Coastal Zones and Small Islands

By

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9

Coastal Zones and Small Islands

LUITZEN BIJLSMA, THE NETHERLANDS

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CONTENTS

EXECUTIVE SUMMARY

Coastal zones and small islands are characterized by highly diverse ecosystems that are important as a source of food and as habitat for many species. They also support a variety of economic activities—which, in many places, has led to a high rate of population growth and economic development. Many studies indicate that overexploitation of resources, pollution, sediment starvation, and urbanization have:

- Led to a decrease in the resilience of coastal systems to cope with natural climate variability (High Confidence)
- Adversely affected the natural capability of these systems to adapt to changes in climate, sea level, and human activities (High Confidence)
- Led to increased hazard potential for coastal populations, infrastructure, and investment (High Confidence).

As demands on coastal resources continue to increase with a growing population and expanding economic activity, coastal systems continue to face increasing pressures, which often lead to the degradation of these systems. In many parts of the world, for example, coastal wetlands are presently disappearing due to human activities.

Since the IPCC First Assessment Report (1990) and its supplement (1992), the interrelationships between the impacts of climate change and human activities have become better understood. Although the potential impacts of climate change by itself may not always be the largest threat to *natural coastal systems*, in conjunction with other stresses they can become a serious issue for *coastal societies*, particularly in those places where the resilience of natural coastal systems has been reduced. Taking into account the potential impacts of climate change and associated sea-level rise can assist in making future development more sustainable. A proactive approach to enhance resilience and reduce vulnerability would be beneficial to coastal zones and small islands both from an environmental and from an economic perspective. It is also in line with the recommendations of the UN Conference on Environment and Development (UNCED) Agenda 21. Failure to act expeditiously could increase future costs, reduce future options, and lead to irreversible changes.

Important findings by Working Group I that are of relevance to coastal impact assessment include the following:

- Current estimates of global sea-level rise represent a rate that is two to five times higher than what has been experienced over the last 100 years (High Confidence).
- Locally and regionally, the rate, magnitude, and direction of sea-level changes will vary substantially due to changes in ocean conditions and vertical movements of the land (High Confidence).
- It is not possible to say if the intensity, frequency, or locations of cyclone occurrence would change in a warmer world (High Confidence).

Since 1990, there has been a large increase in research effort directed at understanding the biogeophysical effects of climate change and particularly sea-level rise on coastal zones and small islands. Studies have confirmed that low-lying deltaic and barrier coasts and low-elevation reef islands and coral atolls are especially sensitive to a rising sea level, as well as changes in rainfall, storm frequency, and intensity. Impacts could include inundation, flooding, erosion, and saline intrusion. However, it has also been shown that such responses will be highly variable among and within these areas; impacts are likely to be greatest where local environments are already under stress as a result of human activities.

Studies of natural systems have demonstrated, among other things, that:

- The coast is not a passive system but will respond dynamically to sea-level and climate changes (High Confidence).
- A range of coastal responses can be expected, depending on local circumstances and climatic conditions (High Confidence).
- In the past, estuaries and coastal wetlands could often cope with sea-level rise, although usually by migration landward. Human infrastructure, however, has diminished this possibility in many places (High Confidence).
- Survival of salt marshes and mangroves appears likely where the rate of sedimentation will approximate the rate of local sea-level rise (High Confidence).
- Generally, coral reefs have the capacity to keep pace with projected sea-level rise but may suffer from increases in seawater temperature (Medium Confidence).

The assessment of the latest scientific information regarding socioeconomic impacts of climate change on coastal zones and small islands is derived primarily from vulnerability assessments based on the IPCC Common Methodology. Since 1990, many national case studies have been completed, embracing examples of small islands, deltas, and continental shorelines from around the world. These studies mainly utilize a scenario of a 1-m rise in sea level and generally assume the present socioeconomic situation, with little or no consideration of coastal dynamics. There is concern that these studies understate nonmarket values and stress a protection-orientated response perspective. Despite these limitations, these studies provide some important insights into the socioeconomic implications of sea-level rise, including:

- Sea-level rise would have negative impacts on a number of sectors, including tourism, freshwater supply and quality, fisheries and aquaculture, agriculture, human settlements, financial services, and human health (High Confidence).
- Based on first-order estimates of population distribution, storm-surge probabilities, and existing levels of protection, more than 40 million people are estimated to experience flooding due to storm surge in an average year under present climate and sea-level conditions. Most of these people reside in the developing world. Ignoring possible adaptation and likely population growth, these numbers could roughly double or triple due to sea-level rise in the next century (Medium Confidence).
- Protection of many low-lying island states (e.g., the Marshall Islands, the Maldives) and nations with large deltaic areas (e.g., Bangladesh, Nigeria, Egypt, China) is likely to be very costly (High Confidence).
- Adaptation to sea-level rise and climate change will involve important tradeoffs, which could include environmental, economic, social, and cultural values (High Confidence).

Until recently, the assessment of possible response strategies focused mainly on protection. There is a need to identify better the full range of options within the adaptive response strategies: protect, accommodate, and (planned) retreat. Identifying the most appropriate options and their relative costs, and implementing these options while taking into account contemporary conditions as well as future problems such as climate change and sea-level rise, will be a great challenge in both developing and industrialized countries. It is envisaged that the most suitable range of options will vary among and within countries. An appropriate mechanism for coastal planning under these varying conditions is integrated coastal zone management. There is no single recipe for integrated coastal zone management; rather, it constitutes a portfolio of sociocultural dimensions and structural, legal, financial, economic, and institutional measures.

Integrated coastal zone management, which has already started in many coastal countries, is a continuous and evolutionary process that identifies and implements options to attain sustainable development and adaptation to climate change in coastal zones and small islands. Constraints that could hinder its successful implementation include, but are not limited to:

- Technology and human resources capability
- Financial limitations
- Cultural and social acceptability
- Political and legal frameworks.

Continued exchange of information and experience on the inclusion of climate change and sea-level rise within integrated coastal zone management at local, regional, and international levels would help to overcome some of these constraints. In addition, more research is required on the *process* of integrated coastal zone management to improve the understanding and modeling capability of the implications of climate change and sea-level rise on coastal zones and small islands, including biogeophysical effects, the local interaction of sea-level rise with other aspects of climate change, and more complete assessment of socioeconomic and cultural impacts.

9.1. Introduction

Coastal zones and small islands contain some of the world's most diverse and productive resources. They include extensive areas of complex and specialized ecosystems, such as mangroves, coral reefs, and seagrasses, which are highly sensitive to human intervention. These ecosystems are the source of a significant proportion of global food production. Moreover, they support a variety of economic activities, including fisheries and aquaculture, tourism, recreation, and transportation. In recent decades, many coastal areas have been heavily modified and intensively developed, which has significantly increased their vulnerability to natural coastal dynamics and the anticipated impacts of global climate change.

Many attempts have been made to define the "coastal zone" and its land and seaward boundaries. Some definitions are based on physiographic characteristics, such as the extent of tidal influence on the land or the geomorphology of the continental shelf; others simply use a fixed distance from the shoreline. In the case of small islands, the coastal zone could include the entire island. While the boundaries of the coastal zone may or may not coincide with political or administrative boundaries, they rarely coincide with those of areas from which demands on the resources of the coastal area are derived (Ehler, 1993).

