IPCC WGII Fourth Assessment Report – Draft for Government and Expert Review

Chapter 6 – Coastal Systems and Low-lying Areas

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Executive Summary

This assessment significantly reinforces and extends the conclusions of the TAR concerning the serious implications of climate change for coastal zones and low-lying areas. The coast is already highly vulnerable to both climate- (e.g. hurricane) and non-climate-related (e.g., tsunami) impacts, and this is imposing substantial costs on coastal societies (VHC) [Sections 6.2.2; 6.5.2]. Future coastal impacts due to climate change and sea-level rise are among the most costly and most certain consequences of climate change (VHC) [Sections 6.4.2; 6.5.3].

Several climate-related trends have been observed in coastal areas over the past 50 to 100 years:

- Net global rise of sea level has contributed to increased coastal inundation, erosion and ecosystem losses, but with considerable local and regional variation due to other factors (HC) [Sections 6.2.5; 6.4.1].
- The observed effects of rising temperature include loss of sea ice, melting of permafrost and associated coastal retreat, and the bleaching of tropical reef corals (HC) [Section 6.2.5].

However, direct impacts of human activities on coasts have generally been more significant than impacts that can be attributed to observed climate change (VHC) [Sections 6.2; 6.5.2] and tropical cyclone impacts, has been accentuated by growing coastal populations and assets (VHC) [Sections 6.2; 6.5.2], added to any increased storm intensity (LC) [Sections 6.3.2; 6.4.1].

In future, coasts are likely to be further impacted by a combination of climate-related changes, in particular an accelerated rise in sea level, further rise in water temperatures, an intensification of tropical cyclones, changes in wave and storm surge characteristics, precipitation/run-off and acidification of seawater (HC) [Section 6.3.2]. As a result impact costs will rise, initially through impacts from climate extremes and variability, whereas in the longer term mean increases will have a greater influence (MC) [Section 6.5.3]. These changes are compounded by the virtual certainty that there will be increasing human use of coastal areas that are already vulnerable, implying that larger numbers of people and human assets will be at risk (VHC) [Section 6.3.1].

This assessment confirms that most low-lying coastal areas are vulnerable to sea-level rise and climate change, and evidence since the TAR makes it clear that the resulting impacts will be overwhelmingly negative for a wider range of coastal systems (HC) [Sections 6.4; 6.5.3], though spatially variable (VHC) [Section 6.4]. Most natural coastal systems appear particularly vulnerable, except where sedimentation is sufficient to maintain relative elevation, or the system can migrate landward (VHC) [Section 6.4.1]. Along populated coasts such migration is increasingly precluded by human infrastructure and development (VHC) [Section 6.4.1]. Coral reefs are vulnerable to a range of stresses and for many reefs, thermal stress thresholds will be crossed, resulting in bleaching, with severe adverse consequences for reef-based fisheries, tourism, and other dependent economic and social systems (HC) [Sections 6.2.5; 6.4.1.4].

The impacts of climate change on the goods and services from coastal ecosystems could have serious implications for the well-being of coastal communities (HC) [Sections 6.4.2; 6.5.3]. Flooding, inundation and freshwater resources are of most concern (HC) [Section 6.4.2]. Secondary and indirect effects include impacts on tourism, fisheries and health (HC) [Section 6.4.2]. Key societal hotspots of coastal vulnerability emerge when stresses on natural systems intersect with low human adaptive capacity and high exposure. These hotspots include populated deltas, coastal urban areas, and small islands (VHC) [Section 6.4.3]. Since the TAR, it has become more apparent that human vulnerability to impacts will be strongly influenced by development trends, especially those related to population, wealth, and technology, as well as the pattern of sea-level and climate change (HC) [Section 6.4.2; 6.7]. Low-lying developing countries and low-income coastal communities and limited access to adaptation choices are most threatened both today and in the future (HC) [Sections 6.4.2; 6.5.2; 6.5.3].

Understanding of adaptation has grown significantly since the TAR. Present responses to climate-related coastal hazards often appear inadequate relative to the high and growing levels of risk (HC) [Sections 6.5.2; 6.5.3]. The benefits of coastal adaptation are generally much greater than the costs of inaction (VHC) [Section 6.6.2], reducing climate risks (HC) [Sections 6.6.3; 6.7]. To improve effectiveness, coastal adaptation choices need to reflect local circumstances, including historic and planned development patterns (VHC) [Section 6.6]. Although protection measures can greatly reduce human impacts, their long-term effectiveness is strongly contested, even for developed countries, due to constraints such as costs, public acceptance and the detrimental consequences for natural systems and their services (VHC) [Section 6.6.3]. A portfolio of adaptation measures may be more effective (HC) [Section 6.6].

Climate change and sea-level rise and impacts from extreme events provide a serious impediment to achieving sustainable development, especially in developing countries, in part due to their lower adaptive capacity. Strengthening integrated multidisciplinary and participatory approaches to coastal management and disaster management will improve the prospects for sustaining coastal resources and communities (HC) [Section 6.7]. Future sea-level rise projections show that risks will continue to increase for many generations, unless there is a substantial and ongoing investment in adaptation (HC) (Sections 6.6.5; 6.7]. Hence, for coastal areas it is more apparent since the TAR that the most appropriate response is a combination of adaptation and mitigation (HC) [Sections 6.6.5; 6.7].

6.1 Scope, summary of TAR conclusions and key issues

This chapter presents a global perspective on the impacts of climate change and sea-level rise on coastal and adjoining low-lying areas, with an emphasis on the new insights that have emerged since the Third Assessment Report (TAR). (Note that marine ecosystems are considered in Chapter 4). Here coastal systems are considered as the interacting low-lying areas and shallow coastal waters, including their human components, and external marine and terrestrial influences on the coast (Figure 6.1). This includes adjoining coastal lowlands, which have often developed through sedimentation during the Holocene (past 10,000 years), but excludes the continental shelf and ocean margins. Inland seas are not covered, except as analogues. In addition to local drivers and interactions, coasts are subject to external events that pose a hazard to human activities and may compromise the natural functioning of coastal systems (Figure 6.1). Terrestrial-sourced hazards include river floods and inputs of sediment or pollutants; marine-sourced hazards include storm surges, high energy swell and tsunamis.

In this chapter, we reinforce the TAR's findings concerning the potential importance of the full range of climate change drivers on coastal systems and the complexity of their potential effects. Individually or collectively, these drivers would affect shorelines in many ways, including increasing levels of inundation; accelerating coastal erosion; and encroaching saltwater into estuaries and river systems. Key vulnerable coastal areas were identified such as the large populated deltaic regions in the low- to mid-latitudes and Pacific, Indian Ocean and Caribbean small islands. The TAR also noted growing interest in adaptation to climate change in coastal areas, a trend which this assessment shows continues to gather momentum. Whereas some countries and coastal communities have the adaptive capacity to minimize the impacts of climate change, others have fewer options and hence they are much more vulnerable to climate change. This is compounded as human population growth in many coastal regions is both increasing socio-economic vulnerability and decreasing the resilience of coastal systems. Integrated assessment and management of coastal systems, together with a better understanding of their interaction with socio-economic and cultural development were seen by the TAR as important components of successful adaptation to climate change.

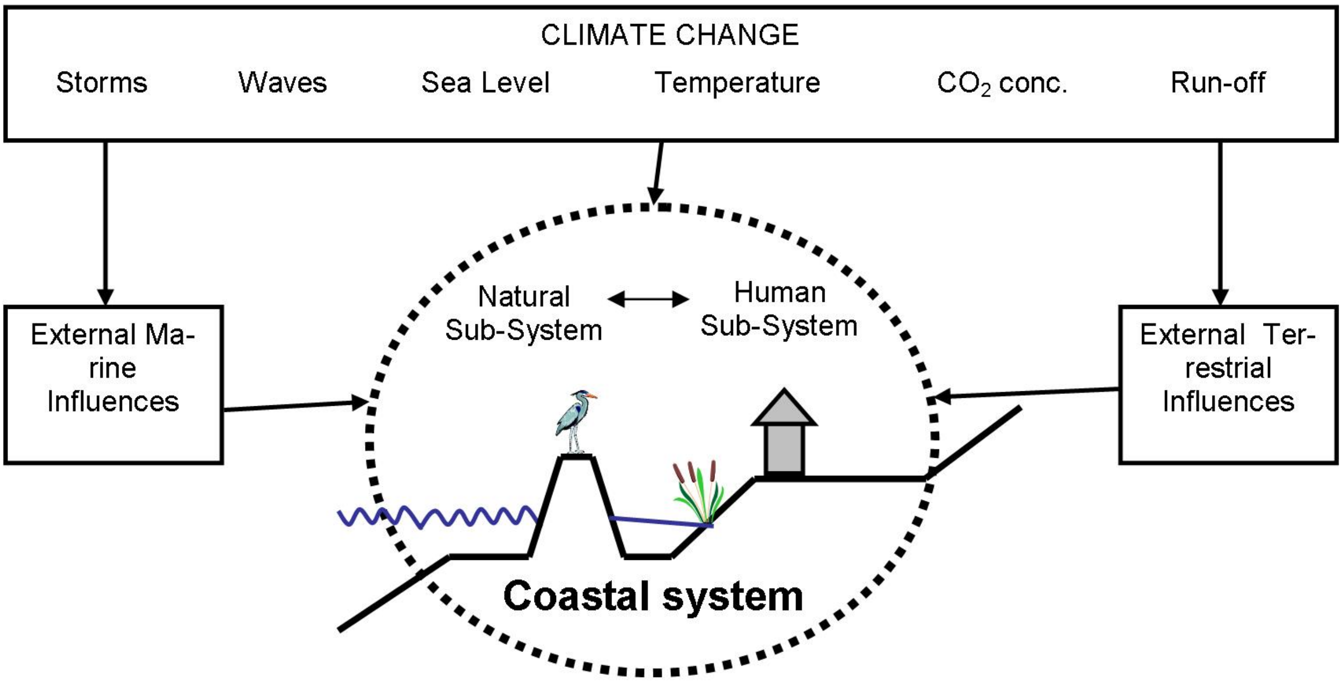

Figure 6.1 *Climate change and the coastal system showing the major climate change factors, including external marine and terrestrial influences.*

This chapter builds on and develops these insights in the TAR by considering the emerging knowledge concerning impacts and adaptation to climate change in coastal areas across a wider spectrum of climate change drivers and from local to global scales. Nonetheless, the issue of sea-level rise still dominates the literature. The chapter follows the common template of this report and includes an assessment of current sensitivity and vulnerability, the key changes that coastal systems may undergo in response to climate and sea level change, including costs and other socio-economic aspects, the potential for adaptation, and the implications for sustainable development. Given that there are strong interactions both within and between the natural and human sub-systems in the coastal system (Figure 6.1), this chapter takes an integrated perspective of the coastal zone, insofar as the published literature permits, including integrated coastal zone management (ICZM).

6.2 Current sensitivity/vulnerability

This section provides key insights into the way in which coastal systems are changing as context for assessing the impacts of, and early effects attributable to, climate change.

6.2.1 Natural coastal systems

Coasts are dynamic systems, undergoing adjustments of form and process (termed morphodynamics) at different time and space scales in response to geomorphological and oceanographical factors (Cowell *et al.*, 2003a; 2003b). Human activity exerts additional pressures that can dominate over natural processes. Often models of coastal behaviour are based on palaeoenvironmental reconstructions at millennial scales and/or process studies at sub-annual scales (Rodriguez *et al.*, 2001; Storms *et al.*, 2002; Stolper *et al.*, 2005). Adapting to global climate change, however, requires insight into processes at decadal to century scales, at which understanding is least developed(de Groot, 1999; Donnelly *et al.*, 2004).

Coastal landforms, affected by short-term perturbations such as storms, often return to their pre-disturbance morphology, implying a simple equilibrium. Many coasts undergo continual adjustment towards a dynamic equilibrium, often adopting different ‘states’ in response to varying wave energy and sediment supply (Woodroffe, 2003). Coasts respond to altered conditions external to the system, such as climate change. However, changes can also be triggered by internal thresholds that cannot be predicted on the basis of external stimuli. For example, many beaches worldwide show evidence of recent erosion but sea-level rise is not necessarily the primary driver. Similar erosion can result from other factors, such as altered wind patterns (Pirazzoli *et al.*, 2004; Regnauld *et al.*, 2004) bathymetric changes offshore (Cooper and Navas, 2004), or reduced riverine sediment input (see Sections 6.2.5 and 6.4.1.1). A major challenge is determining whether observed changes have resulted from alteration in external factors (such as climate change), exceeding an internal threshold (such as a delta distributary switching to a new location), or short-term disturbance within natural climate variability (such as a storm).

There are several climate induced ocean-atmosphere oscillations that vary over time and that can lead to coastal changes (Viles and Goudie, 2003). One of the most prominent is the El Niño-Southern Oscillation (ENSO) phenomenon, an interaction between pronounced temperature anomalies and sea-level pressure gradients in the equatorial Pacific Ocean, with an average periodicity of 2-7 years. Recent research has shown that dominant wind patterns and storminess associated with ENSO may perturb coastal dynamics, influencing beach morphology in eastern Australia (Ranasinghe *et al.*, 2004; Short and Trembanis, 2004), in mid-Pacific (Solomon and Forbes, 1999) and Oregon (Allan *et al.*, 2003), as well as cliff retreat in California (Storlazzi and Griggs, 2000). ENSO may also influence coastal ecosystems; such as groundwater flow from mangroves towards freshwater swamps in Micronesia (Drexler, 2001), and certainly influences bleaching on coral reefs (see Box 6.1). Concern that the frequency and intensity of future ENSO events may change as a component of climate change or with longer-term patterns of climate variability in the Indo-Pacific region has added to the considerable concerns that bleaching events are becoming more widespread because of global warming (Stone *et al.*, 1999).

6.2.2 Change in human utilisation of the coastal zone: Exacerbating climate risks

Few of the world's coastlines are now beyond the influence of human pressures (Buddemeier *et al.*, 2002). Many are human-dominated (Nordstrom, 2000). Utilisation of the coast increased dramatically during the 20th century, a trend which seems certain to continue through the 21st century (Section 6.3.1). Coastal population growth in many of the world's deltas, barrier islands, and estuaries has led to widespread conversion of natural coastal landscapes to agriculture, aquaculture, silviculture and industrial use. It has been estimated that 23% of the world's population lives both within 100 km distance and 100 m elevation of the coast, and population densities in coastal regions are about three times higher than the global average (Small and Nicholls, 2003).

The direct impacts of human activities on the coastal zone have been more significant over the past century than impacts that can be directly attributed to observed climate change (Rogers and McCarty, 2000; Scavia *et al.*, 2002). The major direct impacts include drainage of coastal wetlands, deforestation and reclamation; discharge of sewage, fertilizers and contaminants into coastal waters; extractive activities such as sand mining and hydrocarbon production; harvests of fisheries, salt, hay, and other living resources; introductions of invasive species; construction of seawalls and other structures that harden the coast, change circulation patterns and alter freshwater, sediment, and nutrient delivery; and damming, channelisation, and diversion of coastal waterways. Natural systems are often directly or indirectly altered, and ecological services provided by coastal systems disrupted, by human activities. For example, tropical and subtropical mangrove forests, and temperate salt marshes, provide goods and services (they accumulate and transform nutrients, attenuate waves and storms, bind sediments and support rich ecological communities that sustain villages and megacities), but their large-scale conversions, for agriculture, industrial and urban development or aquaculture have reduced these ecosystem services (Section 6.4.1.3).

The attractiveness of the coast has resulted in disproportionately rapid expansion of economic activity, settlements, urban centres, and tourist resorts; migration of people to coastal regions is common in both developed and developing nations. Sixty percent of the world's 39 metropolises with a population of over 5 million are located within 100 km of the coast, including 12 of the world's 16 cities with populations greater than 10 million. Rapid urbanisation has many consequences; for example, enlargement of natural coastal inlets and dredging of waterways for navigation, port facilities, and pipelines exacerbate saltwater intrusion into surface and ground waters. Increasing shoreline retreat and risk of flooding of coastal cities in Thailand (Durongdej, 2001; Saito, 2001), India (Mohanti, 2000), Vietnam (Thanh *et al.*, 2004), and the United States (Scavia *et al.*, 2002) have been attributed to the degradation of coastal ecosystems by human activities, illustrating a widespread trend.

6.2.3 External terrestrial and marine influences

External terrestrial influences have led to substantial environmental stresses on coastal and nearshore marine habitats (Sahagian, 2000; Saito, 2001; Kremer *et al.*, 2004; National Research Council, 2004; Crossland *et al.*, 2005) (Figure 6.1). The natural ecosystems within watersheds have been fragmented and the downstream flow of water, sediment and nutrients disrupted (Nilsson *et al.*, 2005 see Section 6.4.1.3). Land-use change, particularly deforestation, and hydrological modifications have had downstream impacts, in addition to localised development on the coast. Erosion in the catchment has increased river sediment load; for example, suspended loads in the Huanghe (Yellow) River have increased 2-10 times over the past 2000 years (Jiongxin, 2003). In contrast, damming and channelisation have greatly reduced the supply of sediments to the coast on other rivers through retention of sediment in dams (Syvitski *et al.*, 2005). This effect will probably dominate during the 21st Century (Section 6.4.1).

