IPCC WGII Fourth Assessment Report – Draft for Expert Review

Chapter 6: Coastal Systems and Low-lying Areas

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Executive Summary

1. Sea-level and climate changes influence extreme as well as mean conditions – vulnerability assessments and adaptation responses should take this into account.
2. Coasts are dynamic and as a consequence coastal communities are exposed to significant hazards from present day climate variability and extremes, and other processes, as evidenced by the Indian Ocean tsunami of 26 December 2004.
3. The human use of the coast increased dramatically during the 20th Century and this will continue through the 21st Century – hence, climate and sea-level changes are impacting a rapidly evolving situation – assessment of impacts and adaptation need to address this issue.
4. The coastal zone and low-lying areas experience multiple stresses that compound the adverse consequences and reduce any benefits of global climate change. This also makes it difficult to link coastal changes to sea-level and climate changes and variability observed during the 20th Century.
5. The coastal system may change its behaviour in response to alteration in some boundary condition external to the system or as a result of short-term perturbations, and changes can also be triggered by intrinsic factors responding to thresholds that are internal to the system. The impacts of inter-annual fluctuations such as the North Atlantic Oscillation, El Nino, and Pacific Decadal Oscillation, are more widely appreciated.
6. Significant regional difference in climate change and local variability of the coast, including human development patterns, results in highly localised impacts and adjustments, with significance for adaptation responses.
7. Multiple and concomitant stresses will exacerbate the impacts of sea-level rise and climate change on most natural coastal systems, leading to much larger and generally detrimental changes in the 21st Century than those in the 20th Century.
8. Coastal wetlands appear particularly vulnerable except in those situations where relative elevation can be maintained by sedimentation or other processes. Wetlands may also migrate landward, but this is increasingly precluded by human infrastructure and development (aka “coastal squeeze”).
9. Episodes of coral bleaching are becoming more widespread, frequent and intense and are attributable to near-surface sea temperature exceeding a thermal stress threshold.—these bleaching events will escalate as the world warms.
10. Acidification of the oceans and coastal waters could also have profound adverse effects on coastal ecosystems, including corals.
11. Human vulnerability to sea-level rise and climate change will be strongly influenced by the development pathway – as evidenced by the differences between impacts found using the SRES scenarios.
12. Modelling indicates that sea-level rise will continue for many centuries, irrespective of future emissions, although the magnitude of sea-level rise will be reduced by mitigation. Hence it is unclear what impacts are avoided and what impacts are simply delayed by stabilisation of greenhouse gas concentration in the atmosphere.
13. The consequences of climate change in coastal areas are critical for the water supply and health sectors, but more understanding is required.
14. There is particular concern for the impacts on Asian megadeltas with their large and growing populations, and small islands, particularly low-lying coral atolls .(covered in Chapter 16).
15. Substantial progress has been made in evaluating the economic costs of climate change, not only with respect to sea-level rise, but also with relation to extreme events such as storm surges and strong winds; less progress has been made with respect to non-monetary costs and to social and cultural consequences.

16. Climate-related stresses, notably extreme events, are already imposing substantial costs on coastal systems. These costs will be exacerbated by climate change, most immediately due to extreme events – only in the longer term will costs be dominated by trends such as sea-level rise.
17. The impacts of sea-level and climate changes are overwhelmingly adverse -- few benefits can be identified.
18. Developing countries will bear the brunt of these adverse impacts.
19. It is strongly contested how effectively adaptation can be, e.g., adaptation can greatly reduce the impacts of sea-level and climate changes for human society, but often to the detriment of natural ecosystems.
20. Recent studies suggest that there are limits to adaptation, even in the more developed countries.
21. The influence of development pathway on human vulnerability to sea-level rise and climate change implies that responses could operate in several mutually reinforcing ways – mitigation and climate stabilisation, development pathway and local adaptation: the optimal mix will change with time and is location specific.
22. The nonlinear behaviour of coastal systems, including coastal retreat, add to the uncertainty associated with adaptation.
23. Adaptation must be an ongoing process, if only because global-mean sea-level will continue to rise in the foreseeable future.
24. A more complex picture arising from impact of extreme events and hazards on populated coasts. The increased storm damage is not only from environmental changes but also increased population density, particularly in vulnerable areas, increase in wealth, increase in insurance and a higher propensity to claim, and more complex and vulnerable production and living.
25. There is a fundamental need to integrate and mainstream disaster management and adaptation to climate variability and change into wider coastal management [especially in light of the recent Asian tsunami]

6.1 Scope, summary of TAR conclusions and key issues

This chapter takes 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 since the Third Assessment Report (TAR). The coastal zone contains the dynamic interface between land, sea and atmosphere and is characterised by sharp gradients in environmental factors, abrupt and varying physical and ecological transitions (Levin et al., 2001), and significant and growing human interference (Kremer et al., 2004; Crossland et al., 2005). Hence, it is adjusting over time to a range of drivers, including climate change and sea-level rise.

Here coastal systems are considered in a broad sense, including their interacting natural, ecological and socio-economic components, and external marine and terrestrial influences (Figure 6.1), within the context of coastal management (Kay and Alder, 2005). In the coastal zone, terrestrial ecosystems are influenced by oceanic factors, and *vice versa*. Adjoining coastal lowlands, which have mainly developed through sedimentation during the Holocene (last 10,000 years) are included in the coastal zone. 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. Terrestrial-sourced hazards include river floods and inputs of sediment or pollutants; marine-sourced hazards include storms, surges, tsunamis and algal blooms.

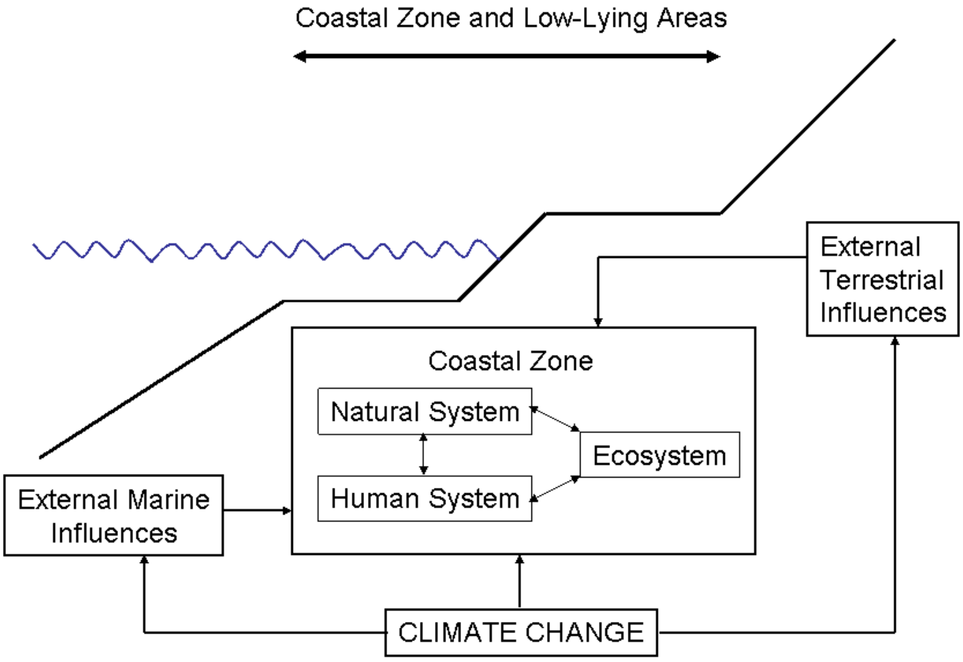


Figure 6.1. *Climate Change and the Coastal System. The overall coastal system comprises a series of interacting sub-systems, which are constrained by external marine and terrestrial influences. All these elements are impacted by climate change, including sea-level rise.*

Coastal areas require separate consideration as they are highly productive, supporting extensive productive agricultural, fisheries and natural ecosystems (Agardy et al., 2005), and concentrate population, settlements and associated infrastructure (Small and Nicholls, 2003), including providing a major attraction for recreation and tourism. Other more generic dimensions of climate change are considered in the relevant chapters, which regional details are considered in the regional chapters. Land-locked and inland seas are not covered, except as analogues.

6.1.1 Review of Third Assessment Report

In addition to sea-level rise, the TAR drew attention to potential importance of the full range of climate change drivers on coastal systems, such as rising seawater temperature. 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. Without adequate adaptive measures, the consequences of such affects would be disastrous for many coastal communities and countries. Especially at risk are the low-lying areas and large delta regions in the low- to mid-latitudes, especially in Asia. In high-latitudes significant climate change impacts on coastal areas were inferred due to a combination of accelerated sea-level rise, a more energetic wave climate resulting from reduced sea-ice cover, and increased temperatures promoting thaw of permafrost and ground ice.

Changes in wave climate and coastal storm patterns with climate change are of particular concern, as over the long-term coastal systems are adjusted in location, plan shape and profile morphology to sediment type and availability, and wave climate, including episodic storm events. Modified coasts with shore protection structures are also threatened as they have generally been designed for present prevailing and extreme wave regimes. Moreover, storm waves and extreme water levels can be expected to reach higher elevations and extend their influence further inland.

Three other themes emerged in the TAR which called for more work:

- the more limited progress in evaluating the potential socio-economic effects of climate change and sea-level rise compared to biophysical impacts, particularly for social or cultural systems;
- impacts on coastal infrastructure, transportation facilities, energy supply systems, coastal resorts, as well as waste facilities, septic tank systems, and water quality and supply, in both the developed and developing world;
- appropriate consideration of non-market goods in coastal and low-lying areas, which appear to have significant economic value based on the goods and services they provide, as well as their natural capital value.

The TAR noted growing interest in adaptation to climate change in coastal areas. While some countries and coastal communities do 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. While techniques for the integration of biophysical and socioeconomic impact assessment and adaptation are developing slowly, human population growth in many coastal regions is increasing socio-economic vulnerability and at the same time 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 as important components of successful adaptation to climate change.

6.1.2 Key Issues

The coast is already extensively populated and subject to a range of pressures as a result of human usage. Climate change poses additional threats to the coastal ecosystems and human use. Higher water temperatures are likely to result in reduced sea-ice cover in high latitudes, and could cause extensive coral bleaching in low latitudes. Global sea-level rise threatens much of the coast, but it is important to recognise that this translates into a wide range of *local* rates of sea-level change due to variable uplift/subsidence at the coast and regional patterns of ocean circulation, ocean warming, atmospheric pressure and surface winds (Gregory *et al*., 2001; Church *et al*., 2004). Increased coastal erosion and more extensive inundation are expected; storm surges may flood greater areas than now, and impacts on primary production, on saline intrusion up estuaries and into groundwater aquifers. These biophysical impacts may cause loss of coastal habitats, property damage, flooding and loss of life, as well as having socio-economic consequences for rural production and urban lifestyles. In many cases the effect of a change in climate is going to exacerbate existing problems. However, there may be opportunities such as increased potential for coastal tourism in some locations (Madisson, 2001).

6.1.3 Structure of chapter

Section 6.2 examines the current sensitivity and vulnerability of the coast, recognising a range of environmental influences on natural coastal systems, the dynamics of these systems in terms of episodic events and other patterns of change, the behaviour of coastal systems and the way that change may be detected or alterations from the trajectory on which the coast has presently embarked. Then a series of future climate and socio-economic scenarios for coastal areas are considered in section 6.3. Section 6.4 considers the key changes that coastal systems may undergo in response to climate and sea level change. Section 6.5 examines the costs and other socio-economic aspects, while Section 6.6 considers adaptation, examining the options, practices, capacities and constraints. Section 6.7 considers the consequences for sustainable development, and Section 6.8 examines a range of issues, including key uncertainties, confidence levels, unknowns, research gaps and priorities.

6.2 Current sensitivity/vulnerability

6.2.1 Natural coastal systems

The coast is extremely dynamic, involving co-adjustment of form and process, termed morphodynamics, at different time and space scales (Cowell *et al.*, 2003a; 2003b). This variability means that coastal communities are already exposed to significant hazards from extreme events, as tragically demonstrated by the Indian Ocean tsunami of 26 December 2004. The nature of the coast varies from place to place in response to boundary conditions (such as geophysical/geological factors, wave conditions and other oceanographic and climatic factors), and human activity, which can dominate all of these natural processes (Woodroffe, 2003). In contrast to palaeoenvironmental reconstructions at millennial scales or process studies on instantaneous (sub-annual) scales, global climate change requires understanding of the processes of change at decadal to century scales (de Groot, 1999; Donnelly *et al.*, 2004). Increasingly models of coastal evolution (physical models such as wave tanks, computer simulations and conceptual models) are being used to understand response to rising sea level or changes in sediment supply after climate change (Rodriguez *et al.*, 2001; Storms *et al.*, 2002).

Coastal system behaviour responds to altered boundary conditions, external to the system, and to short-term perturbations. Changes can also be triggered by internal thresholds that cannot be predicted on the basis of external stimuli. Coastal landforms adopt various ‘states’; some find a simple equilibrium and appear relatively stable, whereas others seek a dynamic equilibrium and undergo continual adjustment (Woodroffe, 2003). Many of the world’s beaches preserve evidence of recent erosion, and sea-level rise is often inferred as an underlying cause of widespread retreat of sandy shorelines (Leatherman, 2001). However, erosion can occur as a result of complex factors, such as altered wind patterns (Pirazzoli *et al*., 2004; Regnauld *et al*., 2004) or bathymetric changes offshore (Cooper and Navas, 2004).

Climate variability is dominated by interannual ocean-atmospheric oscillations, many of which influence coastal dynamics (Viles and Goudie, 2003). One of the most prominent is the El Niño-Southern Oscillation (ENSO) phenomenon, an interaction between pronounced temperature anomalies in the equatorial Pacific and sea-level pressure gradients between the Pacific and northern Australia. A series of physical impacts on coasts across the Pacific have been linked with ENSO variations; for example, the morphology of beach systems in eastern Australia (Short and Trembanis, 2004), accretion and erosion patterns on reef islands in mid-Pacific (Solomon and Forbes, 1999) and rates of cliff retreat on the Pacific coast of the US (Storlazzi and Griggs, 2000). ENSO, with an average periodicity of 2-7 years, also has detectable impacts on coastal ecosystems. For example, reversal of groundwater flow from the mangroves towards freshwater swamps has been observed in Micronesia during ENSO-related drought (Drexler, 2001), as has the spread of less salt-tolerant, invasive species throughout brackish mashes following increased precipitation during El Niño in New England, USA (Minchinton, 2002). Coral reefs can experience mass bleaching, often with mortality of zooxanthellate corals and other species, as a result of anomalous ENSO-related sea surface temperatures (SST), and there is widespread concern that these events are becoming more widespread as a result of global warming (Reaser *et al*., 2000, see below and Box 6.1).

The North Atlantic Oscillation (NAO) exerts a similar influence on northern hemisphere climate variability, exhibiting a 6-10 year periodicity. Positive NAO phases coincide with below-normal pressure in the northern Atlantic, effecting wind and pressure fields that influence temperature and precipitation in the North Atlantic and across Europe (Woolf *et al*., 2002; Wakelin *et al.*, 2003). NAO affects the mass balance of the Greenland ice sheet and the southwards transport of sea-ice (Hilmer and Jung, 2000; Lu and Greatbatch, 2002), as well as influencing sea level and wave heights in the North Atlantic (Hulme *et al*., 2002).

SST anomalies across the equatorial Indian Ocean have recently been related to an Indian Ocean Dipole (IOD); positive IOD events involve relatively cold SST in the eastern Indian Ocean (Saji *et al*., 1999; Webster *et al.*, 1999). One such positive IOD episode in1997-1998 persisted for almost a year and coincided with the 1997-1998 El Niño. However, details of the relationship between ENSO and IOD remain unclear (Ashok *et al*., 2001; Saji and Yamagata, 2003). Other patterns of climate variability have also been recognised, including the Pacific Decadal Oscillation (PDO; a long-lived El Niño-like pattern), the Interdecadal Pacific Oscillation (IPO, a Pacific-wide manifestation of the PDO), and the Arctic Oscillation (AO) and Antarctic Oscillation (AAO) that involve polar and mid-latitudinal atmospheric pressure variations.

A major challenge for coastal scientists is determining whether change in a coastal system has resulted from alteration in external factors, short-term disturbances, or exceeding an internal threshold. Few of the world's coastlines are now beyond the influence of human pressures (Buddimeier et al., 2002), and many are human-dominated (Nordstrom, 2000), and the consequences of these pressures are considered below.

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

Human use of the coast increased dramatically during the 20th century and will continue to increase through the 21st century (see 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 37% of the world's population lives within 100 km, and 49% lives within 200 km, of the coast (Cohen *et al*., 1997); the greatest number of people live at low elevations (Small and Cohen, 1999); and population densities in coastal regions are about three times higher than the global average (Small and Nicholls, 2003).

Natural systems are altered as a result of population growth, and ecological services provided by coastal systems are often disrupted directly or indirectly by human activities. For example, tropical and subtropical mangrove forests provide goods and services because they accumulate and transform nutrients, attenuate waves and storm surge impacts, and their root systems trap and bind sediments (Cahoon and Hensel, 2002; Lin and Dushoff, 2004). They support rich ecological communities of fish and crustaceans, are a source of energy for coastal food chains, and export carbon in the form of plant and animal detritus, stimulating estuarine and nearshore productivity (Jennerjahn and Ittekkot, 2002). But large-scale conversions of coastal mangrove forests to shrimp aquaculture have occurred during the past three decades along the coastlines of Vietnam (Binh *et al*., 1997), Bangladesh and India (Zwieg, 1998), Hong Kong (Tam and Wong, 2002), the

Philippines (Spalding *et al.*, 1997), Mexico (Contreras-Espinosa and Warner, 2004), Thailand (Furakawa and Baba, 2000) and Malaysia (Ong, 2000). The decline or loss of mangroves forests reduces all of these ecosystem services. Similar reductions occur where temperate salt marshes are degraded or converted (Kennish, 2001).