Irrespective of how coastal zones are defined, the following characteristics, which are strongly interrelated, often make them distinctive from other areas:

- A high rate of dynamic changes in the natural environment
- A high biological productivity and diversity
- A high rate of human population growth and economic development
- A high rate of degradation of natural resources
- Exposure to natural hazards such as cyclones and severe storms
- The need for management regimes that address both terrestrial and marine issues.

The global importance of coastal zones and small islands in terms of both ecological and socioeconomic values is widely recognized. Many international organizations, including IPCC, have called for action to implement strategies toward better planning and management of coastal areas and resources to prevent them from being degraded and becoming progressively more vulnerable to the potential impacts of climate change and associated sea-level rise. The World Coast Conference, partly held under the auspices of IPCC, has supported the Framework Convention on Climate Change (UNCED, 1992a) and Agenda 21, Chapter 17 (UNCED, 1992b), requiring action on coastal zone management planning, among many other initiatives, by all signatories (WCC'93, 1993).

This chapter presents an assessment of the latest scientific information on the impacts of climate change on coastal zones and small islands and on strategies that countries may wish to apply in response to these impacts. It builds on the previous IPCC assessments carried out in 1990 and 1992 and on the work of the former Coastal Zone Management Subgroup (CZMS) of IPCC. The chapter concentrates on the scientific work completed since 1990, although earlier work is acknowledged where appropriate.

The structure of this chapter is schematically depicted in Figure 9-1. This figure also shows how this chapter relates to other chapters and Working Group reports of this IPCC Second Assessment Report. In Section 9.2, the functions and values of coastal zones and small islands are discussed. Special emphasis is put on the importance of maintaining the proper functioning of coastal systems with regard to sustainable development and their resilience to climate change. Section 9.3 then discusses the likely consequences of climate change on sea-level rise, sea-surface temperatures, and tropical cyclones in the context of coastal zones and small islands. On this basis, Section 9.4 addresses the effects of climate change on biogeophysical systems, and Section 9.5 examines the socioeconomic impacts. Section 9.6 considers response strategies to climate change and the need to integrate them with other coastal management activities. Finally, Section 9.7 identifies needs and opportunities for future research and monitoring that would help nations to respond more appropriately to the likely impacts of climate change on coastal zones and small islands.

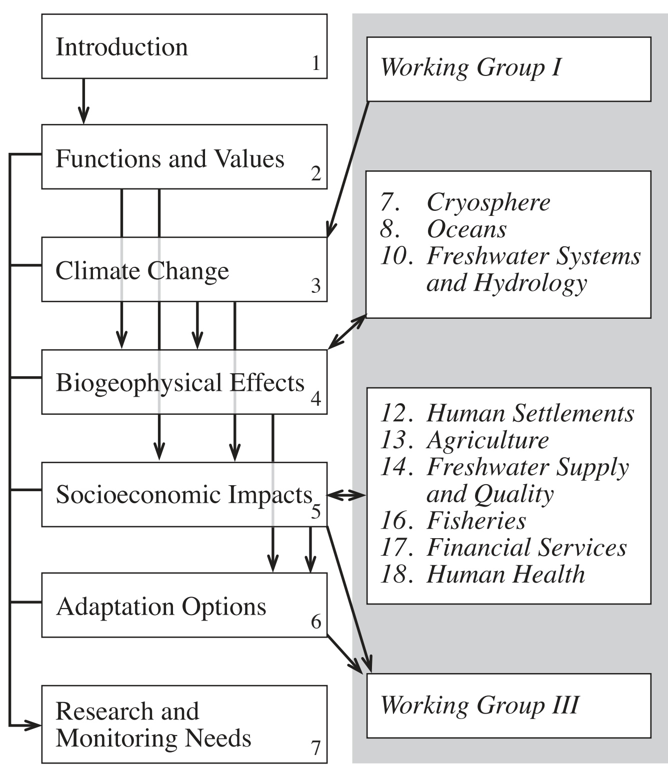


Figure 9-1: Structure of this chapter and interrelationships with other chapters and Working Group volumes of the IPCC Second Assessment Report.

9.2. Functions and Values of Coastal Zones and Small Islands

In large measure, human social and economic well-being depends directly or indirectly on the availability of environmental goods and services provided by marine and coastal systems. Coastal zones and small islands are characterized by highly diverse ecosystems, and a great number of functions are performed over a relatively small area. This concentration of functions, together with their spatial location, makes coastal zones and small islands highly attractive areas for people to live and work in. Coastal human populations in many countries have been growing at double the national rate due to migration to urban coastal centers; it is estimated that 50–70% of the global human population lives in the coastal zone, although there are great variations among countries. The existing rate of socioeconomic development in coastal zones also is unprecedented (WCC'93, 1994).

9.2.1. Functions and Values

The total economic value of coastal systems is more than simply the financial value of the coastal resources that they produce. It also includes their role in regulating the environment, their satisfaction of subsistence needs, and their satisfaction of human intellectual and emotional needs. De Groot (1992a) and Vellinga *et al*. (1994) have categorized the environmental functions performed by natural systems as regulation functions, user and production functions, and information functions. *Regulation functions* are crucial in safeguarding environmental quality. They include regulation of erosion and sedimentation patterns, regulation of the chemical composition of the atmosphere and oceans, flood prevention, waste assimilation, maintenance of migration and nursery habitats, and maintenance of biological diversity. Many natural and seminatural coastal systems thus play a fundamental part in the regulation of essential biospheric processes that contribute to the maintenance of a healthy environment and the long-term stability of the biosphere, including the climate system. *User and production functions* are essential in providing many living and nonliving resources that are utilized by human society. These functions include the provision of space and a suitable substrate for human habitation and a variety of socioeconomic activities. Important socioeconomic activities in coastal zones and small islands include tourism and recreation, exploitation of living and nonliving resources (e.g., fisheries and aquaculture; agriculture; extraction of water, oil, and gas), industry and commerce, infrastructure development (e.g., harbors, ports, bridges, roads, sea-defense works), and nature conservation. *Information functions* relate to the part that nature plays in meeting human intellectual and emotional needs. For example, coastal systems can be a source for cultural inspiration, but they also serve as a storehouse for genetic information. Also, scientific understanding of coastal processes and evolution depends on the geological and biological information that coastal systems contain.