Coasts can be affected by external marine influences (Figure 6.1) such as high-energy swells generated far away (Vassie *et al.*, 2004). Ocean currents, through their influence on heat transfer modify coastal environments, which can also be subject to tsunami (Bryant, 2001), or atmospheric inputs, such as dust (Shinn *et al.*, 2000).

6.2.4 Thresholds in the behaviour of coastal systems

Dynamic coastal systems often show complex, non-linear responses to change. Non-linearity means that interactions between components of a system are not directly proportional (or linear) but change abruptly as thresholds are crossed (Alley *et al.*, 2003). Erosion, transport and deposition of unconsolidated coastal sediment often involve significant time lags (Brunsden, 2001). Better understanding of thresholds in, and nonlinear behaviour of, coastal systems will enhance the ability of managers and engineers to plan more effective coastal protection strategies, including the placement of coastal buildings, infrastructure and defences. Nonlinear geomorphological and ecological responses occur with abrupt changes of inundation and salinity as sea level reaches particular thresholds (Williams *et al.*, 1999; Doyle *et al.*, 2003; Burkett *et al.*, 2005), and coastal floodplains are inundated when natural levees or artificial embankments are overtopped. Two examples of temperature-related thresholds are described in section 6.2.5: melting of polar permafrost which results in coastal erosion, and coral bleaching (Box 6.1).

6.2.5 Observed effects of climate change on coastal systems

Many coasts are experiencing erosion and ecosystem losses (Section 6.4.1), but few studies have unambiguously quantified the relationships between coastal inundation and the rate of sea-level rise (Zhang *et al.*, 2000; 2004; Gibbons and Nicholls, 2006). For instance, coastal land loss is observed on many shorelines around the world, but it usually remains unclear to what extent these losses are associated with relative sea-level rise due to subsidence, and other human drivers of loss, and to what extent they result from global warming (Hansom, 2001; Jackson *et al.*, 2002; Hughes and Paramor, 2004; Burkett *et al.*, 2005) (see also Sections 6.2.1, 6.4.1 and 1.3.3). Some of the clearest evidence of the impact of climate change on coasts over the last few decades comes from high latitude polar coasts, and low latitude coral reefs.

Although warmer conditions in high latitudes can have positive effects, such as longer tourist seasons and improved navigability, there is evidence for a series of impacts. Warmer ground temperatures, enhanced thaw, subsidence associated with melting of massive ground ice where exposed at the coast, and reduced sea ice cover mean a greater potential for wave generation (Johannessen *et al.*, 2002). Reduction in thickness of near-coastal ice and more rapid ice movement and retreat of the glacier fronts in Greenland result from warmer temperatures (Krabill *et al.*, 2004; Rignot *et al.*, 2004a). Similar findings in terms of ice mass have been reported for the Antarctic Peninsula and the Amundsen Sea in Antarctica (Rignot *et al.*, 2004b; Thomas *et al.*, 2004; Cook *et al.*, 2005). Evidence documented from traditional ecological knowledge also points to widespread change of coastlines across the North American Arctic from the Northwest Territories, Yukon, and Alaska in the west to Nunavut in the east (Fox, 2003). Moreover, relative sea-level rise on low-relief coasts leads to rapid erosion of easily eroded lithology, accentuated by melting of permafrost that binds coastal sediments, as recorded at sites in Arctic Canada (Forbes *et al.*, 2004; Forbes, 2005; Manson *et al.*, 2006), northern USA (Smith, 2002b; Lestak *et al.*, 2004), and northern Russia (Koreysha *et al.*, 2002; Nikiforov *et al.*, 2003; Ogorodov, 2003). Mid-latitude coasts with seasonal sea ice also show reduced ice cover; ice extent has diminished in the Bering Sea over recent decades (ARAG, 1999) and data from the Gulf of St. Lawrence show cyclic patterns with a slight net decrease (Forbes *et al.*, 2002).

Global warming poses a particular threat to coral reefs as outlined in Box 6.1. The synergistic effects of various other pressures, particularly human impacts such as overfishing, appear to be exacerbating the thermal stresses on reef systems and, at least on a local scale, exceeding the thresholds beyond which coral is replaced by other organisms (Buddemeier *et al.*, 2004). These impacts and their likely consequence are considered further below; the threat posed by ocean acidification is examined in Chapter 4, the impact of multiple stresses is examined in Chapter 16, and the example of the World Heritage Great Barrier Reef, where decreases in coral cover could have major negative impacts on tourism, is described in Chapter 11.

Box 6.1: Coral bleaching and climate change

Coral bleaching, the paling of corals as a result of loss of symbiotic algae and/or their pigments, has been observed across almost all tropical reefs since the early 1980's. Slight paling occurs naturally in response to seasonal increases in sea temperature and solar radiation. Corals bleach white, when anomalously high sea temperatures (> 1 ^{o}C) above seasonal maxima combine with high solar radiation. Whereas some corals recover their natural colour when environmental conditions ameliorate, their growth rate and reproductive ability may nonetheless be significantly reduced for a period. If bleaching is prolonged, corals die, with branching species being more susceptible than massive varieties (Douglas, 2003).

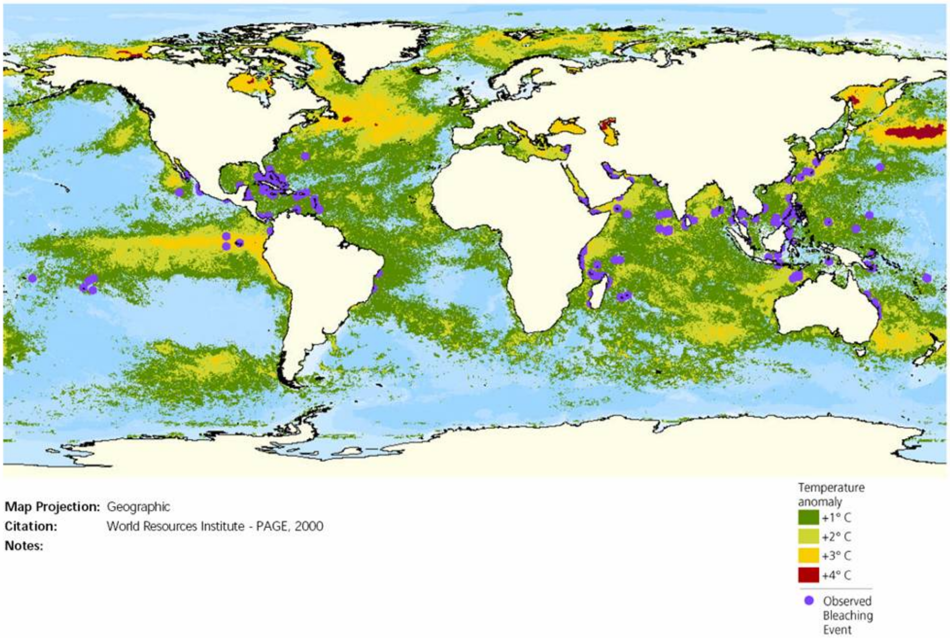

Figure B6.1.1*: Seawater temperature anomalies and coral bleaching from late 1997 to mid-1998. © Earth Trends 2000 World Resources Institute [copyright permission required]*

Major bleaching events were noted in 1982-83, 1987-88, 1994-95, and most extensively in 1998, (Hoegh-Guldberg, 1999; Lough and Barnes, 2000). Severe worldwide bleaching, (Figure B6.1.1), appears to be associated with El Niño events (Bruno *et al.*, 2001), although other regional ocean-atmosphere oscillations such as the Indian Ocean Dipole are also important (Webster *et al.*, 1999; Wilkinson, 2002). An emerging picture is of considerable variability in responses of coral reefs to elevated temperatures in both time and space, and in relation to bleaching susceptibility, occurrence and recovery (Obura, 2005). Since 1998 there have been several extensive bleaching events; for example, in 2002 bleaching occurred on the Great Barrier Reef (Berkelmans *et al.*, 2004 see Box 11.1) and in parts of the Pacific Ocean, and in 2003 there was bleaching in the northern section of the Hawaiian Chain and across the Indian Ocean, although the latter event caused minimal coral mortality. Reefs in the Caribbean have also experienced bleaching and appear to be in decline as a result of the synergistic effects of multiple stresses (Gardner *et al.*, 2005; McWilliams *et al.*, 2005; see chapter 16). Climate models imply that the threshold temperatures at which corals bleach, which are generally 1-2 ^{o}C above the current seasonal maxima, will occur more frequently with the consequence that bleaching will recur with a frequency that reefs cannot sustain, perhaps almost annually on some reefs later this century (Hoegh-Guldberg, 1999; 2004; Sheppard, 2003; Donner *et al.*, 2005). If the temperature threshold remains unchanged more frequent bleaching seems inevitable (see Figure B6.1.2a), although with local variability because different corals have different susceptibilities and with local effects such as reduced bleaching at greater water depths. Other research supports the idea that corals may be able to adapt or acclimate, termed the adaptive bleaching hypothesis, as a result of changes in the combination of coral host and symbiotic algae, creating 'new' ecospecies with different environmental tolerances, and more temperature tolerant algae (Coles and Brown, 2003; Buddemeier *et al.*, 2004; Little *et al.*, 2004; Rowan, 2004; Obura, 2005). Adaptation or acclimation may result in an increase in the threshold temperature at which bleaching occurs (Figure 6.1.2b), but the extent to which this threshold could increase with ongoing global warming remains very uncertain.

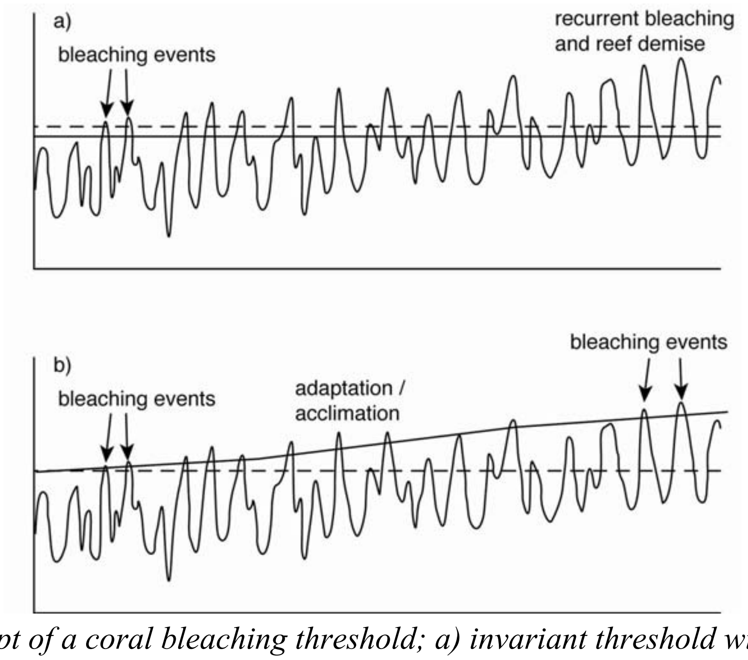

Figure B6.1.2*: Concept of a coral bleaching threshold; a) invariant threshold with coral bleaching when SST is 1-2oC above usual seasonal maximum (with local variation in the case of different species or depth); b) elevated threshold where corals adapt or acclimate to increased SST (based on Hughes et al., 2003)*

Corals remain extremely susceptible to seawater warming and that repeated bleaching events, such as those reported in recent years, have the potential to reduce both coral cover and diversity on reefs over the next few decades.

6.3 Assumptions about future trends for coastal systems and low-lying areas

This section explores possible trends for coastal areas through the 21st century and the resulting scenarios of environmental, socioeconomic and climate change (see Chapter 2). Likely non-climate coastal changes include an increasing population, urban area and economic activity, as well as changing attitudes and approaches to coastal management. The Special Report on Emissions Scenarios (or 'SRES') (see Chapter 2) provide one framework for this purpose to 2100 (Arnell *et al.*, 2004).

6.3.1 Environmental and socio-economic trends

In the SRES, four families of socioeconomic scenarios (A1, A2, B1, and B2) represent different world futures in two distinct dimensions: a focus on economic versus environmental concerns, and global versus regional development patterns. In all four cases, global GDP increases and there is economic convergence at differing rates. Global population also increases substantially to 2050, but in the A1/B1 futures, the population subsequently declines, while in A2/B2 it continues to grow through the 21st Century (see Chapter 2). Relevant, mainly qualitative, trends under the SRES scenarios are provided in Table 6.1.

Table 6.1: *Selected global non-climatic environmental and socio-economic trends relevant to coastal areas derived from the SRES storylines. Regional and local deviations are expected.*

Factor	"A1 World"	"A2 World"	"B1 World"	"B2 World"
Near-coastal population (2080s) (billions)[1]	1.8	3.2	1.8	2.3
Coastward migration	Most likely	Less likely	More likely	Least likely
Human-induced subsidence[2]	More likely		Less likely	
Freshwater and sediment availability (due to catchment management)	Greatest reduction	Large reduction	Smallest reduction	Smaller reduction
Aquaculture	Large increase		Smaller increase	
Infrastructure development	Largest increase	Large increase	Smaller increase	Smallest increase
Extractive industries	Larger		Smaller	
Adaptation response	More reactive		More proactive	
Hazard management	Lower priority		Higher priority	
Habitat conservation	Low priority		High priority	
Tourism growth	Highest	High	High	Lowest

[1] Number of people both within 100 m elevation and 100 km distance of the coast, assuming no migration.
[2] Subsidence due to sub-surface fluid withdrawal and drainage of organic soils in susceptible coastal lowlands.

National and sub-national coastal socio-economic scenarios have also been developed for national policy analysis, including links to appropriate climate change scenarios. Examples include the UK Foresight Flood and Coastal Defence analysis (Evans *et al.*, 2004a; 2004b), the US National Assessment (NAST, 2000), Schleswig-Holstein, Germany [add reference] and the Ebro delta (Otter, 2000).

6.3.2 Climate and sea-level scenarios

Table 6.2 indicates the range of potential drivers of climate change impacts in coastal areas. For some climate drivers the direction of change is reasonably certain, while for others, even direction is uncertain. Global-mean rise in sea level from 1990 to the 2080s (not 2100) in the TAR varies from 9 to 48 cm under the lowest emissions (B1) to 16 to 69 cm under the highest emissions (A1FI – where FI refers to 'fuel intensive'). Local changes in sea level depart from the global-mean trend due to regional variations in oceanic level change, and geological uplift/subsidence. Hulme *et al*. (2002) suggested exploring additional scenarios of ±50% the amount of global-mean rise, plus geological change to allow sensitivity analysis of these effects, but such scenarios have not been widely considered in impact assessment.

Table 6.2: *Climate drivers relevant to coastal zones and their main physical and ecosystem effects. Most changes will be regionally variable. (Change: ↑ increase; ? uncertain or variable).*

Climate Driver (change)	**Main Physical and Ecosystem Effects**
Sea level (↑)	Inundation, flood and storm damage (see Box 6.2); Erosion; Saltwater Intrusion; Rising water tables/ impeded drainage; Wetland loss (and change)
Sea temperature (↑)	Increased stratification/changed circulation; Reduced incidence of sea ice at higher latitudes; Increased coral bleaching; Poleward species migration; Increased algal blooms
Run-off (?)	Changed fluvial sediment supply; Changed flood risk in coastal lowlands; Changed water quality/salinity; Changed circulation; Changed nutrient supply
Wave climate (?)	Changed wave conditions, including swell; Changed patterns of erosion and accretion
Storm track, frequency (?)	Changed surges and storm waves and hence risk of storm damage and flooding (see Box 6.2); Shifting and expansion of cyclone zones; Extra-tropical storm intensity
Tropical storm intensity (↑)	Increased surge and wave heights; Increased risk of flooding and defence failure (see Box 6.2)
CO_2 concentration (↑)	Increased CO_2 fertilisation; Increased ocean acidification, leading to decreased $CaCO_3$ saturation impacts on coral reefs and other ecosystems

Rapid rises in sea level (>1 m/century) could occur given accelerated melting of the Greenland ice sheet (Lowe *et al*., 2006) and/or collapse of the West Antarctic ice Sheet (WAIS) (Overpeck *et al.*, 2006; Rapley, 2006). This appears unlikely during the 21st Century (Vaughan and Spouge, 2002), but attracts interest due to the high impact potential (Sections 6.4.2 and 6.6). The timescale of ocean warming is also long, and sea-level rise is expected to continue for centuries (Meehl *et al.*, 2005; Wigley, 2005), with deglaciation of Antarctica and Greenland possibly contributing large additional rises (Nicholls and Lowe, 2006; Nicholls *et al.*, 2006b).

In contrast to sea-level rise, scenarios of the other factors in Table 6.2 are less developed (Chapter 2). Of these, changes in tropical storm intensity and behaviour portend additional impacts on tropical and mid-latitude coastal ecosystems (see Box 6.3). Theory, modelling, and recent empirical evidence suggest that an increase in sea surface and atmospheric temperature will increase the intensity of tropical cyclones. Analyses of ocean temperature change at over 3000 stations (Levitus *et al.*, 2000; Levitus *et al.*, 2005) have documented an increase in shallow ocean temperature that is highly correlated with the accelerated atmospheric warming over the past 60 years. Reports of an increase in tropical cyclone intensity (Emanuel, 2005; Webster *et al.*, 2005) over the past three decades are consistent with the observed changes in sea surface temperature. Modelled scenarios of extreme water levels as a result of sea-level rise and changes to tropical (and extra-tropical) storm characteristics are presented in Box 6.2.