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 conversion of habitat to agricultural, urban, or industrial land use
- 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
- damming, channelisation, and diversion of coastal waterways

Increased human attraction to the coast, and associated development, has resulted in disproportionately rapid expansion of settlements, urban centres, and tourist resorts. Sixty percent of the world's 39 metropolises with a population of over 5 million are located within 100 km of the coast, and 12 of the world's 16 cities with populations greater than 10 million are located on coasts or estuaries. Most of these large cities are in the developing world, but migration of people to coastal regions is common in both developed and developing nations. Population in many large coastal cities has approximately doubled since 1970 (Seoul, Bangkok, Hong Kong, Calcutta, São Paulo). Dhaka, in the Ganges-Brahmaputra megadelta, is the fastest-growing city in the world; its population has increased more than ten-fold since 1970 and is projected to exceed 22 million by 2015. This 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, 2000; 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.

6.2.3. Extra-coastal effects

External terrestrial influences have led to substantial environmental stresses on coastal and nearshore marine habitats (Sahagian, 2000; Saito, 2001; 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). Land-use change and hydrological modifications have had downstream impacts, in addition to localised influences, including human development on the coast. Erosion has increased the sediment load reaching the coast; 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 has greatly reduced the supply of sediments to the coast on other rivers through retention of sediment in dams (Syvistki *et al.*, 2005), and this effect will probably dominant during the 21st Century.

A section of coast may also be affected by external marine influences (Figure 6.1). Erosion on high-energy coasts may result from swell generated on the other side of the ocean. Tsunami are a still more devastating example (Bryant, 2001). Although rare, these events can wreak havoc on coasts, as shown by the devastation on coasts of Thailand, India, Sri Lanka, the Maldives Seychelles and east Africa (in addition to the extensive damage on the immediately adjacent coasts of Sumatra), caused by the tsunami following an earthquake off the coast of Aceh in December 2004.

6.2.4. Nonlinear dynamics and thresholds in the behaviour of coastal systems

Often dynamic coastal systems do not respond in a deterministic way to forcing factors, but show complex non-linear or chaotic behaviour partly dependent on antecedent conditions that may be better simulated by probabilistic models (Lee *et al*., 2001). Non-linearity means that interactions between components of a system are not directly proportional (or linear) but that the rate at which they change may accelerate, often abruptly, as thresholds are crossed. Much of the climate variability described above, such as inter-decadal oscillations, is characterised by nonlinear dynamics (Alley *et al*., 2003). Geomorphological systems react to external factors, but may also be characterised by nonlinear responses to internal thresholds (Viles and Goudie, 2003). Erosion, transport and deposition of unconsolidated sediment often involve time lags (Brunsden, 2001). Nonlinear dynamics also characterise the ecological response of coastal systems to geological and hydrological changes. For example, sea-level rise on the west coast of Florida appears to have resulted in coastal forest loss, and highly nonlinear, abrupt changes of inundation and salinity occur as sea level reaches particular thresholds (Williams *et al*., 1999; Doyle *et al*., 2003).

Better understanding the nonlinear dynamics of coastal systems will enhance the ability of coastal managers and environmental regulatory agencies to plan more effective coastal protection strategies. Intrinsic thresholds to sea-level rise may be estimated for coastal ecosystems if their elevation, geomorphology, slope, shoreline erosion and accretion rates, mean tide range, mean wave-height elevation, antecedent geology, salinity tolerance, and other factors that determine elevation and plant community structure are understood (Burkett *et al*., in press). Knowledge of thresholds in processes that control coastal geomorphology is also important to community planners, transportation agencies, and emergency preparedness officials who make decisions regarding the placement of coastal buildings and infrastructure.

6.2.5 Detecting early effects of climate change on coastal areas

Episodes of recent rapid shoreline change and wetland losses have been reported along the coastal margins of Scotland (Hansom, 2001), Australia (Jackson *et al*., 2002), the United States (Burkett *et al*., in press), and England (Hughes and Paramor, 2004), but there remains debate about the associated rate of relative sea-level rise and to what extent it is a result of global warming. Each of these studies indicate the difficulties involved with attributing proportions of change to either sea-level rise or human activity during the 20th century. However, changes in two contrasting environments, polar coasts and tropical reefs, do appear to be exacerbated by warmer temperatures.

There is evidence for a reduction in thickness of near-coastal ice, more rapid ice movement and retreat of the glacier fronts in Greenland as a result of warmer temperatures (Krabill *et al*., 2004; Rignot *et al*., 2004a). Similar trends have been reported from Antarctica, for example, from the

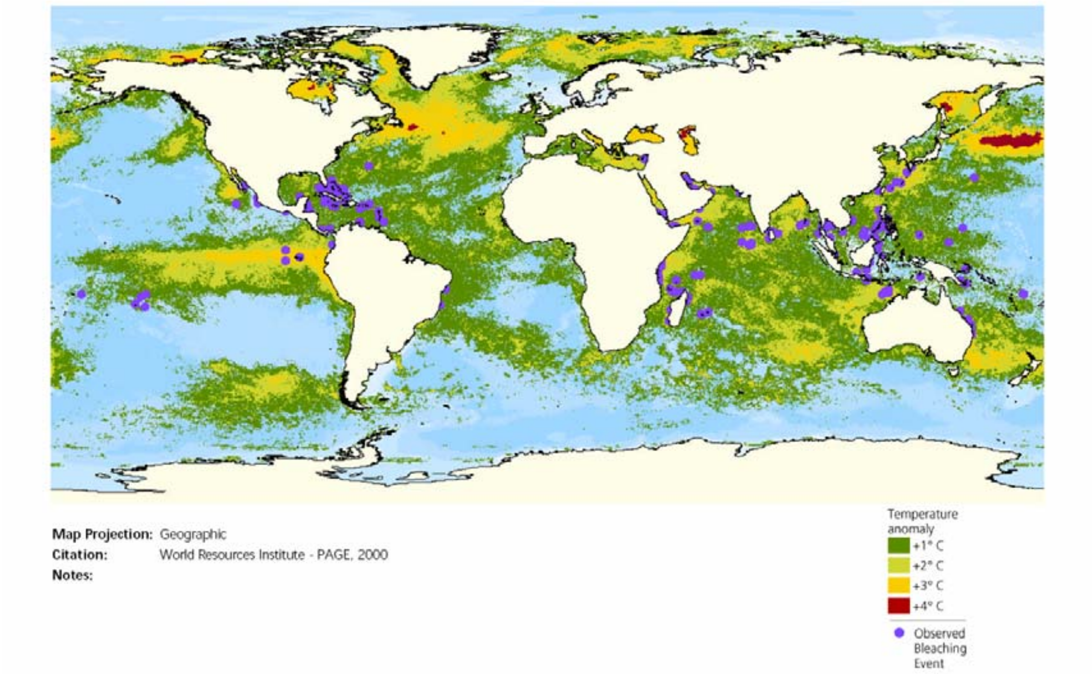
Antarctic Peninsula and Amundsen Sea (Thomas *et al*., 2004; Rignot *et al*., 2004b; Cook *et al*., 2005), although apparently countered by ice thickening in the interior of Antarctica as a result of increased snowfall (Davis *et al*., 2005). The warmer conditions in high latitudes can have positive effects, such as longer tourist seasons, or improved navigability, but there are also more subtle effects on the coast. Rapid shoreline erosion has been occurring on parts of the Arctic coast over recent decades, attributed in part to reduced sea ice cover allowing more wave activity (Johannessen *et al*., 2002).

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 (ACIA, 2004). 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 (Shaw *et al*., 1998; Forbes *et al*., 2004a; Manson *et al*., 2005), northern USA (Smith, 2002; Lestak *et al*., 2004), and northern Russia (Koreysha *et al*., 2002; Nikiforov *et al*., 2003; Ogorodov, 2003). 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; ACIA, 2004). Mid-latitude coasts with seasonal sea ice also show reduced ice cover; ice extent has diminished by 5% in the Bering Sea over the past 30 years (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. Widespread coral bleaching was detected on an unprecedented scale around the globe in response to El Niño-related warming in 1998 (Spencer *et al*., 2000). Bleaching occurs when warmer than usual sea-surface temperatures lead to expulsion of the symbiotic zooxanthellae; the coral surface becomes pale, in many cases leading to mortality (see Box 6.1). The synergistic effects of various others pressures, particularly human impacts such as overfishing, appear to be exacerbating the 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 is considered further below; the impact of multiple stresses is examined in chapter 16, and the example of the 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 world-wide since the early 1980’s (Glynn, 1984). Slight paling occurs naturally in response to seasonal increases in sea temperature and solar radiation but generally this is not evident to the naked eye (Brown et al., 1999). A more marked response occurs, however, when anomalously high sea temperatures (> 1^{o}C) above seasonal maxima combine with high solar radiation. Then, corals bleach white. While 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.



Box 6.1 Figure 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 around the world were noted in 1982-83, 1987-88, 1994-95, and in 1998 (Figure 1) when bleaching was the most extensive on record (Hoegh-Guldberg, 1999). Severe worldwide bleaching generally appears to be associated with El Nino events, though regional effects are also important e.g. the Indian Ocean Dipole driving bleaching in the western Indian Ocean in 1998 (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. For example, while many corals in the western Indian Ocean bleached and subsequently died in 1998, those in the eastern Indian Ocean were minimally affected by the elevated temperatures. Impact and rates of recovery of corals in the central and western Indian Ocean have been similarly patchy with variable recovery in the Seychelles, Maldives , Sri Lanka and Laccadives. Since 1998 there has been extensive bleaching, in 2002 on the Great Barrier Reef (Australia) and in the South East Pacific, and in 2003 in the northern section of the Hawaiian chain and across the Indian Ocean, although the latter event was relatively minor with minimal coral mortality.

Recent research has suggested that corals may be able to adapt to higher temperatures by hosting more temperature-tolerant algae (Rowan, 2004). There are multiple types of symbiotic algae and some corals appear to be flexible in their associations. One type, *Symbiodinium* D, has been shown to be particularly thermo-tolerant in specific physiological responses and is reported now to be more abundant on western Indian Ocean reefs affected by bleaching in 1998 than before that date (Baker et al., 2004). It is possible that this resulted from a change of algal symbiont, thereby improving the corals thermotolerance but the research is in its early stages and requires cautious interpretation. For example, the relative increase in the D type might have been due to mortality of the more heat sensitive C type. Other studies suggest that not all relevant physiological responses of *Symbiodinium* are type specific, and that the animal host also plays an important role in bleaching resistance (Brown et al., 2002; Savage et al., 2002).

The conclusions are that 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 decades.

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

Climate change and sea-level rise is expected through the 21st century and beyond due to human emissions of greenhouse gases. These changes will be superimposed on an evolving coastal system, primarily shaped by human development. Important and relevant changes in the coastal zone that are likely in most plausible futures are a significant increase in population, urban area and economic activity, with these trends being strongest in the developing world. Human changes will have important implications for other coastal parameters such as the status of coastal ecosystems (Figure 6.1). While many studies have focussed overwhelmingly on sea-level rise, to fully understand the potential impacts of climate change on coastal areas, the full range of climate and socio-economic changes need to be considered within an integrated framework.

This section explores the range of possible coastal futures through the 21st century and the resulting scenarios of socioeconomic and climate change (see Chapter 2). While one cannot predict the future by using a set of consistent and plausible scenarios, one can explore sensitivities and implications for a wide range of possible future conditions. A major source of insight are the ‘SRES’ scenarios which comprises four families of socio-economic storylines, and six families of emission scenarios (and hence climate change scenarios) from the late 20th century to 2100 (IPCC, 2000; Chapter 2). This comprises a coherent narrative describing each future world, which is used to develop a consistent set of socioeconomic scenarios, the associated emissions and the resulting climate change. The socio-economic storylines cover a wide range of possible future states, but are not designed to cover the full range of possible future states. While the SRES scenarios have provoked considerable debate, they are useful to explore the broad sensitivity of the coastal system to sea-level rise and climate change (Nicholls, 2004).

Given the long timescales of sea-level rise which means that sea-level rise will continue for many centuries irrespective of future emission scenarios, post-2100 scenarios of sea level are also considered (Nicholls and Lowe, 2004).

6.3.1 Socio-economic scenarios for coastal areas

In the SRES scenarios, the four families of socioeconomic scenarios are termed A1, A2, B1, and B2, and represent different world futures in two distinct dimensions: a focus on economic versus environmental concerns, and global versus regional development patterns (IPCC, 2000; Arnell *et al*., 2004) (Table 6.1). In all four cases, global GDP increases and there is economic convergence, but at differing rates. Global population also increases substantially to 2050 at different rates, but in the A1/B1 futures, the population subsequently declines, while in A2/B2 it continues to grow through the 21st Century. Other superficially similar four-quadrant based socio-economic scenarios have been developed for environmental analysis, but in detail they are distinct (Arnell et al., 2004). Socio-economic scenarios for national policy analysis have also been developed, with quite elaborate coastal descriptions in some cases. Examples are the generic United Kingdom Climate Impacts Programme (2001) socio-economic scenarios for climate impact analysis and the Foresight Flood and Coastal Defence analysis (Evans et al., 2004a; 2004b).

Quantitative global scenarios are available for a few broad regions. To apply in impact analyses, they need to be downscaled to national or smaller scales (Arnell *et al*., 2004; Gaffin et al., 2004; Tol, 2004). This raises questions about the detailed interpretation of the scenarios, beyond what was prescribed in the original SRES report (IPCC, 2000). Hence, the SRES scenarios have been downscaled using a variety of methods, although all these methods have problems (Arnell et al., 2004). Qualitative interpretations of the scenarios are also relevant. For instance, will coastward migration continue, leading to a larger proportion of the global population residing in coastal areas than today? A series of qualitative trends that are relevant to the future of coastal areas and are derived from the SRES narratives and socio-economic scenarios are provided in Table 6.1.

Table 6.1: *Selected Coastal Trends as interpreted for the SRES storylines (adapted from Nicholls, 2004; Hamilton and Tol, 2005). Human-induced subsidence refers to subsidence due to sub-surface water extraction in susceptible coastal lowlands.*

“A1 World” (Globalised world/economic focus) Coastward migration – more likely Human-induced subsidence – more likely Adaptation response – more reactive Hazard management – lower priority Habitat conservation – low priority Tourism growth – highest	“B1 World” (Globalised world/environmental focus) Coastward migration – more likely Human-induced subsidence – less likely Adaptation response – highly proactive Hazard management – higher priority Habitat conservation – high priority Tourism growth – high
“A2 World” (Regionalised world/economic focus) Coastward migration – less likely Human-induced subsidence – more likely Adaptation response – more reactive Hazard management – lower priority Habitat conservation – low priority Tourism growth – high	“B2 World” (Regionalised world/environmental focus) Coastward migration – less likely Human-induced subsidence – less likely Adaptation response – more proactive Hazard management – higher priority Habitat conservation – high priority Tourism growth – lowest

Beyond the SRES scenarios, a wider range of socio-economic scenarios can be considered, at least qualitatively. For instance, scenarios which include greater economic differences than the SRES scenarios, such as Africa not developing through the 21st Century could lead to much more adverse coastal impacts than the scenarios above, even if the magnitude of climate change and sea-level rise is reduced by lower global greenhouse emissions (Nicholls, 2004). Even without sea-level rise, hazards such as tsunamis would adversely affect some coastal regions in coping with climate change.

6.3.2 Climate and sea-level scenarios

Scenarios of terrestrial climate change are well developed on a grid basis and at a variety of scales (global to national and smaller (Chapter 2)). Scenarios of marine climate change are much more poorly developed with a strong emphasis on global-mean sea-level rise. However, as identified in the TAR, there are a range of potential drivers of climate change impacts in coastal areas (Table 6.2), and ideally we require scenarios of all these parameters. For some climate change factors there is at least reasonable certainty about the direction of change, while for others, even the direction of change is uncertain.

Given the certainty about sea-level rise, and the availability of a range of quantitative scenarios, including scenarios linked to the SRES emission scenarios in the TAR, this factor has been widely assessed as a global-mean scenario. The global-mean rise from 1990 to the 2080s 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'). It is well-known that the actual local rise in sea level will depart from this global-mean trend due to both regional variations in oceanic level change, and geological uplift/subsidence. Both these factors remain poorly understood at global scales (e.g., Gregory *et al*., 2001), and hence local scenarios of sea-level rise are not widely available. In the absence of better guidance, Hulme *et al*. (2002) suggested exploring additional scenarios of ±50% the amount of global-mean rise, plus geological change to allow for a sensitivity analysis of these factors. Downscaling tools are also being developed.

Table 6.2. *Climate drivers relevant to coasts and their main physical and ecosystem effects. For drivers with uncertain direction of change, changes are likely to be regionally variable.*

Climate Driver/ Direction of Change	**Physical System and Ecosystem Effects**
Sea temperature: increase with regional variation	Increased coral bleaching; Poleward species migration; Reduced incidence of sea ice at higher latitudes
Run-off: uncertain (consider effect of catchment management)	Changed fluvial sediment supply; Changed flood risk in coastal lowlands;
Wave climate: uncertain	Changed patterns of erosion and accretion;
Storm track, frequency and intensity: uncertain	Changed surges and waves and hence risk of storm damage and flooding (see Box 6.2)
Atmospheric CO_2 concentration: increase	CO_2 fertilisation of coastal ecosystems; decreased $CaCO_3$ saturation impacts on coral reefs and other ecosystems

The main potentially abrupt change for coastal zones is the possible collapse of the West Antarctic Ice Sheet: if the ice shelves of West Antarctica to disintegrate, the ice sheet could be catastrophically released into the ocean by a sliding mechanism (Oppenheimer, 1998). This would raise global-mean sea level by displacement with no requirement for the ice to melt. Vaughan and Spouge (2002) concluded via an expert elucidation process that there is a 5% probability of the WAIS causing a sea-level rise of at least 10 mm/yr (or 1 m/century) within 200 years. In terms of total rise due to the WAIS contribution, they estimated a 5% probability of a rise greater than about 0.5 m by 2100 and about 2.3 m by 2500.