Any coastal system can yield values related to the direct, indirect, and future use of the functions described above, as well as non-use, or intrinsic, values (Turner, 1988, 1991; Barbier, 1994). This is illustrated by Figure 9-2. Empirical

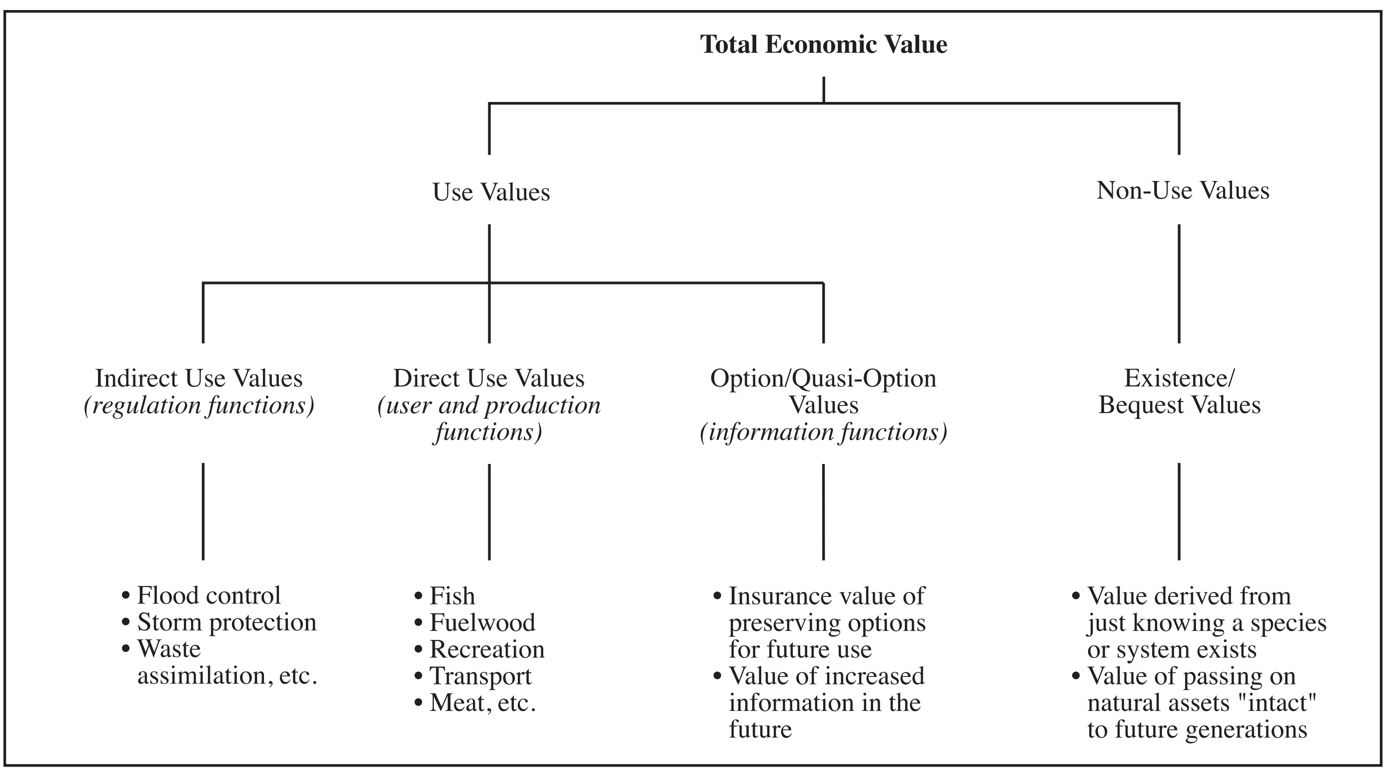


Figure 9-2: Values of coastal systems (adapted from Barbier, 1989).

studies confirm that coastal systems possess significant economic value, in terms of both use and non-use outputs. Mangrove forests, for example, have been shown to sustain more than 70 direct human activities, ranging from fuelwood collection to artisinal fisheries (Dixon, 1989). However, some uses preclude others, so some caution is necessary when the total economic value of such a system is estimated. This caution is also justified by the fact that many functions provide nonmarket goods and services and therefore do not carry appropriate market prices and value. Moreover, individuals and communities may find that nature has a value of its own, independent of human use or perception. They would therefore value nature purely because it exists and would feel a loss if it was damaged or destroyed.

Nonetheless, some studies are available that have produced estimates of the monetary value of coastal functions, using a variety of techniques. For example, recreation and amenity benefits provided by the Broadlands coastal wetland in England are estimated to be around $5 million per year (Bateman *et al*., 1995). The storm buffering function of the Terrebonne coastal wetlands in Louisiana (United States) has been valued in terms of storm damage avoided. If the wetlands continue to recede at their present rate (3–4 m/yr), the present discounted value of increased expected property damage lies between $2.1–3.1 million (Constanza *et al*., 1989). The total monetary value of all functions performed in the Ecuadorian Galápagos National Park amounts to $138 million per year (De Groot, 1992a).

9.2.2. Sustainable Development

In most coastal nations, a considerable part of gross national product (GNP) is derived from activities that are directly or indirectly connected with coastal zones. Therefore, maintaining the proper functioning of marine and coastal systems is of significant concern to a country's economy. In the shorter term, however, large financial benefits may be available at the expense of longer-term sustainability. Many coastal problems that are currently being encountered worldwide can be attributed to the unsustainable use and unrestricted development of coastal areas and resources. These problems include the accumulation of contaminants in coastal areas, erosion, and the rapid decline of habitats and natural resources. Great care must therefore be taken in planning to avoid overdevelopment and degrading or destroying the very environment that attracted coastal development in the first place.

Nonetheless, increasingly large areas of coasts and small islands have been managed with the aim of maximizing the financial "resource take" provided by the user and production functions performed by coastal systems. However, when one particular function is overexploited, this may not only result in the depletion of the resources that this function provides; it can also reduce the performance of other functions below their full potential. For example, when mangroves are logged and cleared in an unsustainable way, it can be at the expense of functions that enable fish to breed and be caught in the same area or that protect the coast from being eroded. The same applies when the capacity of regulation functions is exceeded—for example, when coastal waters are polluted beyond their waste-assimilative capacity. The maintenance of all functions at a sustainable level would provide higher economic returns over a longer period of time.

One can state that sustainable development in coastal zones and small islands is realized only when it enables the coastal system to self-organize—that is, to perform all its potential functions without adversely affecting other natural or human systems. Climate change could pose an additional threat to the full performance of these functions, compounding the pressures that present-day development activities already place on coastal zone capacities. Overexploitation of resources, pollution, sediment starvation, and urbanization may inhibit or destroy the working of functions that are essential to the provision of goods and services that are difficult to value in monetary terms, or in maintaining the resilience of coastal ecosystems to external stresses, such as climate change. For instance, one important regulation function of natural systems in coastal zones and small islands is the provision of a buffering capacity, protecting the land against the dynamics of the sea. As climate changes and sea level rises, this function will become even more important than it is today, preventing coastal areas from being eroded and inundated as much as they would without this natural protection. Nevertheless, although present-day human activities often result in large financial payoffs in the short term, they may also lead to environmental degradation. Such degradation results in the loss of functions, may increase coastal vulnerability to climate change, and has adverse economic effects on tourism, fishing, and other aspects of the coastal economy. In some cases, the long-term costs of these environmental disruptions may be greater than the long-term benefits of the human activity that caused them.

9.3. Aspects of Climate Change of Concern to Coastal Zones and Small Islands

Sea-level rise and possible changes in the frequency and/or intensity of extreme events, such as temperature and precipitation extremes, cyclones, and storm surges, constitute the components of climate change that are of most concern to coastal zones and small islands. Short-term extreme events are superimposed on long-term changes in CO_2 concentrations, climate, and sea level, and all aspects work in concert to bring about environmental change at regional and local levels. In order to understand fully their interactive effects on the coast, it is paramount to know how the means, variability, and extremes of the range of relevant climatic elements will change at local and regional scales. At such scales—with possibly a few exceptions—the predictive capability of models is currently very low, and knowledge about possible future changes in variability and extremes is meager. This section summarizes the main findings regarding sea-level and climate change that pertain to coastal zones (see the IPCC Working Group I volume for a full discussion).