Earlier and faster snowmelt and an intensified hydrologic cycle (see Chapter 3) all portend changes in coastal water quality. While the uncertainties are large, the recent analysis by Milly *et al.* (2005) suggests increased discharges to coastal waters in the Arctic, the Rio de la Plata in Argentina, parts of the Indian sub-continent, China and Australia, while reduced discharges to coastal waters are suggested in the southern cone of South America, Western and Southern Africa, and in the Mediterranean Basin.

Box 6.2: Scenarios of Extreme Water Levels for Impact and Adaptation Analysis

Although inundation by increases in mean sea level over the 21st century and beyond will be a problem for unprotected low-lying areas, the most devastating impacts are likely to be associated with changes in extreme sea levels associated with the passage of storms (e.g. Gornitz *et al.*, 2002). Three examples of simulations of such changes are given below, but the patterns and magnitudes of changes in extreme water levels remain uncertain (e.g. Lowe and Gregory, 2005). Quantifying this uncertainty is a research priority to improve impact and adaptation analysis.

Figures B6.2.1 and B6.2.2 result from barotropic surge models for two flood prone regions, which were driven with climate change predictions.

In northern Bay of Bengal, simulated changes in storminess cause changes in extreme water levels, which when added to appropriate relative sea-level rise scenarios result in significant positive increases in extreme water levels across the Bay (Figure B6.2.1). Around the UK, the increase in extreme sea level is positive. The largest rise occurs in the Thames Estuary with important implications for London's flood defence (Dawson *et al.*, 2005; Lavery and Donovan, 2005). Figure B6.2.3 shows a combination of stochastic sampling and dynamical modelling for Cairns, Australia. The storm component of extreme water level is positive, assuming a 10% increase in tropical cyclone intensity, implying more flooding than sea-level rise only would suggest.

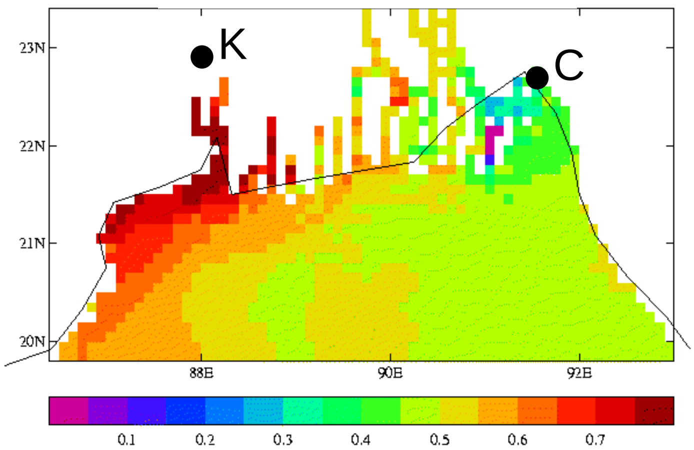

***Figure B6.2.1**: Changes in the height (m) of the 50-year extreme water level in part of the Bay of Bengal by 2040 to 2060. (K - Kolkata (Calcutta), C – Chittagong) (from Mitchell et al., 2006)*

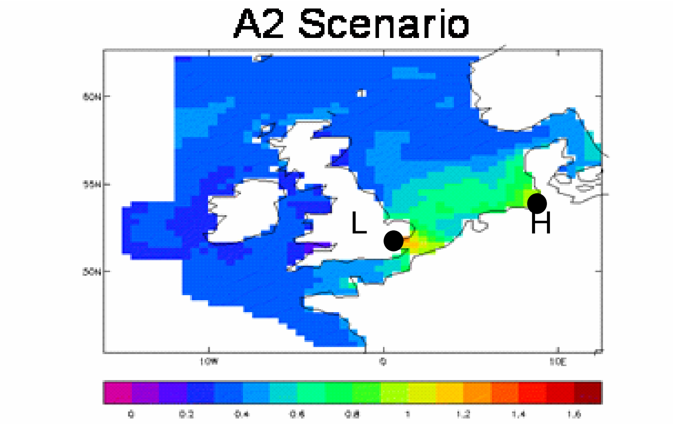

Figure B6.2.2: *Changes in the height (m) of the 50-year extreme water level around the UK for the A2 scenario in the 2080s. (L – London; H—Hamburg) (from Lowe and Gregory, 2005)*

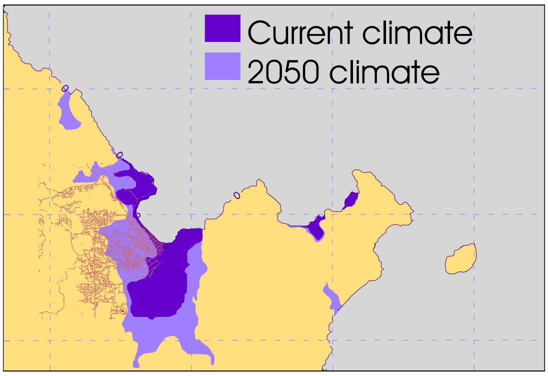

Figure B6.2.3: *Flooding around Cairns, Australia during the >100 year return period under current and 2050 climate conditions. The road network is shown in red (from McInnes et al., 2003)*

6.4 Key future impacts and vulnerabilities

The following sections characterize the coastal ecosystem impacts that are anticipated to result from atmospheric CO_2 enrichment and related changes in air and water temperature, the rate of global sea-level rise, precipitation patterns and runoff, water quality, and storm intensity (Table 6.2). The summary of impacts on natural coastal systems is followed with a discussion of implications for human society, including ecosystem services, and ends with key vulnerabilities and hotspots.

6.4.1 Natural system responses to climate change drivers

6.4.1.1 Beaches, rocky shorelines, and cliffed coasts

Most of the world's sandy shorelines retreated during the past century (Bird, 1985; National Research Council, 1990; Leatherman, 2001). An acceleration in sea-level rise will tend to exacerbate beach erosion and shoreline retreat around the globe (Brown and McLachlan, 2002; Zhang *et al.*, 2004), but there is not a simple relationship between sea-level rise and horizontal movement of the shoreline. Bruun (1962)was the first to posit a direct link between sea-level rise and beach erosion. The widely cited, though controversial (Komar, 1998; Leatherman, 2001; Cooper and Pilkey, 2004; Davidson-Arnott, 2005) Bruun model suggests that shoreline recession is typically about 100 times the rise in sea level based upon a two-dimensional (onshore-offshore) balancing of sedimentary processes. The Bruun model assumes that changes in beach profile are largely determined by the mean water level and sand size.

An indirect, less-appreciated influence of sea-level rise on beach sediment supply is associated with the infilling of coastal embayments: as seas rise, estuaries and lagoons maintain equilibrium by raising their bed elevation in tandem, and hence act as a major sink of sand which is often derived from the open coast (van Goor *et al.*, 2001; Stive, 2004). This process could potentially cause erosion several magnitudes greater than that predicted by the Bruun model in the vicinity of many large tidal inlets (Woodworth *et al.*, 2004). The amount of sediment lost to coastal embayments will depend upon factors such as sediment budget, coastal morphology and hydrodynamic forces that influence beach sediment deposition, removal, and transport.

More generally, it is important to evaluate the significant cross-shore and longshore elements in the coastal sediment budget to diagnose both past coastal behaviour (Sections 1.3.3 and 6.2.1) and predict future behaviour under climate change scenarios. This implies considering coastal processes across a wide range of scales (Stive *et al.*, 2002) within an integrated framework. Cowell *et al*. (2003a; 2003b; 2006) use integrated model approaches and show how these ideas might be applied in practise.

Several recent studies indicate that beach protection strategies and changes in the behaviour or frequency of storms can be more important than sea-level rise in determining future beach erosion rates (Ahrendt, 2001; Leont'yev, 2003). Moreover, the combined effects of beach erosion and storms can lead to the erosion or inundation of other coastal systems. For example, an increase in wave heights in coastal bays is a secondary effect of sandy barrier island erosion in Louisiana, and increased wave heights have enhanced erosion rates of bay shorelines, tidal creeks, and adjacent wetlands (Stone *et al.*, 2003).

The impacts of accelerated sea-level rise on gravel beaches have received less attention than sandy beaches. There is evidence that these systems are threatened by sea-level rise (Orford *et al.*, 2001; 2003; Chadwick *et al.*, 2005), even under high accretion rates (Codignotto *et al.*, 2001) The persistence of gravel and cobble-boulder beaches will also be influenced by storms, tectonic events, and other factors that build and reshape these highly dynamic shorelines.

At the time of the TAR there was little information available regarding the effects of climate change and sea-level rise on cliffed coasts. Monitoring, modelling, and process-oriented research have since revealed some important differences in cliff vulnerability and the mechanics by which groundwater, wave climate, and other climate factors influence cliff erosion patterns and rates. Hard rock cliffs have a relatively high resistance to erosion due to their lithology and material strength (Cooper and Jay, 2002). Conversely, soft rock cliffs, formed in softer bedrock or drift, including many limestones such as chalk, are likely to retreat more rapidly in the future due to increased toe erosion resulting from sea-level rise and retreat may be amplified in many areas by increased precipitation and higher ground water levels (Hosking and McInnes, 2002; Codignotto, 2004; Pierre and Lahousse, 2006). Human activity such as gravel mining and hard coastal defences (such as groins and breakwaters) has contributed to erosion along some cliffed coastlines. Cliff retreat is commonly episodic with relatively large amounts of cliff top (many metres of retreat) being lost locally in a single event, followed by relative quintessence for significant periods (Brunsden, 2001; Eurosion, 2004).

Considerable progress has been made in the long-term prediction of cliff-top, shore profile and plan-shape evolution of soft rock coastlines by simulating the relevant physical processes and their interactions (Hall *et al.*, 2002; Trenhaile, 2002; 2004). An application of the SCAPE (Soft Cliff and Platform Erosion) model (Walkden and Hall, 2005) to part of Norfolk, UK has indicated a range of longshore interactions, with increased erosion due to sea-level rise promoting downdraft beach accretion due to increased sediment supply (Dickson *et al.*, 2006). For soft cliff areas with limited beach development across the shore platform, cliff retreat appears to increase with sea-level rise, but more slowly than the Bruun model would suggest (Walkden and Dickson, 2006).

6.4.1.2 Deltas

Deltaic landforms are naturally shaped by a combination of river, wave, and tide processes. River-dominated deltas receiving fluvial sediment input show prominent levees and channels that meander or avulse, leaving abandoned channels on the coastal plains. Wave dominated deltas are characterised by shore-parallel sand ridges, often coalescing into beach-ridge plains. Tide domination is indicated by exponentially tapering channels, with funnel-shaped mouths. At any time, only part of a delta is active, and this is usually river-dominated. Elsewhere, the abandoned delta plain, which receives only a small fraction of the flow of the river, is progressively dominated by marine processes. This has lead to a diverse set of deltaic plain forms that are impacted by climate-induced changes in both the continental and oceanic realm(Woodroffe *et al.*, 2006). Human development patterns also play an important role in the differential vulnerability of deltas to the effects of climate change. Sediment starvation due to dams, navigation, and flood control works is a common consequence of human activity and is elaborated below.

Changes in surface water runoff and sediment loads can greatly affect the ability of a delta to cope with the physical impacts of climatic change. For example, in the subsiding Mississippi River deltaic plain in North America, sediment starvation and increases in the salinity and water levels of coastal marshes due to human development occurred so rapidly that over 1700 km^2 of intertidal marshes were converted to open water between 1978 and 2000 (Barras *et al.*, 2003). By 2050 an additional 1329 km^2 of coastal land is predicted to be inundated due to regional and local processes alone, with significant additional; losses if accelerated global sea-level rise occurs (Barras *et al.*, 2003). Much of this loss is episodic, as demonstrated during the landfall of Hurricane Katrina (see Box 6.3).

Deltas have long been recognised as highly sensitive to sea-level rise (Ericson *et al.*, 2005; Woodroffe *et al.*, 2006) (Box 6.4). Rates of relative sea-level rise are double or more over the global average in many heavily populated deltaic areas, including the Chao Phraya delta (Saito, 2001), Mississippi River delta (Burkett *et al.*, 2003), and the Yangtze River delta (Liu, 2002; Waltham, 2002) because of human activities. These deltas are all compacting under their own weight (autocompaction), but ground water withdrawals have increased the potential for inundation of their most populated cities (Bangkok, New Orleans, and Shanghai). Most of the land area of Bangladesh consists of the deltaic plains of the Ganges, Brahmaputra, and Meghna rivers. Accelerated global sea-level rise and higher extreme water levels (Box 6.2) may have acute effects on human populations of Bangladesh because of the complex relationships between observed trends in sea surface temperature over the Bay of Bengal and monsoon rains (Singh, 2001), compaction of deltaic sediments, and human activity that has converted natural coastal defences (mangroves) to aquaculture.

Whereas present rates of sea-level rise are contributing to the gradual destruction of many of the world's deltas, most recent losses of deltaic wetlands are attributed to human development. An analysis of satellite images of fourteen of the world's major deltas (Danube, Ganges-Brahmaputra, Indus, Mahanadi, Mangoky, McKenzie, Mississippi, Niger, Nile, Shatt el Arab, Volga, Huanghe, Yukon, and Zambezi) indicated that a total of 15,845 km^2 of deltaic wetlands have been irreversibly lost during the past 14 years (Coleman *et al.*, 2006). All deltas analyzed showed land loss, but at varying rates, and human development activities accounted for over half of the losses. In Asia, for example, where human activities have led to increased sediment loads of major rivers in the past, the construction of upstream dams and other water abstraction is now seriously depleting the supply of sediments to deltas with increased coastal erosion a widespread consequence (Chapter 11). As an example, large reservoirs constructed on the Huanghe River in China have reduced the annual sediment delivered to the it's delta from 1.1 billion metric tons to 0.4 billion metric tons (Li *et al.*, 2004). This effect is likely to grow through Asia and globally (Section 6.2.2; Table 6.1).

6.4.1.3 Estuaries and lagoons

Sea-level rise will generally lead to higher coastal water levels and increasing salinity in estuarine systems, thereby tending to displace existing coastal plant and animal communities inland. Estuarine plant and animal communities may persist as sea-level rises if barriers to migration are not blocked and if the rate of change does not exceed the capacity of natural communities to adapt or migrate. Climate impacts on one or more 'leverage species', however, can result in sweeping community level changes (Harley *et al.*, 2006).

Some of the greatest potential impacts of climate change on estuaries may result from changes in physical mixing characteristics caused by changes in freshwater runoff (Scavia *et al.*, 2002). Earlier and faster snowmelt and an intensified hydrologic cycle all portend changes in coastal water quality (see Section 6.3.2). Changes in the timing of freshwater delivery to estuaries could lead to a decoupling of the juvenile phases of many estuarine and marine fishery species with available nursery habitat.

Freshwater inflows into estuaries influence water residence time, nutrient delivery, vertical stratification, salinity, and control of phytoplankton growth rates in estuaries. Increased freshwater inflows decrease residence time and increase vertical stratification, and *vice versa* (Moore *et al.*, 1997). The effects of altered residence times can have significant effects on phytoplankton populations, which have the potential to increase fourfold per day. Consequently, in estuaries with very short water residence times, phytoplankton are generally flushed from the system as fast as they can grow, reducing the estuary's susceptibility to eutrophication and harmful algal blooms (HABs) (see Section 6.4.2.4).

As atmospheric CO_2 levels increase more CO_2 is absorbed by surface waters. One consequence of increasing the uptake of CO_2 lower pH of seawater (Andersson *et al.*, 2003), and lower carbonate saturation. Coupled atmospheric-ocean models that simulate the effects of atmospheric CO2 level on ocean pH suggest that that the carbonate saturation state of both the global ocean and nearshore coastal waters will decrease significantly through this century (Mackenzie *et al.*, 2001; Caldeira and Wickett, 2005). This has at least two important consequences: the potential of reducing the ability of carbonate flora and fauna to calcify and the potential for enhanced dissolution of nutrients and carbonate minerals in sediments (Andersson *et al.*, 2003; The Royal Society, 2005; Turley *et al.*, 2006). Quantification of these impacts would be beneficial.

As estuarine water temperature increases, algal blooms are likely to become more common. The propensity for harmful algal blooms is further enhanced by the fertilization effect of increasing dissolved CO_2 levels. Increased water temperature also affects important microbial processes such as nitrogen fixation and denitrification in estuaries (Lomas *et al.*, 2002). Water temperature regulates oxygen and carbonate solubility, viral pestilence, pH and conductivity, and photosynthesis and respiration rates of estuarine macrophytes. While the importance of temperature in regulating physiological processes in estuaries is without question (Lomas *et al.*, 2002), predicting the ecological outcome is complicated by the feedbacks and interactions among temperature change and independent physical and biogeochemical processes such as eutrophication.