Sea-level rise is relatively unresponsive to mitigation compared to other climate change factors and is almost certain to accelerate significantly during the 21st Century (Meehl et al., 2005). In an unrealistic but instructive scenario, an ongoing increase of about 10 cm/century for many centuries is the best estimate of sea-level rise even if atmospheric composition stays constant with profound implications for low-lying coastal areas (Wigley, 2005). In a climate experiment, reducing emissions enough to achieve a stabilisation of CO_2 concentration at either 550ppm or 750ppm during the 22nd century the rise in global mean sea level may be delayed by up to a few decades during the 21st Century (Mitchell et al., 2000). However, by 2150 (and 2170), the sea-level rise in the 750ppm (and 550ppm) experiment has equalled the 21st century increases projected for the unmitigated case (48-cm rise)and is still rising at a rate reduced compared to the unmitigated case. This slow response is due to the large thermal inertia of the oceans – global warming at the surface takes these timescales to warm the entire ocean volume and this warming produces thermal expansion (Nicholls and Lowe, 2004). In addition, both the Greenland and Antarctica ice sheets could become significant sources of sea-level rise if global warming continues, although the uncertainties are significant, especially for Antarctica (Vaughan and Spouge, 2002). Greenland could start to irreversible melt if global temperature rise exceeds 2^{o}C (Gregory et al., 2004). A recent climate simulation that coupled a model of the Greenland ice sheet to a climate model and assuming atmospheric concentrations of CO_2 are increased at 2% per annum and reach four times pre-industrial levels by year 70, and are then stabilised experiences a global rise in sea level of about 7-m after 1,000 years, including partial deglaciation of Greenland (Lowe et al., 2005). When the possibility of instability of the West Antarctic Ice Shelf is considered, a 10-m rise or more in global sea level over the next millennia is quite plausible for this climate forcing (Nicholls and Lowe, 2004; 2005). Hence, a rise in global-mean sea level is expected long into the future, which has important long-term implications for potential impacts and coastal planning and management (Section 6.6.3). A wider range of scenarios which more fully explore the range of possible sea levels over these longer timescales remain to be developed, but are required to consider their implications for coastal areas, including responses.

In contrast to sea-level rise, scenarios of the other factors in Table 6.2 are not available for each SRES scenario and are much less developed in general, including an understanding of possible abrupt changes or the benefits of stabilisation. As an example of efforts to address this deficiency, Box 6.2 outlines recent progress in developing scenarios of extreme water levels as a result of sea-level rise and storms which are suitable for impact assessment. Further development of marine climate scenarios consistent with terrestrial climate change scenarios remains a high priority.

Box 6.2: Developing Regional to Local Scenarios of Extreme Water Levels for Impact and Adaptation Analysis

While inundation by the relatively slow 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. Previous studies have estimated future increases in extreme water levels by raising present day extreme levels by the same amount as global-mean sea-level rise, which often greatly reduces the return period of extreme events (e.g., Nicholls, 2004). However, when considering regional to local impacts and especially adaptation needs, this is insufficient, and changes in the storm surge component also need to be considered. For a given return period, the present height of extreme sea level is dependent on mean sea level, the tidal regime, the atmospheric storm intensity and movement, and the shelf and coastal geometry. Climate-driven changes in the return period of extreme sea levels will occur due to mean sea-level rise and changes in the track, frequency or intensity of atmospheric storms. Vertical movement of the land must also be considered. Case studies based on stochastic and dynamic modelling methods are illustrated below.

Australian Case Studies

Three case studies have been conducted at sites around Australia, using a combination of stochastic sampling and dynamical modelling was used to investigate the impact of climate change on extreme water levels. Two studies concerned tropical storms and these were assumed to become more intense, following Walsh and Ryan (2000), while the third case study concerned the passage of westerly cold fronts (Box 6.2 Table 1). In all cases, the storm component of extreme water level was positive, with the biggest effect at Cairns. At the other two sites, sea-level rise appears to dominate likely future changes.

Box 6.2 Table 1: *Summary of Australian Extreme Water Level Analyses*

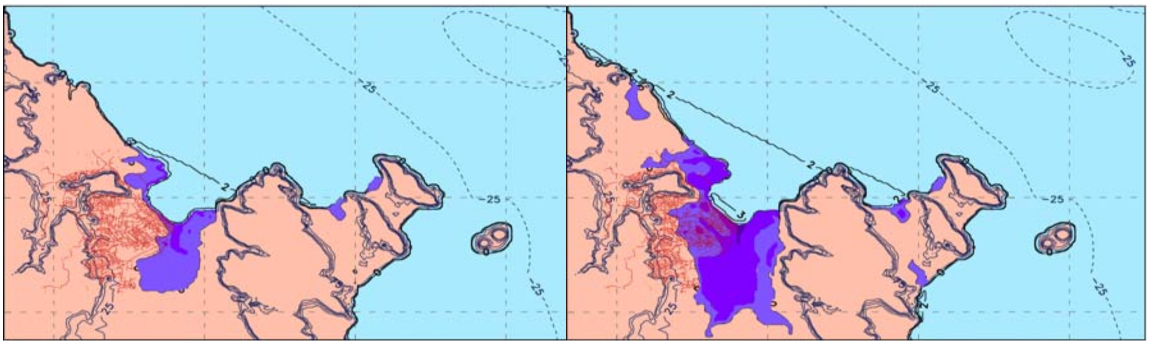
Site	Storm Type	Storm Surge Component (m)	Sea-Level Rise Component (m)	Source
Cairns	Tropical	0.3	0.05 to 0.32	McInnes et al. (2003)
North of Brisbane	Tropical	0.15 to 0.2	0.3	Hardy et al. (2004)
South-East Australia	Westerly cold fronts	0.18	0.07 to 0.49	McInnes et al. (2005); Whetton et al. (2005),

North-West European shelf region

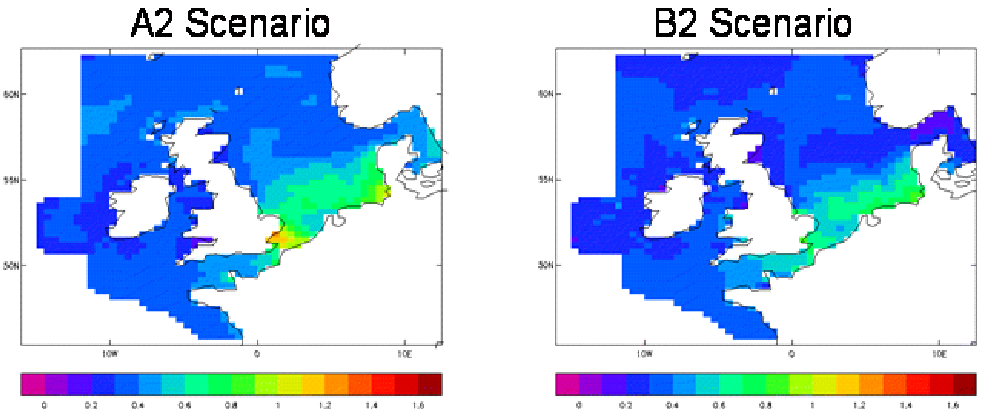
Lowe and Gregory (2005a) used the regional HadRM3 climate model to downscale the HadCM3 global climate simulations for two 30-year time slices: a reference period (1960 to 1990) and a future period (2070 to 2100) in which greenhouse gas and aerosol concentrations were calculated from the IPCC SRES A2 and (lower) B2 emissions scenarios. A 35-km barotropic storm surge model was used to simulate water levels around North-West Europe. Climate change leads to sizeable predicted changes in extreme water levels especially in the southern North Sea, where the largest surges occur. Most regions experiencing a rise in extreme sea levels. When global-mean sea level rise and vertical land movement are included the increases in extreme sea level are positive around the entire UK coastline (Box 6.2 Figure 2), with the largest rise in the Thames Estuary, which has potential implications for flood defence of London (Dawson et al., 2005). Comparison of these results with those from other models, as discussed in Lowe and Gregory (2005a), suggest that the patterns and magnitudes of changes in extreme water levels are uncertain. Quantifying this uncertainty is a research priority.

Bay of Bengal

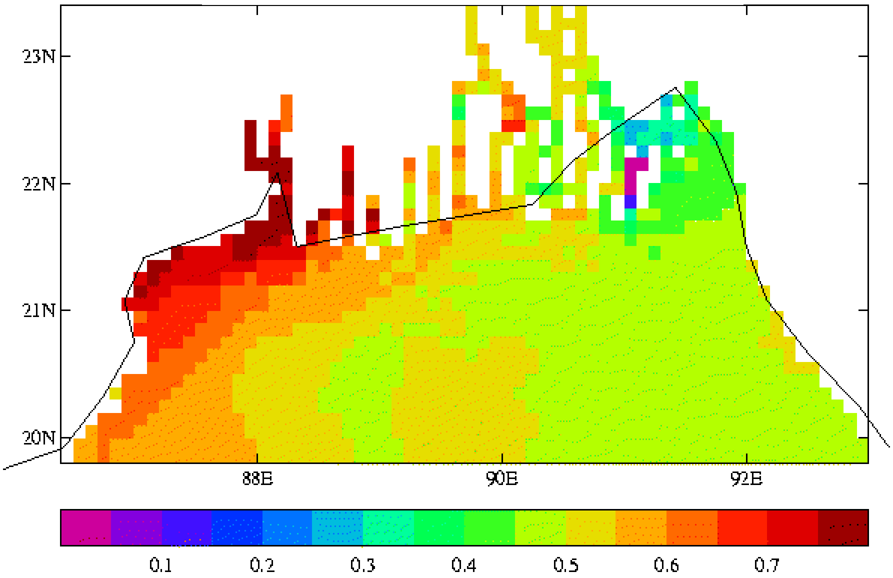
The Bay of Bengal is well-know for devastating coastal flood events, especially Bangladesh. Lowe and Gregory (2005b) used the HadCM2 global climate model, downscaled to 50km using the HadRM2 regional climate model, to drive a 10-km barotropic storm surge model for the Bay of Bengal. Two 20-year time slices were considered: (1) pre-industrial conditions with greenhouse gas concentrations at 1860 values; and (2) 2040 to 2060 period for an IPCC IS92a scenario. The simulated changes in storminess cause changes in extreme water levels, measured relative to pre-industrial conditions, but it is not possible to separate this from natural variability. When global-mean sea level rise and vertical land movement are included, the changes in extreme water level exceed those expected by natural variability alone, with positive increases in extremes across the Bay of Bengal (Box 6.2 Figure 3).



Box 6.2 Figure 1: *Area affected by overland average flooding around Cairns caused by the top 5 % of storm surge events under current climate conditions, and2050 climate conditions assuming only an increase in cyclone intensity and no sea-level rise.*



Box 6.2 Figure 2: *Changes in the height (m) of extreme water levels around the UK (as the change in the height of a 50 year return period flood event, relative to 1960 to 1990). Meteorological driven changes in surges, mean sea-level rise and vertical land movements are included.*



Box 6.2 Figure 3: *Changes in the height (m) of extreme water levels in the Bay of Bengal (as the change in the height of a 50 year return period flood event, relative to pre-industrial conditions).*

Scenario analyses normally stop before 2100 due to the growing uncertainties. For coastal areas it has been argued that this is too short a period of analysis, as sea levels are expected to continue to rise for hundreds if not thousands of years even if greenhouse gas emissions are immediately stabilised (Nicholls and Lowe, 2004).

6.4 Key future impacts and vulnerabilities

6.4.1 Natural system responses to climate change drivers

6.4.1.1 Beaches and cliffed coasts

Most of the world's sandy shorelines retreated during the past century (Bird 1976; NRC 1990), with accretion occurring only where locally abundant sediment is supplied by rivers or where the land surface is elevated by post-glacial rebound or tectonic uplift (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.

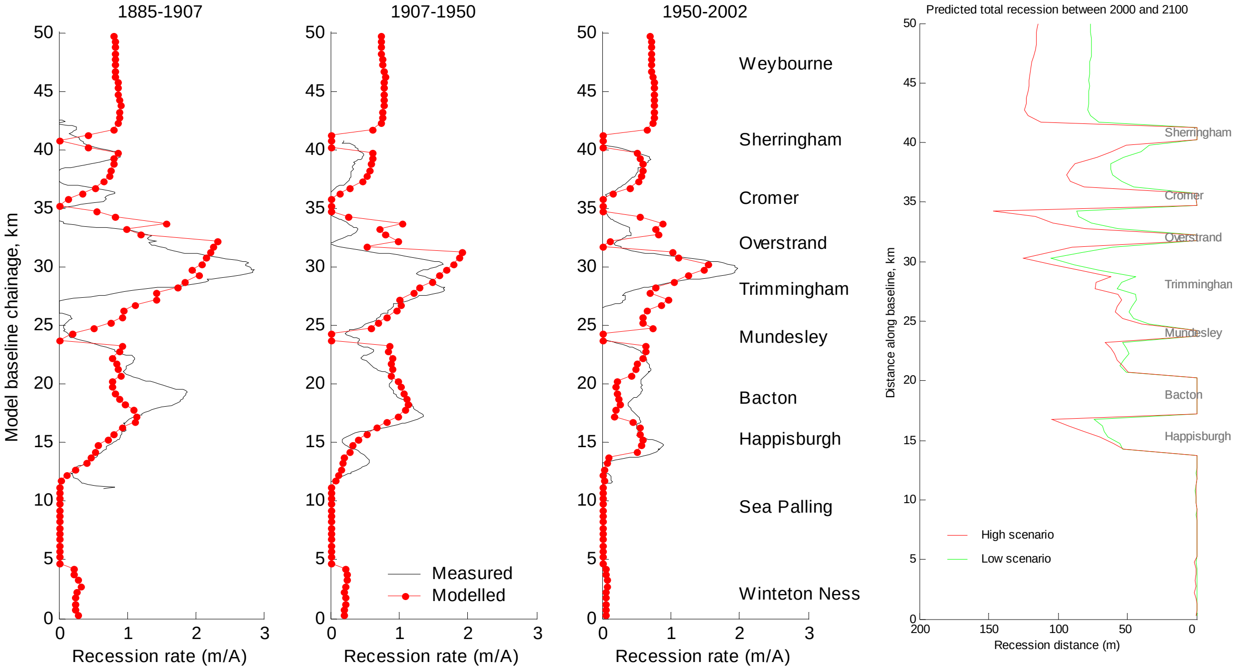
Per Bruun was the first to posit a direct link between sea level rise and beach erosion (Bruun 1962). The widely cited, though controversial (Komar, 1998; Leatherman, 2001; Cooper and Pilkey, 2004), Bruun model suggests that shoreline recession is typically about 100 times the rise in sea level based upon a two-dimensional (onshore-offshore) balancing of sedimentary processes. Since Bruun's early model, advances in modelling coastal retreat have led to the development of indices of vulnerability to sea level rise for the coasts of Argentina (Barros, 1997: Kokot *et al.*, 2004), Canada (Shaw *et al*., 1998), Tasmania (Sharples 2004), and the United States (Gornitz *et al*., 1994, 1997; Thieler and Hammar-Klose, 1999, 2000a, b). Each of these vulnerability assessments are based on an integration of key geomorphological and oceanographic variables that determine shoreline response to sea level change, such as slope, wave height, tidal regime, and sediment characteristics.

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 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 some tidal inlets (e.g., along the North Holland coast due to the sink effect of the Wadden Sea) (Woodworth *et al*., 2004). However, several recent studies indicate that beach protection strategies and changes in the behaviour or frequency of storms are more important than sea level rise in determining future erosion rates in some regions (Ahrendt, 2001; Leont'yev, 2003).

The persistence of gravel and cobble-boulder beaches as sea level rises will be influenced mainly by accretion rates, storms, tectonic events, and other factors that build and reshape coarse clastic shorelines. For example, along the Caleta Valdés coast of Patagonia, a north-south oriented arm of the sea approximately 30 km in length and 3 km wide at its maximum, a gravel spit has been growing rapidly towards the south. From 1971-1987, 1987-1996, and 1996-1999 the rate of growth was 25m, 90m, and 170 m per annum, respectively. An average of 1,400 tons of gravel a day accumulated at the distal end of the spit during the last measurement epoch. The ocean inlet to Caleta Valdés was closed by spit accretion in 2003, creating a marginal lagoon. Erosion of the shoreline, however, is occurring at a rate that will ultimately breach the shoreline of the lagoon despite the high rate of sediment accumulation (Codignotto *et al.*, 2001).

Hard rock cliffs are less prone to erode as sea level rises due to their lithology and material strength (Cooper and Jay, 2002). Conversely, soft rock cliffs, formed in soft bedrock or drift, are likely to retreat more rapidly in the future due to increased toe erosion resulting from sea level rise and may be amplified in many areas by higher ground water levels due to increased precipitation (e.g., Hosking and McInnes, 2002). Soft rock cliffs of the Patagonian coast retreated between 0.45 and 0.50 m year since the early 1950s, and the rate has accelerated during the past decade (Codignotto, 2004).