9.3.1. Sea-Level Rise

9.3.1.1. Global Projections

In 1990, IPCC provided a best estimate and a range of uncertainty of sea-level rise, based on a "business-as-usual" projection of greenhouse-gas emissions for the period 1990–2100. It was estimated that sea level would, on average, rise by about 6 mm/yr, within a range of uncertainty of 3–10 mm/yr (Warrick and Oerlemans, 1990). Subsequent to IPCC90, projections of sea-level rise have been lower, largely as a result of downward revisions in the rate of global warming, which drives sea-level rise (see Section 9.3.2).

Present estimates of sea-level rise have been presented in Chapter 7, *Changes in Sea Level*, of the IPCC Working Group I volume. For a forcing scenario (IS92a) comparable to that of the IPCC 1990 assessment, it is estimated that sea level would, on average, rise by about 5 mm/yr, within a range of uncertainty of 2–9 mm/yr (see Figure 9-3). An important point to bear in mind is that the current best estimates represent a rate of sea-level rise that is about two to five times the rate experienced over the last 100 years (i.e., 1.0–2.5 mm/yr). The current projections of sea-level rise should therefore be of major concern in the context of coastal zones and small islands. Furthermore, model projections show that sea level will continue to rise beyond the year 2100 due to lags in climate response, even with assumed stabilization of global greenhouse-gas emissions (Wigley, 1995).

9.3.1.2. Regional Implications

One cannot assume that changes in sea level at regional and local levels will necessarily be the same as the global-average change, for two broad reasons. First, vertical land movements affect sea level. With respect to the coastal environment, it is relative sea level that is most important—that is, the level of the sea in relation to that of the land. Regionally and locally, vertical land movements can be quite large, even on the decadal time scale. For example, parts of Scandinavia experience uplift (and thus a relative sea-level decline) of about 1 m per century due to the continuing "glacial rebound" following the contraction of the large continental ice sheets at the end of the last Ice Age some 10,000 years ago (Aubrey and Emery, 1993). In contrast, the Mississippi delta is experiencing subsidence (a relative sea-level rise) of about 1 m per century due to consolidation by sediment loading and the diminished supply of additional sediments to the delta required for accretion (Day *et al*., 1993; Boesch *et al*., 1994). Locally, tectonic activity, groundwater pumping, and petroleum extraction can cause large and sometimes abrupt changes in relative sea level (Milliman *et al*., 1989; Han *et al*., 1995b). Subsidence of urban areas due to groundwater withdrawal has been a significant problem in many locations. In Japan, for example, 2.1 million people live in protected areas below high water due to this cause. Box 9-1 includes four examples of observed sea-level change. Emery and Aubrey (1991) have provided a comprehensive discussion of the

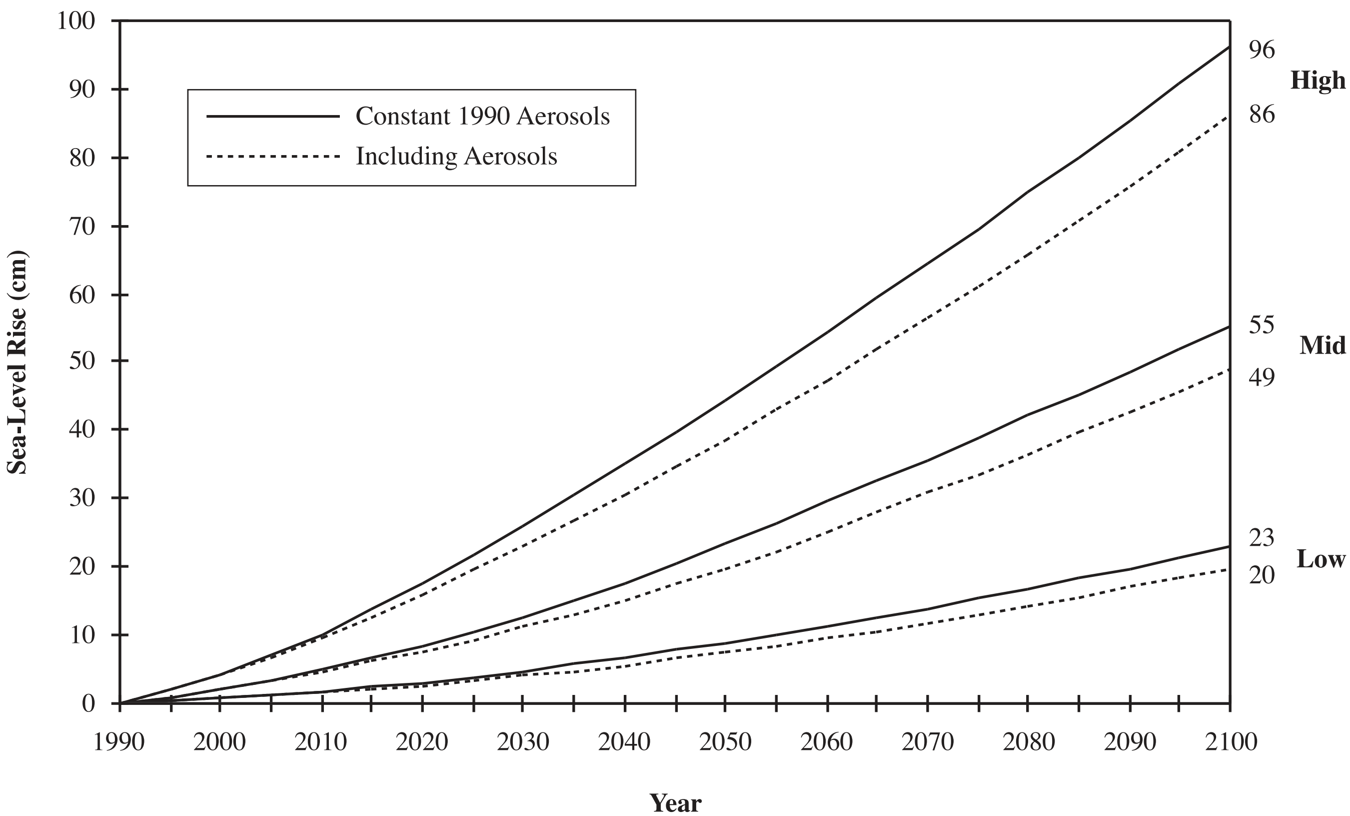


Figure 9-3: 1990–2100 sea-level rise for scenario IS92a (see Chapter 7, *Changes in Sea Level*, of the Working Group I volume).