An effect of rising sea level in some hypersaline lagoonal systems, such as the Laguna Madre of

Mexico and Texas, will be a trend towards decreasing salinity as lower salinity seawater intrudes into the presently hypersaline waters. The lowering of salinity in the Laguna Madre since 1949, attributed primarily to the dredging of the Gulf Intracoastal Waterway and increased drainage from agricultural lands, has shifted seagrass species from the highly salt tolerant shoalgrass (*Halodule wrightii*) to manatee grass (*Syringodium filiforme*), which has a lower salinity tolerance (Quammen and Onuf, 1993).

As sea-level rises the shorelines of estuaries will tend to enlarge and retreat inland unless sedimentation along the shoreline, shoreline armouring, or uplift of the land surface is sufficient to counter the effects of rising water. The probable migration of estuarine shorelines as sea-level rises has been summarised by Pethick (2001), who adopted a dynamic approach based on the Bruun principle resulting in landward retreat of the entire estuarine system. In this view, sea-level rise of 6mm causes 10m of retreat of the Blackwater estuary, UK and only 8m of retreat for the Humber estuary, UK due to its steeper gradient. The Humber estuary will also likely experience a deepening of the main channel, changes in tidal regime and larger waves that will promote further edge erosion (Winn *et al.*, 2003). In Venice Lagoon, Italy, the combination of sea-level rise and geological land subsidence has lowered the lagoon floor, widened tidal inlets, submerged tidal flats and islands, and caused the shoreline to retreat around the lagoon circumference. During the last century the total elevation loss within the Venice lagoon has been estimated at 23 cm, consisting of about 12 cm of land subsidence and 11 cm of sea-level rise (Brambati *et al.*, 2003).

A projected increase in the intensity of tropical cyclones and other coastal storms (Section 6.3.2) could alter bottom sediment dynamics, organic matter inputs, phytoplankton and fisheries populations, salinity and oxygen levels, and biogeochemical processes in estuaries (Paerl *et al.*, 2001). The role of powerful storms in structuring estuarine sediments and biodiversity is illustrated in the stratigraphic record of massive, episodic estuary infilling of Bohai Bay, China during the Holocene, with alternating oyster reefs and thick mud deposits (Wang, 1994; Wang and Fan, 2005).

6.4.1.4 Mangroves, salt marshes and sea grasses

Coastal vegetated wetlands are sensitive to climate change and long-term sea level change as their location is intimately linked to sea level and global analysis suggest significant losses during the 21st Century under scenarios of accelerated sea-level rise (Nicholls, 2004; McFadden *et al.*, 2006). A 1-m rise in sea level over a century could cause the loss of 44% of coastal wetlands by the 2080s. Cahoon *et al*. (2006) developed a broad regional to global geographical model relating wetland accretion, elevation, and shallow subsidence in different plate tectonic, climatic and geomorphic settings for both temperate salt marshes and tropical mangrove forests. In salt marshes, a close correspondence between accretion and sea-level rise suggests they tend to ‘keep pace' with sea-level rise, yet many marshes exhibited significant shallow subsidence. The large variability suggests that the local process environment exerts strong influence. Cahoon *et al.* (2003) describes the impacts of 17 hurricanes on the surface elevation dynamics of 10 salt marshes and mangrove forests around the Gulf of Mexico and Caribbean. The full range of possible responses was observed (i.e., accretion = elevation, accretion > elevation, accretion < elevation) and the results were not always intuitive.

Salt marshes (halophytic grasses, sedges, rushes and succulents) are common features of temperate depositional coastlines. Hydrology and energy regimes are two key factors that influence the zonation of plant species along these coasts. Herbaceous coastal vegetation typically grades inland from salt, to brackish, to freshwater species. Climate change will have its most pronounced effects on brackish and freshwater marshes in the coastal zone through alteration of hydrological regimes (Burkett and Kusler, 2000; Baldwin *et al.*, 2001; Sun *et al.*, 2002), specifically, the nature and variability of hydroperiod and the number and severity of extreme events. Other variables - altered biogeochemistry, altered amounts and pattern of suspended sediments loading, fire, oxidation of organic sediments and the physical effects of wave energy - may also play important roles in determining regional and local impacts. Global analyses suggest that regional losses would be most severe on the Atlantic and Gulf of Mexico coasts of North and Central America, the Caribbean, the Mediterranean, the Baltic and most small island regions due to their low tidal range (Nicholls, 2004).

Sea-level rise does not necessarily lead to loss of saltmarsh areas, especially where there are significant tides, because these marshes accrete vertically and maintain their elevation with respect to current rates of sea-level rise where the supply of sediment is sufficient; (Hughes, 2004; Cahoon *et al.*, 2006). Saltmarshes of some mesotidal and high tide range estuaries (e.g., Tagus Estuary, Portugal) are susceptible to sea-level rise only in a worse case scenario (Hughes *et al*, 2004). Similarly, Morris *et al.* (2002) reported that wetlands with high sediment inputs in the southeast United States would remain stable relative to sea level until the rate of sea-level rise accelerates to nearly four times its current rate. Yet, even sediment inputs from frequently recurring hurricanes cannot compensate for subsidence effects combined with predicted accelerations in sea-level rise in rapidly subsiding marshes of the Mississippi River delta (Rybczyk and Cahoon, 2002).

Mangrove forests dominate intertidal subtropical and tropical coastlines between 25ºN and 25°S latitude. Mangrove communities are likely to show a blend of positive (e.g., from higher levels of CO_2 and temperature) and negative (e.g., increased saline intrusion and erosion) effects, which will largely depend on site specific factors (Saenger, 2002). The response of coastal forested wetlands to climate change has not received the detailed research and modelling that has been directed towards the salt marsh coasts of North America (Cahoon and Hensel, 2002; Morris *et al.*, 2002; Reed, 2002; Rybczyk and Cahoon, 2002) and northwestern Europe (Allen, 2000; Cahoon *et al.*, 2000; Allen, 2003). Nevertheless, it seems highly likely that similar principles are in operation and that the sedimentary response of the shoreline is a function of both the availability of unconsolidated sediment (Walsh and Nittrouer, 2004) and the ability of the organic production by mangroves themselves to fill accommodation space provided by sea-level rise (Simas *et al.*, 2001). Mangroves are able to produce root material that builds up the substrate beneath them (Middleton and McKee, 2001; Jennerjahn and Ittekkot, 2002), and collapse of peat occurs rapidly in the absence of new root growth, as observed after Hurricane Mitch (Cahoon *et al.*, 2003). Groundwater levels play an important role in the elevation of mangrove soils by processes affecting soil shrink and swell; hence, the influence of hydrology should be considered when evaluating the effect of disturbances, sea-level rise, and water management decisions on mangrove systems (Whelan *et al.*, 2005). A global assessment of mangrove accretion rates by Saenger (2002) indicates that vertical accretion is variable but commonly approaches 5mm per year, resulting in gradual elevation of the surface with respect to sea level under present conditions.

A landward migration of mangroves into adjacent wetland communities has been recorded in the Florida Everglades during the past 50 years (Ross *et al.*, 2000), apparently responding to sea-level rise over that period. Mangroves have extended landward into salt marsh over the past five decades throughout southeastern Australia, but the influence of sea-level rise in this region is considered minor compared to that of human disturbance (Saintilan and Williams, 1999) and land surface subsidence (Rogers *et al.*, 2005). Rapid expansion of tidal creeks has been observed in northern Australia (Finlayson and Eliot, 2001; Hughes, 2003). Sea-level rise has been identified as a causal factor in the decline of coastal bald cypress (*Taxodium distium*) forests in Louisiana (Melillo *et al.*, 2000) and die off of cabbage palm (*Sabal palmetto*) forests in coastal Florida (Williams *et al.*, 1999).

Sea grasses cover about 0.1 - 0.2% of the global ocean (Duarte, 2002); about 60 species of sea grasses are known worldwide. Present losses due to human impacts are expected to accelerate if climate change alters environmental conditions in coastal waters (Duarte, 2002). Changes in salinity and temperature and increased sea level, atmospheric CO_2, storm activity and uv irradiance alter seagrass distribution, productivity and community composition (Short and Neckles, 1999). Increases in the amount of dissolved CO_2 and, for some species, HCO_3^- present in aquatic environments will lead to higher rates of photosynthesis in submerged aquatic vegetation, similar to the effects of CO_2 enrichment on most terrestrial plants, if nutrient availability or other limiting factors do not offset the potential for enhanced productivity. Increases in growth and biomass with elevated CO_2 have been observed for the seagrass *Z. marina* (Zimmerman *et al.*, 1997). Algae growth in lagoons and estuaries may also respond positively to elevated dissolved inorganic carbon (DIC), though marine macroalgae do not appear to be limited by DIC levels (Beer and Koch, 1996). An increase in epiphytic or suspended algae would decrease light available to submerged aquatic vegetation in estuarine and lagoonal systems.

6.4.1.5 Coral reefs

As indicated in Chapter 1, reef-building corals are under stress on many coastlines. Reefs appear to have deteriorated as a result of a combination of anthropogenic impacts (particularly overfishing and pollution from adjacent land-masses, (Pandolfi *et al.*, 2003) together with an increased frequency of bleaching associated with climate change (see Box 6.1). The relative significance of these stresses varies from site to site. Coral mortality on Caribbean reefs is generally related to recent disease outbreaks, variations in herbivory and hurricanes (Gardner *et al.*, 2003), whereas Pacific reefs have been particularly impacted by episodes of coral bleaching caused by thermal stress during recent El Niño events (Hughes *et al.*, 2003).

Mass coral bleaching events are clearly correlated with rises of sea-surface temperature (SST) of short duration above summer maxima (Douglas, 2003; Lesser, 2004; McWilliams *et al.*, 2005),. Particularly extensive bleaching was recorded across the Great Barrier Reef and many other reefs in the Indo-Pacific region associated with extreme El Niño conditions in 1998 (Boxes 6.1 and 11.1). Many reefs appear to have experienced similar SST conditions earlier in the 20th century and it is unclear how extensive bleaching was before widespread reporting post-1980 (Barton and Casey, 2005). There is limited ecological and genetic evidence for adaptation of corals to warmer conditions (see Box 6.1). However, there is high confidence that future increases of SST will result in more widespread and more intensive bleaching and the ability of reefs to absorb impacts due to climate change, and to recover, depends on the extent to which they are already degraded, and the timing between events (Sheppard, 2003; Hoegh-Guldberg, 2004). There is an urgent need for widescale monitoring, both of bleaching and reef recovery, using remote sensing to supplement field studies (Mumby *et al.*, 2004; Yamano and Tamura, 2004), and focused management to improve the ecological resilience of coral reefs, for example by reducing other stresses such as eutrophication (Wooldridge *et al.*, 2005).

Other threats to reefs than coral bleaching are associated with climate change (Kleypas and Langdon, 2002). Increased concentrations of CO_2 in seawater will lead to ocean acidification (The Royal Society, 2005; Turley *et al.*, 2006). This will affect aragonite saturation state and reduce calcification rates of calcifying organisms such as corals (LeClerq *et al.*, 2002; Guinotte *et al.*, 2003 see Box 4.4). Sea-level rise appears unlikely to threaten reefs in the immediate term; coral reefs have been shown to keep pace with rapid sea-level rise during the Holocene postglacial transgression (Hallock, 2005). Sea-level rise might even result in recolonisation of Indo-Pacific reef flats by corals as these presently less productive surfaces become available for coral growth (Buddemeier *et al.*, 2004). However, modelling implies that disintegration of degraded reefs after bleaching or reduced calcification may result in increased wave energy across reef flats and shoreline erosion (Sheppard *et al.*, 2005).

Many reefs occur in areas that are impacted by tropical storms, which generate coarse material eroded from the reef front and deposited on the reef top, providing a record of prehistoric storm history (Nott and Hayne, 2001). An intensification of tropical storms (see Section 6.3.2) could have devastating consequences on the reefs themselves and the inhabitants of many low lying islands (see Section 6.4.2). There is limited evidence that global warming may result in increase of coral range; for example, extension of branching *Acropora* poleward to Fort Lauderdale in Florida has been recorded, despite an almost Caribbean-wide trend for reef deterioration (Precht and Aronson, 2004), but there are several constraints, including limited suitable substrate, at the latitudinal limits to reef growth (Riegl, 2003; Woodroffe *et al.*, 2005).

The fate of the small reef islands on the rim of atolls is of special concern. Small reef islands in the Indo-Pacific formed over recent millennia during a period when regional sea level fell (Woodroffe and Morrison, 2001; Dickinson, 2004). However, the response of these islands to future sea-level rise remains uncertain, and is addressed in greater detail in Chapter 16. It will be important to identify critical thresholds of change beyond which there may be collapse of social and ecological systems on atolls. There are limited data, little local expertise to assess the dangers and a low level of economic activity to cover the costs of adaptation for atolls in countries such as the Maldives, Kiribati and Tuvalu (Barnett and Adger, 2003).

6.4.2 Consequences for human society

Since the TAR, we have developed a better but unequal understanding of the impacts of climate change on various socio-economic sectors in coastal zones (see also Section 6.5). This understanding is less than for natural coastal systems. We also recognise that actual impacts depend on more factors than the magnitude of climate change, with adaptation being a critical factor (Section 6.6). Climate change impacts on human society at the coast include (1) sea-level rise leading to the loss of coastal resources and usable land, food production, infrastructural damage, population displacement, etc; (2) changing temperature and rainfall on crops, human health, recreation and tourism. A qualitative overview of climate change impacts on the various socio-economic sectors of the coastal zone summarises the relative importance of the direct impacts for each sector (Table 6.3). The direct impacts can be positive and negative, with negative impacts dominating; less is known about indirect impacts (see Section 6.5).

Table 6.3: *Overview of climate change impacts on socio-economic sectors in coastal zones*

Sector	Temperature change	Extreme events	Floods	Rising water tables	Erosion	Salt water intrusion	Biological effects
Freshwater resources	X	x	x	X	o	X	x
Agriculture and forestry	X	x	x	X	o	X	x
Fisheries and Aquaculture	X	x	x	o	x	X	X
Health	X	x	x	x	o	X	x
Recreation and tourism	X	x	x	o	X	o	x
Settlements/ infrastructure	X	X	X	X	X	X	o

X = more significant; x = less significant; o = negligible or not established

A global pattern of impacts of climate change on socio-economic sectors is evident, with a geographical distribution and diversity of impacts (Figure 6.2). For example, extensive low-lying (often deltaic) areas, e.g. Netherlands, Guyana, and Bangladesh (Box 6.4), and oceanic islands are strongly affected by a rising sea level, whereas the coral reef systems and the polar region are already affected by rising temperature (Sections 6.2.5 and 6.4.1). The impacts are also influenced by magnitude and frequency of existing processes, e.g. the densely-populated East, South and Southeast Asian coasts that are already exposed to cyclones and tsunamis will experience greater impacts of climate change (Chapter 10).

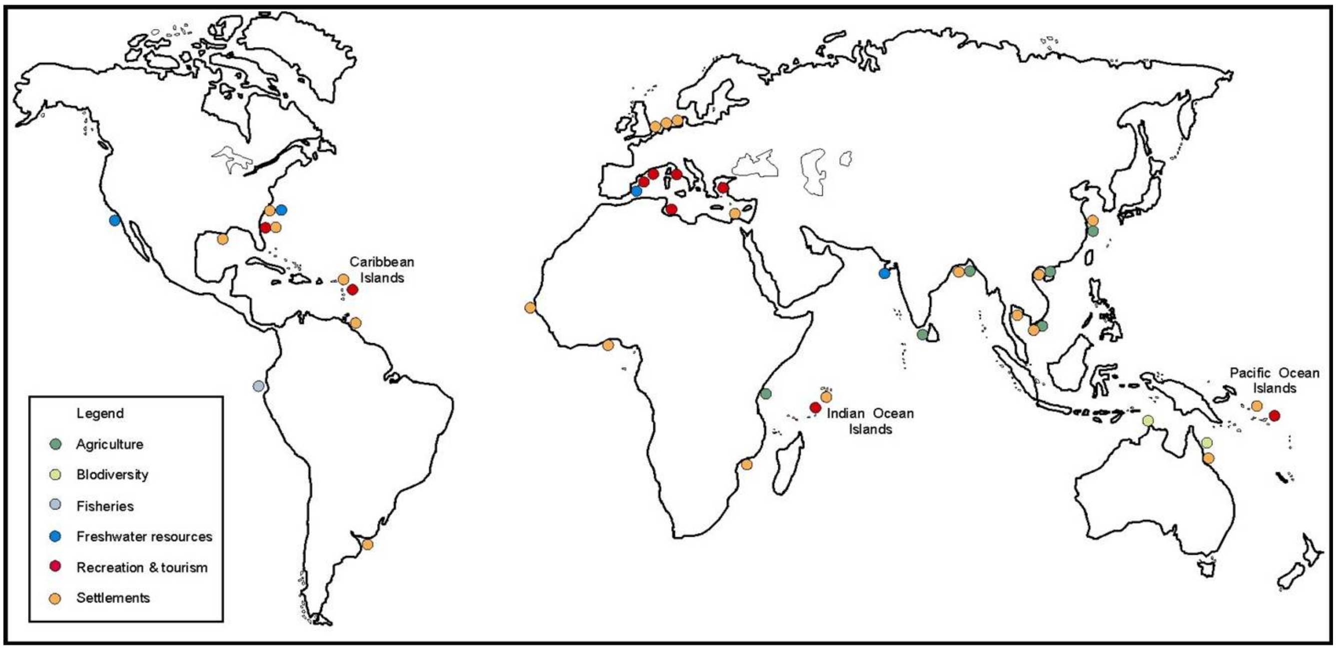

Figure 6.2*: Representative climate change impacts on socio-economic sectors at the coasts identified in this chapter.*

As the coastal ecosystems provide many valuable goods and services (Section 6.2.1), climate change in climate directly or indirectly will affect these services with consequences for human society. Synthesis of literature relating to climate impacts on biodiversity suggests that coastal ecosystems are particularly at risk from climate change (CBD, 2003; Section 6.4.1), with serious implications for human society at the coast.