Considerable progress has been made in the long-term prediction of shore profile and plan-shape evolution of soft rock coastlines by representing all of the relevant physical processes and their interactions in relatively simple terms. This class of models, known as SCAPE (Soft Cliff and Platform Erosion) models (Walkden and Hall, 2005), have been used to assess and predict the effects of sea level rise, wave heights and tidal range on tens of kilometres of beach-cliff systems along the east coast of England (Figure 6.2)(see Box 6.3)



(a) *(b)*

Figure 6.2 *Comparison of measured and modelled recession rates (a) and predicted recession (b) along the English coast. The low scenario in figure on assumes wave energy at historical levels and sea level rise accelerating to 6 mm/annum by 2100. The high scenario has a 10% increase in winter wave energy and sea level rise accelerating to 12 mm/annum by 2100 (Dickson et al., 2005).*

Box 6.3: Broad-Scale Integrated Assessment of the Effects of Climate Change

Understanding the full implications of climate change on coastal areas requires integrated assessment of complete physiographic units (e.g., large lengths of interacting coastline (often termed sub-cells), entire estuaries, small islands) over many decades (Stive, 2004). An example is the recent assessment of climate change implications for sub-cell 3b in north-east Norfolk, UK. This 50-km coast comprises a mixture of soft cliffs and beaches adjoining low-lying coastal lowlands prone to flooding. The study considered possible changes in coastal drivers such as sea level rise, wave height and direction (Kuang and Stansby, 2004), morphological change analysis (Dickson et al., 2005), and its human implications in terms of erosion and flood risk (Koukoulas et al., 2005; Hall et al., 2005).

The analysis was based around an analysis of the shore profile and plan-shape evolution using the SCAPE (Soft Cliff And Platform Erosion) model (Walkden and Hall, 2005a, 2005b, Dickson *et al.*, 2005). SCAPE includes the physical processes of shore erosion and their interactions, represented in relatively simple terms. The shore profile that emerges represents a dynamic equilibrium, which is a function of the incident wave heights, tidal range, rate of sea-level rise, resistance of the coastal material and availability of beach sediments. Seawalls and revetments have been constructed widely in the study area during the 20th Century to delay erosion. They can be simulated by stopping erosion on the upper shore profile, whilst the lower part of the profile continues to erode. If the seawall collapses or is removed, the simulated profile rebounds rapidly to its equilibrium form, causing a significant short-term acceleration in erosion rate, which agrees qualitatively with observations. Validation against historical (1885 to 2002) cliff-toe recession for 50 km of predominantly soft-cliffed coast between Weybourne and Winterton Ness, northeast Norfolk, show good agreement.

42 scenarios combining sea-level rise, changes in wave climate, and different coastal management options have been explored (Dickson et al., 2005; Koukoulas et al., 2005). This included links between erosion risk on the cliffed coast and flood risk on the neighbouring low-lying coast (Hall et al., 2005). Figure 6.3.1 shows the coastal evolution under different climate change scenarios given a natural coast with no engineering control. While changes are greater with a larger rate of sea-level rise, the response is not a simple uniform retreat, and parts of the coast accrete more with the higher sea-level rise. If the effect of existing cliff defences are considered, the response becomes more complex, and the beaches at Happisburgh and further south may erode, significantly raising the flood risk under higher sea-level rise scenarios. Hence, the analysis shows an important trade-off between erosion and flood defence which coastal managers will address as they consider how to respond to climate change.

6.4.1.2 Deltas, estuaries, lagoons

Sea level rise, fluvial sediment delivery, and hydrodynamic-oceanographic changes are critical factors in the morphological evolution of deltas and coastal embayments. Human development patterns play an important role in the differential vulnerability of these dynamic systems to the effects of climate 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). Model simulations suggest another 1329 km^2 of coastal land will be inundated by the 2050 due to regional and local processes. If accelerated global sea level rise were added to the mix of human factors that affect sedimentary processes and plant communities in this region, the projected rate of coastal wetland loss would be higher (Barras *et al*., 2003).

Deltas have long been recognised as highly sensitive to sea-level rise (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 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 greatly increased the potential for inundation of their most populated cities (e.g., New Orleans, Bangkok, and Shanghai). Most of the land area of Bangladesh consists of the deltaic plains of the Ganges, Brahmaputra, and Meghna rivers. Accelerated eustatic sea-level rise 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 trends in monsoon rains (Singh, 2001), compaction of deltaic sediments, and human activity that has converted natural coastal defences (mangroves) to aquaculture.

While present rates of sea-level rise are contributing to the gradual destruction of many of t world's deltas, most of the recent losses of deltaic wetlands are attributed to human development. An analysis of satellite images of fourteen of the world's major deltas (Danub Ganges-Brahmaputra, Indus, Mahanadi, Mangoky, McKenzie, Mississippi, Niger, Nile, Sha el Arab, Volga, Huanghe, Yukon, and Zambezi) indicated that a total of 15,845 sq km of deltaic wetlands have been irreversibly lost during the past fourteen years and the average r of loss is 95 sq km/yr (Coleman *et al*,. 200_). The total conversion to open water was 5,104 km^2. All deltas analyzed showed land loss, but at varying rates, and human development activities accounted for more than half of the losses. In Asia, where human activities have l to increased sediment loads of major rivers in the past, the construction of upstream dams a other water abstraction is now seriously depleting the supply of sediments to deltas with increased coastal erosion a widespread consequence (Box 6.4).

The probable migration of estuarine shorelines has been summarised by Pethick (2001), wh adopted a dynamic approach based on the Bruun principle to indicate rollover. Erosion of t Blackwater estuary in southern England, for example, will result in seaward retreat and mo of sand banks inland. A sea-level rise of 6mm appears likely to result in 10m of retreat of th Blackwater estuary and only 8m of retreat for the Humber estuary in view of its steeper gra The Humber estuary will also likely experience a deepening of the main channel, changes i regime and larger waves that will promote further edge erosion (Winn *et al*., 2003).

There is a great deal of variation in accretion rates among the types of coastal systems described in this chapter, and even among the same shoreline type at different locations. The Holocene record of massive, episodic estuary infilling in Bohai Bay, China (the westernmost of the three bays of the Bohai Sea) reveals coupled layers of buried oyster reefs and overlying mud layers averaging over 10 m in depth. The stratigraphic sequence, with such a binary structure, implies alternating relatively stable or tranquil stages, during which the reefs were built up, and the relatively dynamic and active stages during which reef material was reworked and overlying muddy layers occurred (Wang 1994; Fan and Wang, 2005), but the importance, if any, of sea level fluctuation in these depositional cycles is not clear. Sediment supply is the dominant factor controlling progradation of the Huanghe Delta in the northern Gulf of Bohia, while Volga River delta progradation and retreat in the Caspian Sea is mainly controlled by sea level fluctuations (Li *et al.*, 2004).

Sea-level rise will generally lead to higher coastal water levels and increasing marine influence in estuarine systems. Increasing the salinity of estuaries will tend to shift existing coastal plant and animal communities further 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. 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, and possibly to a lesser extent from temperature changes, sea-level rise, and CO_2 enrichment (Scavia *et al*., 2002).

Freshwater inflows into estuaries, which are strongly influenced by precipitation patterns over coastal watersheds, determine 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, whereas decreased freshwater inflows will increase estuarine water residence time and decrease stratification (Moore *et al*., 1997). The effects of altered residence times can have significant effects on phytoplankton populations, which have the potential to double up to twice per day. Consequently, estuaries with water residence times less than a day, phytoplankton are generally flushed from the system as fast as they can grow, reducing the estuary's susceptibility to eutrophication and harmful algal blooms (Scavia *et al*., 2002).

Freshwater inflows deliver reactive carbon and nutrients to estuaries. Modeling results by Andersson and Mackenzie (2004) suggest that coastal ocean waters were likely a net global source of CO_2 to the atmosphere during most of the past 300 years because of the organic matter brought in by rivers and calcification. Their observations and model results indicate that present estuaries are likely a net source of CO_2 to the atmosphere whereas more distal areas of the coastal zone, i.e. the shelves, are net sinks. Another impact they suspect of increasing the uptake of CO_2 by estuaries is the lowering of the pH of the water because of the well documented reaction: $CO_2 + H_20 + CO_3^{2-} = 2HCO_{3-}$ (Andersson *et al*., 2003). This reaction also leads to a lowering of the carbonate saturation state of the water because of the titration of the carbonate ion (CO_3^{2-}) by the invading CO_2. Mackenzie *et al.* (2001) have shown using IPCC emission scenarios that the saturation state of both the global ocean and coastal waters will decrease significantly through this century. The lowering of the saturation state 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 metastable carbonate minerals in sediments and in some cases the water column (Andersson *et al*., 2003).

Sea-level rise is likely to accelerate shoreline erosion around coastal lagoons. In the Gippsland Lakes in southeastern Australia, revegetation is being planned to counter salt water intrusion, partly through a permanent opening of the lakes entrance (Pittock, 2003). In other sheltered lagoon areas an increase in the area of wetlands may follow, and algal blooms may be more frequent if temperatures rise. An effect of rising sea level in some hypersaline lagoonal systems, such as the Laguna Madre of Mexico and the United States, 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).

6.4.1.3 Coastal vegetated wetlands and seagrasses

Coastal vegetated wetlands are sensitive to climate change and long-term sea level change as their location is intimately linked to sea level. It is estimated encroaching seas will inundate 21% of the coastal wetlands of the U.S. mid-Atlantic coastal region by the end of this century (Najjar *et al.*, 2000). By 2080s, given about 40-cm of sea-level rise, 5% to 18% of the world's coastal wetlands might be lost, with up to 38% lost given a high (75-cm) rise scenario (Nicholls and Lowe, 2004). Under unmitigated emissions losses continue to increase into the 22nd Century, possibly reaching as much as 42% losses by the 2140s. Mitigation scenarios reduce the amount and more importantly the rate of sea-level rise (Section 6.3.2). Stabilisation scenarios which reduce greenhouse gas concentrations to 750 and 550 ppm CO_2 by the 22nd Century lead to much smaller maximum coastal wetland losses of 32% and 30% by the 2080s, and 36% and 30% by the 2140s. Moreover, as the rate of sea-level rise stops increasing, so wetland losses slow and depending on their response might even cease during the mid 22nd Century. Moreover, coastal protection works in low-lying areas will give rise to "coastal squeeze" and exacerbate the losses of coastal forests, marshes, and submerged aquatic vegetation, thereby limiting their potential for landward displacement.

Mangrove forests dominate intertidal subtropical and tropical coastlines between 25° N and 25° S latitude, and salt marshes dominate the mid- to upper intertidal areas of more temperate coastlines (Kennish, 1986). The response of mangrove shorelines to climate change has not received the detailed research and modelling that has been directed towards the salt marsh coasts of North America (Reed, 2002; Rybczyk and Cahoon, 2002; Morris *et al*., 2002) and northwestern Europe (Allen, 2000; 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 clastic 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 (Jennerjahn and Ittekkot, 2002; Middleton and McKee, 2003), and collapse of peat can occur rapidly in the absence of new root growth, as observed in the aftermath of Hurricane Mitch (Cahoon *et al.*, 2003). Spatial variability in sedimentation rates within mangroves is not as well documented as for salt marshes globally, but studies of accretion rates in Micronesian mangroves indicated sedimentation at up to 11mm/yr amongst prop roots (Krauss *et al*., 2003).

A landward migration of mangroves into adjacent freshwater 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. Similarly, mangroves have extended landward into salt marsh over the past five decades throughout southeastern Australia. In this region, however, sea-level change has been minor and direct human disturbances and, possibly, increases in rainfall are implicated (Saintilan and Williams, 1999). Rapid expansion of tidal creeks has been observed in northern Australia (Finlayson and Eliot, 2001; Hughes, 2003). Sea-level rise has been associated with the decline of coastal baldcypress (*Taxodium distichum*) forests in Louisiana (Melillo *et al*., 2000) and die off of cabbage palm (*Sabal palmetto*) forests in coastal Florida (Williams *et al*. 1999).

Salt marshes (halophytic grasses, sedges, rushes and succulents) are common features of 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 coast of North and Central America, the Caribbean, the Mediterranean, the Baltic and most small island regions (Nicholls *et al*., 1999; Nicholls, 2004).

However, evidence from southeast England, and elsewhere (Cahoon *et al.*1999; 2000; Hughes, 2004), indicates that 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 *et al.* (2004) found that saltmarshes of mesotidal and high tide range estuaries (e.g., Tagus Estuary, Portugal) are susceptible to sea level rise only in a worse case scenario. Similarly, Morris *et al*. (2002) reported that wetlands with high sediment loading 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 deposits 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).

By altering the hydrology of wetlands, climate change will have significant consequences on CO_2 and CH_4 exchange between wetlands and atmosphere (Juutinen *et al*., 2003). Choi *et al.*, (2001) suggest that coastal wetlands could become a more significant sink for atmospheric CO_2 as they expand landwards due to sea level rise. Salt marshes and mangroves release negligible amounts of GHG and store more carbon per unit area than other peatlands (Chmura *et al*., 2003), so their fate has relevance to both mitigation and adaptation planning.

Seagrasses cover about 0.1 - 0.2% of the global ocean (Duarte, 2002); about 60 species of seagrasses are known worldwide. Like other coastal habitats, human impacts on seagrasses have caused extensive declines in their productivity and extent. Present losses are expected to accelerate, particularly in Southeast Asia and the Caribbean, if human development continues to expand in the coastal zone grows and 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 μν irradiance as well as human impacts alter seagrass distribution, productivity and community composition (Short and Neckles, 1999). During the El Nino event of 1997-1998, in San Diego Bay, USA, the *Ruppia maritima* (widgeongrass) increased in abundance and replaced the dominant species *Zostera marina* (eelgrass) due to changes in environmental conditions induced by a warming of 1.5 - 2.5°C in the bay (Johnson *et al*., 2003). Seagrasses are particularly sensitive to changes in light, which attenuates exponentially with water depth. Sea level rise will alter the location of maximum depth limit of plant growth, directly affecting seagrass distribution (Short and Neckles, 1999).

The anticipated overall increase in dissolved inorganic carbon (DIC) in seawater is roughly 1:10 relative to the increase in global atmospheric CO_2 (Goudriaan, 1993). Increases in the amount of dissolved CO_2 and, in 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 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.

6.4.1.4 Coral reefs and atoll island systems

It is widely recognised that coral reefs are degraded and under stress on many coastlines, and that there has been decline of reef-building corals. Historical data indicate that reef condition has deteriorated over recent centuries and overfishing has been implicated as a major cause (Pandolfi *et al.*, 2003). The reduction of coral cover during recent decades has been increasingly documented; coral mortality on Caribbean reefs is related to recent disease outbreaks, variations in herbivory and hurricanes, whereas Pacific reefs have been particularly impacted by episodes of coral bleaching caused by thermal stress during recent ENSO events (Hughes *et al.*, 2003). Mass coral bleaching events are correlated with sea-surface temperature rises of short duration above summer maxima (Douglas, 2003; Lesser, 2004). The largest recorded bleaching event occurred in 1998 (Lough, 2000; see Box 6.1). There is limited ecological and genetic evidence for adaptation of corals to warmer conditions (Coles and Brown, 2003; Little *et al*., 2004; Obura, 2005), and an urgent need for focused management to improve the ecological resilience of coral reefs (Hoegh-Guldberg, 2004).

Coral reefs appear to have deteriorated as a result of a combination of anthropogenic impacts (particularly overfishing and pollution from adjacent land-masses) together with an increased frequency of bleaching associated with climate change (see Box 6.1). The relative significance of these stresses is still a subject of debate and is likely to vary from site to site. There is some evidence that global warming may result in extension of coral range; for example, poleward extension of branching *Acropora* to Fort Lauderdale in Florida (Precht and Aronson, 2004), despite an almost Caribbean-wide trend for reef deterioration (Gardner *et al*., 2003). However, the ability of reefs to absorb impacts due to climate change, and to recover, depends upon the extent to which they are already degraded and their resilience undermined, and the timing between events (Sheppard, 2003). Remote sensing offers potential for widescale monitoring, both of bleaching and reef recovery, although its effectiveness depends on spatial and spectral resolution, water depth, the variability of substrate and coral cover and the severity of the bleaching event (Mumby *et al*., 2004; Yamano and Tamura, 2004).

Sea level rise appears unlikely to threaten reefs in the immediate term (Kennedy and Woodroffe, 2002). 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, decreased calcification rates may lessen coral ability to keep up with rapid sea-level rise because increasing atmospheric carbon dioxide concentrations and altered aragonite saturation state will reduce calcification rates of corals (LeClerq *et al*., 2002; Guinotte *et al*., 2003). Modelling implies that disintegration of degraded reefs after bleaching may result in increased wave energy across a reef flat and shoreline erosion (Sheppard *et al*., 2005).

Many reefs occur in areas that are impacted by tropical storms, and storms generate coarse material that is ripped from the reef front and reef flat and added to the reef top. Tropical storms do not appear to have increased in occurrence (Raghavan and Rajesh, 2003), but it is possible that they will intensify, and occur over a greater area. Resulting impacts include greater storm surge heights as a result of both higher sea level and greater storm intensity (McInnes *et al*., 2003; Walsh *et al*., 2004; Box 6.2). Intensification of tropical cyclones, as predicted particularly for extra-tropical areas by Geng and Sugi (2003) may have effects on reefs towards their southern latitudinal limit (Lim and Simmonds, 2002).