Box 9-1. Four Examples of Observed Sea-Level Change

Figure 9-4 shows tide-gauge measurements of sea-level changes in Stockholm (Sweden), Fort Phrachula (Bangkok, Thailand), Honolulu (Hawaii, United States), and Nezugaseki (Japan). In a period of rising global sea levels, these four places show different trends in sea-level change due to their being situated in different geological settings. This illustrates the importance of local conditions on relative sea level. In Stockholm, glacial rebound is causing the land to rise out of the sea, resulting in a sea-level fall relative to the land of ~4 mm/yr. In Bangkok, human influence is apparent: Although over the period 1940–1994 relative sea-level rise averages 13.19 ± 0.73 mm/yr, two separate trends can be distinguished; the first, until about 1960, averages ~3 mm/yr, and the second, from 1960 onward, is ~20 mm/yr. The latter trend reflects the increased effort in groundwater pumping since 1960 (Emery and Aubrey, 1991). Nezugaseki shows the dramatic effects of an earthquake, which caused a 15-cm land submergence in 1964, along a coast generally dominated by emergence (Emery and Aubrey, 1991). The Honolulu record is believed to reflect a stable site and it is the only one of the four examples that approximates the global trend.

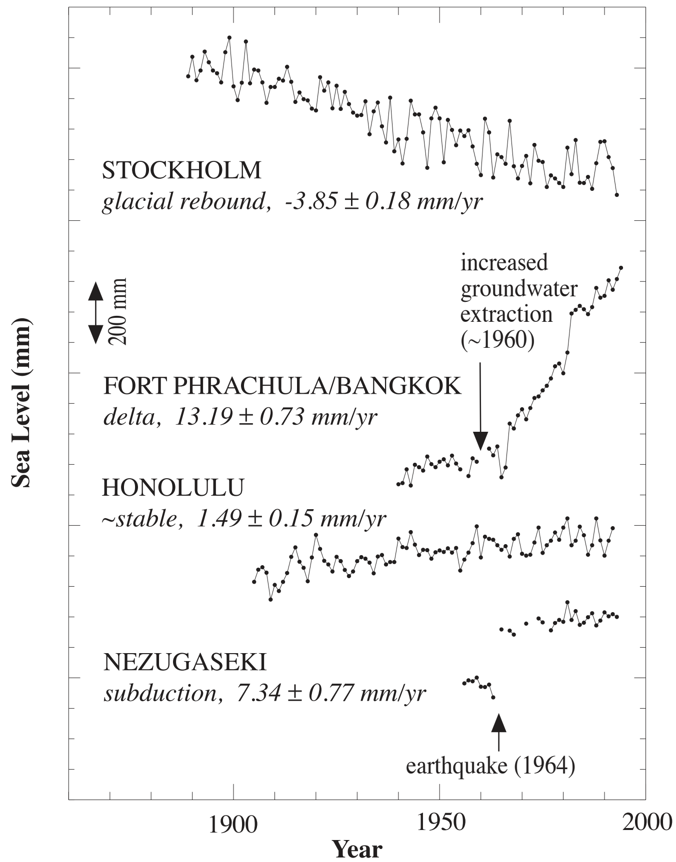


Figure 9-4: Relative sea-level records for Stockholm, Fort Phrachula (Bangkok), Honolulu, and Nezugaseki, indicating the geological settings and observed trends of the four sites (data provided by the Permanent Service for Mean Sea Level, Bidston).

effects of vertical land movements on relative sea level. In assessing coastal impacts, such vertical land movements must be considered in conjunction with climate-related changes in sea level.

Second, there are dynamic effects resulting from oceanic circulation, wind and pressure patterns, and ocean-water density that cause variations in the level of the sea surface with respect to the geoid—that is, the surface that the ocean would describe in the absence of currents, winds, and so forth. These variations have been observed to be on the order of 1 m for major current systems such as the Gulf Stream, Kuroshio, and the Antarctic Circumpolar Current (Pugh, 1987; Levitus, 1982). Climate change may affect ocean circulation, which can result in regional changes of this sea-surface "topography." Recent advances in ocean-atmosphere modeling offer some idea of the possible magnitude of such changes (e.g., Mikolajewicz *et al*., 1990; Gregory, 1993; Murphy, 1992; Church *et al*., 1991; Cubasch *et al*., 1992). Model results show ranges of regional sea-level change that are on the order of two to three times the global-average change (see Box 8-2 in Chapter 8). However, it should be emphasized that confidence in coupled ocean-atmosphere model predictions of regional sea-level changes still must be considered low, as reliable regional scenarios of this effect are not yet available for impact analysis.

9.3.2. Climate Changes

One of the certainties regarding global climate change is that the *atmospheric concentration of carbon dioxide* (the major player among the greenhouse gases), now about 360 ppmv, has increased by about 29% over the preindustrial concentration and will continue to increase in the future, even if rather stringent policies on CO_2 emissions were adopted. Although controversial, there is some evidence that increased CO_2 would lead to significant increases in net primary productivity through enhanced photosynthesis (Melillo *et al*., 1993), which could potentially have far-reaching implications for coastal vegetation and the coastal environment.

Recent projections of *global warming* (Mitchell and Gregory, 1992; Wigley and Raper, 1992; see also Chapter 6, *Climate Models—Projections of Future Climate*, of the IPCC Working Group I volume) are somewhat lower than those presented in IPCC90 (about 0.2°C per decade, as compared to 0.3°C per decade averaged over the next century). Nonetheless, the best-estimate projection still falls within a very large range of uncertainty. Thus, such projections are plausible scenarios of what could occur, not necessarily of what will occur. This caution should be applied even more emphatically to regional details of climate change as they are derived from general circulation models (GCMs). While refinements have been made since

IPCC90, the overall judgment is that confidence in the predicted patterns of climate change at spatial scales relevant to coastal zones and small islands must still be regarded as low (Gates *et al*., 1992, 1990; Mitchell *et al*., 1990; McGregor and Walsh, 1993). Nonetheless, there are some broad regional results that are consistently produced by equilibrium and transient GCM experiments that have relevance to the coastal zone. These results include (Mitchell *et al*., 1990; Gates *et al*., 1992):

- The mean surface air temperature increases more over land than over oceans (by about a factor of two), and at higher latitudes during winter. The climate of the coastal zone tends to be moderated by ocean temperature and will thus be strongly influenced by sea-surface temperature changes. Northern Hemisphere warming is greater than Southern Hemisphere warming because of the larger extent of land.
- In general, global models show increases in precipitation throughout the year in the high latitudes and during the winter in mid-latitudes. Most models show some increase in Asian monsoon rainfall.
- At scales relevant to coastal zones and small islands, predictions of changes in other climate elements, such as windiness, storminess or radiation, cannot yet be considered reliable.

Although changes in *sea-surface temperatures* (SSTs) are projected to be less than those on land, they are not necessarily less significant. As Edwards (1995) has pointed out, a 2°C change in SST in the tropical and subtropical oceans is considered to be anomalous, but is on the order of temperature changes associated with strong El Niño/Southern Oscillation (ENSO) events. In comparison, the projected change in mean sea-surface temperature for these regions is on the order of 1–2°C by the year 2100. Thus, by 2100, SSTs that are now considered anomalous could well be normal occurrences. Such warming would be unprecedented in the recent geological past.

