable shoreline, because coastal sediments are re-worked to offshore, onshore or alongshore by coastal wave- or storm-induced currents. Sediment shortage to the coast due to decreased sediment discharge from rivers by human activities makes imbalance resulting in coastal erosion. Typically after construction of dams, many rivers in the world have such erosion problems at present (e.g., Nile river delta (RD), ; Ebro RD, Sanchez-Arcilla *et al.,* 1998; Po RD, Simeoni and Corbau, 2009; Godavari-Krishna RD, Nageswara Rao *et al.,* 2011; Yangtze RD. Yang *et al.,* 2006; Yellow RD, Chu *et al.,* 1996).

Deltas are an essentially seaward migrating coastal system with sediment supply from rivers. For examples, formerly mega-deltas in Southeast and East Asia gained 40 km2 land annually by delta progradation, however they are shrinking and at risk of destruction because of the reduction of sediment supply and relative sea-level rise.

Sediment discharge was reduced from 2.5 GT/y to less than 1 GT/y in Southeast to East Asia (Saito *et al.,* 2007). The coastal erosion occurs not only as the shoreline retreat landward, but also subaqueous erosion in nearshore areas (delta front) of river deltas. The maximum depth of the subaqueous erosion depends on wave condition (~4 m at Chao Phraya river delta, Uehara *et al.,* 2011; ~10 m at Yangtze RD, Yang and Milliman, 2011; ~15 m at Yellow river delta, Wang *et al.,* 2006). Declined sediment supply to coastal areas also has impacted coastal wetlands, which is discussed later.

Construction of dams and reservoirs has impacted not only sediment delivery to the ocean, but also sediment source and characters, and sedimentation at river-mouth areas. Reduced sediment delivery by dam reservoirs has encourage river channel scouring downstream of the dams, resulting in changes of sediment source and characters supplied to the coast (Wang *et al.,* 2011). At the river mouth areas, there are some impacts due to changes of water diversion schemes: 1) salinity intrusion in the estuary may increase related to decrease of water discharge regulated and this would affect rice farming and irrigation, 2) if the dams replace annual floods by a constant outflow, siltation in the estuary is predicted to increase due to tidal pumping effect into the estuary from the sea (Wolanski and Spagnol, 2000).

Sand and gravel mining in river channels and dredging for navigation channels in deltas also give essential impacts on coastal zones in terms of sediment delivery. These are important as aggregates for construction materials particularly developing countries. However available data is very limited for evaluation of its impacts on the coast. More than 8.7 x 108 m3 of sand were excavated from 1986 to 2003 in the Pearl river delta, resulting in deepening of the main channels. Consequently, the water levels in upstream of the delta were decreased, and present brackish-water has intruded upward 10–20 km more than in the 1980s (Luo *et al.,* 2007).

5.6.2.3. Impacts of Relative Sea-Level Rise on Deltas

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.,* 2010). Deltas are among the most valuable coastal ecosystem, but they are very dynamic and the factors that influence their health are complex (Day and Giosan, 2008). On deltas, the rate of relative eustatic sea-level rise is often smaller than the rate for isostatic-controlled subsidence and of the same order of magnitude as natural sediment compaction. Accelerated compaction associated with petroleum and groundwater extraction can exceed natural subsidence rates by an order of magnitude. The reduction in sediment delivery to deltas due to trapping behind dams, along with the human control of routing river discharge across delta plains, contributes to the sinking of world deltas. Consequences include shoreline erosion, threatened mangroves swamps and wetlands, increased salinization of cultivated land and ground water, and hundreds of millions of humans put at risk (Syvitski, 2008).

Thirty-three deltas chosen to represent the world's deltas in the past decade show that 85% of the deltas experienced severe flooding, resulting in the temporary submergence of 260,000 km2 and the delta surface area vulnerable to flooding could increase by 50% under the current projected values for sea-level rise in the twenty-first century (Syvitski *et al.,* 2009). Sea-level rise induces a significant increase in water level in the coastal plain and fluvio-delta plains, particularly in flood seasons (Wassmann *et al.,* 2004), enhancing more flooding in the fluvio-delta plains resulting in sediment deposition onto the plains, and decreasing sediment delivery to the coast. Sediment delivery by rivers is trapped in river channels in deltas (in-channel deposition) also due to relative sea-level rise, resulting in shortage of sediment discharge to the coastal zone in the Po river delta (Syvitski *et al.,* 2005).

Subsidence is a common feature of large river deltas and leads to amplified hazards from relative sea-level rise in the coastal cities built on deltaic plains (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 defense and water management infrastructure (Nicholls *et al.,* 2010). Increased sediment consolidation due to artificial loads can lead to significant augmentation of subsidence and relative sea-level rise (Mazzotti *et al.,* 2011). For the Fraser River delta, areas with recent large structures may undergo relative sea-level rise of as much as ~1–2 m. Thus, anthropogenic subsidence must be accounted for in local mitigation measures against flood and coastal erosion (Mazzotti *et al.,* 2011). A subsidence map of the city of New Orleans offers also insight into the failure of the levees during Hurricane Katrina (Dixon *et al.,* 2006). The rate of compaction of underlying sediments might be a more significant factor than was thought (Day and Giosan, 2008). High-resolution topographic data and monitoring are essentially important for detecting subsidence. Interferometric synthetic aperture radar (InSAR) and LIDAR are useful and powerful tools for detecting of land subsidence, land topography change and land-use change in deltas: the Nile RD (e.g., Becker and Sultan, 2009), Yangtze RD (Perissin *et al.,* 2007), Mississippi RD (Dixon *et al.,* 2006), Armo RD (Pranzini, 2007).

5.6.2.4. Coastal Wetland Loss

Wetlands loss in coastal lowlands, particularly in deltas, is on-going problem. 42 deltas in the world show wetland loss with an average annual rate of 26,000 km2 for the last 14 years, caused by convention of the delta plain to agricultural and industrial use more than natural causes (Coleman *et al.,* 2008). Over the past few centuries, 25% of the deltaic wetlands associated with the Mississippi Delta have been lost to the ocean (Blum and Roberts, 2009). Fluctuations in sea-level rise rates and sediment supply mainly dominate the formation and evolution of coastal wetlands. The wetlands with high sediment input, mainly riverine are only ones likely to survive accelerated sea-level rise, from comparative study of the wetlands of Mediterranean deltas and lagoons (Day *et al.,* 2011). High sediment input and high capture efficiency of sediments are necessary for sediment accumulation (Day *et al.,* 2011). Deposition rate is affected not only by inundation frequency but also sediment availability (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).

Sediment supply from rivers is essentially important for wetland development. However the reduction of sediment discharge from rivers and relative SLR also has crucially impacted wetlands. As millennial-scale mean storage rates necessary to construct the flood plain and delta over this period exceed modern Mississippi River sediment loads, significant drowning is inevitable, even if sediment loads are restored, because sea level is now rising at least three times faster than during delta-plain construction (Blum and Roberts, 2009). In a case of the Plum Island Estuary (Massachusetts, United States), salt marshes expanded rapidly during the eighteenth and nineteenth centuries due to increased rates of sediment delivery following deforestation associated with European settlement. Therefore existing marshland could survive, but not form under the low suspended sediment concentrations observed in the estuary today. These results suggest that many of the expansive marshes that characterize the modern North American coast are metastable relicts of high nineteenth century sediment delivery rates, and that recent observations of degradation may represent a slow return to pre-settlement marsh extent (Kirwan *et al.,* 2007).

Mangrove ecosystems are threatened by climate change, and particularly relative sea-level rise may be the greatest threat to mangroves. Most mangrove sediment surface elevations are not keeping pace with sea-level rise. Rising sea level will have the greatest impact on mangroves experiencing net lowering in sediment elevation, where there is limited area for landward migration. The Pacific Islands mangroves have been demonstrated to be at high risk of substantial reductions (Gilman *et al.,* 2008). Retreat (landward migration) of mangrove seaward margin is well correlated with relative SLR in American Samoa for the last four decades. The force of SLR relative to the mangrove surface is causing landward migration (Gilman *et al.,* 2007). Changes in rainfall pattern have been suggested as a mechanism for the landward incursion of mangrove into salt marsh (Eslami-Andargoli *et al.,* 2009). An example from Moreton Bay, Southeast Queensland, Australia, show that a significant positive relationship was demonstrated between rainfall variables and landward mangrove expansion, but not for seaward expansion. They concluded that rainfall variability is one of the principal factors influencing the rate of upslope encroachment of mangrove. However, the rate of expansion may vary from site to site due to site-specific geomorphological and hydrological characteristics and the level of disturbance in the catchment.

Wetland loss in back barrier regions related to SLR has another causes in comparison with deltas regions. FitzGerald *et al.* (2007) showed that marsh loss was related to several linked processes, including subsidence, marsh front erosion, and catastrophic scour during large magnitude hurricanes in Barataria Bay. Long-term conversion of wetlands to intertidal and subtidal environments has steadily increased tidal exchange between Barataria Bay and the Gulf of Mexico, resulting in larger inlet tidal prisms.

5.6.2.6. SLR and Ocean/Storm Surges

More than 10 million people a year experience flooding due to storm surges alone, and most of these people are living on Asian deltas. Flooding may originate from intense precipitation directly onto a delta, from river overbanking or from hurricane-induced storm surges. (Syvitski *et al.,* 2009). Ocean surges onto coastal lowlands caused by tropical and extra tropical storms, tsunamis, and SLR affect all coastal lowlands and present a threat to drinking water resources of many coastal residents. In 2005, two such storms, Hurricanes Katrina and Rita struck the Gulf Coast of the US. The private and public water wells' casing and/or the associated plumbing were severely damaged and surge water entered water wells' casing and the screened aquifer (Van Biersel *et al.,* 2007).

5.7. Projected Impacts

The following sections focus on climate change projections of some of the most critical physical parameters that will deliver impacts to coasts around the world. As much as possible, the regional variability of these parameters will be emphasized, although our understanding of, and ability to specify and project, regional variability remains limited. Further, coastal impacts will commonly arise not just from one changing parameter alone, but from multiple changes of parameters and the interactions of changes, for example the impacts arising from tropical storm waves and surges coming ashore on rising seas.

5.7.1. Sea-Level Change

Not every location in the world will experience the same rate and ultimate magnitude of climate-forced sea level change. There will be a global contribution and a regional adjustment that will vary, plus or minus or zero, in response to a variety of processes, not all of which are understood well enough to be accurately projected.

5.7.1.1. Global Sea-Level Change

In the 2007 IPCC Assessment Report #4, climate scenarios (SRES B1, B2, A1B, A1T, A2, and A1FI) projected a range of global sea level rise from 0.18 to 0.59 m between 1980-1999 and 2090-2099 (Meehl *et al.,* 2007). They found for all of these scenarios that the mean sea level rise during the present century "very likely" exceeds the global sea level rise of 1.8 ± 0.5 mm yr^{-1} measured during 1961-2003. For the last decade of the twenty-first century, scenario A1B projects a central estimate of sea level rise of 3.8 mm yr^{-1}.

In all scenarios, the greatest portion of the projections is due to the thermal expansion of seawater, accounting between 70 and 75% of the central rate estimates (Meehl *et al.,* 2007). Also contributing to the rate estimates are the melting of glaciers, ice caps, and the Greenland ice sheet. Antarctica ice sheet does not contribute, because models project it to gain more ice through interior snowfall than it loses through melting. In essence, AR4 found the contribution of the ice sheets to sea level rise is relatively small. The projections of 2007, however, do not reflect uncertainties related to feedbacks in the climate-carbon cycle, nor to potential changes in the ice sheets. The projections reflect some adjustment for potential contributions from ice sheets but only for observations in 1993-2003, which may not reflect future trends (IPCC, 2007; Meehl *et al.,* 2007).