The fate of the small reef islands on the rim of atolls has raised especial concern. Modelling assuming that the volume of sediment is conserved, using a modified shoreline translation model, predicts ocean shore erosion and sediment redeposition further lagoonward (Kench and Cowell, 2001; Cowell and Kench, 2001). However, islands appear to have formed as a result of deposition of sediment over the late Holocene (Woodroffe and Morrison, 2001), and it has been suggested that onset of island deposition on many Pacific atoll rims was triggered by a slight fall of sea level (Dickinson, 2004). However, the response of these islands to sea-level rise remains uncertain. Within storm-prone areas, individual cyclones play a significant role in supplying new sediment to the islands, although they may have devastating consequences for the inhabitants of the islands. It will be important to identify critical thresholds of change beyond which atoll social and ecological systems, such as those in the Maldives, Kiribati and Tuvalu, may collapse because there are limited data, little local expertise to assess the dangers and a low level of economic activity to cover the costs of adaptation (Barnett and Adger, 2003).

6.4.2 Consequences for human society

Climate change affects human settlements in coastal areas in two main ways: (1) sea-level rise leads to the loss of coastal freshwater resources and usable land, infrastructural damage, population displacement, etc; (2) increased temperature and rainfall impacts human health, recreation and tourism. A qualitative overview of climate change impacts on the socio-economic sectors of the coastal zone also shows the single most important impact in each sector (Table 6.3). The impacts vary across sectors and can be positive and negative within each sector, although for direct impacts, negative impacts appear to dominate.

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

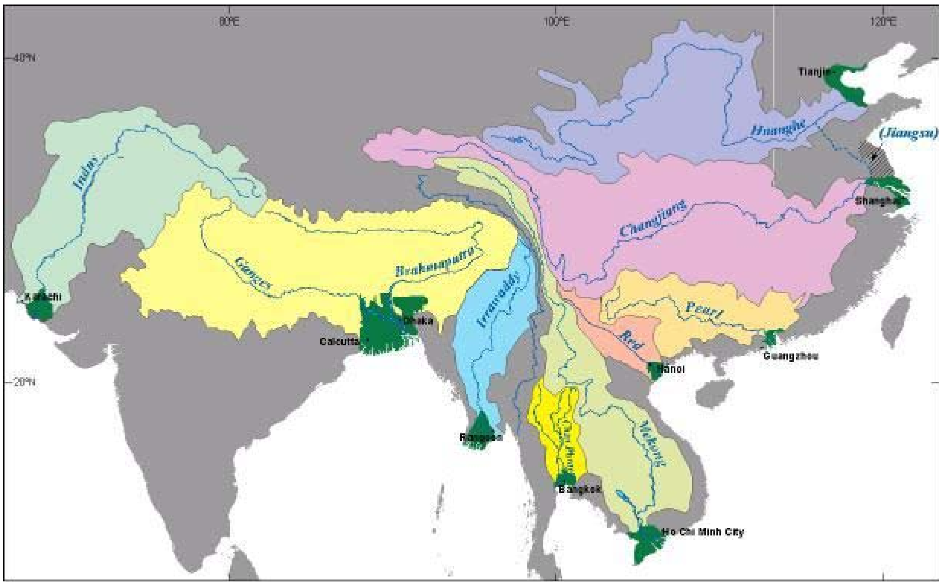
Sector	Temperature change	Extreme events	Flooding	Rising water table	Erosion	Salt water intrusion	Biological effects
Water resources	X	X	X	XX		XX	X
Agriculture and forestry		X	X	X		X	
Fisheries and aquaculture	X	X	X		X	X	XX
Human health	XX	X	X	X			X
Recreation and tourism	X	X	X		XX		X
Human settlements and infrastructure		XX	XX	X	X		

Adapted from Klein and Nicholls, 1999; C-CIARN, 2001.
XX = single most important impact in sector

A global pattern of highly vulnerable coastal areas has emerged (Figure 6.3). Societal vulnerability is regionally specific in terms of socio-economic conditions as well as physical drivers. For example, extensive low-lying coastal areas, such as Estonia, and oceanic islands are strongly affected by a rising sea level whereas the coral reef systems and the polar region are particularly affected by temperature increase. Large populated deltas appear especially sensitive and potentially vulnerable to a range of changes, making them highly vulnerable to sea-level rise and climate change (Box 6.4). Coasts, which are already exposed to cyclones and tsunamis, are further exacerbated by climate change. African coasts with their relatively low economic development have a high vulnerability with economic risks representing a high percentage of the GDP (Niang-Diop *et al.*, 2004; see Chapter 9). More developed countries, such as Japan, can reduce their vulnerability by adaptation, which can be costly.

Box 6.4 Megadeltas: Hotspots for Vulnerability [Cross-Chapter Case Study]

Deltas are recognised as highly vulnerable landforms given sea-level rise, climate change and other human-induced changes. There are a number of large populated deltas around the world such as the Mississippi, Nile and Parana, with a concentration of seven major deltas around the uplifting Himalayan-Tibetan massif (Box 6.4 Figure 1). These have extensive, productive and heavily populated deltaic plains which are fed by runoff, snowmelt and sediments and are influenced seasonally by monsoonal rainfall (Woodroffe et al., 2005). In addition to intensive agriculture, aquaculture and silviculture, most also contain rapidly growing populations (Table 1) and all are associated with at least one actual or emerging megacity (population ≥8 million people).



Box 6.4 Figure 1: *The Asian megdeltas (Taken from Woodroffe et al., in review)*

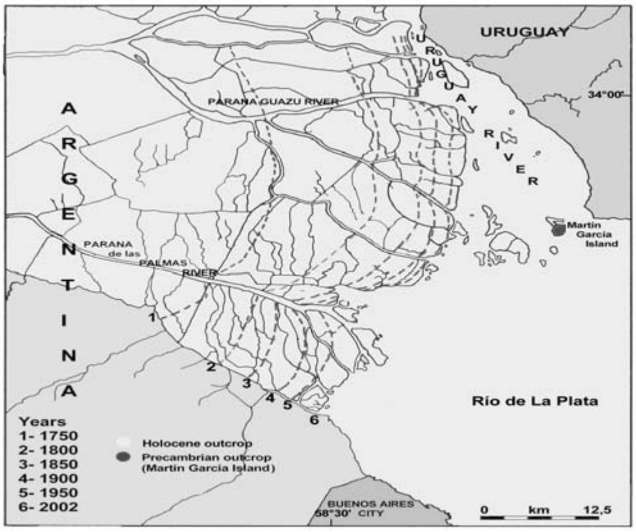
Box 6.4 Table 1: *Asian Megadelta Characteristics (from Woodroffe et al., in review)*

Megadelta	Area (km^2)	Population (2000) (millions)	Population Density (2000) (/km^2)	Projected Population (2015) (millions)	Increase 2000 to 2015 (%)
Indus	19800	3.1	154	4.4	45
Ganges-Brahmaputra	115600	129.9	1124	166.2	28
Irrawaddy	31500	10.6	336	12.2	15
Chao Phraya	11600	11.5	990	16.5	44
Mekong	37900	15.8	416	19.0	21
Song Hong (Red)	9900	13.3	1343	16.1	21
Pearl	5900	9.8	1669	27.2	176
Changjiang	15600	25.9	1663	33.1	28
Huanghe	25100	14.1	560	16.6	18
[Jiangsu]	30300	19.9	658	15.0	-25
TOTAL	303200	253.9	-	326.3	-

These extensive low-lying delta plains have developed as a result of substantial sediment input (ranging up to a billion tonnes a year in the case of the Ganges-Brahmaputra rivers) into shallow seas over 6000 years of relative sea-level stability.

Deltas are shaped by river, wave and tide processes. River-dominated systems receiving fluvial sediment input show prominent levees, and channels that meander or avulse, leaving abandoned channels on the plains. Wave domination is 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 the 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 wave or tide processes. This has lead to a diverse set of deltaic plain forms, and this will lead to different responses to climate change.

Delta plains are affected by changes in land use. Drainage and irrigation works impact the movement of water, and have more subtle effects on sediment and sediment geochemistry. A widespread problem is the acidification of potential acid sulphate soils with oxidation of pyrite. More recently the detection of high arsenic levels, especially in the plains of the Ganges-Brahmaputra, imply that altered land use may mobilise arsenite. In the case of the Huanghe, human influence has over-ridden the natural pattern of avulsion of channels. Natural levees are frequently built up as a component of flood control, decreasing the frequency with which they are overtopped but increasing the magnitude of flooding when overtopping does occur. Such activities have ramifications for the supply of sediment and nutrients to these plains. Still larger impacts are felt where rivers are dammed and sediment supply downriver is decreased. The Indus is now extensively dammed and sediment supply to the coast has been reduced to unprecedented low levels. The Changjiang is being affected by the Three Gorges Dam, and downstream impacts in terms of sediment partitioning are inevitable. Through the 21st Century, all populated major deltas are likely to be similarly affected, making them more sensitive to sea-level rise and other climate change.



Despite the fact that deltas represent some of the largest sedimentary deposits in the world, the shorelines of many of the world's deltas are undergoing erosion and wetland loss (Coleman et al., 200_). Land formation in the Parana delta, Argentina since 1750 each 50 years was 230, 148, 118 and 96 km^2 consecutively (Codignotto 2004) (Figure [Box] 6.4.2). Hence, accretion of the delta front is declining, and there has been localised erosion (Dragani and Romero 2004), even though river flow did not decrease during this period.

It is important to recognise that erosion is a part of the natural dynamics of some sections of the delta, in which sediment supply has decreased as a result of distributary switching, becoming progressively accentuated as the delta has built seaward during the late Holocene. This is exacerbated where subsidence or compaction exceeds the rate of supply of new sediment, or when it is accentuated by human dewatering through groundwater extraction. However, much more extensive erosion can be attributed to human impact as a result of the construction of dams. Wise sustainable management of these systems requires more attention to sediment pathways and consideration of the relationship between elevation of the plains surface and river flood and storm surge levels. The consequences of not considering sediment fractionation have become clear on the Nile and Mississippi systems. Hence, delta response to climate change will be strongly interact with these other ongoing changes.

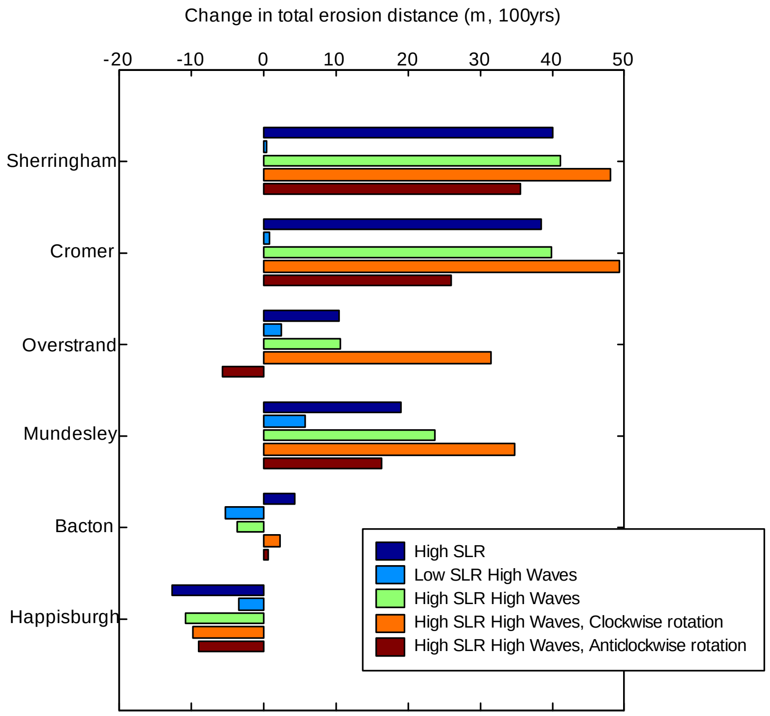


Figure 6.3.1: *Erosion on the cliffed coast of sub-cell 3b over 100 years under varied climate change scenarios and assuming no engineering control. Sherringham is in the north and Happisburgh is in the south-east. Negative values imply accretion. Low SLR 0.2 m/century. High SLR 1.2 m/century. High Waves 10% increase in winter wave heights. Clockwise and anticlockwise rotation refers to a 10^o change in orientation.*

Not enough is known about global sectors which are important, e.g. tourism and recreation, although a literature is emerging (Section 6.5.3), and our understanding of impacts on the developing countries are rather limited. Certain sensitive socio-economic sectors are worthy for investigation, notably water resources and human health, as a small magnitude of climate change can adversely affect large numbers of population.

Certain difficulties exist in the assessment of the consequences of climate change at the coasts. Changes in sea-level rise at the regional and local levels differ from global projections due to regional climate and geological factors (Section 6.3.2). Some linkages between climate change and the socio-economic sectors have nonlinearities, thus complicating the development pathways. Also, densely populated coasts and the protection of the coastal zone for human activities come into conflict with the functioning of coastal ecosystems (Nicholls and Klein, 2005).

Nevertheless, some generalizations on key vulnerabilities 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 highly localized impacts and adjustments, with significance for adaptation responses. Second, human vulnerability to sea-level rise and climate change will be strongly influenced by the development pathway, as evidenced by the differences between impacts found using the SRES scenarios (e.g., Nicholls and Tol, 2005). Third, modelling indicates that sea-level rise will continue for many centuries, irrespective of future emissions, although the magnitude of sea-level rise will be reduced by mitigation (Section 6.3.2). Hence 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, 2004)

Within the coastal zone, the climate thresholds vary by region and by scale and are evident in some cases. One critical threshold is the link between warmer sea temperature of 1-2°C and coral bleaching (Todd, 2003; see Box 6.1). Less clear are the thresholds associated with the Atlantic Thermoclinal Circulation (THC) and the breakdown of the Greenland and the West Antarctic ice sheets (Section 6.3.2). While rates of sea-level rise exceeding 1m/century appear unlikely, they remain possible with West Antarctic Ice Sheet (WAIS) collapse a potential culprit. Three European case studies explored a deliberately extreme and possibly implausible sea-level rise scenario of 5-m in a century due to the WAIS collapse mechanism, as a sensitivity analysis of adaptation to extreme change. The case studies were the Thames estuary (Lonsdale et al., in review; Dawson et al., 2005), the Rhone delta (Poumadere et al., 2005) and the Netherlands (Olsthoorn et al., 2005). In the Rhone delta abandonment is the clear response, and even in the Thames and the Netherlands, abandonment is possible, although the outcome is less clear. In contrast, a global analysis using the FUND model suggested that significant protection of 30% to 50% of the developed coasts would be economically viable, even under the most extreme scenario of a total WAIS collapse in 100 years. Thus, the threshold in terms of limits to adaptation is ambiguous and requires further research.

6.4.2.1 Water resources

The direct influences of sea level rise on water 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, in press). The impacts of sea-level rise are likely to be felt disproportionately in certain areas, reflecting both natural and socio-economic factors that enhance the levels of risks. For some metropolitan areas located at the coast, the deterioration of groundwater from pumping is accelerated by seawater intrusion.

Climate change has a strong impact on coastal salt water intrusion and the salinization of groundwater (Table 6.3) (see Chapter 3). 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 fresh water discharges and precipitation. In Europe, the impacts are greatest in the Mediterranean and Black Sea regions. At the same time, floods from rains along the Red Sea coast benefit groundwater recharge and aquifer storage (Al-Selfry *et al*., 2004).

In the absence of climate change, the future population in water-stressed watersheds depends on the population scenarios. By the 2050s there is still little difference between the emissions scenarios, but the different population assumptions have a clear effect (Arnell, 2004). Climate change increases water resources stresses in some parts of the world where runoff decreases, including the Mediterranean Basin, parts of Europe, central and southern America, and southern Africa. In other water-stressed parts of the world, particularly in southern and eastern Asia, climate change increases runoff. The broad geographic pattern of change is consistent between the six climate models, although there are differences of magnitude and direction of change in southern Asia (Arnell, 2004).

6.4.2.2 Agriculture, forestry, and fisheries

Climate change has led to abundance fluctuations in marine fish population worldwide (see Chapter 4) including coastal and estuarine fisheries (Genner *et al*., 2004; Daufresne *et al*., 2003). Indirectly, some negative impacts have been produced, such as the potential increase of marine diseases and harmful algal blooms, reduction of estuarine primary productivity and increased mortality of fish and shellfish.

The linkages between climate and aquaculture involved more subtle indirect relationships that affect the movement of nutrients and fish behaviour, including migration and reproduction. Aquaculture also shares much in common with terrestrial husbandry and the evaluation of impacts should be considered together with adjacent coastal enterprises (see Chapter 5). Meteorological data that serve agriculture can also be relevant for aquaculture, although the relative importance of the parameters and their temporal aptness may be different, and thresholds may be dissimilar, particularly at the coasts (Kapetsky, 2000).

Climate and weather directly control the distribution, production and many other aspects of species and biodiversity. Most species and ecosystems will be impacted and their adaptive capacity limited by 1-2°C increases in global mean temperatures (Leemans and Eickhout, 2004)

Rice is a major crop in deltaic areas, especially in Asia and climate impacts studies have identified potential losses and possible gains in rice yields (Wassmann et al. 2004). Rice production also contributes to climate warming through the release of methane (see Chapter 5). Extreme events, such as cyclones, have negative impacts on coastal areas with high-value plantation crops, e.g. West Malaysia, Sri Lanka and Kenya (see Chapter 5).

6.4.2.4 Human settlements, infrastructures and migration

The population in the coastal areas is found mainly to near-coastal plains in Europe and parts of Asia, and to a lesser extent to densely populated urban areas. Hence, there are wide variations in coastal populations amongst nations (Small and Nicholls, 2003). Large populations in many coastal areas around the world are, to a greater or lesser extent, vulnerable to hazardous events associated with natural coastal dynamics such as storm surges, floods and tsunamis. Human-induced climate change and sea-level rise will increase this vulnerability (Klein *et al.*, 2002). In North American, rapid coastal development and population growth, a growing demand for waterfront properties, and urban sprawl have a deleterious effect on the coastal systems (see Chapter 14).