More is known about the impacts of thresholds on socio-economic sectors than in the TAR. For example, critical limits relating to temperature could have consequences for reefs and hence coastal tourism (Todd, 2003; see Box 6.1), while aragonite saturation and ocean acidification might have consequences for coastal fisheries (The Royal Society, 2005; Turley *et al.*, 2006). Although assigned low probability, extreme sea-level rise due to major ice sheet collapse (Section 6.2.3) could have severe impacts on all socio-economic aspects of coastal western Europe (Arnell *et al.*, 2005; Tol *et al.*, 2006) and by implication, globally.

Some generalizations on the impacts and the consequences of human society at the coasts and low-lying areas are possible. First, significant regional differences in climate change and local variability of the coast, including human development patterns, result in variable impacts and adjustments along the coast, with implications for adaptation responses (Section 6.6). Second, human vulnerability to sea-level rise and climate change will be strongly influenced by the characteristics of socio-economic development. There are large differences in coastal impacts when one compares the different SRES worlds which cannot be attributed solely to magnitude of climate change (Nicholls and Lowe, 2006; Nicholls and Tol, 2006). Third, although the magnitude of sea-level rise will be reduced by mitigation

(Section 6.3.2), due to the slow response of sea-level rise to mitigation, it is unclear what impacts are avoided and what impacts are simply delayed by the stabilization of greenhouse gas concentration in the atmosphere (Nicholls and Lowe, 2006).

The impacts of climate change are likely to be greater in developing countries than in developed countries due to inequalities in health status, access to adequate food, clean water, and other essential resources (DEFRA, 2004; section 6.5). This is illustrated by the following examples. In Latin America, Guyana, has 90% of its population and important economic activities are within the coastal zone (Khan, 2001). Low-lying densely populated areas e.g. in India, China and Bangladesh (Chapter 10) are equally vulnerable. One quarter of Africa's population is clustered around resource-rich coastal zones and has a high vulnerability in terms of economic risks accounting for a high percentage of the GDP (Nyong and Niang-Diop, 2006; Chapter 9).

The different sectors outlined in Table 6.3 are now discussed.

6.4.2.1 Freshwater resources

The direct influences of sea-level rise on freshwater resources come principally from new or accelerated coastal erosion, more extensive coastal inundation and higher levels of sea flooding, increases in the landward reach of sea waves and storm-surges, seawater intrusion into surface waters and coastal aquifers, and further encroachment of tidal waters into estuaries and coastal river systems (Hay and Mimura, 2005). Although the coast contains a substantial proportion of the world's population, it has a much smaller proportion of the global renewable water supply, and the coastal population is growing faster than elsewhere, thus exacerbating this issue (Chapter 3).

Freshwater supply problems due to climate change are most likely in developing countries with a high proportion of coastal lowland, arid and semi-arid coasts, coastal mega-cities particularly in the Asia-Pacific region, and small island states, reflecting both natural and socio-economic factors that enhance the levels of risks (Ragab and Prudhomme, 2002). For some metropolitan and tourist areas located at the coast, the deterioration of groundwater from pumping is accelerated by seawater intrusion (FAO, 2005; Marshall, 2005).

Climate change has a strong impact on coastal salt water intrusion and the salinization of groundwater with consequent impacts on food resources (Table 6.3) (Chapter 3). Globally, by 2050 stream runoff is estimated to change by +40% to -30% in different coastal regions (Milly *et al.*, 2005). Locally, the impacts on coastal aquifers are through salt-water intrusion and their scale of impacts is dependent on aquifer dimensions, geological factors, ground water abstraction, reduction in freshwater discharges and precipitation. Increased freshwater input, including floods from climate change on some arid coasts, e.g., the Red Sea, may benefit groundwater recharge and aquifer storage (Al-Selfry *et al.*, 2004).

Identifying future coastal areas of stressed freshwater resources is not easy, particularly where there are strong seasonal demands, poor or no metering, and loss of water through theft or the distribution system (Hall, 2003). Based on the SRES emissions scenarios, it is estimated that the increase in water stress would have a significant impact by the 2050s, when the different population scenarios have a clear effect (Arnell, 2004). But, regardless of the scenarios applied, critical regions with a higher sensitivity to global change have been identified in coastal regions that include parts of the western coasts of Latin America and the Algerian coast (Alcamo and Henrichs, 2002).

6.4.2.2 Agriculture, forestry, and fisheries

Coastal ecosystems are highly sensitive to variations in weather and climate which affect the distribution, production, and many other aspects of species and biodiversity. Climate change would impact most seriously on coastal biodiversity such as the Great Barrier Reef and the Kakadu wetlands in Australia with consequences on human dimensions (Chapter 11). Goods and services provided by the mangroves could diminish if the mangroves are seriously degraded due to salt intrusion and freshwater reduction, such as the Indus delta (Chapter 10).

Coastal forestry is little studied in its own right. Based on limited literature, the impacts of climate change on coastal forestry vary widely. The east coast areas of North Island, New Zealand, are likely to experience growth reductions under projected rainfall decreases (Chapter 11). A shift of natural vegetation zones (and crops) is expected in response to increase in flood occurrence in Northern Europe and decrease in water available in southern Europe (Chapter 12). In Latin America, afforestation with foreign species is likely to impact along the littoral lagoon bars and wetlands (Chapter 13).

Climate change is expected to have a significant impact on crop production in coastal areas. Globally an increased agricultural production potential due to climate change and CO_2 fertilization should in principle add to food security, but locally the situation may be very different (Chapter 5). For example, an increase in frequency of extreme climate events during specific crop development stages, together with higher rainfall intensity and longer dry spells, may reduce the yield of durum wheat and sunflowers in the European Mediterranean (Chapter 12). In the Asian deltaic areas, potential losses and possible gains in rice yields could be identified with the impacts of future sea-level rise on water levels (Wassmann *et al.*, 2004) (cf. Box 6.4; Chapter 14). Extreme events, such as cyclone landfall, have negative impacts on coastal areas with high-value plantation crops, e.g. in Sri Lanka, Kenya (Chapter 5), and North Queensland in March 2006 (Cyclone Larry).

Climate variability and change is now recognized as a major factor affecting fisheries abundance and yield worldwide (see Chapter 4), including coastal and estuarine fisheries (Daufresne *et al.*, 2003; Genner *et al.*, 2004). The future impacts on fisheries are greater for temperate endemics than for tropical species and on coastal fisheries relative to pelagic fisheries (Chapter 11). Species have migrated poleward, e.g. southern species moving into North Sea coastal waters and also along North American coasts (Chapter 4). The biotic communities and productivity of coastal lagoons may experience a variety of changes, depending on the changes in freshwater flows and salt intrusion which affect the species (Chapter 4 and 9).

The linkages between climate and mariculture involved more subtle indirect relationships that affect the movement of nutrients and fish behaviour, including migration and reproduction. Also, it is difficult to separate climatic impacts from impacts of overfishing and increasing destruction of coastal and estuarine habitats. Overexploitation of inshore and inland fisheries threaten the fisheries resources of East, South and Southeast Asia (Chapter 10).

In the future, the increase in atmospheric CO_2 and subsequent ocean acidification has impacts on tropical coastal fisheries associated with loss of corals and on the life cycles of some marine fish and shellfish species. However, the estimates of economic consequences of ocean acidification are uncertain (The Royal Society, 2005). More certain is that the intensification of ENSO events and increases in SST, wind stress, hypoxia and the deepening of the thermocline, which will reduce spawning areas and fish catch of anchovy in Peru (Chapter 13). There is also concern that climate change may affect the abundance and distribution of pathogens and harmful algal blooms (HABs), thereby influencing diseases of aquatic organisms as well as human health (section 6.4.2.4). The linkage between temperature changes with HABs is still not robust, and the extent of coastal eutrophication affected by future climate variability will vary with local physical environmental conditions and current eutrophication status (Justic *et al.*, 2005).

6.4.2.2 Human settlements, infrastructure, and migration

Climate change and sea-level rise affects coastal settlements and infrastructure in several ways. One is the loss of natural coastal habitats removes the natural defences of coastal communities against storm surge (Box 6.3). Salt water intrusion leads to loss of freshwater marshes and forests, and sea-level rise will erode the effectiveness of barrier islands as storm surge buffers. Changes in tropical storm intensity and behaviour portend additional impacts on tropical and mid-latitude coastal ecosystems (section 6.3.2). Human-induced climate changes and sea-level rise will increase this vulnerability (Klein *et al.*, 2002). Also, rapid coastal development and population growth, a growing demand for waterfront properties, and urban sprawl have a deleterious effect on the coastal ecosystems.

Box 6.3: Hurricane Katrina and coastal ecosystem services.

Whereas an individual hurricane event cannot be attributed to climate change, it can serve to illustrate the consequences for ecosystem services if the intensity and/or frequency of such events were to increase in the future. One result of Hurricane Katrina, which made landfall in coastal Louisiana and Mississippi on August, 29, 2005, was the loss of 306 km^2 of coastal wetlands, levees, and islands that flank New Orleans in the Mississippi River Deltaic plain (USGS, 2006). The Chandeleur Islands, which lie southeast of the city were reduced to roughly half of their former extent during this storm. Collectively, these natural systems serve as the first line of defence against storm surge in this highly populated region. Areas in red in the figure below were converted to open water during Hurricane Katrina. The Chandeleur Islands serve as an important wintering ground for migratory waterfowl and neo-tropical birds; a large population of North American redhead ducks, for example, feed on the rhizomes of sheltered sea grasses leeward of the Chandeleur Islands (Michot, 2000). Historically the region has ranked second only to Alaska in U.S. commercial fisheries production and this high productivity has been attributed to the extent of coastal marshes and sheltered estuaries of the Mississippi River delta. Over 1300 people lost their lives during Hurricane Katrina and the economic losses totalled more than $100 billion (NOAA, 2005). Roughly 300,000 homes and over 1,000 historical and cultural sites were destroyed along the Louisiana and Mississippi coasts. Impacts of tropical cyclones are further discussed in Chapters 7 and 14. (Figure source: U.S. Geological Survey)

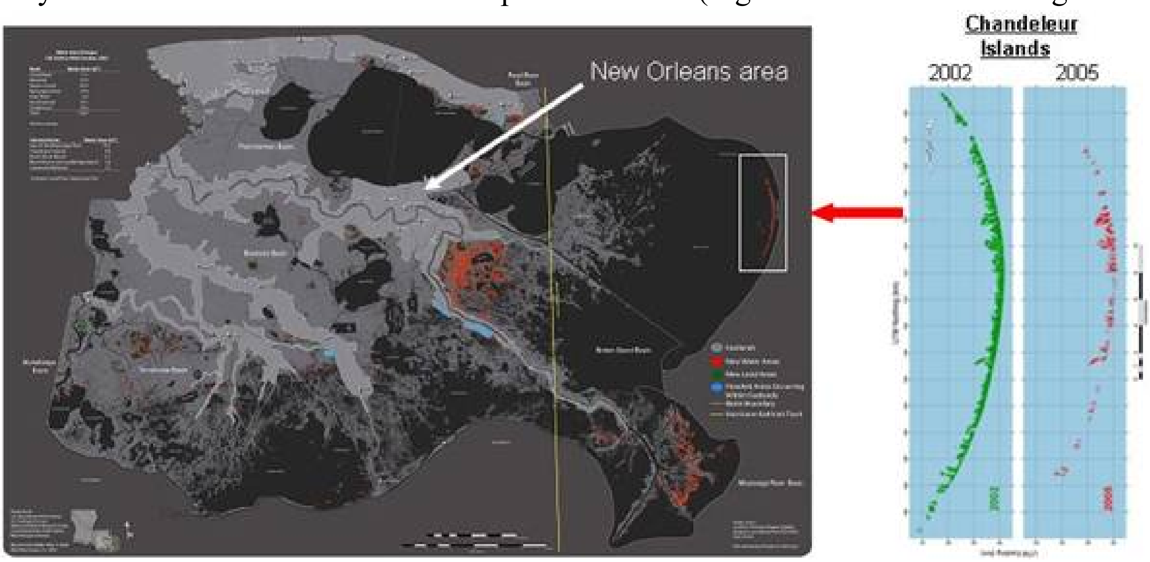

Figure B6.3.1.

Some coastal cities are heavily dependent upon artificial coastal defences, e.g. Tokyo and Rotterdam. Where these cities are undergoing natural subsidence, extreme water level increases threaten breaching of flood defences, as in the case of Hurricane Katrina and its impacts on New Orleans. A strong tradition of coastal defence has developed as in the Netherlands (Jonkman *et al.*, 2005) and much of the coasts of many European and East Asian countries, (e.g. Japan), are engineered (Chapter 10). Climate change, especially sea-level rise will exacerbate flood risk, placing greater pressures on infrastructure, such as port facilities. Many of the coastal cities at risk require incorporation of upgraded design criteria for flood embankments and barrages (e.g. Thames barrier in London and the Delta works in the Netherlands, Shanghai's defences in China and planned protection for the Venice lagoon. (Fletcher and Spencer, 2005) (see Section 6.6).

Regionally, the global impact to coastal flooding on human populations and the value of related infrastructures relates not just to coastal topography and other environmental factors but also to the number of people potentially exposed to storm surges. The greatest increase in human vulnerability to sea-level changes may lie in the coastal strips of South and Southeast Asia, and the urbanized coastal lowlands around Africa (Nicholls, 2004).

There is now a better understanding of flooding as a natural hazard and how climate change and other factors are likely to influence coastal flooding in future (Hunt, 2002). Potentially hundreds of millions of people are threatened with flooding by sea-level rise (Figure 6.3). although when one takes account of protection upgrade, the numbers of people actually flooded is much smaller (Nicholls and Tol, 2006). Hence understanding adaptation is vital to this question (Section 6.6). The threatened population will tend to be urbanised, both in large and smaller settlements (Klein *et al.*, 2002; Small and Nicholls, 2003).

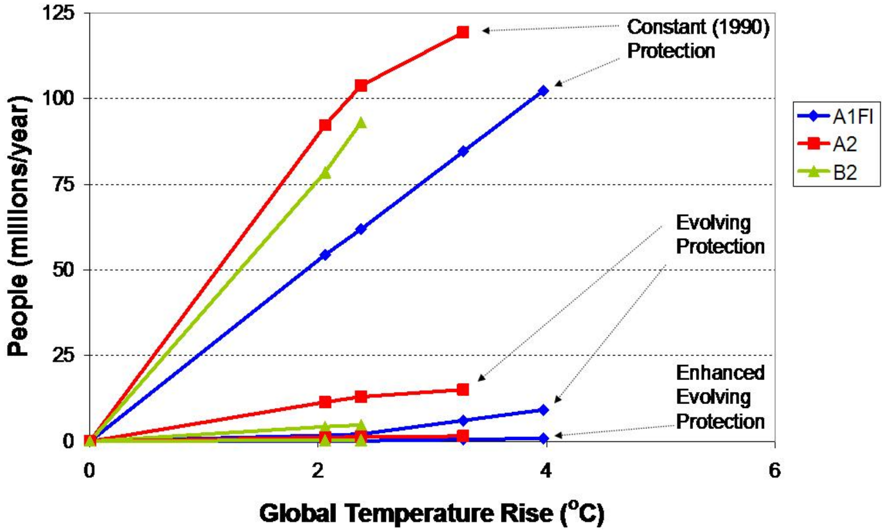

Figure 6.3: *Additional people flooded in coastal areas due to climate change, socio-economic scenario and protection response in the 2080s based on the Hadley model (based on Nicholls and Lowe, 2006).*

The prediction of precise locations for increased flood risk resulting from climate is difficult as flood risk dynamics have multiple social, technical, and environmental drivers (Few *et al.*, 2004). Urban systems are vulnerable to low-probability extreme events beyond their design basis and to systemic failures (domino effects), e.g. the transportation system especially along the Gulf and Atlantic coasts are vulnerable to coastal flooding and storm surges (Chapter 14). The number of flood disasters and mortality impacts is heavily skewed toward Asia with its large coastal population (Chapter 10) with

Bangladesh, China, Japan, Vietnam and Thailand having serious coastal flooding problems (Chapter 10), and to a lesser extent Europe (Chapter 12).

6.4.2.3 Human health

Coastal communities, and particularly in low income countries, are vulnerable to climate variability and long-term climate change, particularly extreme weather and climate events (such as cyclones, floods, and droughts). An increased frequency or intensity of flood and storm surge events would have severe and immediate effects on human health (Table 6.4). As recent events have shown, populations at risk of major flood in high, middle and low income countries. Within countries, low income groups disproportionately affected.