Since AR4 was published, a number of scientists have attempted to account for the limitations of the AR4 projections using different approaches (Fig. 5.1). For example, Rahmstorf (2007) developed a semi-empirical technique based on a relationship between measured global air temperature and measured global sea level rise. During the 20th century, he found that sea level was raised 3.4 mm/yr per degree C. Using this relationship, and air temperatures predicted by models running IPCC scenarios, he projected sea level rise of 0.5 to 1.4 m by 2100 (relative to 1990 level). A mix of investigators using various statistical approaches also reported larger estimates of sea level rise than did AR4. For example, Horton et al (2008) projected a range of 0.47 to 1.00 m by 2100; Vermeer and Rahmstorf (2009) projected 0.75 to 1.9 m; Jevrejeva et al (2010) projected 0.59 to 1.8 m; and Grinsted *et al.* (2009) projected 0.3 to 2.15 m. This latter study concluded that future sea level rise was unlikely to occur within the AR4 projections and that this was due to underestimates of contributions from large ice sheets.

[INSERT FIGURE 5-1 HERE
Figure 5-1: Range of sea level changes for AR4 and for several studies that followed (modified from Rahmstorf, 2010).]

A recent study by Rignot (2011) on the mass balance of Greenland and Antarctica ice sheets support an increasing contribution of melting ice sheets to global sea level rise. Kahn *et al.* (2010) focused on Greenland and found its main glaciers over the past decade have more than doubled the amount of water they are adding to the world's rising seas.

In a review of the sea-level-change literature, Nichols *et al.* (2011) suggested a "pragmatic estimate" of sea-level rise of 0.5 to 2.0 m for a 4° C increase in global temperature by 2099. (SRES emission scenarios A1B, A2, and A1FI all projected temperature increases greater than 4° C). They emphasized that the high end of the range was possible but very unlikely to occur; and it was difficult to assign its occurrence an accurate probability. Should it transpire, however, the impacts would be staggering with up to 187 million people, or 2.4% of the global population, forced to move away from an encroaching sea (Nichols *et al.,* 2011). Enhanced coastal protection works could mitigate such displacements of people, although Nichols et al (2011) argue the potential success of such works varies greatly around the world, being least likely to be effective in Africa, portions of Asia, and small island nations.

5.7.1.2. Regional Variations of Sea-Level Change

Sea level will not uniformly rise around the world at the average global rate but will rise faster in some places and slower in others in regional patterns that are just beginning to be understood. The following presents recent results about these regional patterns that arise mostly from spatial variations in dynamic sea level--forced by circulation in ocean and atmosphere and variations in seawater temperature and salinity--and in static equilibrium sea level--forced by gravity, elasticity of the earth, and changes in the earth's rotation (Kopp *et al.*, 2010). Locally, both dynamic and static sea level add to or subtract from average global sea level forming unique regional patterns. Net sea level change can also reinforce or mitigate other processes leading to sea level changes, like relative rises from land subsidence on the world's deltas (e.g. Tornqvist *et al.*, 2006) or relative falls from land uplift near melting glaciers (e.g. Larsen *et al.*, 2003).

The regional patterns of dynamic sea level have been recently modeled by a number of investigators including Stammer (2008), Yin *et al.* (2009), Yin *et al.* (2010), and Landerer *et al.* (2007). Yin *et al.* (2010) used state-of-the-art climate models under the SRES A1B emissions scenario and found that during the twenty-first century, the Atlantic Meridional Overturning Circulation (AMOC) would weaken. Relatively low sea levels in the North Atlantic's Labrador Sea, which were present in part because of deepwater formation associated with overturning circulation, would rise. These initially low sea levels extended southward from the Labrador Sea along northeastern North America where they would also rise (Yin *et al.*, 2010). The model suggests shores from Cape Hatteras on the mid-Atlantic coast of the U.S. to north of Newfoundland in Canada would be impacted. Dynamic sea levels along the densely populated east coast of the U.S. are projected to reach 0.23 m in Boston, 0.23 m in New York City, and 0.15 m in Washington, DC. South of Cape Hatteras dynamic sea levels are projected to be far less, only 0.04 m in Miami, Florida. These dynamic sea levels are in addition to the global average and, hence, northeastern North America is exposed to some of the highest and most rapid sea levels over the twenty-first century (Yin *et al.*, 2009). In contrast, in Europe, the model predicts a fall in dynamic sea level. This basin wide pattern across the North Atlantic is consistent with a theory of AMOC slowdown and its consequences (Bingham and Hughes, 2008).

In the North Pacific, deepwater formation and overturning circulation is absent and, unlike northeastern North America, there is no rapid dynamic sea level rise along the coast of eastern, or northeastern, Asia. A relatively large dynamic sea level rise is confined to the subtropical gyre well offshore of Japan. Dynamic sea level rise by 2100 on the eastern Asian coast is generally less than 0.1 m, specifically, 0.08 m at Tokyo and 0.06 m at Shanghai, or about two thirds less than the projected dynamic sea level rise at New York City. During the twenty-first century along the northeastern Asian shore, specifically the Kamchatka Peninsula of the Russian Federation, dynamic sea level falls, exposing this coast to less total sea level rise than many areas of the world.

In the southern hemisphere, other major cities will be exposed to relatively low projected dynamic sea level rises, like Sydney (less than 0.1 m), Sao Paulo (about 0.0 m), and Cape Town (less than 0.0 m) (Yin *et al.*, 2010). Many island nations will similarly be exposed to low dynamic sea levels, like Tuvalu (less than 0.1 m) and Maldives (less than 0.05 m). This does NOT mean that these islands will necessarily be less vulnerable to sea level rise, however. Vulnerability is a function of both sea level rise (global and regional) and land elevation, and many the world's tropical islands are extremely low, like the Maldives, reportedly the lowest-lying nation in the world with an average elevation of natural terrain of only 1.5 m and a peak elevation of 2.3 m.

Static equilibrium sea level is forced by different processes than dynamic sea level and yields different regional sea level variations (Kopp *et al.*, 2010). For example, the diminishment of ice sheets in Greenland and Antarctica by melting will change the rotational characteristics of the earth, which will feedback to change sea levels. The melting will also lower the gravitational attraction the ice sheets have for surrounding seas because their masses have been reduced (Mitrovica *et al.*, 2009; Mitrovica *et al.*, 2010). As a consequence, and counter intuitively, close to the ice sheets, sea level will fall even though water from ice melt is introduced into the sea. This lowering of sea level due to gravitational effects would operate as far as roughly 2,000 km from the melting ice sheet (Mitrovica *et al.*, 2009). Farther away than about 2,000 km, static equilibrium sea level would progressively rise.

The spatial pattern of sea level change from the melting of an ice sheet would be different for each ice sheet and each would represent a unique fingerprint that reveals the pattern's source (e.g. Mitrovica *et al.* 2009). For example, with Greenland ice sheet melt, sea level would fall around Greenland and would rise at a rate of only 0.1 mm/yr in the North Atlantic at Newfoundland and increase progressively southward to a maximum rate of 1.3 mm/yr in the South Atlantic (Mitrovica *et al.*, 2001). In contrast, with the collapse of the West Antarctic Ice Sheet (WAIS), local sea level will fall relative to global sea level along coasts on the southern half of South America and in Asia, while it will rise along coasts of North American and in the Indian Ocean (Mitrovica *et al.*, 2009). With complete collapse of WAIS, coasts in North America could realize static equilibrium sea level rises of 30% of the average global sea level rise. For example, Washington, DC could experience a 5 m rise from water released from the collapse of WAIS plus a static equilibrium rise of 1.3 m for a total of 6.3 m total rise. Such an event is illustrative of the processes, but is not expected to occur in the twenty-first century.

Kopp *et al.* (2010) presented one of the initial attempts at combining dynamic and static equilibrium sea level rises in a coupled model so the combined effects, and the relative importance of individual effects, can be evaluated. They focused on Greenland ice sheet melt. At a high melt rate, the dynamic sea level rose sharply along the northeast North American coast as discussed above. Such dynamic effects will likely dominate early after melt commences, while static equilibrium becomes more important with additional input of melt water. The coupled models suggest that for a high melt rate, static equilibrium effects become dominate over dynamic effects in about 25% of the ocean after nine years; this dominance spreads to 75% of the ocean after 37 years. Interestingly, they found that static effects counteracted dynamic effects at New York City; after 40 years, the local sea level rise including dynamic and static effects was below global sea level rise (Kopp *et al.*, 2010). In contrast, after 100 years, the island nation of Kiribati in the South Pacific had experienced local sea level rise 20 cm greater than global sea level due primarily to static equilibrium effects.

5.7.2. Tropical Cyclones, Storm Surges, and Waves

Superimposed on a rising sea will be storms and their associated surges and waves. Both surges and waves raise the reach of the water higher than a rising sea—storm surge primarily through the push of wind against the shore, and storm waves primarily through running up on the shore. Below, we examine recent advances in our understanding of how climate change is, or is not, changing characteristics of tropical cyclones, storm surges, and waves to either enhance or mitigate their potential impacts.

5.6.2.1. Tropical Cyclones

There has been considerable disagreement among investigators on how climate change would, or would not, change tropical cyclones. Part of the conflict is because the historical hurricane record for the north Atlantic, which has been extended back in time to the mid-nineteenth century, has limitations. Today, with satellites and storm-penetrating aircraft, we are able to document virtually all occurrences of tropical storms worldwide, whereas before air- and space-borne observing platforms were widely available, some storms were not adequately observed and recorded (e.g. Landsea, 2007). This made examining the past record of hurricanes for trends potentially caused by climate change challenging. Scale limitations of global climate models in resolving the details of hurricanes have also proved challenging (e.g. Emanuel *et al.*, 2008). Nonetheless, there have been important advances in capabilities to project the occurrence and characteristics of tropical cyclones since the publication of AR4. Here we will discuss improved understanding of the relationships between climate change and tropical cyclone frequency, intensity, and precipitation.

Knutson *et al.* (2010), in a review of tropical cyclones and climate change for the World Meteorological Organization, made a series of projections based “roughly” on the A1B IPCC emissions scenario. In terms of tropical-cyclone frequency, they find that the global mean will either decrease or remain constant as the world warms to 2100. They project global decreases of -6 to -34%. Knutson *et al.* (2010) reported the decrease is larger in the southern hemisphere than in the northern, possibly because of differences in projected sea surface temperatures (Zhao *et al.*, 2009) and/or wind shear (Vecchi and Soden, 2007). There is “some confidence” for the accuracy of both global and hemisphere projections, although confidence for individual basin projections remain low. Emanuel et al (2008) reported in more detail on downscaling AR4 simulations and the finding of decreasing global frequencies of tropical cyclones. Knutson et al (2008) focused on the Atlantic basin using a regional climate model that was able to reproduce hurricane counts over the past several decades, and found that under future climate scenarios that the Atlantic tropical cyclone frequency should be lower by 2100.