Regionally, the global pattern of coastal flooding impact on human populations will relate not just to coastal topography but also to the number of people potentially exposed to storm surges. The greatest increase in vulnerability to sea level changes lies in the coastal strips of South and Southeast Asia, and the urbanized coastal lowlands around the African continent (Nicholls *et al.*, 1999). However, the prediction of precise locations for increased flood risk resulting from climate change is not feasible as flood risk dynamics have multiple social, technical and environmental drivers (Few *et al*., 2004).

By 2015, 22 mega cities in the world, mainly in the Asia-Pacific region, will be impacted by weather-related coastal hazards that include erosion, storm and wind damage, flooding and salinization of surface waters. The most significant impacts arise from erosion and flooding (Klein *et al*., 2002). One flood model predicts that in 1990 approximately 10 million people per year worldwide experienced coastal flooding arising from storm surges. By the 2080s, depending on the SRES scenario adopted, the model calculates that between 2 million and 50 million additional people per year will experience flooding. The model generally assumes that coastal flood defence measures would be improved during this period (Nicholls, 2004). If no measures are taken to adapt to sea level rise, the worst case scenario could see nearly 40 times more people per year affected by sea floods by 2100 (Nicholls, 2002).

Increasing attention is being given to the possibility of rapid or catastrophic climate change (Hulme, 2003). Though such changes are generally considered of low probability, their implications for future patterns of flood risk from high rainfall and windstorms could be highly significant for coastal cities.

6.4.2.5 Human health

Although the linkages between climate and human health are often complex, the impacts are likely to be more severe in developing countries where vulnerability to extreme weather (especially disasters) and infectious disease is high. Outbreaks of infectious diseases occur following heavy rains and flood events in developing countries,, particularly, leptospirosis, malaria, and diarrhoeal diseases (Chapter 8.2.2, (Ahern et al., 2005). In industrialized countries, outbreaks of infectious diseases rare due to the improved water and sanitation infrastructure, and public health concerns are more related mental health problems (Hajat *et al.*; 2003).

Climatic variables, particularly precipitation and temperature are linked to drinking-waterborne diseases, foodborne diseases, and coastal water quality issues. It is well established by laboratory and field studies that enteric pathogens proliferate at higher temperatures, and that transmission the vector borne diseases if related to meteorological factors. (Rose *et al*., 2001).The evidence for an effect of ENSO on malaria and cholera are strong compared with other mosquito-borne and rodent borne diseases, but effects depend on local ecology and transmission dynamics (Kovats, *et al*., 2003). Linkages between weather, terrestrial ecology and human health are important for vector and rodent borne diseases, such as rodent-borne hantavirus. Some important malaria vectors breed in brackish wetlands, and so changes in these habitats could affect disease transmission (increases or decreases).

Marine ecology also plays a role in determining human health risks, such as from cholera, and other enteric pathogens, harmful algal blooms, and shellfish and reef fish poisoning (Hunter, 2003; Lipp et al., 2004; Peperzek, 2005; Pascual et al., 2002)

A range of health effects are associated with precipitation extremes and severe tropical storms (Greenough *et al*., 2001). Populations at risk of coastal flooding due to climate change are described in Section 6.5.3. The SRES estimates of people affected by coastal flooding and spread of malaria are more sensitive to assumptions about future population trajectories than choice of climate models. Catastrophic flooding may induced migration or population dislocation that would have significant effects on population health (Patz *et al.* 2000).

Deforestation and ensuing changes in land-use, human settlement, commercial development, road construction, and water control systems singly, and in combination, have been accompanied by increases in or re-emergence of diseases such as malaria and schistosomiasis in some regions of the world (Patz, 2001).

Future research is required in several areas of climate change and health in the coastal areas. First, GCMs need to be downscaled to model more site-specific relevant projections. Second, basic relationships among temperature, sea-level rise, other climatic factors, and the ecology of disease agents need to known (Rose *et al*., 2001). The relation between weather factors and vector-borne diseases are complicated and delicate (Kovats *et al*., 2003). Third, the climate-health connections should take into account factors such as vulnerability of populations, water and sanitation systems, and the quality of and access to health care infrastructure. Fourth, the pathways should relate human health to food security in areas where climate change has negatively affected fisheries, aquaculture and agriculture.

6.4.2.6 Recreation and tourism

Climate is the major factor for travel to the sunny beach destination from Northern Europe to the Mediterranean (15% of international tourists) and from North America to the Caribbean. By 2020, international tourists are estimated to number 1.56 billion arrivals (World Tourism Organization, no date).

Higher temperatures are likely to change summer destinations preferences, especially for northern Europe and summer heat waves in Mediterranean may lead to a shift in tourism to spring and autumn (Parry, 2000). 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). Water shortages due to extended droughts will also affect tourism flows to Southeast Mediterranean where water use has a strong seasonal cycle (Kent, *et al*., 2002). While new climate dependent niches are emerging, empirical data do not suggest reduced competitiveness of the sun, sea and sand destinations (Aguiló, *et al*., 2005). Therefore, climate change is likely to affect major segments of international tourist flows.

While a temperature increase directly extends the summer recreation season of the mid-latitude coasts for water sports and beach-oriented recreation, the indirect effects are the impacts arising through changes in the quantity and quality of natural resources used for outdoor recreation (Loomis and Crespi, 1999). For example, sea-level rise may lead to erosion and degradation of beaches and coastal dunes, making less desirable for tourism or reduces the ability of wetlands to support recreational activities.

The analysis of the recreation effects of climate change is in its infancy. Two recent statistical studies attempted to define the climate sensitivity of recreation visits on a national basis (Loomis and Crespi, 1999; Mendelsohn and Markowski, 1999). The current aggregate days of activity and the economic value to visitors are projected to 2060 and the results suggest losses in consumer benefit for some activities and gains for others.

The stabilization of GHG concentration at various levels will have implications for the spatial and temporal patterns of tourism with some gainers and more losers. Based on the 550 ppm scenario, more regions lose good conditions than getting them, although the rate of change is much lower than at the B1A and B2A scenarios (Viner and Amelung, 2005).

Several extreme events can influence tourism flows. A warmer sea temperature of 1-2°C causes coral bleaching and could have serious implications for the diving industry. Within increasing global mean temperature, coral bleaching is likely to increase in intensity and frequency to the extent that in the Caribbean and South East Asia, it will occur annually by 2020, and in the Pacific by 2040 (Todd, 2003). In the El Nido resort on Palawan Island in the Philippines, coral bleaching in 1998 led to the decline of divers from 80% to around 10% and the resort has to target the honeymooners market (Todd, 2003). Acidification of the oceans and coastal waters could also have profound adverse effects on coastal ecosystems, including corals. 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, 2005).

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

An accurate 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 (IPCC 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:

- deltas and low-lying coastal wetlands
- seagrasses and coral reefs
- estuaries and lagoons along sedimentary coasts
- ice-dominated coastlines (see Chapter 15)
- soft rock cliffs
- sand, gravel, and cobble-boulder coastlines with low accretion rates
- low-lying small islands and atolls (see Chapter 16)

An acceleration of sea level rise can directly affect the vulnerability of all of these systems, but sea level rise will not occur uniformly around the world. Changes in sea level are dependent upon regionally-specific changes in ocean and atmospheric circulation as well as the rate warming, which is primarily a function of depth. Since the rate of sea level rise is dependent upon the rate of atmospheric warming, development pathways that influence emissions are also a consideration in predicting effects on coastal systems. The need to understand these relations and integrate them for the purposes of impact assessment and adaptation planning has stimulated the development of tools such as the “sea level scenario generator” by Warrick et al. (2005). This modelling approach allows the user to select one or more SRES development pathway and input local land surface movements or tide gauge records to project future changes in sea level along a given coastline or ocean basin.

Our understanding of human adaptive capacity is less developed than our understanding of autonomous adaptation in unmanaged 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 clearly emerged, such as:

- the intrusion of salt water into fresh water aquifers on small islands and atolls,
- flooding due to increased storm surge associated with sea level rise and the deterioration of natural coastal defenses,
- and more frequent outbreaks of shellfish-borne diseases brought about by increased water temperature.

A global assessment of the key vulnerabilities for human populations in the coastal zone is challenging because of the complexities and vagaries associated with human adaptive capacity.

Based on a critical review of the literature described in this chapter, however, we can infer a global trend towards a significant and increasing exposure of human populations and infrastructure in the coastal zone, particularly in urbanised and densely populated coastal areas such as low-lying populated deltas, including those in Asia (Box 6.4). It is also clear that multiple and concomitant 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 6.4 summarises key vulnerabilities.

Table 6.4: *Key vulnerabilities in coastal zones due to climate change and sea-level rise*

- Human communities in low-lying coastal areas, especially those facing constraints with respect to adaptation.
- Situations where the cost-benefit ratio with respect to adaptation is high (e.g., low-lying islands and deltas).
- As a system, low-lying coasts are inherently vulnerable to sea-level rise, but especially so with respect to densely-populated megadeltas, atolls and coastal wetlands.
- Those coastal areas that are subject to multiple natural and human-induced stresses, such as subsiding coasts, those where natural defences are lost or declining, those where inland migration is not possible (e.g., Mississippi delta, the Netherlands, Gulf of Thailand, much of the Mediterranean, Male (capital of the Maldives) and Venice).
- As already observed, those coastal areas already experiencing adverse effects of temperature rise, including ice-bound coasts and coral reefs.
- Coastal areas exposed to storm surges and extreme winds and high tides are already experiencing substantial impacts that will be exacerbated by climate change (e.g., Bay of Bengal, Florida and the Caribbean, Rio de la Plata).

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 pathways and outcomes not only key considerations in evaluating greenhouse gas emissions and climate change, but they are also important in assessing adaptive capacity because greater access to wealth and technology generally increases adaptive capacity while poverty limits adaptation options.

An increase in global mean temperature has been used to assess climate change impacts on coastal resources and other socio-economic sectors (Hitz and Smith, 2004). For the coastal sector, adverse impact will likely increase with an increase in both mean temperature and sea level rise (high confidence) but it is not possible to determine whether the relationship between impacts and the sea level is linear or exponential. The results are consistent with other studies which also showed increased inundation as sea level rises, damages from higher storm surges, costs for more coastal defences, and other adverse impacts, such as saltwater intrusion (Hitz and Smith, 2004).

With respect to stabilization levels of CO_2 emissions, the 750 ppm level cannot avoid rapid or dangerous climate change, the 550 ppm level can avoid most but at considerable costs, and the 400 ppm level avoids the dangerous effects on society as a whole. In terms of choice of a development pathway, the B2 scenario is considered as the most suitable to avoid/delay dangerous climate change (Parry, 2005). As we can control development pathway to some extent, so we can envisage developing in ways that enhance or minimise coastal vulnerability to climate change. The A2 world would appear to be the least desirable of the four SRES futures in terms of impacts, but global patterns of consequences for coastal areas for four SRES pathways and time slices at 2020s, 2050s, and 2080s are insufficient for quantitative analysis at any scale.

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

6.5.1 Methods and tools

As shown in Section 6.4.2, sea-level rise and climate change will have important consequences for coastal societies. Economic analysis of sea-level rise and climate change measure impacts in monetary terms and can be divided into three groups of studies (Nicholls et al., 2005):

(1) direct costs of sea-level rise
(2) total economic costs of sea-level rise, and
(3) adaptation to sea-level rise.

Direct cost estimates are common across climate change impact literature as they are simple to estimate and easy to explain. The direct cost of change is the product of price and impact, including adaptation and residual damage costs. For sea-level rise, the simple direct cost is the product of land loss and land value for unprotected areas, plus the product of length of dikes and dike costs for protected areas. Direct cost estimates have been made increasingly elaborate, such as the FUND model, which assesses a subset of the effects of sea-level rise comprising land and wetland loss, population displacement and coastal protection via dike construction, and wetland loss (Tol, 2004).

Direct cost estimates are only approximate estimates of the true economic impact, as they ignore the fact that land prices may rise if land is lost, food prices may rise if agricultural land gets scarcer, etc. The appropriate way to estimate these additional effects is to use a computable general equilibrium model (CGE). CGEs consider markets for all goods and services simultaneously, taking international trade and investment into account (e.g., Darwin and Tol, 1998; Bosello et al., 2004). In such calculations, the total economic impact is often larger than the direct cost estimate, reflecting an overall deflation of the economy (Darwin and Tol, 1998). Also, the spatial pattern of total economic costs is quite different to the spatial pattern of direct costs due to competitive advantage. Countries with relatively limited land area are hit by both land loss and loss of competitive advantage; while countries with relatively plentiful land gain in competitive advantage.

Several adaptation models have been used. The adaptation model in Nicholls (2004) assumes that the design frequency of the coastal protection is determined by per capita income and is applied uniformly across an entire nation. The different costs of adaptation in deltaic and non-deltaic countries, and the time required to adapt are also considered. Alternatively, the level of adaptation can be based on an analysis of the costs of coastal protection (including additional wetland loss due to coastal squeeze) and its benefits, that is, the avoided costs of land loss, and this approach has been incorporated with direct cost estimates in the FUND model (Tol, 2004). Assuming perfect adaptation based on benefit-cost analysis, FUND determines dryland and wetland loss, population displacement and protection costs and residual damage costs for any sea-level rise, or socio-economic scenario.

Most existing models are based on an assumed 0 to 1-m rise in sea level over a century. Use of the economic models outside this range could result in quite misleading conclusions. In an analysis of extreme sea-level rise, Nicholls et al (in review), tuned the FUND model to a new global data analysis considered bilinear costs of coast protection as a function of the rate of sea-level rise to overcome these limitations. Further development of these models, including the underlying datasets is an urgent requirement to provide better and more spatially-explicit analyses.

6.5.2 Under current climate conditions

Globally, and whether measured in terms of number of events, deaths, people affected or damage costs, natural disasters have increased substantially over the past few decades (Munich Re, 2004). However, the limited information available specifically for the costs and other socio-economic aspects of climate-related coastal hazards such as storm surges, heavy rain, flooding, erosion, salinization and strong winds, reveals a much more complicated situation.

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. Finding an accurate way to report these unreported or hidden costs is a challenging problem that has received increasing attention in recent years. A report by the Heinz Center (2000) concluded 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. Within the family, relationships after a disastrous coastal storm can become so stressful that family desertion and divorce may increase (Morrow, 1997). 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 (Heinz Center, 2000). Unsafe roads and heavy traffic can lead to increased traffic accidents, and increased use of alcohol and drugs is common in the months and years following a coastal disaster (Morrow and Enarson, 1997).

Official reports of deaths and injuries from storms are typically available within hours after a storm. After a few days, generally little or no attempt is made to identify the extent to which an illness, death, business closure, or environmental problem is disaster related. The costs of storms to those who depend upon renewable coastal resources for their livelihood are often economically and socially disastrous to families and communities in the coastal zone, but these effects may take months or years to occur (Heinz Center, 2000). Accounting of all true 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. 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. For every person killed, around 3,000 people are exposed to natural hazards. Bangladesh accounts for more than 60 percent of the registered deaths in this period. 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 the Asia-Pacific region about 47 million people or 1.21% of the total population, live in the area below high tide level, while 270 million people or 5.33% live below the storm surge level. In China, high storm surge and heavy rainfall generated by typhoons in high spring tide during flood season caused between 1990 and 1998 an annual average economic loss of US$14.96 million and 16.5 million people flooded, corresponding to 0.02-0.43% GDP and 0.6-20.1% of the national population, respectively (Mimura 2000). Causes of port-related disasters in Japan disasters include high waves and storm surges by typhoons, as well as earthquakes and tsunamis. The number of cases has been decreasing as the protective measures are developed. However restoration expenditure exceeds US$240million (Yoshikura, 2000).

The frequency of hazard occurrence, and the significance of specific hazards, are best illustrated using recent national and case studies, including the 1991 cyclones in coastal Bangladesh (139,000 fatalities) and the 1999 cyclone in Orissa, India (over 10,000 people killed, 774,000 houses destroyed, 15 million people made homeless and US$2.5 billion damage costs) (Ministry of Environment and Forests, Government of India, 2004; UNEP, 2002). Hurricane Mitch caused great damage on the coasts of Honduras and Nicaragua in 1998, but most of the 17,000 fatalities occurred inland of the coastal zone, as a result of floods, flash floods, landslides and debris flows triggered by the hurricane. The severity of these secondary hazard events was magnified by environmental degradation that occurred over several decades. These were possibly aggravated, in turn, by the drought and fires associated with an ENSO event the previous year. All these hazard events coincided with a highly vulnerable population in both social and economic terms and weaknesses in early warning and disaster preparedness that led to large losses of life. This emphasizes the need to consider all weather-related hazards and their inter-relationships (UNDP, 2004). Winds rather than surge were the major cause of property damage from Hurricane Andrew in Florida in 1992 (Ross and Lott, 2003).

An analysis of cyclones affecting the state of Andhra Pradesh, India, in the last quarter century shows that the increasing vulnerability is attributable mainly to economic and demographic factors and not to any increase in frequency or intensity of cyclones. The decrease of alertness in disaster management that often occurs after a few years' lull in occurrence of cyclones, known as the ‘fading memory syndrome,’ also contributes to increases in loss of lives and property damage (Raghavan and Rajesh, 2003). Cyclone experience and education may have contributed synergistically to a change in risk perceptions and a reduction in the vulnerability of Cairns’ residents to tropical cyclone and storm surge hazards (Anderson-Berry, 2003).