Tropical cyclones (also known as hurricanes or typhoons, depending on region) affect vast coastal areas in tropical and subtropical countries. Tropical cyclones and associated storm surges can cause enormous loss of life and have devastating impacts on coastal ecosystems and morphology. It is therefore of critical importance to know how the frequency, magnitude, and areal occurrence of such storms will change in a warmer world, if at all. Unfortunately, the evidence from theoretical and numerical models and from observational data is, as yet, inconclusive. While current GCMs provide some indication of possible tropical cyclone formation, identifying "tropical disturbances" (e.g., see Broccoli and Manabe, 1990; Haarsma *et al*., 1993), they cannot explicitly model such storms at the present grid-scale resolution (Mitchell *et al*., 1990). However, recent work has been moving in this direction (e.g., Bengtsson *et al*., 1994). Alternatively, theoretical storm models have been used to examine the maximum storm intensity in relation to SSTs (Emanuel, 1987) but cannot easily be extended to address questions of regional changes in tropical storm intensity or frequency under conditions of climate change (Schlesinger, 1993; Lighthill *et al*., 1994).

At present, there is no evidence of any systematic shift in *storm tracks*. The tracks are governed by the location of cyclogenesis and prevailing meteorological conditions; thus far, there is no evidence of shift in the preferred locations of cyclogenesis. Empirical studies have found correlations between ENSO and the regional patterns of tropical cyclone activity (as well as the Southeast Asian monsoon, Atlantic hurricanes, Pacific precipitation patterns, and other phenomena) (Nicholls, 1984; Evans and Allan, 1992; see also Chapter 3, *Observed Climate Variability and Change*, of the IPCC Working Group I volume). Progress is being made on model simulations of the present features of ENSO-like events (e.g., Philander *et al*., 1992), which could lead to a predictive capability for the future. Recent coupled-model simulations under enhanced CO_2 show a tendency toward ENSO-like patterns in the Pacific, with accompanying temperature and precipitation variability (see Chapter 6, *Climate Models—Projections of Future Climate*, of the IPCC Working Group I volume), but realistic simulations of ENSO are not yet possible. The behavior of ENSO is critical in understanding the future coastal effects of both climate change and sea-level rise in the Pacific region and elsewhere (Pittock and Flather, 1993; Pittock, 1993). In short, it is not yet possible to say whether either the intensity or frequency of tropical cyclones (or ENSO) would increase or the areas of occurrence would shift in a warmer world.

Despite the often repeated assertion that *climate variability* could increase in a warmer world, there is little evidence from climate models to support this notion (Gates *et al*., 1992). However, Working Group I has identified at least one exception that has potentially large implications for coastal areas: Various GCMs consistently predict a higher frequency of convective precipitation in mid- to high-latitude regions of the world. This anticipated change may imply more intense local rainfall, with a decrease in the return period of extreme rainfall events (e.g., Gordon *et al*., 1992). This could interact with sea-level rise to further increase the likelihood of flooding in low-lying coastal areas (Titus *et al*., 1987; Nicholls *et al*., 1995).

Without any change in variability, however, a change in mean value still implies a change in the frequency of *extreme events*. Because such events by definition are at the tails of the probability distribution, the change in return periods can be quite large relative to the change in mean value. In the absence of information about changes in variability, this simple concept has been employed to create scenarios of changes in extremes—for example, for temperature in Britain (Warrick and Barrow, 1991), rainfall in Australia (Pittock *et al*., 1991), and storm surges in the United States (Stakhiv *et al*., 1991). As has been pointed out at the beginning of this section, in most cases it is the combination of climate extremes—temperature, precipitation, winds, sea levels—and how they are affected by longer-term changes in climatic means that are especially important for considering the future effects of global warming on coastal zones and small islands. Yet little understanding of the possible interaction of different aspects of climate change in the coastal zone exists.

9.4. Biogeophysical Effects

In the 1990 IPCC Impacts Assessment, Tsyban *et al*. (1990) suggested that the most important aspects of climate change on the coastal zone would be the impact of sea-level rise on coastal residents and marine ecosystems. They argued that a rise in sea level would:

- Inundate and displace wetlands and lowlands
- Erode shorelines
- Exacerbate coastal storm flooding
- Increase the salinity of estuaries, threaten freshwater aquifers, and otherwise impair water quality
- Alter tidal ranges in rivers and bays
- Alter sediment depositional patterns
- Decrease the amount of light reaching water bottoms.

It was recognized then—and highlighted again in the IPCC 1992 supplement (Tsyban *et al*., 1992) and at the meeting *The Rising Challenge of the Sea* (IPCC CZMS, 1992; O'Callahan, 1994)—that such effects would not be uniform around the world and that certain coastal environments would be especially at risk. These included tidal deltas and low-lying coastal plains, sandy beaches and barrier islands, coastal wetlands, estuaries and lagoons, mangroves, and coral reefs. Small islands became a major focus of concern because some of the more extreme predictions foreshadowed that low atoll and reef islands would completely disappear or become uninhabitable, with the total displacement of populations of several small island nations (Roy and Connell, 1991).

Many of the early studies on the effects of climate change emphasized sea-level rise and were based on a simple inundation model that vertically shifted the land-sea boundary landward by the amount of the projected global rise. However, it has become increasingly clear from recent studies that the geomorphological and ecological responses to a rising sea level will be complex and will also reflect a large number of other factors, including other aspects of climate change. No longer can effects be defined simply in terms of inundation of the sea upon the land, nor by just shifting the land-sea contour by an amount corresponding to the projected vertical increase in global sea level. Biogeophysical effects will vary greatly in different coastal zones around the world because coastal landforms and ecosystems are dynamic and both respond to and modify the variety of external and internal processes that affect them. Effects will depend not only on the local pattern of sea-level rise and climate change (as shown in Section 9.3) but also on the nature of the local coastal environment and on the human, ecological, and physical responsiveness of the particular coastal system being considered (J.R. French *et al*., 1995).

Since the IPCC 1990 assessment, considerable progress has been made in understanding the effects of sea-level rise and climate change on coastal geomorphological and ecological systems. Studies have shifted from the use of simple, monothematic approaches to more complex yet pragmatic methods (Woodroffe, 1994). Three groups of approaches can be distinguished:

- Retrospective studies concerned with reconstructing past geomorphological and ecological responses to sea-level change in the Holocene, particularly during its rising stage
- Contemporary studies of geomorphological and ecological trends over the past several decades
- Mathematical and simulation modeling of coastal geomorphological and ecological systems using simplified sea-level rise scenarios and process assumptions.

In all three cases, emphasis has been on sea-level rise, with little consideration of other climate-change aspects, although sometimes increased seawater temperatures and storminess have been included. Invariably, global sea-level rise scenarios have been applied, irrespective of their appropriateness at the local or regional level. Further, several authors (e.g., Bird, 1993a; J.R. French *et al*., 1995) have argued that it is not always appropriate to employ Holocene stratigraphical reconstructions as analogues for the future behavior of coastal systems, primarily because of the modern complications of human impacts that may now have an overriding effect on geomorphological and ecological responses.