Reviewing a number of earlier studies, Knutson *et al.* (2010) concluded that during the projected warming of the twenty-first century, the intensity of tropical cyclones will likely increase, although this may not occur everywhere in all generating basins. They estimated increases of mean annual wind speeds ranging from +2 to +11% and falls of central atmospheric pressure from roughly +3 to +21%. Using models capable of examining the intensity of very strong storms through downscaling, Bender *et al.* (2010) recently found for the Atlantic basin a doubling of the frequency of Saffir-Simpson Scale Category 4 and 5 hurricanes by 2100. (Category 4 hurricanes have 210-249 km/hr sustained wind speeds; Category 5 hurricanes have greater than 249 km/hr sustained wind speeds.) This occurs even with the projected overall decrease in frequency of tropical cyclones (Knutson *et al.*, 2008; Knutson *et al.*, 2010). The greatest intensity increases of very intense storms are projected to occur in the western Atlantic Ocean. This is a particularly important result because Category 4 and 5 hurricanes have accounted for 48% of normalized damage from hurricanes in the United States for the period 1900 to 2005 (Pielke *et al.*, 2008; Bender *et al.*, 2010)

Knutson *et al.* (2010) conclude from seven available studies that precipitation from tropical cyclones will likely increase as the world warms. The estimated magnitudes range from +3 to +37%, although assessing uncertainties of these estimates is difficult. Unknown is how the increase in precipitation from storms will compare to the decreasing frequency of storms in computing annual precipitation averages. For example, the effects of decreasing frequency of all tropical cyclones could, potentially, be greater than the effects of increasing precipitation in individual storms. How these effects balance has not been established.

5.7.2.2. Storm Surges and Waves

The magnitudes of storm surge and waves are, in part, functions of storm intensity. Hence, stronger wind speeds in future tropical cyclones will generally translate to larger surges and waves, everything else being equal. (Of course, other factors are important as well, including the geometry of specific locales, that is the topography, bathymetry and shape of the coast and offshore. For example, where coasts are shaped like a funnel, in general, surges rise in height but waves fall in height.) Storm surges and waves are superimposed, the waves riding on top of the surges as well as on the rising sea, to deliver impacts to the coast. Here, we examine in more detail how surges and waves may vary with climate change.

Tropical cyclones Nargis and Sidr have recently killed over 100,000 people in Myanmar and Bangladesh, many of the deaths a result of extreme storm surges (Dasgupta *et al*., 2010). Tens of millions of people worldwide live within reach of storm surges. These numbers will increase in the future. Mousavi *et al*. (2011) examined the combined flooding of sea level rise and storm surges of low-lying Corpus Christi, Texas, USA through much of the twenty-first century, using several of the IPCC emissions scenarios. Mean projections indicate the sea level and storm surge flooding by 2030 will increase by 0.3 m, and by 2080 will increase by 0.8 m. Both are increases relative to the 2000s. Wang *et al*. (2008) examined how climate change effects storm surges on the Irish coast using the SRES A1B emissions scenario and found a significant increase in the elevation of extreme surges by 2060 along the west and east coasts of Ireland. Similarly, Woth *et al*. (2006) found climate induced increases in storm surge extremes along the North Sea coast.

Dasgupta *et al*. (2010) investigated the exposure of 84 countries to storm surges by assuming a future increase of 10% in extreme water levels. With a number of assumptions, they concluded that a present exposure of 7.82% of land area to sea level rise and storm surge flooding would increase to 13.36% in the future. The exposed population would rise from 36 million people to 67 million people. The top five most exposed countries in terms of land areas were, in order: Kuwait, Korea, Namibia, Tunisia, and Oman. The top five countries exposed in terms of population were, in order: Kuwait, Yemen, UAE, Tunisia, and Korea.

The potential increase in wave heights within a warming climate is, of course, important for delivering more energy to the coast. Further, breaking waves increase local sea levels through wave setup and the vertical reach of wave runup on beaches (e.g. Stockdon *et al*., 2005). These elevations are in addition to sea level rise and storm surge, hence increasing wave setup and runup during warming would increase the total vertical reach of the sea.

Changes in wave characteristics have been examined using data acquired from buoys and satellites over the past few decades. In a global study, Young *et al*. (2011) found increasing wind speed, and to lesser extent increasing wave heights, over the past two decades. For extreme conditions, increasing wave heights were more pronounced. With only twenty years of record, the authors did not relate these trends to climate change; the trends could be part of long-term oscillations. Chini *et al*. (2010) found only small changes to offshore wave characteristics off East Anglia, UK from climate change. They did find sea level rise leads to an increase in wave height in shallow water. Using climate change scenarios, Grabemann and Weisse (2008) estimated that in the southern and eastern North Sea by 2100 extreme wave heights may increase by 0.25 to 0.35 m. They also projected that occurrences of extreme waves in a warmer world will increase.

5.8. Assessing Vulnerabilities, Risks, and Costs

[Contributions from AS and YS were expected here]

5.8.1. Introduction

[Multiple interaction stresses (physical, social) in coastal system including Economic, social, and environmental context for uncertain futures under alternative development pathways]

5.8.2. Valuation Approaches to Assess Vulnerability

[Debate on uncertainties]

5.8.3. Coastal Systems

TBD

5.8.4. Human Activities

TBD

5.8.5. Cost of Inactions

TBD

5.8.6. Uncertainties and Needs for Long-Term Planning

TBD

5.9. Adaptation and Managing Risks

5.9.1. Approaches

5.9.1.1. Adaptation in Context

Adaptation to coastal risks from climate variability and change occurs in the context of existing governance and social-ecological systems, regardless of whether adaptation is proactive and planned or reactive and ad hoc. This context enables and constrains the possibilities for adaptation as well as what actually occurs. 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 in each country and location; ownership rules related to coastal land and resources (e.g., private property vs. public trust); the wide range of actors and 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 economic sectors dependent on or located in the coastal zone; past, present and planned development decisions; urban, business and industrial activities in or dependent on the coastal zone; the degree of demographic concentration; the resulting existing degree of build-up; the technologies employed (e.g. water systems, roads, electricity); the state of human welfare; as well as any past or existing social conflict and social capital; access to power and relationships among powerholders and affected stakeholders. Cultural factors play important roles, e.g. on worldviews, gender, class or caste relationships, concurrent pressures and trends of cultural transformation and so on.

The physical and ecological context of relevance for adaptation is the geologic/geomorphological type of coastline, the prevalent climate (with its typical patterns of climate variability and extremes), the local ecology and specific ecosystems and species present (in particular threatened or endangered species at risk; ecological thresholds); 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 adaptations are physically feasible or environmentally appropriate (although these feasibility limits are not necessarily always known or fixed, and there remains significant uncertainty around ecologically sound interventions).

5.9.1.2. Adaptation in and through Multi-Purpose Coastal Management

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 following three:

- Minimization of risks and impacts from coastal hazards to ensure public safety and welfare
- Economic development and use of coastal resources (incl. for non-economic purposes)
- Protection of coastal environmental resources, natural assets, and ecosystems

Maximizing on each of these goals, balancing them, and making trade-offs where necessary among these goals is a familiar problem to coastal managers today. 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., Vignola *et al.*, 2009; IUCN 2008), and Disaster Risk Reduction and Management (Shaw *et al.,* 2010; IPCC SREX report, forthcoming).

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

Adaptation – as it becomes integral to what coastal managers do – does and 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 acknowledge to a greater extent than its predecessors 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 (such as 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) (see references in Table 5.6). 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 (see Section 5.?) (e.g., Jentoft, 2009; McFadden, 2008; Mercer, 2010; Shipman and Stojanovic, 2007).

5.9.2. Practices (Past and Future)

There is a wide variety of processes and tools for managing coastal areas. Coping with the dynamics of physical processes and rapid population growth and investment in coastal areas has built a body of knowledge 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 (Horstman *et al.,* 2009). Analysis of how adaptation to sea level rise integrates with existing coastal management practices has advanced since AR4 but is still at a relatively early stage [review this statement when SREX is released; revise, reference further].

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 recommendations with respect to different ecosystems and species and recognizing different social contexts (Gilman *et al.,* 2008; Hansen *et al.,* 2010). 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 (McLeod *et al.,* 2010). 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.,* 2010).

The scope of scale of integration is advancing. 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. These greater scales allowed for further analysis of feedbacks and the set of scenarios informed a risk-based approach which provided probabilistic predictions of coastal behavior with an assessment of expected annual damages and illustrated trade-offs associated with different management approaches (Dawson *et al.,* 2009). Inundation models benefit from the increased availability of more accurate lidar data of coastal elevations (Gesch, 2009), although these data are not widely available. [Can someone add on coastal process modeling?]

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, 2010). 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). Integrated assessment models of cost effectiveness could also advance in their ability to incorporate ecosystem losses and consequences for fisheries and coastal infrastructure (Warren, 2011). [Need to coordinate this section with working group 3].

Efforts to develop improved vulnerability indices and identify hotspots which may serve to focus or prioritize management efforts are also continuing 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).

IPCC AR4 addressed impacts associated with temperature rise, extreme events, floods, rising water tables, erosion, saltwater intrusion, and biological effects. Since 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, a combination which poses challenges for designing these processes (Few *et al.,* 2007).

5.9.3. Adaptation Costs

[Important subsection]

Efforts to assess the costs and benefits of adaptation options are continuing to evolve, although significant further work is needed (Nicholls *et al.,* 2010). 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 cost-benefit analysis, although the limitations of that approach with respect to the treatment of nonmarket values makes it difficult to rely solely on this approach in adaptation (UNFCCC, 2010b). Other applicable approaches cost-effectiveness, a risk-based approach oriented to no-regrets, or win-win options, or multi-criteria analysis. All assessment types need to consider the distribution of burdens and benefits across groups, sectors, or other entities (UNFCCC, 2010b). [I expect that] Strengths and limitations of these approaches with respect adaptation are reviewed in Chapter 17 where analysis is expected to address adaptation costs and residual damage, adaptation deficits and barriers, and co-benefits of adaptation. A major review of methods and findings oriented towards national planning needs has also been produced under the Nairobi Work Plan (UNFCCC, 2010a). (Many new studies have become available since the last major synthesis published in 2009. A major recommendation of the Nairobi Work Plan publication "Potential costs and benefits of adaptation options: A review of existing literature. Technical paper” was to conduct additional synthetic analysis incorporating the substantial addition of studies (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 issues methodological issues have been identified as key issues further methodological development. 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). Other differences extend from approach to the integration of adaptation and mitigation options and the degree to which economy-wide and cross-sectoral linkages are represented (UNFCCC, 2010b). In addition, the objectives of the assessment, the type of adaptation options considered, and the objectives in undertaking adaptation actions may also influence costs and benefits (UNFCCC, 2010b).

Argawala and Fankhauser (2008) summarize key features of the large number of studies that focus on the costs of sea level rise impacts and adaptation. In that effort 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 (Argawala and Fankhauser, 2008).

Since AR4 and the Argawala and Fankhauser (2008) study, new 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 cast of high-end sea level rise scenarios (Parry *et al.,* 2009). The analysis may also underestimate because it focuses 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 costs estimated in (Nicholls, 2007); however, that deficit is not well understood and requires further definition and quantitative analysis (Parry *et al.,* 2009). The magnitude of the deficit is likely to be influenced by preferences for safety.

Economic models and valuation studies are placing increasing emphasis on the need to address ecosystem impacts and the value of ecosystem 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.

[Still needed:
Refine work above
Discussion of local case studies on costs
Discussion of limitations of information on assessing adaptation options other than building dykes and beach nourishment ""For the majority of the options knowledge gaps exist, data are missing or their reliability is insufficient. This means that based on our current knowledge it is impossible to evaluate the costs and benefits of the various policy alternatives and adaptation options that we presented." Page 37 deBruin et al. (2009)]

5.9.4. Constraints and Limits

In AR4, a principal finding in the coastal chapter 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*., forthcoming; 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; see also Chapter X in AR5); 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 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 AR4 as 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) find 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 under one stress alone (e.g., Desantis *et al*., 2007; Spalding *et al*., 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) argue, 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 (e.g., by type or source or emergence in the decision-making process), and they have placed variable emphasis on certain barriers. For example, common barriers identified include negative environmental consequences, technological feasibility, costs, institutional barriers (stemming from laws, regulations, procedural requirements or ineffective governance), entitlements and entrenched habits, political calculus, deeply held cultural values, worldviews and beliefs (and thus social acceptability), lack of awareness, knowledge or location-specific information, social justice concerns, or negative interactions between different policy goals (see Section 5.8.5 for more discussion on trade-offs). Table 5.4 provides some examples of barriers found in the literature specific to coastal adaptation (for a wider discussion of adaptation barriers and limits see Chapter X in AR5).