The United States has sustained 62 weather-related disasters between 1980 and 2004 in which overall damage costs were at least US$1 billion. Total damages costs (adjusted for inflation) were over US$350 billion (NOAA, 2005). The combination of more active hurricane seasons and increases in coastal population (for example, the coastal population in Florida has increased a rate of growth four times that of the U.S. in general) and per capita incomes are key factors in the increasing frequency of major weather-related disasters along the Atlantic and Gulf coasts. Analysis of landfalling hurricanes since 1925 indicates that seven hurricane seasons similar to the seasons experienced between 1940 and 1969 would have resulted in damages of US$10 billion or more if they had occurred with 1995 patterns of coastal development (Pielke and Landsea, 1998). 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).

A key problem for Venice, Italy, is the increasing frequency of storm surges, with the sea flooding the city now reaching an unsustainable level. During the instrumental period the tide gauge measured a 31-cm rise in relative sea level (Camuffo and Sturaro, 2004). The average annual erosion rate in the beach communities of Delaware’s Atlantic coast varies between 2 and 4 ft/yr and is threatening the sustainability of the area as a major summer recreation attraction (Daniel, 2001). Severe storm damage to beaches on Spain's Costa del Sol at the end of the 1980s, together with concern for the tourist industry then suffering stagnation and broader unease over the irreversible transformation of the coast through human activities, all coalesced to prompt the implementation of planning controls and new protective measures (Garcia *et al*., 2000).

6.5.3 With climate change

Substantial progress has been made in evaluating the economic costs and benefits of climate change, not only with respect to sea-level rise, but also with relation to extreme events such as storm surges and strong winds; less progress has been made with respect to non-monetary costs and to social and cultural consequences. As shown in the previous section, climate-related stresses, notably extreme events, are already imposing substantial costs on coastal systems. These costs will be exacerbated by climate change - most immediately this will also be due to extreme events. Only in the longer term will costs be dominated by trends such as sea-level rise. The impacts of such changes in climate and sea level are overwhelmingly adverse and developing countries will bear the brunt of these adverse impacts. Benefits, such as those arising from warmer winters, nights and oceans, have also been identified. These include reduced cold water mortalities of many valuable fish and shellfish species (Ch 5), increased opportunities for nearly year round use of fishing vessels and coastal shipping facilities (Ch 7), reduced mortalities of the homeless in coastal communities (Ch 7), reduced hull strengthening and icebreaking costs due to reduced sea ice (Ch 7), and reduced caloric demand in marine mammals (Ch 5). Competitive advantage effects due to sea-level rise have been identified computable general equilibrium models (Section 6.5.1): countries with large land areas generally benefit, while investment in protection is least painful where capital is most productive (Bosello et al., 2004).

Climate change could lead to a gradual shift of tourist destinations towards higher latitudes and altitudes. Climate change would also imply that the currently dominant group of international tourists – sun and beach lovers from Western Europe – would stay closer to home, implying a relative fall in total international tourist numbers. However, the changes induced by climate change are generally much smaller than those resulting from population and economic growth (Hamilton et al., 2005). Domestic tourism may double in colder countries and fall by 20% in warmer countries. For some countries international tourism may treble whereas for others it may cut in half. Climate change may double tourist expenditures in colder countries, and halve them in warmer countries (Bigano et al., 2005). If potential land loss due to sea-level rise is allowed, tourism would be significantly damaged in some small coastal countries and especially small island states such as the Maldives.

One of the most certain consequences of global warming is an increase of global (eustatic) sea level (Section 6.3). The resulting inundation from rising seas will heavily impact low-lying areas; at least 100 million persons live within one metre of mean sea level and are at increased risk in the coming decades. The very existence of some island states and deltaic coasts is threatened by sea level rise. The highly multiplicative association between long-term sandy beach erosion and sea level rise means that the already-severe coastal erosion problems witnessed in the 20th century will be exacerbated in the 21st century under plausible global warming scenarios (Section 6.4). As the beach is lost, fixed structures nearby are increasingly exposed to the direct impact of storm waves, and will ultimately be damaged or destroyed unless expensive protective measures are taken.

Until recently the direct cost method has dominated the climate change impact literature (Smith et al., 2001). However, economy-wide, indirect effects of the impacts of climate change are substantial compared to the direct effects, and are distributed differently. Loss of land due to sea-level rise deflates the entire global economy. General equilibrium effects are strongest in economies that rely most on agriculture. Although energy is substituted for the loss of land, the price of energy demand falls with the shrinking economy, preferentially hurting energy exporting nations (Bosello et al., 2004).

While some 10 million people experienced coastal flooding annually in 1990, by 2100 the number of people flooded could range between 0.4 to 39 million/year, depending on the SRES future (Nicholls, 2004). Unless adaptive measures are not taken, all reasonable scenarios of sea-level rise result in increased flooding during the 21st century. There are significant uncertainties. The number of people estimated to experience flooding in 2100 is 16-388 million for the mid (55-cm) global-mean sea-level rise scenarios, and up to 510 million people/year for the high (96-cm) scenario. The economic impact of land loss due to sea-level rise in Thailand is estimated to be a decrease in GDP of 0.361% and 0.685% (relative to GDP in 1993) due to a sea-level rise of 50cm and 100cm, respectively. The Bangkok metropolitan area and the manufacturing sector will have the most serious damage, about 61% and 38% in comparison to the total damage respectively (Ohno, 2000). Studies of the cities of Alexandria, Rosetta and Port-Said on the Nile delta coast of Egypt indicate that a sea-level rise of 50 cm will cause over 2 million people to abandon their homes, the loss of 214,000 jobs and the loss of land valued at over $ 35.0 billion (E1-Raey, 1997).

Figure 6.4 shows the consequences of a 0.65 m rise in sea level using the FUND model (Section 6.5.1). Here, selected consequences and the total costs are shown for aggregations of both developing and develop countries, as well global values. 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.

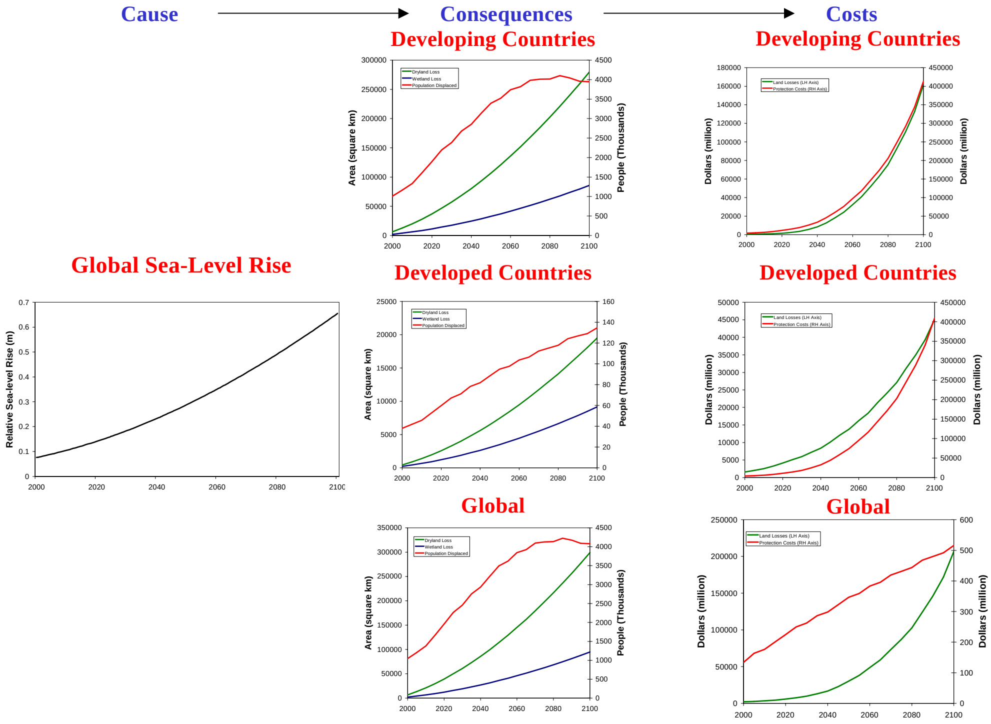


Figure 6.4: *Causes, selected consequences (people displaced) and the total costs of sea-level rise, for developing and developed countries, and as a global total. Based on Tol (in press).*

6.6 Adaptation: Options, practices, capacities and constraints

The foregoing sections have highlighted the potential for significant impacts on, and hence risks to, both natural and human coastal systems as a consequence of the enhanced greenhouse effect. The present section begins by highlighting issues that arise when contemplating or implementing interventions designed to reduce either these risks or existing impacts. This is followed by descriptions of the tools relevant to adaptation, options for adaptation of coastal systems, and of current and planned adaptation initiatives, including adaptation as a component of integrated coastal management. 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 climate and sea-level extremes variability and change

Adaptation must be an ongoing process, if only because global-mean sea level will continue to rise in the foreseeable future, irrespective of future emissions (Section 6.3). For coastal and low-lying areas a number of issues arise in relation to the ability to select and implement adaptation initiatives that are both effective and efficient. Resolving these issues is the aim of strategies that address current shortcomings in adaptive capacity, and therefore contribute in a meaningful manner to sustainable development.

Issues and Challenges

The paramount 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 (Finkl, 2002). Box 6.3 summarises recent progress in integrated assessment to support adaptation planning. The highly interactive nature and nonlinear behaviour of coastal systems means that failure to take an integrated approach to the risk characterisation increases the likelihood that the effectiveness of management interventions (i.e. adaptation) will be reduced, and perhaps even negated (Zhang et al., 2004; Leont'yev, 2003; Bertness and Ewanchuk, 2002). Thus the long-term effectiveness of such adaptive measures as beach nourishment 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).

There is a need to change from the static approach used to predict the rates of migration of coastal landforms to a more dynamic viewpoint (Pethick, 2001). Rationalization of shore protection measures is a new and productive trend that fosters research and technology transfer to the management sector (Finkl, 2002). A number of empirical relationships and deterministic numerical models have become important tools in the evaluation and design of coastal adaptation interventions, but opinions differ as to their validity (Thieler et al., 2000; Stive, 2004). Various barriers, including widely differing data formats, codes, directories, systems, and metadata used by individual programmes, make it difficult to integrate data from different research and monitoring initiatives in order to understand the ecology, status, and changes of coastal areas (Hale et al., 2003). Indicators and reference points are important for decision making but identifying them is proving difficult (Rice, 2003). Conditions of coastal areas are deteriorating all over the world despite over 30 years of practical experience in integrated coastal management (ICM) (Belfiore, 2003; Agardy et al., 2005).

Tools for Assessing Adaptation Needs and Options

Many different technologies exist to facilitate adaptation to increases in natural coastal hazards resulting from climate change (Klein et al., 2001). With the growing attention to adaptation, as well as the need for effective and efficient interventions, development and use of appropriate decision support tools has increased dramatically (Gambolati et al., 2002; van Vuren et al., 2004; Danard et al., 2003; Huang et al., 2001; Bloczynski et al., 2000; García et al., 2000). Development of GIS based decision support systems is possibly the next major challenge for the application of GIS technologies to the coastal zone (Thumerer et al., 2000).

Options

The coastal manager has many practical options for adapting to climate change (Yohe, 2000; Townend and Pethick, 2002; Queensland Government, 2001; Daniel 2001). 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. Preparedness is also essential (Dorland et al.,1999). Managers and planners should be moving away from a prescriptive interventionist approach towards a more adaptive one (Townend, 2002). Managing climate change impacts on African human settlements will require coastal defences (Magadza; 2000). Given that socio-economic activities and population are highly concentrated in the coastal zone in Asia, protection will predominate (Du and Zhang, 2000). Dyke heightening and strengthening will dominate in China (Li et al., 2004). Growing impacts of human activities on coastal ecosystems in general has emphasised the value of marine protected areas (Lubchenco et al., 2003). By ensuring there is adequate space, natural systems such as mangrove forests can migrate inland, as they did during the Holocene sea-level transgression (Alongi, 2002). Managed realignment is now firmly on the agenda in both England and Germany, reflecting a radical departure from the recent past. In some areas the change is driven by long-term, multi-causal factors, and in others by habitat mitigation needs, and by conservation (Rupp-Armstrong and Nicholls, submitted).

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 (Hay et al, 2003). There is a fundamental need to integrate and mainstream disaster management and adaptation to climate variability and change into wider coastal management, especially given lessons learned from the recent Indian Ocean tsunami.

Current practises and planned adaptation

There are many reasons for favouring planned rather than reactive adaptation (Hay et al., 2003). Because the pace of greenhouse induced sea-level rise is unknown, some anticipation and monitoring is required to implement appropriate pre-emptive responses (Yohe and Neumann,1997). Five generic approaches for proactive adaptation of relevance to coastal zones can be identified (Klein and Tol, 1997; Klein, 2001; Nicholls and Klein, 2005) and applied (e.g. Cooper et al., 2002; Tol et al., 2001). They provide an alternative to the previous overly simplistic response options of protection, accommodation or retreat, and are thus much more aligned with coastal zone management and planning approaches (Kay and Alder, 2005). But there is a mismatch between the broad geographical scale at which strategic planning usually takes place and the narrower spatial scale of decision-making on coastal management interventions. Moreover, the time horizons of coastal planning are generally too short to mandate consideration of climate change impacts. Both sets of scale issues inhibit anticipatory response capacity of institutions (Few et al., 2004). Protecting land through ‘hard’ shore-protection measures has tended to be favoured over retreat or accommodating sea-level rise, although for continental coasts retreat is increasingly favoured.

Integrated coastal management
Since it offers advantages over purely sectoral approaches, integrated coastal management (ICM) has been 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 (Nicholls and Klein, 2005; Isobe, 2001; Kang, 2003). The effectiveness with 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). Development of institutional capabilities for ICM and upgrading awareness are highly recommended for adaptation in the long run (El-Raey, 1997). ICM in Central American has been limited by information gaps, restricted technical and financial capacity, and strong sectoralism. Some recent projects, both governmental and supported by NGOs, offered new experience and lessons on regional ICM (Windevoxhell et al., 1999).

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.

Tol (2002a) estimated the costs of optimal protection from a 1 m rise in sea level and the number of persons displaced. Values are estimated on a national basis and aggregated subsequently to regional and global totals. The results are presented in Table 6.5.

Table 6.5*: Optimal Coastal Protection Costs and Number of Persons Displaced as a Result of 1 m Rise in Sea Level (from Tol, 2002a)*

Region	Protection Costs (10^9 US$)	Number of Emigrants (10^6)
OECD America (excluding Mexico)	83	0.13
OECD Europe	136	0.22
OECD Pacific (excluding South Korea)	63	0.04
Central and Eastern Europe and former Soviet Union	53	0.03
Middle East	5	0.05
Latin America	147	0.71
South and South East Asia	205	2.30
Centrally Planned Asia	171	2.39
Africa	92	2.74

Tol (2002b) also presented estimates of the number of forced migrants and the resulting costs, for given scenarios of coastal protection (see Figure 6.5). The number of migrants first rises steeply as sea level rise accelerates, stabilizes, and then gradually falls as more and more land is protected. In the central case the number of forced migrants never exceeds 75,000 people per year. Initially the costs of migration follow a similar pattern, but subsequently reflect a trend of ever increasing values attached to each migrant associated with rising GDP. Thus, in this model which includes a protection response, the number of people displaced is much smaller than in many previous estimates which focussed on potential population displacement without any adaptation.

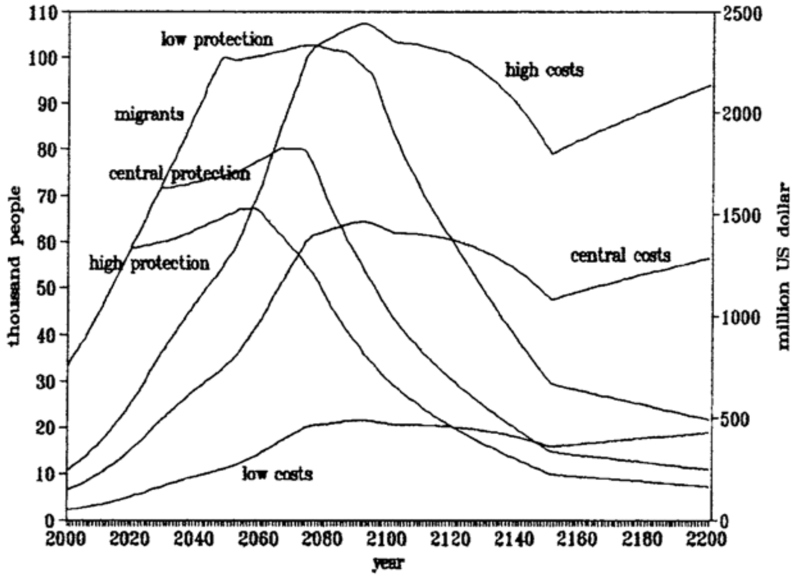


Figure 6.5: *The cost of forced migration due to sea level rise. Shown are the number of migrants per year when dryland loss (with protection) is set to its central estimate, plus or minus its standard deviation. Also depicted are high, middle and low estimates of the costs when dryland loss and the number of migrants are set to their central estimates (from Tol, 2002b).*

A global MPA network meeting the World Parks Congress target of conserving 20–30% of the world's seas might cost between $5 billion and $19 billion annually to run and would probably create around one million jobs (Balmford et al., 2004). GDP generally expands as a consequence of additional investments in coastal protection. Costs of protection are typically borne collectively, while potential damages threaten individuals or their immediate communities (Neumann et al., 2000). Indicative construction costs of key coastal defence types in England and Wales are (values are average total cost in GBP/km (2003 pounds)): earth embankment (550,000), culverts (2,000,000), protected embankments and sea walls (2,700,000), dunes – planting and fencing but not replenishment (53,000) and structures such as groynes and breakwaters on shingle beaches (5,100,000) (Evans at al., 2004b). Estimates of fixed construction costs for dikes or levees built to protect against a one metre rise in sea level in the United States range from US$150 to US$800 per linear foot (1990 dollars). Corresponding cost estimates for sea wall and bulkhead construction range from US$150 to US$4,000 per linear foot (1990 dollars). The range in costs reflects location-specific factors such as the amount of site and foundation preparation work necessary, drainage requirements and differences in materials and labour costs (Neumann et al., 2000).