Table 6.4: *Health effects of climate change in coastal areas*

Exposure/hazard	**Health outcome**	**Cross-ref** **[add links to Regional Chapters]**
(Catastrophic) flooding	Deaths (drowning, other causes), injuries, infectious disease (respiratory, intestinal, skin), mental health disorders, impacts from interruption of (normal) health services, health effects of population displacement.	Sections 6.4.2; Box 6.3 Mechanisms by which flooding affects health discussed in detail in Chapter 8
Impairment of food quality and/or food supplies Climate change effects on HABs	Food poisoning: bacterial contamination, shellfish poisoning, ciguatera, health effects of toxic cyanobacteria, malnutrition.	Section 6.4.2.2
Impairment of water quality and/or access to potable water supplies	Diarrhoeal disease, giardia, cholera, hepatitis, etc. Water-washed and faecal-oral infections.	Chapter 7 and Section 6.4.2.1 Climate and cholera discussed in Chapter 8.
Change in transmission intensity or distribution of vector-borne disease. Changes in vector abundance.	Increases or decreases in malaria, dengue, and other local infections	Chapter 16 for Small Island State issues Chapter 8 for discussion on vector-borne disease
Effects of climate change and sea-level rise on livelihoods, population movement, and "environmental refugees"	Health effects are less well described. Large-scale population movement would have severe health effects.	Section 6.4.2.3 Limited health literature.

The potential impacts of climate change on populations in coastal regions will be determined by the future health status of the population and its capacity to cope with climate hazards, and control infectious diseases, and other public health measures. Coastal communities that rely on marine resources for food, in both terms of supply and maintaining food quality (food safety) are vulnerable to climate related impacts, in both health and economic terms. Marine ecological processes linked to temperature changes also play a role in determining human health risks, such as from cholera, and other enteric pathogens, harmful algal blooms, and shellfish and reef fish poisoning (Pascual *et al.*, 2002; Hunter, 2003; Lipp *et al.*, 2004; Peperzak, 2005).

Convincing evidence on the impacts of observed climate change on coastal disease patterns is absent (Kovats and Haines, 2005). Although there is an association between ENSO on cholera risk in Bangladesh and malaria epidemics in South Asia and the coastal regions of Venezuela and Colombia (McMichael, 2003), the knowledge on the mechanisms by which increased SST affects disease transmission is still poor (Kovats *et al.*, 2003).

The projection of potential health impacts of climate change is still difficult, because the sensitivity and adaptive capacity of the exposed population vary with other factors (Ebi and Gamble, 2005). Socio-economic factors may be more critical for public health, e.g. wealthier societies have better nutrition, better general health, and a greater access to public health measures and technologies targeted at controlling diseases. There are complex relationships between ecosystems and human well-being and future ecosystem changes may affect human health (Butler *et al.*, 2005). A large amount of uncertainty still exist on climate change on human health (Kovats *et al.*, 2005).

6.4.2.4 Recreation and tourism

Climate change has major potential impacts on coastal tourism which is dependent on the 'sun, sea and sand' formula. Globally, travel to sunny and warm coastal destinations is the major factor for tourists from Northern Europe to the Mediterranean (16% of world's tourists) and from North America to the Caribbean (1% of world's tourists) (WTO, 2003). By 2020, the total international tourists are estimated to number 1.56 billion arrivals (WTO, undated). Climate change may influence tourism directly via the decision-making process by influencing tourists to choose different destinations; and indirectly as a result of sea-level rise and effects on coastal erosion (Agnew and Viner, 2001). Increased awareness of interactions between ozone depletion and climate change and its subsequent impact on ultraviolet exposure of human skin is another factor influencing tourists' travel choice (Diffey, 2004).

Climate change is likely to affect the major segments of international tourist flows, prior to travel, enroute, and at the destination (Becken and Hay, undated). As tourism is still a growth industry, the changes in tourist numbers induced by climate change are generally much smaller than those resulting from population and economic growth (Bigano *et al.*, 2005; Hamilton *et al.*, 2005). Higher temperatures are likely to change summer destinations preferences, especially for northern Europe and summer heat waves in the Mediterranean may lead to a shift in tourism to spring and autumn (Madisson, 2001) and growth in summer tourism in the Baltic and North Seas (Chapter 12). Under a scenario of gradual warming, tourists would spend their holidays in different places than they currently do and the preferences for climates at tourist destinations differ among age and income groups (Lise and Tol, 2002). Although new climate niches are emerging, the empirical data do not suggest reduced competitiveness of the sun, sea and sand destinations as they are able to restructure to meet tourists' demands (Aguiló *et al.*, 2005).

Box 6.4: Deltas: hotspots for vulnerability

Deltas, some of the largest sedimentary deposits in the world, are widely recognised as highly vulnerable to the impacts of climate change, particularly sea-level rise and precipitation changes, as well as being subject to stresses imposed by human modification of catchment and delta plain land use. Most deltas are already undergoing natural subsidence that results in accelerated rates of relative sea-level rise above the global average. Many are impacted by the effects of declining sediment input as a consequence of entrapment in dams or water extraction and diversion. Delta plains, particularly those in Asia, are densely populated and large numbers of people are often impacted as a result of external terrestrial influences (river floods, sediment starvation) and/or external marine influences (storm surges, erosion) see Figure 6.1.

Nearly 300 million people inhabit 40 of the largest deltas in the world and many of these deltas are associated with significant an expanding urban areas. Using a generalised modelling approach to approximate the effective rate of sea-level rise, basing estimates of sediment trapping and flow diversion on a global dam database, and modifying estimates of natural subsidence to incorporate accelerated subsidence through human extraction of groundwater and/or hydrocarbons, Ericson *et al*. (2005) have shown that much of the population of these 40 deltas is at risk through coastal erosion and land loss, primarily as a result of the decreased sediment delivery by the rivers, but also through the accentuated rates of sea-level rise. They estimate, using a coarse digital terrain model and global population distribution data, that more than 1 million people will be directly affected by 2050 in each of the Ganges-Brahmaputra-Meghna delta in Bangladesh, the Mekong delta in Vietnam and the Nile delta in Egypt. More than 50,000 people are likely to be directly impacted in each of a further 9 deltas, and more than 5,000 in each of a further 12 deltas (Figure B6.4.1). This generalised modelling approach indicates that 75% of the population affected live on the largest Asian deltas, and a large proportion of the remainder are on deltas in Africa. Within the Asian deltas, the surface topography is complex as a result of the geomorphological development of the deltas, and the population distribution shows considerable spatial variability, reflecting the intensive land use and the growth of some of the world's largest megacities (Woodroffe *et al.*, 2006). Many people in these, and other, deltas worldwide, are already subject to flooding from both storm surges and seasonal floods, and there it is necessary to develop further methods to assess individual delta vulnerability (Sánchez-Arcilla *et al.*, 2006).

Figure B6.4.1: *Relative vulnerability of coastal delta populations as indicated by the indicative population potentially displaced by current sea-level trends to 2050, including local effects. Extreme ≥ 1 million people, high = around 500,000 people - and medium is > 5000 people potentially displaced (Ericson et al., 2005).*

Other possible impacts of climate change on tourism include acidification of the oceans and the coastal waters could also have profound effects on coastal ecosystems, including corals; also, temperature and rainfall pattern changes may impact water quality in coastal areas and this may lead to more beach closures. Overall, air temperature rise is more important to tourism than is sea-level rise, except where factors such as sea-level rise promotes beach degradation and viable adaptation options to sustain the beach (via nourishment or recycling) are not available (Bigano *et al.*, 2005).

In high-risk coasts, such as hurricane-prone coastlines, insurance costs for tourism could increase substantially or may no longer be available. This exacerbates the impacts of extreme events or restricts new tourism in high-risk regions (Scott *et al.*, 2005), e.g. four hurricanes in a two-month period in 2004 caused over US$1 billion in infrastructure damage and lost business in 2004 and 2005 in Florida's tourism industry (Chapter 14). Various studies attempt to predict the impacts of climate change on tourism. According to one study (Viner and Amelung, 2005), changes are less for tourist destinations 550 ppm scenario, and more at B1A and B2.

6.4.3 Key vulnerabilities and hotspots: influences of the magnitudes and rates of climate change and development pathways

A comprehensive assessment of the potential impacts of climate change must consider at least three components of vulnerability: exposure, sensitivity, and adaptive capacity. Significant regional differences in present climate and expected climate change give rise to different exposure among human populations and natural systems to climate stimuli (McCarthy *et al.*, 2001). The previous sections of this chapter broadly characterize the sensitivity and natural adaptive capacity (or resilience) of several major classes of coastal environments to changes in climate and sea-level rise. Differences in geological, oceanographic, and biological processes can also lead to substantially different impacts on a single coastal system type at different locations. Some global patterns and hotspots of vulnerability are evident, however, and the following natural coastal system types appear most vulnerable to either climate change or associated changes in sea-level rise and carbon flux (Table 6.5).

Table 6.5: *Relative vulnerability of coastal system types considering their exposure, sensitivity, and natural adaptive capacity. Those marked with asterisk (*) are generally most vulnerable.*

Coastal System Type	Exposure	Sensitivity	Natural Adaptive Capacity
* Deltas and low-lying coastal wetlands	High	High	Low-Medium[1]
* Low-lying small islands and atolls	High	High	Low
* Coral reefs	High	Medium-High	Low
* Ice-dominated coasts	High	High	Low-Medium[1]
* Soft rock cliffs	Medium-High	Low-High	Low-High
* Sand and gravel beaches	High	Low-High[1]	Low-Medium[1]
Estuaries and lagoons	Low-Medium	Low	Medium[1]
Sea grasses	Low	Low	Medium
Hard rock cliffs	Medium-High	Low	Medium

[1] highly dependent on sediment supply.

An acceleration of sea-level rise would directly affect the vulnerability of all of these systems, but sea-level rise will not occur uniformly around the world (Section 6.3.2). Variability of waves and storms, as well as sediment supply and the ability to migrate landward also influence the vulnerability of many of these coastal system types. Hence, there is an important element of regional variation among coastal system types that must be considered when conducting site-specific vulnerability assessments.

Our understanding of human adaptive capacity is less developed than our understanding of responses by natural systems, which limits the degree to which we can quantify societal vulnerability in the world's coastal regions. Nonetheless, several key aspects of human vulnerability have emerged. It is also apparent that that multiple and concomitant non-climate stresses will exacerbate the impacts of climate change on most natural coastal systems, leading to much larger and detrimental changes in the 21st Century than those of the 20th Century. Table 6.6 summarises some of the key vulnerabilities that arise from the combination of natural and societal factors. Note that some examples such as atolls and small islands and deltas recur.

Table 6.6: *Key hotspots of societal vulnerability in coastal zones.*

Natural and societal factors that create hot spots of vulnerability	Examples from this Chapter
Human communities in low-lying coastal areas, especially those facing major technical or economic constraints with respect to adaptation	Atolls and small islands, New Orleans
Coastal areas where the cost-benefit ratio with respect to adaptation is high	Venice, Asian megadeltas
Coastal areas that are subject to multiple natural and human-induced stresses, such as subsidence or declining natural defences	Mississippi, Nile and Asian megadeltas, Netherlands, Mediterranean, Maldives
Coastal areas already experiencing adverse effects of temperature rise	Coral reefs, Arctic coasts (USA, Canada, Russia
Coastal areas exposed to significant storm surge hazards	Bay of Bengal, Gulf of Mexico/Caribbean, Rio de la Plata, Parang delta, North Sea
Where coastal freshwater resources are likely to be particularly and adversely affected by climate change	W. Africa, W. Australia, Atolls and small islands
Where coastal economies are highly dependent upon tourism and major adverse effects on tourism are likely	Caribbean, Mediterranean, Florida, Thailand, Maldives
Where coastal systems are highly threatened but inland migration is least practicable	Many developed coasts, Low small islands, Bangladesh

While physical exposure is an important aspect of the vulnerability for both human populations and natural systems, a lack of adaptive capacity is often the most important factor that creates a hotspot of human vulnerability. Adaptive capacity is largely dependent upon development status. Developing nations may have the societal will to relocate people who live in low-lying coastal zones, but without the necessary financial resources, their vulnerability is much greater than a developed nation in an identical coastal setting. Hence, development is not only a key consideration in evaluating greenhouse gas emissions and climate change, but is also fundamental in assessing adaptive capacity because greater access to wealth and technology generally increases adaptive capacity while poverty limits adaptation options.

6.5 Costs, benefits and other socio-economic consequences of climate change impacts

The costs, benefits and other socio-economic consequences of climate chrange for coastal and low-lying areas have been determined for many aspects, including heat stress and changes in plant and animal metabolism (Chapter 4), disease (Chapter 8), water supply (Chapter 3), and coastal forests, agriculture and aquaculture (Chapter 5). This section will focus on evaluating the socio-economic consequences of sea-level rise, storm damage and coastal erosion.

6.5.1 Methods and tools for characterising socio-economic consequences

Since the TAR there has been further progress in moving from classical cost–benefit analysis to comprehensive assessments that integrate monetary, social, and natural science criteria. For example, Hughes *et al.* (2005) report the emergence of a complex systems approach for sustaining and repairing marine ecosystems. This links ecological resilience to governance structures, economics, and society. Such developments are in response to the growing recognition of the intricate linkages between the physical coastal processes, the diverse coastal ecosystems, and resources at risk from climate change, the many ecological functions they serve and services they provide, and the variety of human amenities and activities that depend on them. Thus a more complete picture of climate change impacts emerges if assessments take into account the locally embedded realities and constraints that affect individual decision makers' and community responses to climate change (Moser, 2000; 2005). Increasingly, frameworks such as Integrated Assessment are being used to facilitate this integration. They also provide an interdisciplinary learning process for experts and decision makers as well as engagement of all stakeholders (Turner, 2001). Evaluations of societal and other consequences increasingly combine impact-benefit/cost-effectiveness analytical methods with scenario analysis. For example, a recent analysis of managed realignment schemes took into account social, environmental and economic consequences when evaluating direct benefits. It also determined the indirect benefits resulting from efforts to reduce the effects of sea-level rise (Coombes *et al.*, 2004).

Direct cost estimates are common across climate change impact literature as they are relatively simple to estimate and easy to explain. Such estimates are also becoming increasingly elaborate. For example, one study of sea-level rise considered land and wetland loss, population displacement, and coastal protection via dike construction (Tol, 2006). Socioeconomic variables, such as income and population density, are important in estimating wetland value but are often omitted when making such estimations (Brander *et al.*, 2003). But direct cost estimates ignore such effects as changes in land and food prices if land is lost. One way to estimate these additional effects is to use a computable general equilibrium model to consider markets for all goods and services simultaneously, taking international trade and investment into account (e.g. Bosello *et al.*, 2004). However, the major economic effects of climate change may well be associated with out-of-equilibrium phenomena (Moser, 2006).

Given the recent and anticipated increases in damages from extreme events, the insurance industry and others are making increased use of catastrophe models. These cover event generation (e.g. storm magnitude and frequency), hazard simulation (wind stresses), damage modelling (extent of structural damage), and financial modelling (costs). Stochastic modelling is used to generate thousands of simulated events and develop probabilistic approaches to quantifying the risks (see Chapter 2 and Aliff, 2006).

Methodologically, many challenges remain. Not the least is that the need for integration of monetary, social and natural science criteria requires a transdisciplinary response from the social and natural sciences. Work to date has insufficiently crossed disciplinary boundaries (Visser, 2004). Although valuation techniques are continually being refined, and are now better linked to risk-based decision making, they remain imperfect, and in some instances controversial.

6.5.2 Socio-economic consequences under current climate conditions

Under current climate conditions developing countries bear the main brunt of climate-related extreme events, but it is equally evident that developed countries are not insulated from disastrous consequences. The societal costs of coastal disasters are typically quantified in terms of property losses and human deaths. Post-event impacts on coastal businesses, families and neighbourhoods, public and private social institutions, natural resources, and the environment generally go unrecognised in disaster cost accounting (Baxter, 2005). Finding an accurate way to document these unreported or hidden costs is a challenging problem that has received increasing attention in recent years. Studies (e.g. Heinz Center, 2000) are now confirming that family roles and responsibilities after a disastrous coastal storm undergo profound changes associated with household and employment disruption, economic hardship, poor living conditions, and the disruption of pubic services, such as education and preventive health care. Indirect costs imposed by health problems (see Section 6.4.2.5) result from damaged homes and utilities, extreme temperatures, contaminated food, polluted water, debris- and mud-borne bacteria, and mildew and mould Within the family, relationships after a disastrous coastal storm can become so stressful that family desertion and divorce may increase (Morrow, 1997). Unsafe roads and heavy traffic can lead to increased traffic accidents. Increased use of alcohol and drugs is common in the months and years following a coastal disaster (Morrow and Enarson, 1996). Accounting for the full range of costs is difficult, though essential to the accurate assessment of climate-related coastal hazards.