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

The wide range of barriers identified in Table 5.4 reflects different coastal management contexts (types of coastlines, degree of development and wealth etc.), different foci on levels of governance and actors/decision-makers, as well as different methods used in identifying them (surveys, observation of public consultations, in-depth interviews. This variety does not allow for a quantitative meta-analytical integration, and yet critical insights have emerged since 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 5.4, 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 et al. 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 (from recognizing the need for adaptation to increasing knowledge, generating and assessing options, decision-making and implementation, and monitoring, evaluation and ongoing learning and adjustments) (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 s well as budgetary constraints, with informational, communication, political, and public support barriers playing important additional roles (e.g., Storbjörk & Hedrén, 2011; Moser and Tribbia, 2006/2007; Ledoux *et al*., 2005). By contrast, studies focused on lay 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 (livelihood, job mobility, investment) barriers (e.g., Ryan et al. forthcoming [REQUESTED PERMISSION TO CITE]; Adger *et al*., 2011; Saroar *et al*. ,2010). Fifth, some factors can act as enablers and added capacity to adapt, while acting in barriers at others (Burch *et al*., 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). Thus, barriers are not uniformly and in all contexts barriers, and their importance varies with the presence of concurrent factors.

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.* forthcoming; Ekstrom, Moser and Thorn, 2011), some critical barriers arise from the interactions across policy domains (some of them concerned with adaptation in different sectors and others concerned with non-climatic policies), existing laws and regulations, and historical legacies (long-term impacts of past decisions and policies). Dawson *et al.* (2009), for example, show that – due to the interconnectivity of geomorphological 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 (see also Section 5.9.5).

5.9.5. 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 (e.g., agriculture, urban stormwater runoff) and industrial activities, and threats from infectious diseases (e.g., Melbourne-Thomas et al. 2011; Bunce et al. 2010a; Halpern et al. 2008). 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). In other words, while mitigation of GHG emissions is essential to reduce the pace of anthropogenic climate change and many of its immediate impacts, such efforts will not suffice to minimize the risks emerging from accelerated sea-level rise (ref WG1- relevant chapters). At the same time, decisions will be made in the course of economic development, planning, and coastal resource management that can positively or negatively affect adaptation and mitigation goals. Systematic assessment of potential synergies and tradeoffs between mitigation, adaptation, and other, non-climatic policy goals, ongoing monitoring of coastal change to assess the adequacy of policy and management approaches, 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 (ranging from transportation to construction to agriculture) – and various coastal management activities – involve emissions of greenhouse gases (CO_2, CH_4, N_2O). Moreover, all these activities and developments in the coastal zone will be impacted to varying degrees by climate change (ref previous sections in Chapter 5). The first few items in Table 5.5 show examples of such positive interactions.

[INSERT TABLE 5.8 HERE
Table 5-8: Positive synergies and tradeoffs between selected coastal adaptation and mitigation options.]

In addition to positive interactions, the possibility for negative interactions (or tradeoffs) exist as well.

Klein et al. (2007, p.749) defined tradeoffs 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). [check also with how this is discussed now in AR5, other chapters; potentially harmonize or leave discussion here as is]. A finer differentiation would distinguish various types of constraints: The first may prevent the full implementation of selected adaptation and mitigation measures due to insufficient supporting means and conditions. The second may prevent the full implementation due to concerns over unwanted outcomes of the selected adaptation or mitigation measure. 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 5.5). The second and third sections of Table 5.5 list a range of adaptation and mitigation options and show their respective potential negative implications for the complementary goal.

To date, such synergies and trade-offs are understood in principle in the research community, but clear guidance based on extensive empirical research is not yet available. Moreover, the specifics are context-dependent and not available. In practice, due to divisions of labor in impacts assessment, planning, decision-making, implementation and monitoring, trade-offs are not assessed as a common practice, and often only recognized when the resulting problems emerge [need help with ref?].

5.10. Case Studies

[Eventually, several cases studies, usually in boxes to appear in our chapter and also reworked with similar case studies to appear in other chapters where cross cutting issues are relevant. E.g. In AR4 Cyclone Katrina appeared as examples in several chapters depending on focus.

Need to think of what type of case studies – sometimes as standalone material that forms part of the other sections. Important to include cases from all over the world, more and less developed, and highlighting different impacts

- Dutch’s paradigm shift in dealing with sea level. Example of also key vulnerability and perception [CA4] *(to be included in next draft as Box)*
- Coral reefs (bleaching, acidification)]

5.11. Uncertainties and Data Gaps

Despite what we know about the coastal area, we will still require better understanding of the coastal ecosystems not on their own right but also the impacts from overexploitation and habitat destruction that have been responsible for most of the historical changes. In many cases, the stressors originate outside the coastal areas and have impacts on renewable coastal resources. On the impacts of climate change, while a relatively large number of studies have investigated how ecological systems respond to changes in mean values of climate, the combined effects of mean and variance are poorly understood, particularly in understanding their sensitivity on decadal timescales.

While attention has been focused on sea-level rise and flooding, there are significant gaps in knowledge of climate change impacts on particular coastal sectors. Climate modelling of diseases that could affect the coastal areas is based on 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). 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).

As the coast can be subject to considerable non-climate impacts, e.g. earthquakes and tsunamis, a balanced idea of the risks not only from climate change but also non-climate events is necessary. This means more information on the value of national economy in the coastal zones vulnerable to climate change (e.g. cyclones) and sea-level rise and to non-climate events (earthquakes and tsunamis). Information on risks to shelter, food production especially in the rice-growing areas of Asia, ports and coastal airports which connect countries world-wide and other significant infrastructure is also required.

Arising from climate change, sea-level rise seems to be the major climate stressor in the long-term on the coastal areas. There is a need to understand better the coastal morphodynamics arising from climate change and sea-level rise. For many sedimentary coasts, one fundamental question is the sediments and rate of sedimentation in response to sea-level rise. For coastal lagoons, it is a better understanding of lagoon functioning using hydro-ecological modeling (Thompson and Flower, 2009). For many coastal sectors 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).

Vulnerability assessment of sea-level rise can be improved for the local areas. While scenarios of sea-level rise are available and the vulnerability can be assessed through a number of various methodologies (e.g. DINAS) it is important to improve the assessment of local areas. The increasingly availability of GIS, especially LIDAR, makes it easy to assess the impacts of sea-level rise locally. Currently LIDAR data are easily available for the USA coasts but not for the rest of the world yet. Many developing countries, especially low-lying countries such as Bangladesh, the deltaic areas of Asia and small island states would need easy access to such information to assess the impact of sea-level rise as soon as possible.

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 *assessing* 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 drown and cannot migrate inland and/or the coastal communities can move inland. More alternative options are required.

Although mentioned in the AR4 and given more attention in the AR5, the impacts of ocean acidification would have serious consequences on the coastal zone. Since the AR4 new information is available on the likelihood of increased rates of ocean acidification. Although acidification is being addressed through international mitigation efforts, coastal policies need to address ocean acidification at the local and regional levels. More detailed and useful information would be required for the implementation of such policies

Of various adaptation approaches to climate change, the coastal zone management (CZM) is the major framework and has 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 CZM 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.

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). 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). Also a wide range of barriers in adaptation is present and but not the lack of information.

Within the coastal areas, future needs in adaptation measures are fairly clear : a better response to uncertainties of climate change; managing interaction between river flooding and sea-level rise; and regional analyses of changes in coastal ecosystem stocks (de la Vega-Leinert and Nicholls, 2008). In the long run, it would be necessary to link vulnerability, adaptation and mitigation (Martens *et al.*, 2009). This include more integrated scientific response to climate change; improvement of assessment methodologies from inter- and transdisciplinary perspective; reframing of current scientific understanding to mitigation, adaptation and vulnerability; translate new scientific insights into innovative policy and practice.

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 affected by climate change and sea-level rise. This is well developed in Europe (especially North Sea countries), the Mediterranean and Australia, and but less so in the developing countries, except in certain regions, e.g. Caribbean islands, Pacific Islands. An Adaptation Knowledge Platform is currently being developed for Asia-Pacific but no coastal portal is available for Southeast Asia and East Asia.

Lastly, coastal research relating to climate change needs to be positioned in 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 foci of climate research in 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).

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DUDA (Grey literature):

Compendium on resources and tools

http://unfccc.int/adaptation/nairobi_workprogramme/knowledge_resources_and_publications/items/5457.php

Adaptation practices – database

http://unfccc.int/adaptation/nairobi_work_programme/knowledge_resources_and_publications/items/4555.php

Table 5-1: Ecosystems goods and services offered by coastal ecosystems.
[Note: Last column is to be removed and table to be revised]

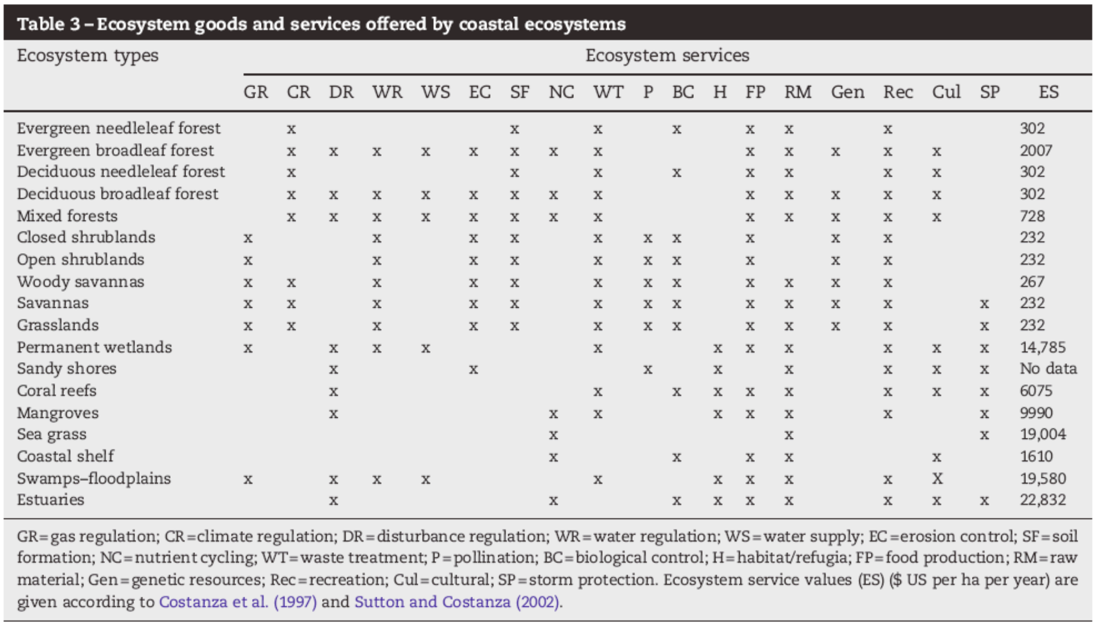

Table 3 – Ecosystem goods and services offered by coastal ecosystems

Ecosystem types	Ecosystem services																		
	GR	CR	DR	WR	WS	EC	SF	NC	WT	P	BC	H	FP	RM	Gen	Rec	Cul	SP	ES
Evergreen needleleaf forest		x					x		x		x		x	x		x			302
Evergreen broadleaf forest		x	x	x	x	x	x	x	x				x	x	x	x	x		2007
Deciduous needleleaf forest		x					x		x		x		x	x		x	x		302
Deciduous broadleaf forest		x	x	x	x	x	x	x	x				x	x	x	x	x		302
Mixed forests		x	x	x	x	x	x	x	x				x	x	x	x	x		728
Closed shrublands	x			x		x	x		x	x	x		x		x	x			232
Open shrublands	x			x		x	x		x	x	x		x		x	x			232
Woody savannas	x	x		x		x	x		x	x	x		x	x	x	x			267
Savannas	x	x		x		x	x		x	x	x		x	x	x	x		x	232
Grasslands	x	x		x		x	x		x	x	x		x	x	x	x		x	232
Permanent wetlands	x		x	x	x				x			x	x	x		x	x	x	14,785
Sandy shores			x			x				x		x		x		x	x	x	No data
Coral reefs			x						x		x	x	x	x		x	x	x	6075
Mangroves			x					x	x			x	x	x		x		x	9990
Sea grass								x						x				x	19,004
Coastal shelf								x			x		x	x			x		1610
Swamps–floodplains	x		x	x	x				x			x	x	x		x	X		19,580
Estuaries			x					x			x	x	x	x		x	x	x	22,832