The cost of implementing the engineering components of integrated portfolios of climate change responses in England and Wales showed a marked contrast between the 'protection'-led approaches requiring nearly £80 billion capital investment in defence-raising compared to the more 'management'-led approach requiring a significantly more limited investment in defence infrastructure of £20 billion (Evans et al., 2004b).

Lee (2001) examined the effects of future coastal defence policies and 'natural' processes on habitats within Special Areas of Conservation (SAC), Special Protection Areas (SPA) and Ramsar sites around the coast of England and Wales for a 50 year time frame. The likely costs of freshwater and brackish habitat replacement, on a hectare-for-hectare basis, was estimated to be in the order of £50-60 million, including site purchase, set-up and on-going management costs.

Economic analyses of flood protection in coastal China have shown large financial benefits relative to costs (Table 6.6).

***Table 6.6**: Losses, Costs and Benefits[1] of Adaptation to Sea-level Rise, Pearl Delta Region, China (Values are in billion Yuan) (from Hay and Mimura, in press)*

	Sea-Level Rise								
	30 cm			65 cm			100 cm		
Tidal Level	Loss	Cost	Benefit	Loss	Cost	Benefit	Loss	Cost	Benefit
Highest Recorded	13.6	1.76	11.8	41.6	2.91	38.7	60.6	4.75	55.8
100 year High Water	19.0	2.08	16.9	38.9	3.37	35.5	67.1	5.11	52.0

[1] Loss – the adverse economic consequences of the event, without adaptation
Cost – the cost of adaptation measures
Benefits – the economic benefits arising from the adaptation measures

6.6.3 Limits and trade-offs in adaptation

Section 6.3.2 showed that sea-level rise will continue for many centuries, with the magnitude depending on a range of factors including future greenhouse gas emissions and the timescale of response of ocean expansion and the Greenland and Antarctica ice sheets. Even a slow rate will have profound long-term impacts on low-lying island communities and on vulnerable ecosystems (such as coral reefs), even if human society can adapt. At the other extreme, a global rise of sea level of ≥10 m is possible in the coming millennia and it is likely that adaptation strategies will need to protect against impacts that could extend well into the next millennium.

Recent studies suggest that there are limits to adapting to such changes, as well as to the more immediate increases in variability and extreme events, even in the more developed countries (Nicholls et al., submitted). Without either adaptation and mitigation, the impacts of sea-level rise will be substantial, making entire island nations unviable before 2100; the global effect is much smaller (Tol, 2004; Nicholls and Tol, 2005). Adaptation would reduce impacts by a factor of 10 to 100, and would come at a minor cost compared to the damage avoided. Because the momentum of sea level rise is so large, mitigation can reduce impacts only to a limited extent. Stabilising carbon dioxide concentrations at 550 ppm would cut impacts up to 2100 by about 10%. However, if the costs of emission reduction are also factored in, the avoided impacts are less by up to 25% (average 10%). This is partly due to the reduced availability of resources for adaptation, and partly due to the increased sensitivity to wetland loss by adaptation (Tol, 2004).

Even for present climate, adaptation to climate hazards is often inadequate. The ability to accommodate further increases in climate-related risks is frequently poor, while increases in coastal development and population will magnify risks of coastal flooding, including degrading or destroying coastal ecosystems such as salt marshes. Most measures to compensate and control the salinisation of coastal aquifers are expensive and laborious (Essink, 2001). Frequent floods put enormous constraints on development. 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 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). The world's coral reefs show rapid decline as a result of environmental change. Coral reef communities and organisms are stressed, potentially mortally, by rising temperature, rising atmospheric/surface ocean CO_2 levels, rising human populations, and by local aspects of climate change other than temperature. Further increase in all of these stressors is certain, but in a practical sense adaptation options are limited (Buddemeier, 2001). Conditions of coastal areas are deteriorating all over the world despite over 30 years of practical experience in ICM. In many instances worldwide, ICM has failed to ensure the environmental health of coastal ecosystems while obtaining benefits from coastal development (Belfiore, 2003).

Knowledge gaps are important barriers to understanding potential impacts and thus to developing adaptation strategies for coastal systems (Crimp et al. (2003). Following Hurricane Hugo in 1989 most owners of beachfront property in South Carolina, USA, repaired or rebuilt their homes despite extensive damage to their structures, and presumably with the full knowledge of the risks of proximity to the shoreline (Neumann et al., 2000). The public often has conflicting views on the issues of sustainability, hard and soft defences, economics, the environment and consultation. Information needs of local residents and 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 at al., 2003).

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. These systems vary in their ability to adapt to significantly large deviations from average climatic conditions, as well as to high rates of change. For example, managed retreat may prevent the loss of intertidal and saltmarsh habitats and their associated bird populations, while strengthening of embankments and the creation of storm surge barriers and dams, for example, might lead to the reduction of these habitats. The decision as to which option is chosen is likely to be largely influenced by local economic considerations (Knogge et al., 2004). Managers of saltmarshes 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, where 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). The particular strategy adopted in response to perceived threats from sea-level rise depends on many factors, and include the value of the land or infrastructure under threat, the financial and economic resources that can be brought to bear, the local landscape of coastal management policy and the ability to understand and implement adaptation options (Yohe, 2000).

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 are inferior as viewed within a sustainability framework (Noronha, 2004). Provision of long-term sustainable coastal defences must start with the premise that "coasts need space" and that government must work to increase public awareness, scientific knowledge, and political will to facilitate such a retreat from the almost sacrosanct existing shoreline (Pethick, 2002). Economic, social and ecological 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 and the most practical choice of adaptation initiative will inevitably involve local seminars and workshops for relevant stakeholders (Kobayashi, 2004).

6.6.4 Adaptive capacity

The adaptive capacities of local communities to cope with the effects of severe climate impacts decline if there is a lack of availability 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. It has been suggested that the concept of adaptive capacity be adopted as the umbrella concept as this would foster much-needed communication between the natural hazard and the climate change communities. Perhaps more importantly, it offers greater potential in application, especially when attempting to move away from disaster recovery to disaster prevention and preparedness (Klein et al., 2003). Adaptive capacity and vulnerability are related, but there are two contrasting views - viewing vulnerability as an end point (i.e. as a residual of climate change impacts after adaptation) suggests that adaptations and adaptive capacity determine vulnerability, whereas viewing vulnerability as a starting point (i.e. as a general characteristic generated by multiple factors and processes) implies that vulnerability determines adaptive capacity. Moreover, if the underlying causes and contexts of vulnerability are not taken into account there is a danger of underestimating the magnitude, scope and urgency of climate change (O'Brien et al., 2004). As adaptation depends on socio-economic status, the rank order of most vulnerable countries is not the same as the rank order of most exposed countries (Tol, 2004).

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 buffers such as dunes and wetlands should be preserved and enhanced, as climate change will make use of this buffering capacity. 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). Emerging perspectives on collective action and social capital are informing the nature of adaptive capacity and normative prescriptions of policies of adaptation. Specifically, social capital is increasingly understood within economics to have public and private elements, both of which are based on trust, reputation, and reciprocal action. The public-good aspects of particular forms of social capital are pertinent elements of adaptive capacity in interacting with natural capital and in relation to the performance of institutions that cope with the risks of changes in climate (Adger, 2003). 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 and enhances the capacity for disaster prevention and preparedness, disaster recovery and for adaptation to climate change (Klein et al., 2003). Globalisation has brought about changes that increase vulnerability and reduce resilience and adaptive capacity (Pelling and Uitto, 2001).

Constraints and limitations

Yohe and Tol (2002) described a method to assess the potential contributions of various adaptation options to improving systems' coping capacities. They suggest focusing attention directly on the underlying determinants of adaptive capacity. For some factors, such as the status of coastal wetlands for contrasting worlds with little and high environmental concern (Table 6.2) appear to be more significant determinants of change during the 21st century than is sea-level rise, highlighting the importance of the socio-economic conditions as a fundamental control of impacts with and without climate change (Nicholls, 2004). Since community hazard vulnerability is both complex and multidimensional, both hazard awareness education and personal hazard experience are significant and important contributors to community vulnerability. But despite 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).

Strengthening strategies

Policies that reduce consumption, improve environmental management, and increase the quality of life of vulnerable and other marginal groups will collectively advance sustainable development and social and economic equity, and hence enhance 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). West (2003) identified specific initiatives that will promote science-based decisions on oceans and coastal activities, and suggested several policy directions for national action including full and open data exchange and promoting public participation, and proposed improvements in coordination among oceans-related bodies at regional and global levels. Parson et al. (2003) proposed a programme of research and analysis to advance capability for assessment of climate impacts, vulnerabilities and adaptation options and identified specific priorities for scientific research on the responses of ecological and socioeconomic systems to climate and other stresses, for improvement in the climatic inputs to impact assessments and for further development of assessment methods to improve their practical utility to decision-makers. Contreras-Espinosa1 and Warner (2004) urged that comprehensive watershed plans be developed and more scientific information be obtained in order to fully understand the connections between upstream processes and coastal wetlands in Mexico. Smith (2002) described the role of the social sciences in capacity building in ocean and coastal management, ranging from conventional discipline-based education, especially at tertiary level, through applied short courses for practitioners at all levels of management. Coastal data partnerships help overcome the technical, social and organizational barriers. Characteristics of successful data partnerships include a common need for shared data, strong collaborative leadership, committed partners willing to invest in the partnership, and clear agreements on data standards and data policy. Emerging data and metadata standards that become widely accepted are crucial. New information technology is making it easier to exchange and integrate data. Data partnerships result in creation of broader databases than would be possible for any one organization to create by itself (Hall 2002).

6.6.5 The links between adaptation and mitigation in coastal zones

There is importance and urgency to pursue both adaptation and mitigation as responses to climate change (King, 2004). The risks to human and natural systems as a consequence of sea-level rise, particularly increased coastal flooding due to storm surges, need to be considered within a policy process that considers climate change in terms of both mitigation (reducing greenhouse gas emissions) and adaptation (improved coastal management and planning) (Nicholls, 2002). Due to the long thermal lags of the ocean system the response of sea-level rise to mitigation of greenhouse gas emissions is slower than for other climate factors (Section 6.3.2), suggesting a mixture of adaptation and mitigation policies need to be considered for coastal areas. This requires joint evaluation of mitigation and adaptation strategies in coastal areas, ideally using a new probabilistic risk-based methodology and with assessments continued beyond 2100 in order to assess the full implications of different policy options (Nicholls and Lowe, 2004). The influence of development pathway on human vulnerability to sea-level rise and climate change implies that responses could operate in several mutually reinforcing ways – mitigation leading to climate stabilisation and development pathways facilitating local adaptation. The optimal mix will change with time and is location specific.

But adaptation cannot be readily compared to mitigation, because most adaptation is done by different people, and at a fundamentally different scale than mitigation (Nicholls et al., 2005). Although researchers like to talk about multi-scale, multi-stakeholder research of immediate policy relevance, reality is different (Tol, 2004). In addition, mitigation takes resources away from adaptation - for health-related impacts in poor countries, money is better spent on adaptation than on mitigation. Adaptation to sea-level rise would reduce impacts by a factor 10 to 100. Adaptation would come at a minor cost compared to the damage avoided. On the other hand, because the momentum of sea-level rise is so large, mitigation can reduce impacts only to a limited extent. Stabilising carbon dioxide concentrations at 550 ppm would cut impacts up to 2100 by about 10%. However, if the costs of emission reduction are also factored in, then avoided impacts are less by up to 25% (average 10%). This is partly due to the reduced availability of resources for adaptation, and partly due to the increased sensitivity to wetland loss by adaptation (Tol, in press).

6.7 Implications for sustainable development

Given the growing concentration of people and the existing natural capital in the coastal zone, as well as the inertia of sea-level rise, sea-level rise and climate change have important implications for sustainable development. Only a few developed countries are presently concerned about climate change risks and giving adequate attention to long-term planning and management of their coasts (Nicholls and Klein, 2005; Tol et al., accepted). Most other developed countries are increasing their management efforts, while developing countries are still concerned with today's problems and the concerns of the coasts vary significantly. Also, when considering the sustainability of coasts, scale is an important consideration as coasts are often tens of kilometres or narrower in width.

A whole science of sustainability is being developed (Kates *et al*., 2001) to link sustainability with the different SRES futures and view them as alternative development pathways. The B1 pathway had the lowest emission and the lowest impacts in the analysis of Nicholls (2004). When adaptation is considered, human impacts are still lower than A2 and B2 (Nicholls and Tol, 2005). Sustainable development futures tend to share a mix of characteristics including low GHG emissions (Morita *et al*., 2001). For scenarios that address local and regional sustainability issues (e.g. SRES B1), human communities appear better prepared to adapt to future climate change (see Table 6.1). For scenarios with slow economic development, high population growth, and less technological change (e.g. SRES A2), vulnerability would be high and communities would be less prepared to adapt to adapt to future climate change (Swart *et al*., 2003).

As climate change is increasing viewed as an opportunity for sustainable development (Wilbanks, 2003), new analytical approaches can be developed specific to scale and place (Adger *et al*., 2005a; 2005b) as illustrated by the following examples for the coasts. For the common problem of coastal flooding, several sustainability options have demonstrated their usefulness for coasts and low-lying areas. Non-structural flood protection measures lend themselves well to application in climate change adaptation strategies. As uncertainty in the assessment of climate change impacts is high, flexibility of adaptation strategies is particularly advantageous (Kundzewicz, 2000).

Integrated assessment based on the collaboration between researchers and local communities and across disciplines can be useful to obtain scenarios of climate change, as illustrated for several Arctic communities in the next 40 years. Although this kind of synthesis model has limitations, it demonstrates the value of output that cuts across scientists, communities and disciplines (Kruse *et al*., 2002).

Within the coastal zone, the human dimension involving all relevant stakeholders is crucial to broaden the framing of the climate change problem beyond the environmental dimension (Swart *et al*., 2003). The processes of social learning are the most important aspect for the transformations towards more sustainable resource management regimes (Pahl-Wostl, 2002; Tompkins and Adger, 2004). For example, community-based management enhances the adaptive capacity in two ways: building networks that are important for coping with extreme events and retaining the resilience of the underpinning resources and ecological systems (Tompkins and Adger, 2004).

In some cases, technology can still be considered, e.g. renewable energy by tapping energy from waves, tides, current, thermal gradient of sea water. OTEC (ocean thermal energy conversion) systems are now available.

In the light of the 2004 Indian Ocean tsunami, a paradigm change in coastal management is likely by integrating disaster management and adaptation to climate variability and change into wider coastal management. At the same time, coastal habitat restoration, e.g. for mangroves, in the post-tsunami phase would also boost hazard mitigation, protect biodiversity, encourage eco-tourism, and protect carbon storage.

ICM programmes involving climate change and disaster management for the sustainable development of coasts have yet to be implemented adequately for the world’s coasts

6.8 Key uncertainties, confidence levels, unknowns, research gaps and priorities

Our level of knowledge is not consistent with the potential severity of the problem of climate change and coastal zones. Hence, there are a range of unknowns and uncertainties, which lead to the identification of research gaps and priorities. In general terms, more focussed research on the natural and human dimensions of coastal systems and climate change, including the coupled human-natural system behaviour would substantially reduce these uncertainties and increase the effectiveness of long-term coastal planning and policy development. In this regard, the LOICZ Science Plan outlines a range of relevant scientific objectives which bridge this human-natural system divide (Kremer et al., 2004).

In summary, the following specific issues have emerged concerning the climate change and sea-level rise, and their potential implications for coastal areas:

1. Our understanding is still concentrated on the natural system response to sea-level rise with limited consideration of other changes. Efforts to develop a better understanding of the implications of the full range of climate change effects on the coast through the 21st Century (e.g., Table 6.2) are required. This will include process understanding, and climate

and socio-economic scenario developments to consider the widespread implications of these processes.

2. Analyses of climate change are required are required across a range of scales to support policy development, including local scale studies if we are to fully understand the impacts and responses to climate change and sea-level rise.
3. Given the inertia of sea-level rise, analyses need to continue beyond 2100 so that the full implications of these changes can be considered in coastal policy. Appropriate climate scenarios, including the Greenland and Antarctic ice sheets are required.
4. A focus on the most vulnerable environments would offer considerable benefits. Many large delta are increasingly threatened by sea-level rise and climate change, and yet the delta dynamics at the relevant scales remains poorly understood (Woodroffe et al., in review). A focussed programme that focussed on basic engineering, natural and social science and its integration for sustainable delta management could offer great dividends.
5. Economic models of sea-level rise impacts have been developed significantly over the last few years, but they require further development to resolve a wider range of processes at a finer spatial resolution to answer important questions pertinent to mitigation and adaptation in coastal zones.
6. Adaptation has a tremendous capacity to reduce the impacts of sea-level rise and climate change, but we remain uncertain are the limitations to adaptation, and the most appropriate strategies for adaptation such as protection versus a planned retreat. Focussed research which explored limits to adaptation and considered how to select different adaptation strategies would be very useful.
7. Implementation of climate-related adaptation also requires attention to make sure that this issue is considered in coastal management and planning.
8. More understanding on the pathways in which climate change in coastal zones can affect various socio-economic sectors, particularly in areas such as water supply and health.
9. In dealing with various socio-economic sectors, more attention to be given on climate impacts in relation to poverty alleviation and food security in developing countries.
10. Re-examine and consider critically important thresholds or discontinuities in climate change impacts.
11. More understanding of the impact of extreme events on economic and political instability.

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