In spite of the increased research effort, there is still no generally accepted global typology of coastal types relating to the potential effects of sea-level rise and climate change. There have been some attempts based on the resistance of the coast to environmental forces (e.g., Van der Weide, 1993), some based on both natural and socioeconomic features and processes (Pernetta and Milliman, 1995), and some through the development of a coastal vulnerability index that captures the different characteristics of a coastal region (e.g., Gornitz, 1991). The development of such a typology is clearly an area for substantial international research in the future. Moreover, the emphasis of recent studies on coastal types has been quite uneven. For instance, there has been little research on the potential effects of sea-level rise and climate change on high-latitude coasts, bold coasts, rocky shores, coastal cliffs, coarse clastic coasts, gravel barriers, coastal sand dunes, and seagrass beds. This lack of emphasis, however, does not necessarily imply that anticipated effects on these coastal types are less serious. Studies that show a strong correlation between sea-level rise and erosion of, for example, coastal cliffs, gravel barriers, and sand dunes include Griggs and Trenhaile (1994), Carter and Orford (1993), and Van der Meulen *et al*. (1991), respectively.

There are several comprehensive reviews on the biogeophysical effects of climate and sea-level change on coastal environments (e.g., Bird, 1993b; Oude Essink *et al*., 1993; Wolff *et al*., 1993). In addition to these general reviews there is a series of regional summaries covering a large area of the world—including the Mediterranean (Jeftic *et al*., 1992), European coastal lowlands (Tooley and Jelgersma, 1992), Southeast Asia (Bird, 1993a), the South Pacific (Hay and Kaluwin, 1993), wider Caribbean (Maul, 1993), the Western Hemisphere

(Ehler, 1993), and the Eastern Hemisphere (McLean and Mimura, 1993)—as well as some edited volumes on specific themes, including geomorphic response (J.R. French *et al*., 1995), coastal wetlands (Parkinson, 1994), and developing countries (Nicholls and Leatherman, 1995a). This section assesses first the biogeophysical effects of climate change on three distinct coastal geomorphic systems, then the effects on two important ecological systems, and finally the effects on coastal biodiversity.

9.4.1. Sedimentary Coasts, Sandy Beaches, Barriers, and Dunes

Open coasts, primarily made up of unconsolidated sands and gravels and exposed to wind and wave action, are common on all inhabited continents and islands of all sizes. About 20% of the world's coast is sandy and backed by beach ridges, dunes, or other sandy deposits. International studies reported by Bird (1985, 1993b) indicate that over the last 100 years about 70% of the world's sandy shorelines have been retreating; about 20–30% have been stable and less than 10% advancing. He has listed at least twenty possible reasons for the prevalence of erosion and has indicated that sea-level rise is only one possibility. Although Stive *et al*. (1990), Leatherman (1991), and others have recognized a causal relationship between erosion and sea-level rise, many attempts to correlate accelerated coastal erosion with global sea-level rise over the last 100 years have not been convincing because of the difficulties in excluding other factors, including human impacts. Analyses of erosional trends on sandy shorelines over the past several decades indicate a predominance of local rather than common explanations—suggesting that, if sea-level rise has been a contributor, its contribution may have been masked by other mechanisms.

Two other approaches have been used to gauge the effect of sea-level rise on sedimentary coasts. First, models have been used to predict beach-profile changes that will result from a rise in water level. Model studies have been reviewed by international expert committees such as the Scientific Committee on Oceanic Research (SCOR, 1991), as well as by individuals (e.g., Healy, 1991; Leatherman, 1991). The best-known model is that of Bruun (1962), who formulated a two-dimensional relationship between rising sea level and the rate of shoreline recession based on the concept of profile equilibrium, which has been the subject of much evaluation (e.g., Dubois, 1992). SCOR (1991) has noted that testing and application of the models for beach response to a long-term rise in sea level have been hampered by significant lag times of beach changes—amounting to months or years—and the importance of other elements of the sediment budget that produce shoreline erosion or accretion irrespective of any sea-level rise. Profile changes assumed by the models have been reasonably well-verified by laboratory and field studies, but the predictive equations are found to yield poor results when the effects of profile lag times and complete sediment budgets are not included in the analysis. One solution to these uncertainties is to determine a range of beach-recession scenarios rather than a single estimate—although SCOR (1991) has concluded that the status of models for the beach response to elevated water levels is far from satisfactory; predictions of the associated shoreline recession rates yield uncertain results; and there is clear need for substantial research efforts (field and laboratory) in this area. A new generation of shoreface-profile evolution models is presently being developed (e.g., Stive and De Vriend, 1995).

Second, morphostratigraphic studies, particularly of sandy barriers, have been undertaken, although frequently these studies predate the recent interest in attempting to predict future coastal response to climate change and sea-level rise. Nevertheless, sandy-barrier responses to rises in sea level in the Holocene can be used as historical analogues. Although transgressive sedimentary sequences, where coastal barriers migrate landward as a result of shoreface erosion and washover, are widespread in North America, Europe, and Australia, other responses to sea-level rise include *in situ* growth (the stationary barrier) and even seaward advance (the regressive sequence). As with other approaches, field-based evolutionary morphostratigraphic models do not yield a consistent response to sea-level rise. Rate of sediment supply and coastal configuration are just two of the other factors that influence how sandy shorelines will respond. In addition to field-based studies, some indication of the complex way that sand barriers have responded to post-glacial sea-level rise has been shown through computer-simulation techniques (Cowell and Thom, 1994; Roy *et al*., 1994).

Collectively, all of these results suggest that with future sea-level rise there will be tendencies for currently eroding shorelines to erode further, stable shorelines to begin to erode, and accreting coasts to wane or stabilize. Locally, changes in coastal conditions and particularly sediment supply may modify these tendencies (Bird, 1985, 1993b).

9.4.2. Deltaic Coasts, Estuaries, and Lagoons

Deltas form where terrigenous sediment brought down to the coast by rivers accumulates more rapidly than can be removed by waves, tides, and currents. Although there is a wide spectrum of delta types around the world, all are the result of the interaction between fluvial and marine processes. Since ancient times, deltas have been of fundamental importance to civilizations due to the presence of highly productive agricultural lands, fisheries, and human settlement. Many modern delta regions, with their dense populations and intensive economic activities, are now in crisis because of past management practices such as dam, dyke, and canal construction and habitat destruction, which have led to problems such as enhanced subsidence and reduced accretion, salinity intrusion, water quality deterioration, and decreased biological production (Day *et al*., 1993; Boesch *et al*., 1994).

Deltaic coasts are particularly susceptible to any acceleration in the rate of sea-level rise (as well as storm frequency or intensity). As Baumann *et al*. (1984) have recognized, delta survival is a battle of sedimentation versus coastal submergence. Most deltas are subsiding under the weight of accumulating sediment, a process that often is enhanced by artificial groundwater withdrawal. Any global sea-level rise will exacerbate existing problems of local submergence. Bird (1993b) has argued that a rising sea level will have two major effects on low-lying deltaic areas: First, it is likely to cause extensive submergence, especially where there is little prospect of compensating sediment accretion. Second, progradation of most deltaic coastlines will be curbed, with erosion becoming more extensive and more rapid.