GR = gas regulation; CR = climate regulation; DR = disturbance regulation; WR = water regulation; WS = water supply; EC = erosion control; SF = soil formation; NC = nutrient cycling; WT = waste treatment; P = pollination; BC = biological control; H = habitat/refugia; FP = food production; RM = raw material; Gen = genetic resources; Rec = recreation; Cul = cultural; SP = storm protection. Ecosystem service values (ES) ($ US per ha per year) are given according to Costanza et al. (1997) and Sutton and Costanza (2002).

Table 5-2: [to be based on tables following the Table 5-8 entry (see pages 71-81)]

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

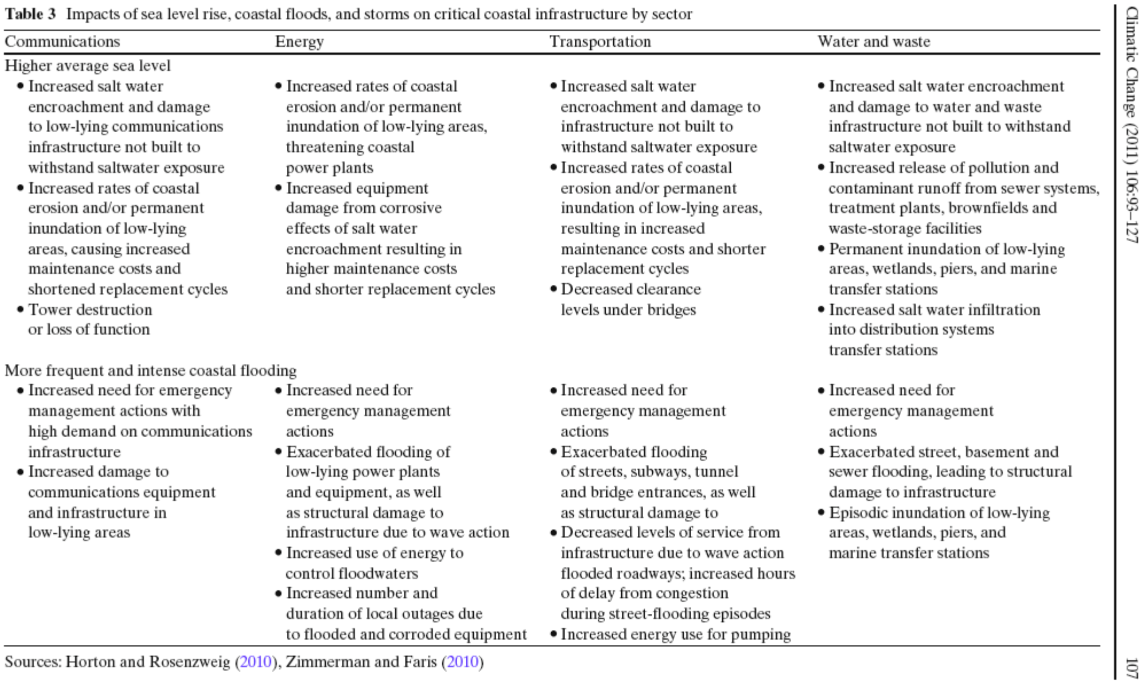

Table 3 Impacts of sea level rise, coastal floods, and storms on critical coastal infrastructure by sector

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 infrastructure due to wave action • Decreased levels of service from 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)

Climatic Change (2011) 106:93–127

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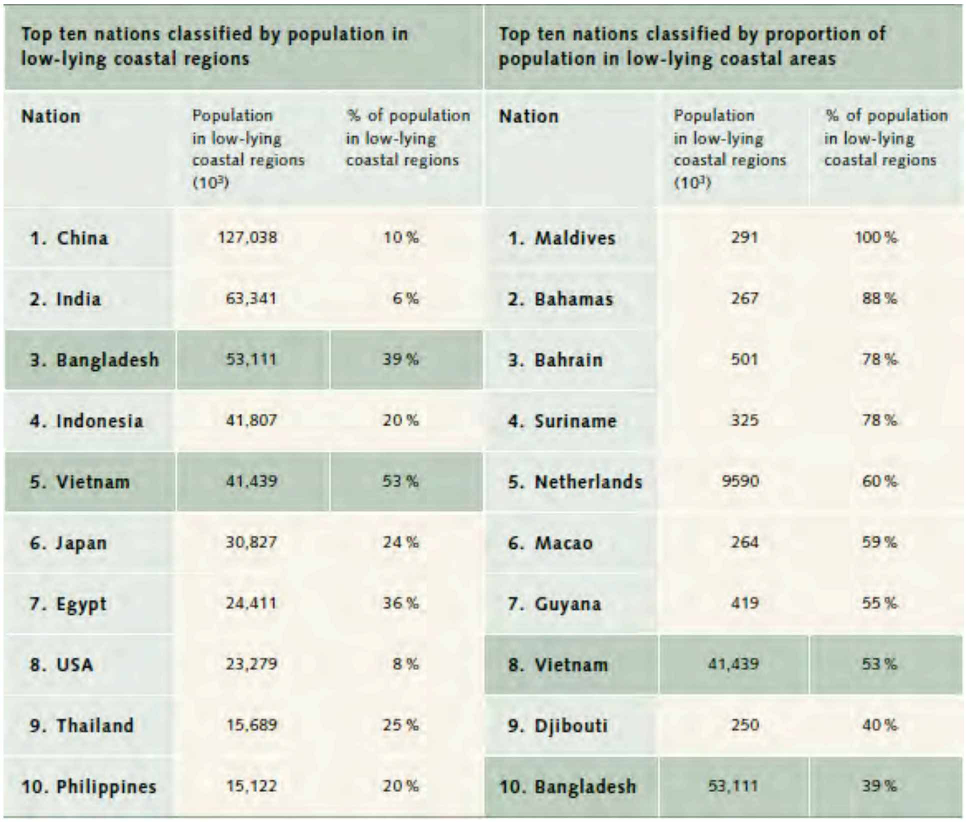
Table 5-4: Top ten nations with the largest populations and the highest proportions of population in low-lying coastal areas (Countries with fewer than 100,000 inhabitants are not included; 15 SIDs with total of 423,000 inhabitants are also excluded)



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 %

Source: Bollman *et al* 2010.

Table 5-5: Major coastal tourism hotspots and their major climate and non-climate impacts.

Hotspot	Climate and non-climate impacts
Mediterranean	WS, W, LB, D
Caribbean	WS, EE, W, MB, SLR, D, PD, TCI
Indian Ocean	EE, W, LB, MB, SLR, TCI
Pacific Ocean	EE, W, LB, MB, SLR, TCI

WS = warmer summers
EE = increase in extreme events
SLR = sea-level rise
W = water scarcity
PD = political destabilization
MB = marine biodiversity loss
LB = land biodiversity loss
D = increase in disease
TCI = travel cost increase from mitigation policy

Source: WTO 2007

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); VanKoningsveld et al (2008)	Nursey-Bray & Shaw (2010); Jentoft (2009); Dawson et al. (2009); Sales (2009); McFadden (2008); Shipman & Stojanovic (2007)	Romieu et al. (2010), Mercer (2010); Mitchell et al. (2010); Polack (2010); Gero et al (2011)	Espinosa-Romero et al. (2011); McGinnis & 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 & 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 integrated and learning-oriented approaches • Time and effort required to change departmental priorities	Storbjörk & Hedrén 2011, Storbjörk 2010

	• 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 et al. 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 & 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 • Lack of public awareness and demand • Lack of technical assistance from state or federal agencies • Limited social acceptability	Tribbia & Moser 2008; Moser & Tribbia 2006/2007

	• 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

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 REVIEWERS FOR NEW REFERENCES (SINCE CUT-OFF DATE FOR AR4). ALSO: WE MAY BE ABLE TO ADD CONFIDENCE LANGUAGE TO THESE, IF DESIRED/ABLE TO DO SO.]*
Coastal sea grass and tidal marsh restoration	Increased carbon storage[a]	Storm buffer, species habitat, fish nursery	Whiting & Chanton 2001; Turner et al. 2005
Mangrove restoration species	Carbon storage[a]	Habitat and species protection, flood control, soil preservation	Alongi 2002; Kristensen et al. 2008
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 & 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 & 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 & 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 & 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 stressors on near- and offshore coastal and marine ecosystems and species	Gill 2005; Boehlert & 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) suggests this benefit may be smaller than previously thought given the losses of sequestered carbon in soils that erode during coastal storms.