Tropical cyclones have major economic, social and environmental consequences for coastal areas [see Box 6.2]. According to a UNDP (2004) analysis, up to 119 million people are on average exposed every year to tropical cyclone hazard and some people experience an average of more than four events every year. Worldwide, from 1980 to 2000, a total of 251,384 deaths have been associated with tropical cyclones, though this is less than the 300,000 killed in Bangladesh in 1970 by a single cyclone. For every person killed, around 3,000 people are exposed to natural hazards. Bangladesh accounts for more than 60 percent of the cyclones deaths globally between 1980 and 2000. Countries with the largest exposed populations have highly populated coastal areas and especially densely populated deltas (China, India, the Philippines, Japan, Bangladesh) (UNDP, 2004). In Cairns, cyclone experience and education may have contributed synergistically to a change in risk perceptions and a reduction in the vulnerability of residents to tropical cyclone and storm surge hazards (Anderson-Berry, 2003). Whereas the annual number of tropical cyclones and typhoons making landfall in Japan showed no significant trend over the period 1950 to 2004, the number of the port-related disasters in Japan decreased. This is attributed to increased protection against such disasters, though annual average restoration expenditures over the period still amount to over US$250 million (Hay and Mimura, 2006).

The United States has sustained 67 weather-related disasters between 1980 and 2005 in which overall damage costs were at least US$1 billion. Total damages costs for the period, adjusted for inflation, were over US$500 billion (NOAA, 2005). While there are differing views as to whether climatic factors have contributed to the increasing frequency of major weather-related disasters along the Atlantic and Gulf coasts (Pielke and Landsea, 1998; Pielke Jr *et al.*, 2005), the damage costs associated with these events are undisputedly high, and will increase with climate change. Along the east coast of the United States sea-level rise over the last century has exacerbated the damage to fixed structures from modern storms that would have been less severe a century ago (Zhang *et al.*, 2000).

Erosion of coasts is a world-wide problem (Section 6.4). The following examples emphasise that rates can be high under present climatic conditions. The average annual erosion rate in the beach communities of Delaware’s Atlantic coast varies between 60 and 120 cm/yr and is threatening the sustainability of the area as a major summer recreation attraction (Daniel, 2001). About 20% of Europe’s coastline suffered serious erosion impacts in 2004. The area lost or seriously impacted by erosion is estimated to be 15 km^2 per year. And the cost of mitigation actions is increasing - in 2001, public expenditure for coastline protection was an estimated US$ 4 billion, up from US$ 3 billion in 1986 (Eurosion, 2004). Major questions – yet to be addressed in public debate – include the feasibility, implications, and acceptability of shoreline retreat; the appropriate type of shoreline protection (e.g.

beach nourishment, hard protection, or other typically expensive responses) in situations where rates of shoreline retreat are increasing; and doubts as to the longer-term sustainability of such interventions.

6.5.3 Socio-economic consequences with climate change

Substantial progress has been made in evaluating the socio-economic consequences of climate change, including changes in variability and extremes. In general, the results show that socio-economic costs will likely escalate as a result of climate change, as already shown for the broader impacts (Section 6.4). Most immediately, and in general, this will reflect increased variability and extreme events. Only in the longer term, and again in general, will costs (in the widest sense) be dominated by trends in average conditions, such as mean sea-level rise (van Aalst, 2006). The impacts of such changes in climate and sea level are overwhelmingly adverse. But benefits have also been identified, including uced cold-water mortalities of many valuable fish and shellfish species (Chapter. 4), increased opportunities for nearly year round use of fishing vessels and coastal shipping facilities (Chapter. 7), expansion of areas suitable for aquaculture (Chapter. 5), reduced mortalities of the homeless in coastal communities (Chapter. 7), reduced hull strengthening and icebreaking costs, and the opening of new ocean routes due to reduced sea ice (Chapter. 7). Countries with large land areas generally benefit from competitive advantage effects due to sea-level rise. Investment in protection is least painful where capital is most productive (Bosello *et al.*, 2004).

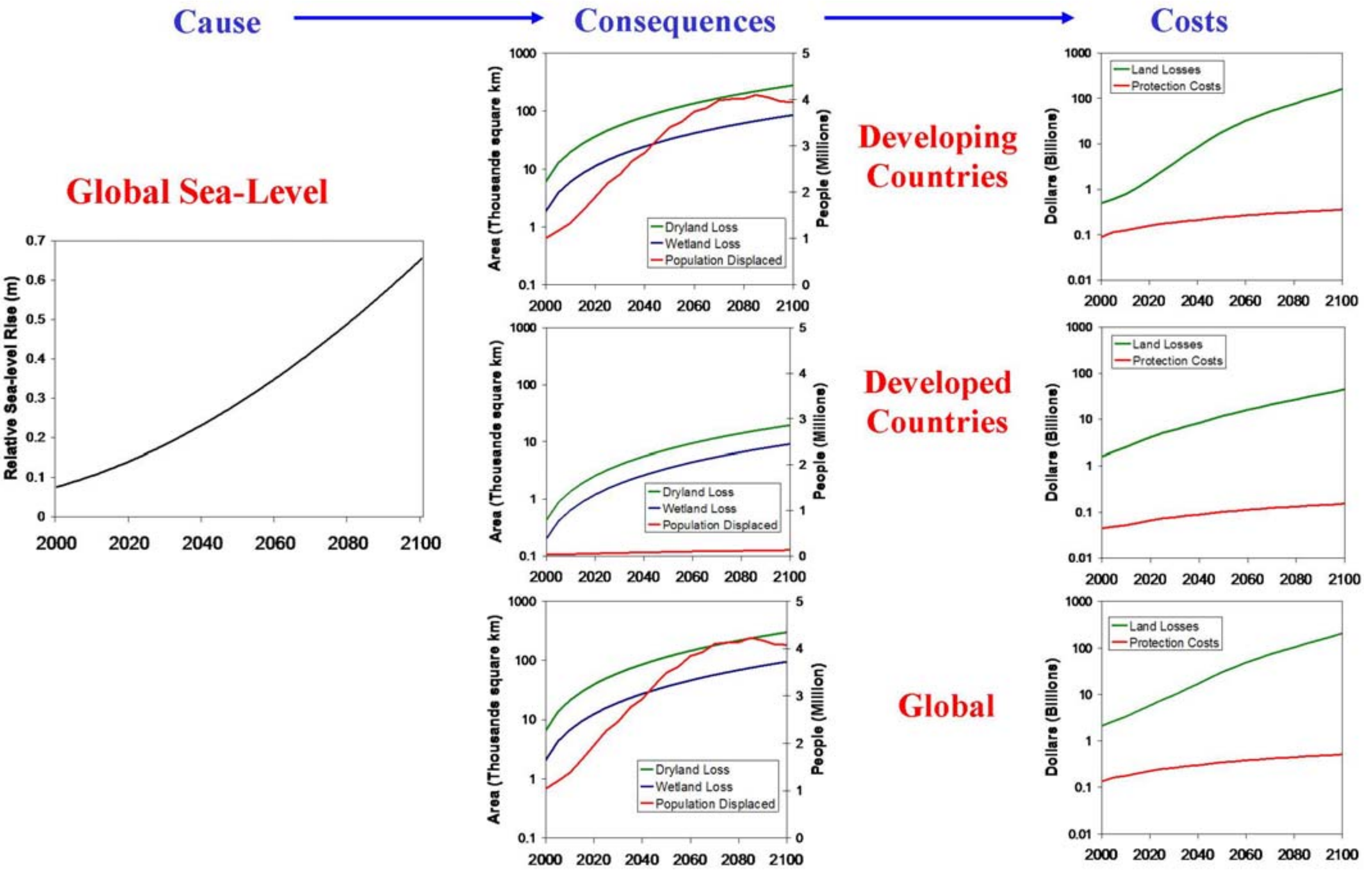

Figure 6.4: *Causes, selected consequences (people displaced) and the total costs of sea-level rise, for developing and developed countries, and as a global total. (based on Tol, 2006).*

According to Nicholls (2004) some 10 million people experienced coastal flooding annually in the 1990s. By the 2080s, and in the absence of enhanced protection, this number could rise to between 55 to 120 million people per year, varying with the SRES scenario (Figure 6.3). All reasonable scenarios of sea-level rise result in increased flooding during the 21st century, but there are significant uncertainties. The number of people estimated to experience flooding in the 2080s for a high scenario is as much as 450 million people per year in the worst case (Nicholls, 2004). Figure 6.4 shows the consequences and total costs of a rise in sea level for developing and developed countries, and globally. The consequences of sea-level rise will be far greater for developing countries, and protection costs will be higher, relative to those for developed countries.

Such global assessments are complemented by regional, national and more detailed studies. Examples are:

- The number of people in Europe subject to significant coastal erosion or flood risk in 2020 may exceed 158,000, while half of Europe's coastal wetlands are expected to disappear as a result of sea-level rise (Eurosion, 2004);
- Loss of land due to a sea-level rise of 50cm and 100cm could decrease Thailand's GDP by 0.36% and 0.69%, respectively; due to location and other factors the manufacturing sector in Bangkok could suffer the greatest damage, amounting to about 61% and 38% of the total damage, respectively (Ohno, 2000);
- In the cities of Alexandria, Rosetta and Port-Said on the Nile delta coast of Egypt, a sea-level rise of 50 cm could result in over 2 million people abandoning their homes, the loss of 214,000 jobs and the loss of land valued at over $US35.0 billion (El-Raey, 1997).

6.6 Adaptation: Options, practices, capacities and constraints

This section first highlights issues that arise with interventions designed to reduce risks to natural and human coastal systems as a consequence of climate change. A key conclusion is that reactive and standalone efforts to reduce climate-related risks to coastal systems are less effective than is the case if responses are part of integrated coastal zone management (ICZM), including long term national and community planning (Kay and Adler, 2005). Within this context, subsequent sections describe the tools relevant to adaptation in coastal areas, options for adaptation of coastal systems, and current and planned adaptation initiatives. Examples of the costs of, and limits to, coastal adaptation are described, as are the trade-offs. Constraints on, limitations to, and strategies for strengthening adaptive capacity are also described. Finally, the links between coastal adaptation and efforts to mitigate climate change are discussed.

6.6.1 Adaptation to changes in climate and sea level

6.6.1.1 Issues and challenges

One constraint on successful management of climate-related risks to coastal systems is the limited ability to characterise in appropriate detail how these systems, and their constituent parts, will respond to climate change drivers and to adaptation initiatives (Section 6.2.4 and Finkl, 2002). Of particular importance is understanding the extent to which natural coastal systems can adapt and therefore continue to provide essential life-supporting services to society. The highly interactive nature and nonlinear behaviour of coastal systems means that failure to take an integrated approach to characterising climate-related risks increases the likelihood that the effectiveness of adaptation will be reduced, and perhaps even negated (Bertness and Ewanchuk, 2002; Leont'yev, 2003; Zhang *et al.*, 2004). Despite the growing emphasis on beach nourishment (Hanson *et al.*, 2002), the long-term effectiveness and feasibility of such adaptive measures remains uncertain. The question of who pays and who benefits from adaptation is another issue of concern. Public acceptance of the need for adaptation, and of specific measures, also needs to be increased (Neumann *et al.*, 2000). Several other significant and diverse challenges are described in Table 6.7 and discussed further in the identified section.

Table 6.7: *Major Impediments to the Success of Adaptation in the Coastal Zone.*

Impediment	Reference	Section
Adopt more dynamic approach in predictions of landform migration	(Pethick, 2001)	6.6.1.2
Rationalization of shoreline protection measures	(Finkl, 2002)	6.6.1.4
Differences in information acquisition and storage impede exchange and integration	(Hale *et al.*, 2003)	6.6.1.3
Identifying indicators and thresholds of relevance to coastal managers	(Rice, 2003)	6.6.1.2
Poorly understood relationship between coastal conditions and management approach	(Kay and Adler, 2005)	6.6.1.3
Lack of long term data for key coastal descriptors	(Hall, 2002)	6.6.1.2
Ineffective institutional arrangements and weak governance	(Moser, 2000)	6.6.1.3

6.6.1.2 Tools for assessing adaptation needs and options

Since the TAR a substantially increased number of tools have become available to support assessments of the need for adaptation and to identify and select appropriate adaptation interventions (Klein *et al.*, 2001). A selection of such tools is described in Table 6.8.

Table 6.8: *Selected Tools that Support Coastal Adaptation Assessments and Interventions*

Description	**Selected Examples**
Indices of vulnerability to sea-level rise	(Thieler and Hammar-Klose, 2000; Kokot *et al.*, 2004)
Integrated models for knowledge management and adaptation assessment	(Vafeidis *et al.*, 2004; Warrick *et al.*, 2005)
Geographic information systems for decision support	(Green and King, 2002; Bartlett and Smith, 2005)
Scenarios – a tool to facilitate thinking and deciding about the future	(DTI, 2002; Ledoux and Turner, 2002)
Community vulnerability assessment tool	(NOAA, 2006)
Flood simulator for flood and coastal defences	http://www.discoverysoftware.co.uk/
Estimating the socio-economic and environmental effects of disasters	(ECLAC, 2003)
ICZM process sustainability – a score card	(Milne *et al.*, 2003)
Monetary economic valuation of the environment	(Ohno, 2000; Ledoux *et al.*, 2001)
Models for evaluation and design of coastal adaptation interventions	(Thieler *et al.*, 2000; Stive, 2004)
Evaluating and mapping return periods of extreme events	(Bernier *et al.*, 2006)
Compendium of methods and tools to evaluate vulnerability and adaptation to climate change	(UNFCCC, 2005)

6.6.1.3 Integrated coastal zone management

Since it offers advantages over purely sectoral approaches, ICZM is widely recognised and promoted as the most appropriate process to deal with climate change, sea-level rise and other current and long-term coastal challenges (Isobe, 2001; Nicholls and Klein, 2005). The extent to which climate change and sea-level rise are considered in coastal management plans is one useful measure of commitment to integration and sustainability. Responses to sea-level rise and climate change need to be implemented in the broader context and the wider objectives of coastal planning and management (Kennish, 2002;

Moser, 2005). ICZM is a focussed and balanced planning process (Christie *et al.*, 2005). Generation of equitably distributed social and environmental benefits is a key factor in ICZM process sustainability, but difficult to achieve. Attention must also be paid to legal and institutional frameworks that support integrative planning on local and national scales. Different social groups have contrasting, and often conflicting views on the relative priorities to be given to development, the environment and social considerations, as well as short and long-term perspectives (Visser, 2004).

6.6.1.4 Adaptation options

The capacity of coastal ecosystems to regenerate after disasters and to continue to produce resources and services for human livelihoods and well-being can no longer be taken for granted. Rather, socio-ecological resilience must be understood at broader scales and actively managed and nurtured. Incentives for generating ecological knowledge and translating it into information that can be used in governance are essential. Multilevel social networks are crucial for developing social capital and for supporting the legal, political, and financial frameworks that enhance sources of social and ecological resilience. The sharing of management authority requires cross-level interactions and cooperation, not merely centralization or decentralization. In many cases, improved, strong leadership and changes of social norms within management organizations are required to implement adaptive governance of coastal social-ecological systems (Adger *et al.*, 2005).

Those involved in managing coastal systems have many practical options for simultaneously reducing risks related to current climate extremes and variability and adapting to climate change (Yohe, 2000; Daniel, 2001; Queensland Government, 2001; Townend and Pethick, 2002). This reflects the fact that many disaster and climate change response strategies are the same as those which contribute in a positive manner to present-day efforts to implement sustainable development, including enhancement of social equity, sound environmental management and wise resource use (Helmer and Hilhorst, 2006). This will accelerate the convergence of the time horizons for coastal planning and climate change adaptation and can, in turn, enhance the anticipatory response capacity of institutions (Few *et al.*, 2004). But in many cases the timeframes for development are shorter than the timescales for natural changes in the coast. There is a fundamental need to integrate and mainstream disaster management and adaptation to climate variability and change into wider coastal management. This is especially so given relevant lessons learned from the recent Indian Ocean tsunami, despite it not being climate related. For example, the level of risk awareness among the populations was very low. This was identified as one of the main reasons for the high death toll. In a few cases, particularly in Indonesia and Thailand, isolated communities had retained an ancestral memory of similar disasters and had fled to higher grounds when alerted by the initial tremors, illustrating the effectiveness of risk awareness in reducing the human cost of disasters (UNOCHA, 2005). Thus identifying and selecting adaptation options can be guided by experience and best practice for reducing the adverse impacts of analogous, though causally unrelated, phenomena such as subsidence (natural and/or human induced) and tsunami (Olsen *et al.*, 2005).

Klein *et al*. (2001) describe three trends: growing recognition of the benefits of "soft" protection and of “retreat and accommodate” strategies; an increasing reliance on technologies to develop and manage information; and an enhanced awareness of the need for coastal adaptation to reflect local natural and socio-economic conditions. The decision as to which adaptation option is chosen is likely to be largely influenced by local socio-economic considerations (Knogge *et al.*, 2004). Moser (2000) identified several factors that prompted local communities to act against coastal erosion: threats or actual litigation; frustration among local officials regarding lack of clarity in local regulations - hence confusion as well as exposure to litigation; and uneasiness or concern with soaring numbers of applications for shoreline hardening structures coupled with perception of negative environmental impacts of hardening, including beach loss. The particular adaptation strategy adopted depends on many factors, and includes the value of the land or infrastructure under threat, the financial and economic resources that can be brought to bear, politics and cultural values, the local landscape of coastal management policy and the ability to understand and implement adaptation options (Yohe, 2000).

6.6.1.5 Current adaptation practises and planned adaptation

Figure 6.5 highlights the evolution of planned adaptation practices in the coastal zone and provides examples of current adaptation interventions.