For Table 5-2. Sensitivity: [Table S2 in Hoegh-Guldberg & Bruno, 2010] Survey of recent literature on the impacts anthropogenic climate change on marine ecosystems

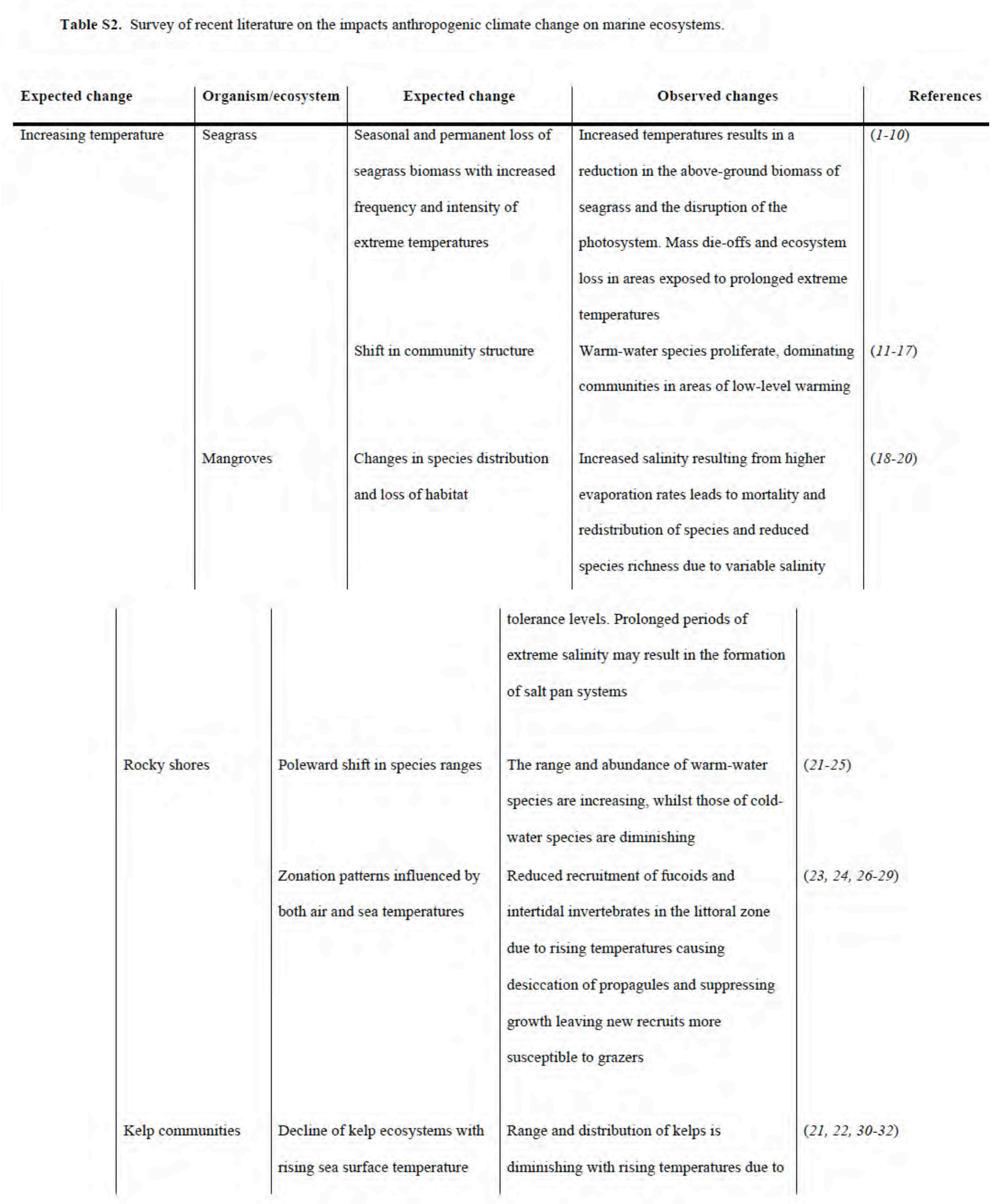
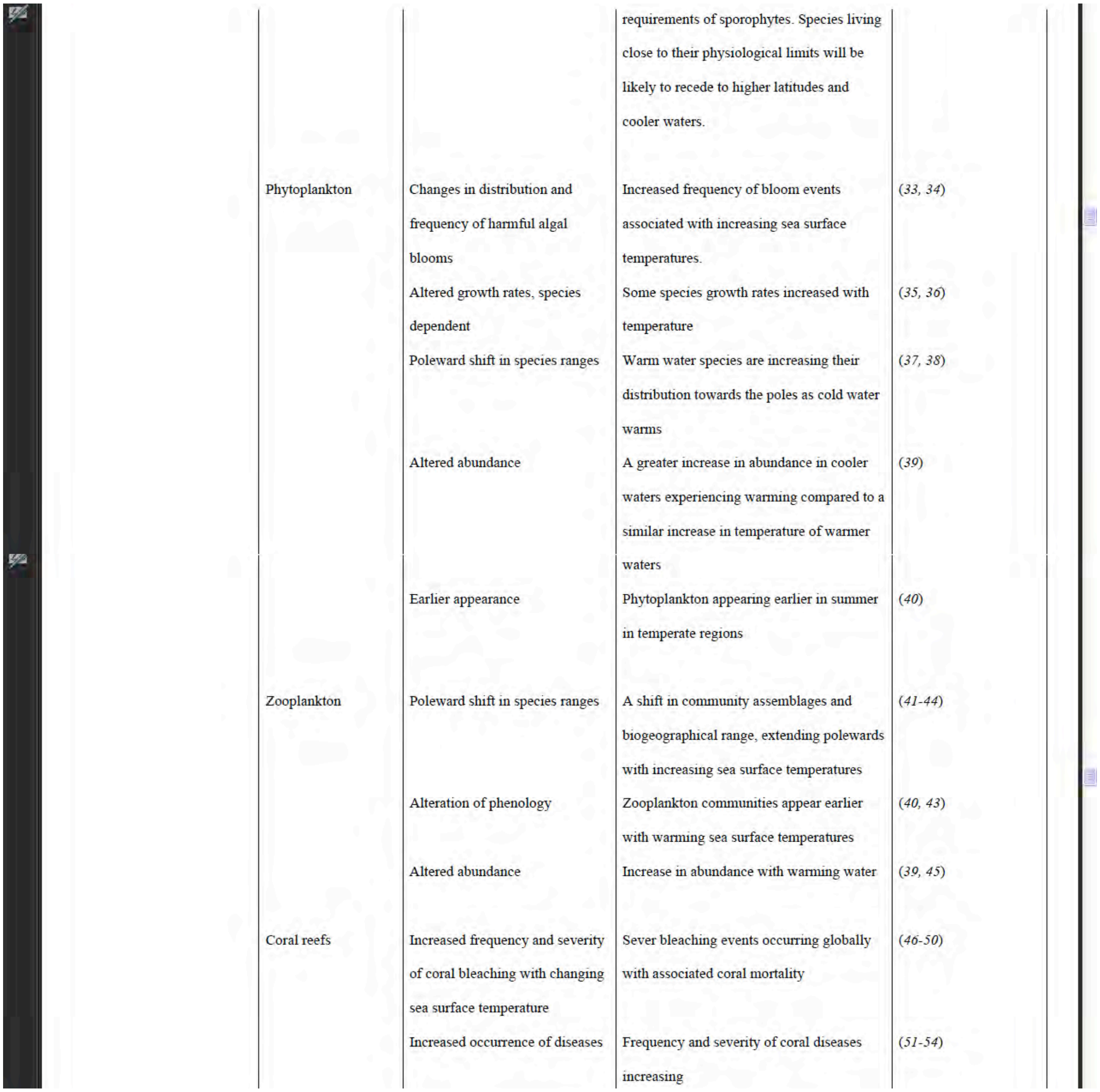


Table S2. Survey of recent literature on the impacts anthropogenic climate change on marine ecosystems.

Expected change	Organism/ecosystem	Expected change	Observed changes	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	(*1-10*)
		Shift in community structure	Warm-water species proliferate, dominating communities in areas of low-level warming	(*11-17*)
	Mangroves	Changes in species distribution and loss of habitat	Increased salinity resulting from higher evaporation rates 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 the formation of salt pan systems	(*18-20*)
	Rocky shores	Poleward shift in species ranges	The range and abundance of warm-water species are increasing, whilst those of cold-water species are diminishing	(*21-25*)
		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	(*23, 24, 26-29*)
	Kelp communities	Decline of kelp ecosystems with rising sea surface temperature	Range and distribution of kelps is diminishing with rising temperatures due to	(*21, 22, 30-32*)



		requirements of sporophytes. Species living close to their physiological limits will be likely to recede to higher latitudes and cooler waters.	
Phytoplankton	Changes in distribution and frequency of harmful algal blooms	Increased frequency of bloom events associated with increasing sea surface temperatures.	(*33, 34*)
	Altered growth rates, species dependent	Some species growth rates increased with temperature	(*35, 36*)
	Poleward shift in species ranges	Warm water species are increasing their distribution towards the poles as cold water warms	(*37, 38*)
	Altered abundance	A greater increase in abundance in cooler waters experiencing warming compared to a similar increase in temperature of warmer waters	(*39*)
	Earlier appearance	Phytoplankton appearing earlier in summer in temperate regions	(*40*)
Zooplankton	Poleward shift in species ranges	A shift in community assemblages and biogeographical range, extending polewards with increasing sea surface temperatures	(*41-44*)
	Alteration of phenology	Zooplankton communities appear earlier with warming sea surface temperatures	(*40, 43*)
	Altered abundance	Increase in abundance with warming water	(*39, 45*)
Coral reefs	Increased frequency and severity of coral bleaching with changing sea surface temperature	Sever bleaching events occurring globally with associated coral mortality	(*46-50*)
	Increased occurrence of diseases	Frequency and severity of coral diseases increasing	(*51-54*)

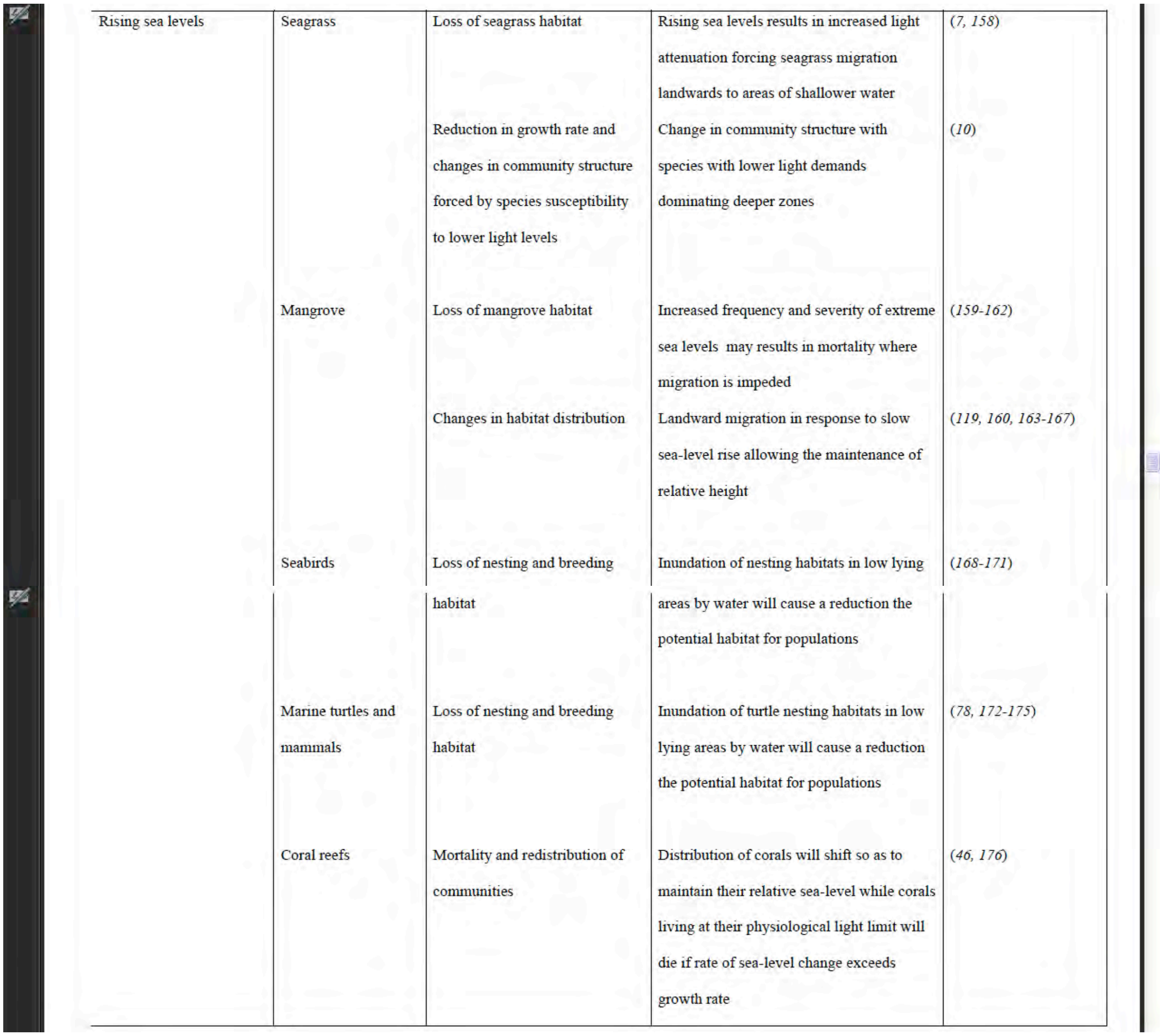
	Loss of coral reef species due to coral bleaching and mortality	Loss of coral reef fish, crustacea and other invertebrate diversity and abundance with loss of live coral habitat due to rising temperatures	(*55-59*)
Seabirds	Poleward shift in species ranges and a shift in abundance toward species tolerant 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	(*60-64*)
	Birds migrating earlier in temperate and subtropical regions	Alteration of breeding date with changing temperature, favouring early breeding and altered selection patterns	(*65, 66*)
	Altered breeding seasons, affecting nesting and laying times	Extended breeding seasons in the temperate and tropical regions with earlier nesting and laying times	(*62, 67, 68*)
	Breeding success affected by climate change and prey availability	Temperature and associated changes in prey availability and match-mismatch of breeding affect population success	(*69-71*)
	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	(*72*)
Marine turtles	Poleward shift in species foraging ranges	Temperature change has implications on migratory patterns, forcing a poleward shift in populations	(*73, 74*)
	Change in the sex ratios	Changes in temperatures affect the sex ratio with rising temperatures favouring female populations	(*75-77*)
	Changes in breeding	Warmer foraging and nesting grounds affect the timing of breeding, clutch number and	(*78-81*)

			nesting season length	
	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	(*82-84*)
	Polar Ice Habitats	Ice thinning and loss results in greater UV penetration to the marine system	Prolonged periods of ice loss, or thin ice affects the growth and distribution of benthic and pelagic microalgae and cyanobacteria altering productivity	(*85, 86*)
		Changes to seasonal ice loss patterns	Changes to the seasonal ice break events alters the marine eukaryotic communities and system function	(*87*)
		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	(*88*)
	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	(*89-93*)
		Migration dates altered with warming	Earlier dates of mean migration and spawning in temperate and subtropical species	(*94*)
Alteration Wind strength	Phytoplankton 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	(*85, 95-97*)
		Changes in community structure with surface mixing	Alteration of the surface stratification with wind-driven upwelling can cause alterations in community structure and bloom	(*98, 99*)

			formation	
	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	(*96, 97, 100, 101*)
	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	(*102, 103*)
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	(*104*)
	Mangroves	Breakdown in control of latitudinal distribution through propagule current translocation	Changes to currents responsible for propagule distribution results in the redistribution of mangroves	(*105*)
		Changes in local distribution patterns with changing sediment transport patters	Changes in current-driven sediment distribution affects growth rates and success of plant	(*106*)
	Kelp communities	Local extinction of cold-water species with changes in currents and the appearance of warm-water species	Alteration of larval supply changes the distribution of species and success in altered thermal conditions	(*107*)
	Rocky shores	Poleward shift of warm water species	Tropical species appearing in temperate latitudes due to changes in distribution of larvae	(*108*)
	Phytoplankton 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	(*109, 110*)
Decline in mixed layer depth/increasing stratification	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	(*39, 63, 64*)
	Pelagic fish	Abundance and distribution changes due to thermal stratification of upper ocean	Stratification and associated plankton community changes alters food supply for fishes, altering community structure and distribution	(*39, 111*)

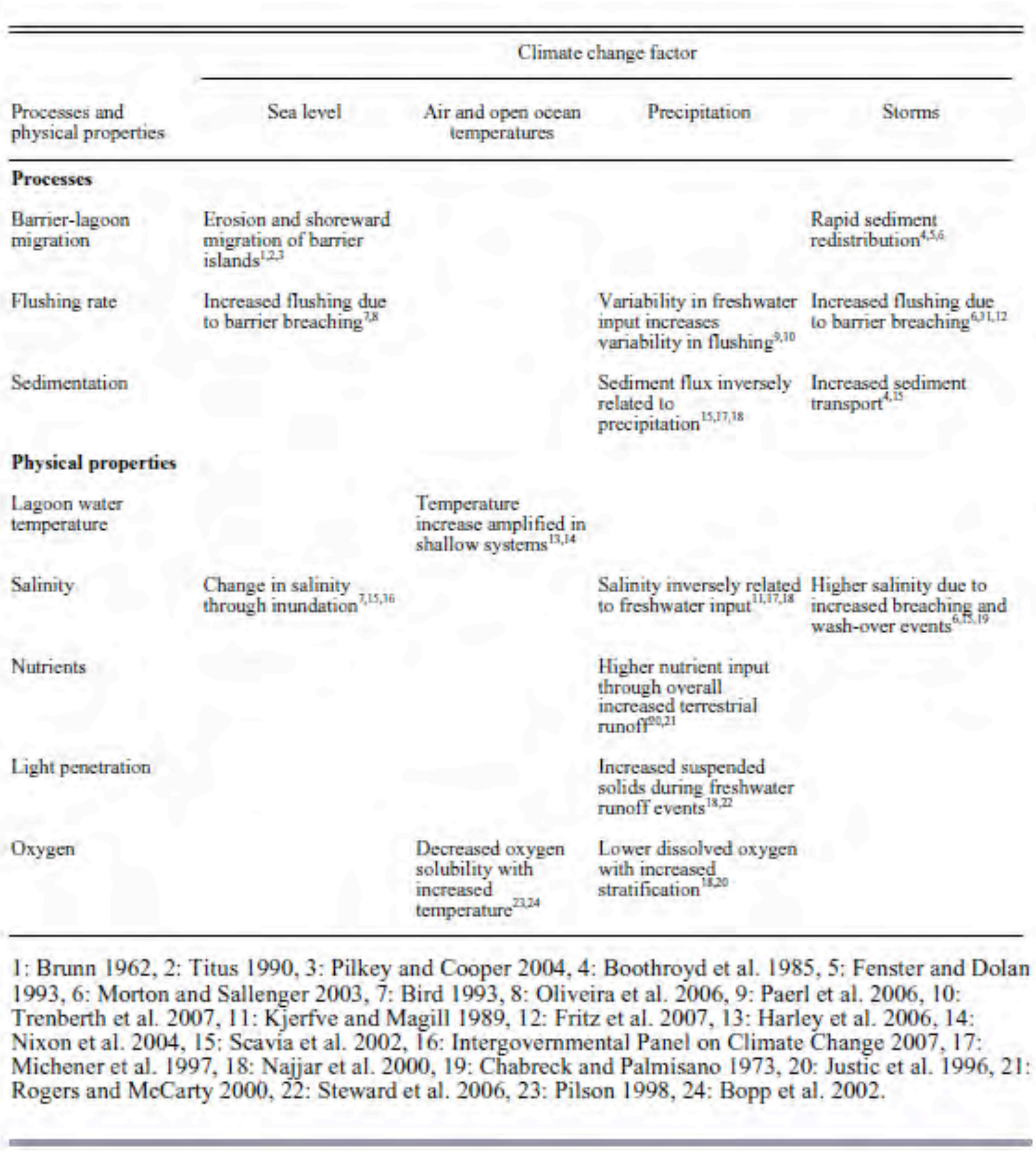
	Phytoplankton and Zooplankton	Changes in distribution and abundance due to altered stratification zones	Vertical stratification resulting from changes in sea surface temperatures strengthens existing thermoclines in warmer stratified waters and encourage the development of their formation in cooler turbulent waters creating suitable habitat for zooplankton	(*39, 111*)
		Decline in phytoplankton abundance	As the mixed surface layer diminishes phytoplankton productivity decreases	(*97, 112, 113*)
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	(*7, 114-116*)
		Changes in sedimentation regimes cause mortality	Sediment deposition caused my storm activity and increased rainfall runoff smothers seagrass	(*114, 115*)
		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	(*115, 117, 118*)
	Mangroves	Change in community abundance associated with increased rainfall events	Mangrove community distribution increase due to altered salinity, nutrient and sediment loading	(*119-122*)
		Reproductive success and growth influenced by storm activity	Prolonged periods of flooding may cause the mortality and impeded propagation of juvenile plants	(*119*)
	Rocky shore	Increased wave energy alters community structure	Storm-driven wave damage change in species zonation patterns	(*24, 123*)
		Increased storm frequency affects community structure and function group prevalence	Fucoid species will be lost and associated invertebrates, allowing those species that can withstand high energy environments, such as mussels and barnacles, to dominate	(*124*)
		Increased freshwater inputs alters zonation	Changes in species zonation driven by changes in salinity due to extreme rain events	(*125*)
	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	(*32, 126-129*)

	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	(*130-137*)
		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	(*138-142*)
		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	(*141-145*)
	Phytoplankton and Zooplankton	Terrestrial run-off causes nutrient enrichment of surface waters	Increased nutrient state causes a change in community structure and dynamics causing a shift from heterotrophy to autotrophy	(*146-150*)
		Storm-forced upwelling of nutrient rich waters causes community change	Nutrient rich water promotes phytoplankton growth	(*151*)
	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	(*152-156*)
	Seabirds	Increased feeding	Increased plankton abundance drives foraging success and breeding population dynamics	(*102*)
		Restriction and alteration of foraging and migration	Storm events prevent birds from travelling usual routes and cause changes in flight patterns	(*157*)



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	(*7, 158*)
		Reduction in growth rate and changes in community structure forced by species susceptibility to lower light levels	Change in community structure with species with lower light demands dominating deeper zones	(*10*)
	Mangrove	Loss of mangrove habitat	Increased frequency and severity of extreme sea levels may results in mortality where migration is impeded	(*159-162*)
		Changes in habitat distribution	Landward migration in response to slow sea-level rise allowing the maintenance of relative height	(*119, 160, 163-167*)
	Seabirds	Loss of nesting and breeding habitat	Inundation of nesting habitats in low lying areas by water will cause a reduction the potential habitat for populations	(*168-171*)
	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	(*78, 172-175*)
	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	(*46, 176*)

For Table 5-2. Sensitivity: [Table 2 in Anthony *et al.,* 2009] Direct effects of projected global climate change factors on processes and physical properties of coastal lagoons



	Climate change factor			
Processes and physical properties	Sea level	Air and open ocean temperatures	Precipitation	Storms
Processes				
Barrier-lagoon migration	Erosion and shoreward migration of barrier islands[1,2,3]			Rapid sediment redistribution[4,5,6]
Flushing rate	Increased flushing due to barrier breaching[7,8]		Variability in freshwater input increases variability in flushing[9,10]	Increased flushing due to barrier breaching[6,11,12]
Sedimentation			Sediment flux inversely related to precipitation[15,17,18]	Increased sediment transport[4,15]
Physical properties				
Lagoon water temperature		Temperature increase amplified in shallow systems[13,14]		
Salinity	Change in salinity through inundation[7,15,16]		Salinity inversely related to freshwater input[11,17,18]	Higher salinity due to increased breaching and wash-over events[6,15,19]
Nutrients			Higher nutrient input through overall increased terrestrial runoff[20,21]	
Light penetration			Increased suspended solids during freshwater runoff events[18,22]	
Oxygen		Decreased oxygen solubility with increased temperature[23,24]	Lower dissolved oxygen with increased stratification[18,20]	

1: Brunn 1962, 2: Titus 1990, 3: Pilkey and Cooper 2004, 4: Boothroyd et al. 1985, 5: Fenster and Dolan 1993, 6: Morton and Sallenger 2003, 7: Bird 1993, 8: Oliveira et al. 2006, 9: Paerl et al. 2006, 10: Trenberth et al. 2007, 11: Kjerfve and Magill 1989, 12: Fritz et al. 2007, 13: Harley et al. 2006, 14: Nixon et al. 2004, 15: Scavia et al. 2002, 16: Intergovernmental Panel on Climate Change 2007, 17: Michener et al. 1997, 18: Najjar et al. 2000, 19: Chabreck and Palmisano 1973, 20: Justic et al. 1996, 21: Rogers and McCarty 2000, 22: Steward et al. 2006, 23: Pilson 1998, 24: Bopp et al. 2002.