Coastal Adaptation (IPCC CZM, 1990)	Adaptation Objectives (Klein and Tol, 1997)	Adaptation Responses (after DEFRA, 2001; Eurosion, 2004)	Example
Protect	Increased robustness	Hold the line	Beach nourishment
		Advance the line	Land claim; empoldering
Accommodate	Increased flexibility	Flexible engineering solutions	'Flood proof' buildings
Retreat	Enhanced adaptability	Retreat the line	Managed realignment
		Limited intervention	Improvised sea wall
		No intervention	Monitoring only
	reversing maladaptive trends	Sustainable adaptation	Wetland restoration
	Improved awareness and preparedness	Community-focussed adaptation	Flood hazard mapping; flood warnings

Figure 6.5: *Evolution of planned coastal adaptation practices.*

6.6.2 Costs and benefits of adaptation

The body of information on costs of adaptation has increased dramatically since the TAR, covering the range from specific interventions to global aggregations. Most analyses quantify the costs of responses to the more certain and specific effects of sea-level rise. A selection of findings is presented in Table 6.9. They reveal a wide range in adaptation costs, but in general these investments are cost effective (see also, for example, Section 6.4.2.3).

6.6.3 Limits and trade-offs in adaptation

Recent studies suggest that there are limits to the extent to which natural and human coastal systems can adapt to climate change. This includes the more immediate changes in variability and extreme events. Limits can be identified even for the more developed countries (Moser, 2005; Nicholls *et al.*, 2006b). For example, without either adaptation and mitigation the impacts of sea-level rise will be substantial, suggesting that some island and predominantly low-lying nations may become unviable by 2100; the overall global effect is much smaller (Nicholls and Tol, 2006; Tol, 2006). Adaptation would reduce impacts by a factor of 10 to 100, and would come at a minor cost compared to the damage avoided, while mitigation of climate change will take decades or more to reduce coastal impacts (Section 6.2.3).

Table 6.9: *Selected information on costs and benefits of adaptation*

Optimal coastal protection costs and number of people displaced given a 1m rise in sea level (Tol, 2002)		
Region	Protection Costs (10^9 US$)	Number of People Displaced (10^6)
Africa	92	2.74
OECD Europe	136	0.22
World	955	8.61

Construction costs for coastal defence in England and Wales (average total cost in $US/km) (Evans et al., 2004b)			
Earth embankment	970,000	Culverts	3.5 million
Protected embankment	4.7 million	Sea wall	4.7 million
Dunes (excl replenishment)	93,000	Groynes, breakwater (shingle beach)	9 million

Costs ($US per linear km) to protect against one m sea-level rise – USA (Neumann et al., 2000)			
Dike or levee	450,000 – 2.4 million	Sea wall; bulkhead construction	450,000 – 12 million

Capital costs ($US per linear km) for selected coastal management options in New Zealand (Jenks et al., 2005)	
Sand dune replanting, with community input (maintenance costs minimal)	6,000 – 24,000
Dune restoration, including education programmes (maintenance costs minimal)	15,000 -35,000
Dune reshaping and replanting (maintenance costs minimal)	50,000 – 300,000
Sea walls and revetments (maintenance costs high – full rebuild every 20 – 40 years)	900,000 – 1.3 million

Direct losses, costs and benefits of adaptation to 65 cm sea-level rise in Pearl Delta, China (Hay and Mimura, 2005)			
Tidal level	Loss (US$ billion)	Cost (US$ billion)	Benefit (US$ billion)
Highest recorded	5.2	0.4	4.8
100 year high water	4.8	0.4	4.4

Even at present, adaptation to reduce climate risks is often inadequate. The ability to accommodate further increases in climate-related risks is frequently lacking. Moreover, increases in coastal development and population will magnify risks of coastal flooding (Section 6.2.2; Pielke Jr *et al.*, 2005). Most measures to compensate and control the salinisation of coastal aquifers are expensive and laborious (Essink, 2001). Frequent floods put enormous constraints on development. For example, Bangladesh has struggled to put sizeable infrastructure in place to prevent flooding, but with limited success (Ahmad and Ahmed, 2003). Vietnam's transition from state central planning to a more market oriented economy has had negative impacts on social vulnerability, with a decrease in institutional adaptation to environmental risks associated with flooding and typhoon impacts in the coastal environment (Adger, 2000). In a practical sense adaptation options for coral reefs are limited (Buddemeier, 2001) as is the case for most ecosystems. The continuing observed degradation of many coastal ecosystems, despite the considerable efforts to reverse the trend, suggests that it will also be difficult to alleviate the added stresses resulting from climate change.

Knowledge and skill gaps are important impediments to understanding potential impacts, and thus to developing appropriate adaptation strategies for coastal systems (Crimp *et al.*, 2004). The public often has conflicting views on the issues of sustainability, hard and soft defences, economics, the environment and consultation. Identifying the information needs of local residents, and facilitating access to information, are integral components in the process of public understanding and should be addressed and assessed on a case-by-case basis (Myatt *et al.*, 2003; Moser, 2005; 2006; Luers and Moser, 2006).

There are divergent views as to how effective adaptation can be, e.g., adaptation can greatly reduce the impacts of sea level and climate changes on socio-economic systems, but often to the detriment of natural ecosystems. The latter systems vary in their ability to adapt to significantly large deviations from average climatic conditions, as well as to high rates of change. By way of illustration, managed retreat may prevent the loss of intertidal and saltmarsh habitats and their associated bird populations. Strengthening of embankments and the creation of storm surge barriers and dams might lead to the reduction of these habitats (Knogge *et al.*, 2004).

The ecological impacts of managed retreat, including increasing development intensity inland, also need to be taken into consideration. Some general principles that can guide decision making in this regard are currently lacking. Stakeholders in salt marshes will be faced with difficult choices including questions as to whether traditional uses should be retained, whether invasive alien species or native species increasing in abundance should be controlled, whether planned retreat is an appropriate response to rising relative sea level or whether measures can be taken to reduce erosion. Decisions will need to take into account social and economic as well as ecological concerns (Adam, 2002). In the Humber Estuary sea-level rise is reducing the standard of protection provided, and increasing erosion. Adaptation initiatives include creation of new inter-tidal habitat, to not only gain more stable and cost-effective defences but also to offset the loss of protected sites, including loss due to coastal squeeze (Winn *et al.*, 2003).

Policies for developments that relate to the coast have to be sensitive to resource use conflicts, resource depletion and to pollution or resource degradation. Absence of an integrated holistic approach to policymaking, and a failure to link the process of policy-making with the substance of policy, results in outcomes that some would consider inferior when viewed within a sustainability framework (Noronha, 2004). Proponents of managed retreat argue that provision of long-term sustainable coastal defences must start with the premise that "coasts need space" and that governments must work to increase public awareness, scientific knowledge, and political will to facilitate such a retreat from the “sacrosanct” existing shoreline (Pethick, 2002). Economic, social, ecological, legal and political lines of thinking have to be combined in order to achieve meaningful policies for the sustainable development of groundwater reserves and for the protection of subsurface ecosystems (Danielopol *et al.*, 2003). Socio-economic and cultural conditions might represent barriers to choosing and implementing the most appropriate adaptation to sea-level rise for Indonesian cities. Socio-economic and cultural conditions might represent barriers to choosing and implementing the most appropriate adaptation to sea-level rise. Many can be resolved by way of local seminars and workshops for relevant stakeholders (Kobayashi, 2004; Tompkins *et al.*, 2005).

6.6.4 Adaptive capacity

Adaptive capacity is the ability of a system to evolve in order to accommodate climate changes or to expand the range of variability with which it can cope (see Chapter 17 for further explanation, including definitions of related terms such as resilience and vulnerability). The adaptive capacity of coastal communities to cope with the effects of severe climate impacts declines if there is a lack of physical, economic and institutional resources employed to reduce climate-related risks and hence the vulnerability of high-risk communities and groups. But even a high adaptive capacity may not translate into effective adaptation as there also needs to be a commitment to sustained action (Luers and Moser, 2006). It has been suggested that the concept of adaptive capacity be adopted as the umbrella concept. It offers great potential in application, especially when attempting to move away from disaster recovery to disaster prevention and preparedness (Klein *et al.*, 2002).

Current pressures are likely to adversely affect the coastal ecosystem's integrity and thereby its ability to cope with additional pressures, including climate change and sea-level rise. This is a particularly significant factor in areas where there is a high level of development, large coastal populations and high levels of interference with coastal systems. Natural coastal habitats, such as dunes and wetlands, have a buffering capacity which helps reduce the adverse impacts of climate change. Equally, improving shoreline management for non-climate change reasons will also have benefits in terms of responding to sea-level rise and climate change (Nicholls and Klein, 2005). In the case of coastal megacities, maintaining and enhancing both resilience and adaptive capacity for weather-related hazards are desirable policy and management goals. The dual approach brings benefits in terms of linking analysis of present and future hazardous conditions. It also enhances the capacity for disaster prevention and preparedness, disaster recovery and for adaptation to climate change (Klein *et al.*, 2002).

6.6.4.1 Constraints and limitations

Yohe and Tol (2002) assessed the potential contributions of various adaptation options to improving systems' coping capacities. They suggest focusing attention directly on the underlying determinants of adaptive capacity. The status of coastal wetlands for contrasting worlds with little and high environmental concern appear to be more significant determinants of change during the 21st century than is sea-level rise. This highlights the importance of the socio-economic conditions as a fundamental control of impacts with and without climate change (Nicholls, 2004). Hazard awareness education and personal hazard experience are significant and important contributors to reducing community vulnerability. But despite such experience and education, a community is still highly likely to suffer unnecessary and avoidable loss associated with the tropical cyclone and storm surge hazards (Anderson-Berry, 2003). These losses will differ across socio-economic groups, as has been highlighted recently by Hurricane Katrina. The constraints and limitations on adaptation by coastal systems, both natural and human, highlight the need for deeper public discourse on adaptation needs, challenges and allocation and use of resources.

6.6.4.2 Capacity strengthening strategies

Policies that enhance social and economic equity, reduce poverty, increase consumption efficiencies, decrease the discharge of wastes, improve environmental management, and increase the quality of life of vulnerable and other marginal coastal groups can collectively advance sustainable development, and hence strengthen adaptive capacity and coping mechanisms. Adopting a static policy approach towards sea-level rise conflicts with sustaining a dynamic coastal system that responds to perturbations via sediment movement and long-term evolution (Crooks, 2004).

Many proposals to strengthen adaptive capacity have been made, including the following: full and open data exchange (Hall, 2002); scenarios as a tool for communities to explore future adaptation policies and practices (Poumadère *et al.*, 2005); public participation, coordination among oceans-related agencies (West, 2003); research on responses of ecological and socio-economic systems (Parson *et al.*, 2003) research on linkages between upstream and downstream process to underpin comprehensive coastal management plans (Contreras-Espinosa and Warner, 2004); enhanced regional cooperation and coordination (Bettencourt *et al.*, 2005); and short-term training for practitioners at all levels of management (Smith, 2002a).

6.6.5 The links between adaptation and mitigation in coastal and low-lying areas

Adaptation (e.g. improved coastal planning and management) and mitigation (reducing greenhouse gas emissions) are responses to climate change, which can be considered together (King, 2004), as elaborated in Chapter. 18. The response of sea-level rise to mitigation of greenhouse gas emissions is slower than for other climate factors (Section 6.3.2), and mitigation alone will not stop growth in potential impacts. However, mitigation reduces the rate of future rise and the ultimate rise, limiting the need for adaptation. Hence, Nicholls and Lowe (2006) argued that adaptation and mitigation need to be considered together when addressing the consequences of climate change for coastal areas. Collectively they can provide a more robust response to human-induced climate change than consideration of each policy alone. Tol (2006) found that the emissions reductions required to stabilise CO_2 concentrations at 550 ppm are substantial. But due to the momentum in sea-level rise, only 10% of the impacts on coastal areas would be avoided, necessitating significant investment in adaptation. Note that delayed needs for adaptation may be a significant benefit of mitigation (Hall *et al.*, 2005).

Adaptation will provide immediate and longer-term reductions in risk in the area that is adapting. On the other hand, mitigation reduces future risks, in the longer term and at the global scale. Identifying the optimal mix is problematic as it requires consensus on many issues, including definitions, indicators and the significance of thresholds. Importantly, mitigation removes resources from adaptation and benefits are not immediate, so investment in adaptation may appear preferable, especially in developing countries (Goklany, 2005). But the limits to adaptation may mean that the costs of climate change are being underestimated (Section 6.6.3), especially in the long-term. These issues imply considering impacts beyond 2100, in order to assess the full implications of different mitigation and adaptation policy mixes (Nicholls *et al.*, 2006a).

6.7 Implications for sustainable development

Coastal ecosystems are dynamic, spatially-constrained, and attractive for development. This leads to increasing multiple stresses, under current conditions (Section 6.2.2), often resulting in significant degradation and losses, especially to economies highly dependent on coastal resources, such as small islands. Trends in human development along coasts amplify their vulnerability, even if climate does not change. For example, in China 100 million people moved from inland to the coast in the last twenty years (Dang, 2003), providing significant benefits to the national economy, but presenting major challenges for coastal management. This qualitative trend is mirrored in most populated coastal areas.

Climate change and sea-level rise increase the challenge of achieving sustainable development in coastal areas, with the most serious impediments in developing countries, in part due to their lower adaptive capacity. Adapting effectively to climate change and sea-level rise will involve substantial investment, with resources diverted from other productive uses. Even with the large investment possible in developed countries, residual risk remains, as shown by Hurricane Katrina in New Orleans (Box 6.3), requiring holisitic responses (Evans *et al.*, 2004b; Jonkman *et al.*, 2005). Long-term sea-level rise projections mean that risks will grow for many generations unless there is a substantial and ongoing investment in adaptation. Hence, for coastal areas the most appropriate response appears to be a combination of adaptation and mitigation (Sections 6.3.2 and 6.6.5).

There will be substantial benefits if plans are developed and implemented in order to address coastal changes due to climate and other factors, such as those processes that also result in relative sea-level rise (Rodolfo and Siringan, 2006). This requires increased effort to move from reactive to more proactive responses in coastal management. Strengthening integrated multidisciplinary and participatory approaches will also help improve the prospects for sustaining coastal resources and communities. There is also much to be learnt from experience and retrospective analyses of coastal disasters (McRobie *et al.*, 2005). Technological developments are likely to assist this process, most especially in softer technologies associated with monitoring (Bradbury *et al.*, 2005), predictive modelling and broad-scale assessment (Burgess *et al.*, 2003; Cowell *et al.*, 2003a; Boruff *et al.*, 2005) and assessment of coastal management actions, both present and past (Klein *et al.*, 2001). Traditional practices can be an important component of the coastal management toolkit.

6.8 Key uncertainties, research gaps and priorities

This assessment shows that the level of knowledge is not consistent with the potential severity of the problem of climate change and coastal zones. While knowledge is not adequate in any aspect, uncertainty increases as we move from the natural sub-system, to the human sub-system, with the largest uncertainties concerning their interaction (see Figure 6.1). An understanding of this interaction is critical to a comprehensive understanding of human vulnerability in coastal and low-lying areas (Section 6.4.3). There also remains a strong focus on sea-level rise, which needs to be broadened to include all the climate drivers in the coastal zone (Table 6.2). Lastly, any response to climate change has to address the other non-climate drivers of coastal change in terms of understanding potential impacts and responses, as they will interact with climate change. As recognised in earlier IPCC assessments, these other drivers general exacerbate the impacts of climate change.

In general terms, the following initiatives would substantially reduce these uncertainties and increase the effectiveness of long-term coastal planning and policy development:

- Establishing better baselines of actual coastal changes and their climate and non-climate drivers, through additional observations and expanded monitoring. This would help to better establish the causal links between climate and coastal change which tend to remain inferred rather than observed (Section 6.2.5).
- Improving predictive capacity for future coastal change due to climate and other drivers, through field observations and experiments and model development. A particular scientific challenge will be understanding thresholds under multiple drivers of change (Sections 6.2.4; 6.4.1).
- Developing a better understanding of the human systems in the coastal zone. At the simplest this could be an inventory of assets at risk, but much more could be done in terms of deepening our understanding of the qualitative trends suggested in Table 6.1 (see also Section 6.4.2).
- Improving impact assessments within an integrated assessment framework that includes natural-human sub-system interactions. This requires a strong inter-disciplinary approach. Priority should be given to the most vulnerable areas, such as coastal cities, populated deltas and small islands (Section 6.4.3).
- Developing methods for identification and prioritisation of coastal adaptation options. The effectiveness and efficiency of adaptation interventions need to be considered, including immediate benefits and the longer term goal of sustainable development (Sections 6.6; 6.7).

These issues need to be explored across the range of spatial scales: from local to global scale assessments, and given the long timescales of sea-level rise, implications beyond the 21st Century should not be ignored. Thus this research agenda needs to be taken forward across a broad range of activity from the needs of coastal management and adaptation to global integrated assessments and the benefits of mitigation. While some existing global research efforts are pushing in the direction that is recommended (e.g., the IGBP/IHDP LOICZ Science Plan Kremer *et al.*, 2004), much more effort is required to achieve these goals, especially those referring to the human, integrated assessment and adaptation goals, and at local to regional scales (Few *et al.*, 2004).

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