For Table 5-2. Sensitivity: [Table 4 in Bohensky et al. (in press)]

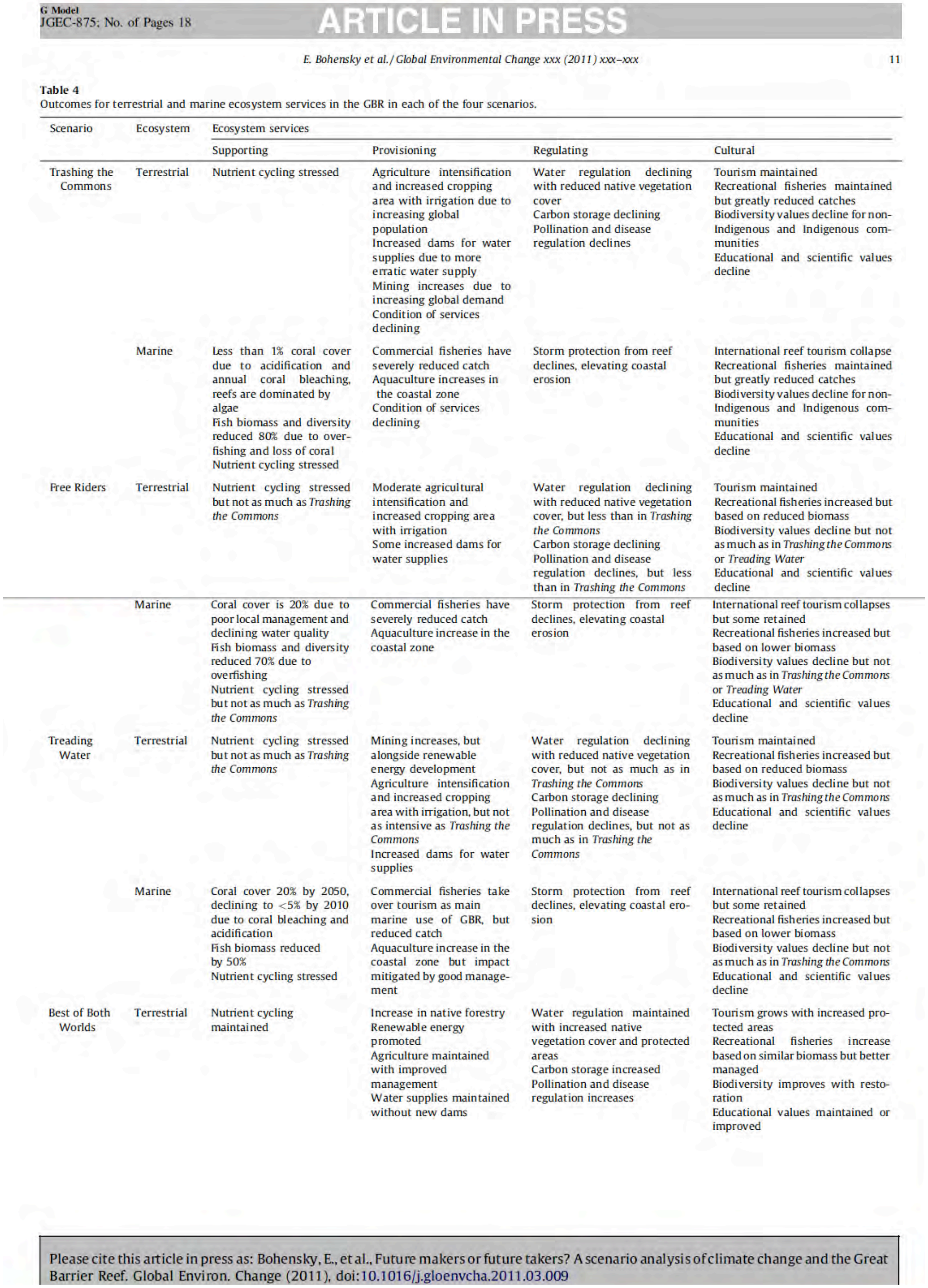


Table 4
Outcomes for terrestrial and marine ecosystem services in the GBR in each of the four scenarios.

Scenario	Ecosystem	Ecosystem services			
		Supporting	Provisioning	Regulating	Cultural
Trashing the Commons	Terrestrial	Nutrient cycling stressed	Agriculture intensification and increased cropping area with irrigation due to increasing global population Increased dams for water supplies due to more erratic water supply Mining increases due to increasing global demand Condition of services declining	Water regulation declining with reduced native vegetation cover Carbon storage declining Pollination and disease regulation declines	Tourism maintained Recreational fisheries maintained but greatly reduced catches Biodiversity values decline for non-Indigenous and Indigenous communities Educational and scientific values decline
	Marine	Less than 1% coral cover due to acidification and annual coral bleaching, reefs are dominated by algae Fish biomass and diversity reduced 80% due to overfishing and loss of coral Nutrient cycling stressed	Commercial fisheries have severely reduced catch Aquaculture increases in the coastal zone Condition of services declining	Storm protection from reef declines, elevating coastal erosion	International reef tourism collapse Recreational fisheries maintained but greatly reduced catches Biodiversity values decline for non-Indigenous and Indigenous communities Educational and scientific values decline
Free Riders	Terrestrial	Nutrient cycling stressed but not as much as *Trashing the Commons*	Moderate agricultural intensification and increased cropping area with irrigation Some increased dams for water supplies	Water regulation declining with reduced native vegetation cover, but less than in *Trashing the Commons* Carbon storage declining Pollination and disease regulation declines, but less than in *Trashing the Commons*	Tourism maintained Recreational fisheries increased but based on reduced biomass Biodiversity values decline but not as much as in *Trashing the Commons* or *Treading Water* Educational and scientific values decline
	Marine	Coral cover is 20% due to poor local management and declining water quality Fish biomass and diversity reduced 70% due to overfishing Nutrient cycling stressed but not as much as *Trashing the Commons*	Commercial fisheries have severely reduced catch Aquaculture increase in the coastal zone	Storm protection from reef declines, elevating coastal erosion	International reef tourism collapses but some retained Recreational fisheries increased but based on lower biomass Biodiversity values decline but not as much as in *Trashing the Commons* or *Treading Water* Educational and scientific values decline
Treading Water	Terrestrial	Nutrient cycling stressed but not as much as *Trashing the Commons*	Mining increases, but alongside renewable energy development Agriculture intensification and increased cropping area with irrigation, but not as intensive as *Trashing the Commons* Increased dams for water supplies	Water regulation declining with reduced native vegetation cover, but not as much as in *Trashing the Commons* Carbon storage declining Pollination and disease regulation declines, but not as much as in *Trashing the Commons*	Tourism maintained Recreational fisheries increased but based on reduced biomass Biodiversity values decline but not as much as in *Trashing the Commons* Educational and scientific values decline
	Marine	Coral cover 20% by 2050, declining to <5% by 2010 due to coral bleaching and acidification Fish biomass reduced by 50% Nutrient cycling stressed	Commercial fisheries take over tourism as main marine use of GBR, but reduced catch Aquaculture increase in the coastal zone but impact mitigated by good management	Storm protection from reef declines, elevating coastal erosion	International reef tourism collapses but some retained Recreational fisheries increased but based on lower biomass Biodiversity values decline but not as much as in *Trashing the Commons* Educational and scientific values decline
Best of Both Worlds	Terrestrial	Nutrient cycling maintained	Increase in native forestry Renewable energy promoted Agriculture maintained with improved management Water supplies maintained without new dams	Water regulation maintained with increased native vegetation cover and protected areas Carbon storage increased Pollination and disease regulation increases	Tourism grows with increased protected areas Recreational fisheries increase based on similar biomass but better managed Biodiversity improves with restoration Educational values maintained or improved

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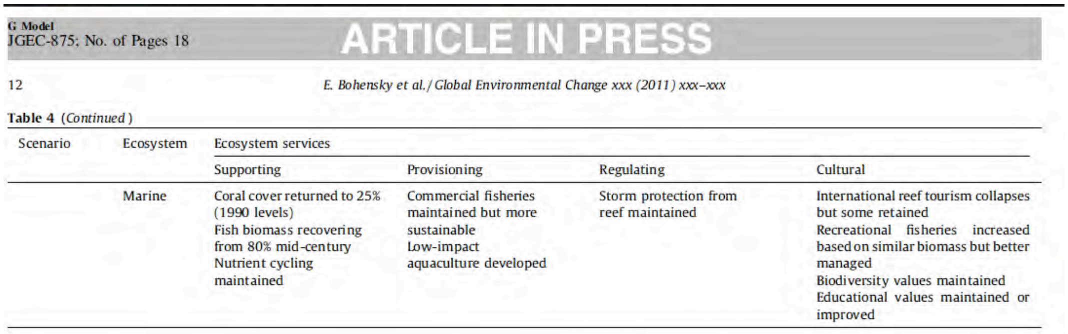

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Table 4 (*Continued*)

Scenario	Ecosystem	Ecosystem services			
		Supporting	Provisioning	Regulating	Cultural
	Marine	Coral cover returned to 25% (1990 levels) Fish biomass recovering from 80% mid-century Nutrient cycling maintained	Commercial fisheries maintained but more sustainable Low-impact aquaculture developed	Storm protection from reef maintained	International reef tourism collapses but some retained Recreational fisheries increased based on similar biomass but better managed Biodiversity values maintained Educational values maintained or improved

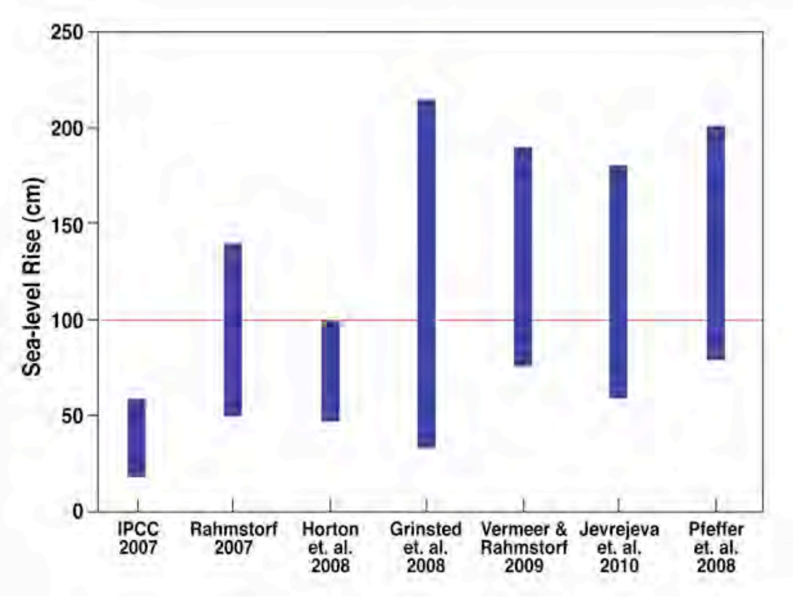

Figure 5-1: Range of sea-level changes for AR4 and for several studies that followed (modified from Rahmstorf, 2010).