Similar conclusions have come from a host of case studies around the world, including those reported from Europe and the Mediterranean in Jeftic *et al*. (1992), Tooley and Jelgersma (1992), Poulos *et al*. (1994), and Woodroffe (1994); from the Americas in Day *et al*. (1993, 1994); and from Southeast Asia in McLean and Mimura (1993). While there appears to be general agreement among all of the studies on the implications of reduced sediment discharge, subsidence, and rising sea level, there have been few attempts to determine the relative vulnerability of deltaic regions or to model the effects of sea-level rise on deltas. Exceptions to the former include Ren's (1994) study of the Chinese coast, in which six variables (relief, land subsidence, shoreline displacement, storm surge, tidal range, and coastal defenses) have been used to evaluate risk classes of eight vulnerable areas. Exceptions to the latter include the conceptual model of general deltaic functioning developed by Day *et al*. (1994) and their two-state variable model, which simulates height in sea level and land elevation over time as a function of varying rates of sea-level rise, subsidence, and vertical accretion. Model results of the "date of immersion" (i.e., when sea level equals land elevation) have been produced for several sites in the Mississippi, Camargue, and Ebro deltas. Intradelta variations have been highlighted in the model results. In natural situations, such variations commonly result from variations in subsidence and/or changes in active and passive distributary positions across deltas, as demonstrated for the Nile (Stanley and Warne, 1993) and Rhine-Meuse (Tornqvist, 1993) deltas, respectively.

Studies on the physical response of tidal rivers and estuaries to predicted sea-level rise have covered two main areas—geomorphic changes and saltwater penetration—although the American Society of Civil Engineers (ASCE) Task Committee (1992) has indicated that several hydraulic processes such as tidal range, prism and currents, and sedimentation would also be modified. Bird (1993b) has suggested that estuaries will tend to widen and deepen. This may enhance their role as sediment sinks, causing greater erosion of the neighboring open coast (Stive *et al*., 1990). However, Pethick (1993) has shown that along the southeast coast of Britain, where relative sea-level rise is already 4–5 mm/yr due to local subsidence, estuarine channels are becoming wider and shallower by local redistribution of sediment as the intertidal profile shifts both upward and shoreward. In some areas, these effects may be offset by increased catchment runoff, greater soil erosion, and increased sediment yield as a result of climate changes. However, as with deltas, critical factors will be relative sea-level change, including local subsidence (e.g., Belperio, 1993), and sediment availability (e.g., Chappell, 1990; Parkinson *et al*., 1994). In macrotidal estuaries in Northern Australia, channel widening initiated by rising sea level will contribute sediment to the adjacent estuarine plains, which may offset the effect of flooding and lead to steady vertical accretion. One consequence of this would be to endanger backwater swamps and freshwater ecosystems on the estuarine plains (Chappell and Woodroffe, 1994).

The effects of sea-level rise on saltwater penetration in rivers and estuaries have recently been reviewed by Oude Essink *et al*. (1993) and Van Dam (1993), who have suggested that saline water will gradually extend further upstream in the future. More serious is the accelerated effect of saline water intruding into groundwater aquifers in deltaic regions and coastal plains. In these areas, the effect of sea-level rise can be exacerbated by the withdrawal of freshwater, which may result in either subsidence and/or replacement by seawater. Subsidence and landward migration of saltwater are already serious problems in many coastal deltaic areas around the world. Two examples are Myanmar (Aung, 1993) and China (Han *et al*., 1995b).

9.4.3. Coral Atolls and Reef Islands

Coral atolls and reef islands appear especially susceptible to climate change and sea-level rise. Based on the sea-level rise scenarios of the 1980s and the application of simple models, Pernetta (1988) developed an index of island susceptibility for the South Pacific region and concluded that the most susceptible nations included those "composed entirely of atolls and raised coral islands, which will be devastated if projected rises occur," and consequently "such states may cease to contain habitable islands." Three related effects were envisaged: erosion of the coastline, inundation and increased flooding of low-lying areas, and seawater intrusion into the groundwater lens, which would cause reductions in island size, freeboard, and water quality, respectively.

Since that time, a series of vulnerability assessments of atolls and reef islands have been carried out. Studies include the atoll states and territories of Tuvalu, Kiribati, Tokelau, and the Marshall Islands in the Pacific and the Maldives and Cocos (Keeling) Islands in the Indian Ocean (Aalbersberg and Hay, 1993; Woodroffe and McLean, 1992; McLean and D'Aubert, 1993; Holthus *et al*., 1992; Connell and Maata, 1992; Pernetta, 1992; McLean and Woodroffe, 1993). Generally, these studies have documented the likelihood of more complex and variable responses than initially suggested, recognizing that the balance between reef growth, island accumulation or destruction, and sea-level rise will be locally important. Differences in response can be further expected between islands within and beyond storm belts, between those composed primarily of sand and those of coral rubble, and between those that are or are not anchored to emergent rock platforms. The presence or absence of natural physical shore-protection structures in the form of beachrock or conglomerate outcrops and biotic protection in the form of mangrove or other strand vegetation will also result in different responses between islands.

It is not clear to what extent reef islands will erode or whether sediment from the adjacent reef or lagoon will contribute to the continued growth of islands. McLean and Woodroffe (1993) have envisaged at least three possible responses in the face of sea-level rise: the Bruun response, the equilibrium response, and continued growth, which would result in shoreline erosion, redistribution of sediment, and shoreline accretion, respectively. Each of these processes can be observed on many reef islands today, as well as in the stratigraphic record, suggesting that the factors identified above are significant determinants of island stability. Moreover, as Spencer (1995) has pointed out, coral-island responses to future sea-level rise will vary as a result of constraints on the development of modern reefs and the varying inherited topographies upon which future sea-level will be superimposed.

On small islands, the freshwater lens is an important resource and often is the primary source of potable water on atolls. Recent studies suggest that the first approximation of the response of the freshwater lens to sea-level rise (the Ghyben-Herzberg principle) is not appropriate on small coral islands. The layered-aquifer model—which, among other things, considers geological structure and distinguishes between Pleistocene and Holocene stratigraphic units—is considered more appropriate for assessing freshwater inventories on such islands. If recharge and island width remain constant or expand, freshwater lenses may actually increase in size with a rise in sea level because of the larger volume of freshwater that can be stored in the less-permeable upper (Holocene) aquifer (Buddemeier and Oberdorfer, 1990). On the other hand, if recharge or island width are reduced, a diminution in both freshwater quantity and quality can be expected. In many places, increasing demand and recharge contamination are likely to be more serious issues than freshwater inventory *per se*.

Although recent reviews on coral islands have emphasized their variability and resilience (e.g., Hopley, 1993; McLean and Woodroffe, 1993), such islands remain among the most sensitive environments to long-term climate change and sea-level rise, especially where these effects are superimposed on destructive short-term events such as hurricanes, damaging human activities, and declining environmental quality. In spite of a more optimistic outlook in recent years, Wilkinson and Buddemeier (1994) have maintained that coral-reef islands may be rendered uninhabitable by climate change, especially sea-level rise, and that will necessitate relocation of any remaining human populations (see also Section 9.5).

9.4.4. Coastal Wetlands

Coastal wetlands are frequently associated with deltas, tidal rivers, estuaries, and sheltered bays. Geomorphic and hydrologic changes resulting from sea-level rise will have important effects on these biological communities, as well as on unvegetated tidal flats. The survival of the latter is dependent very much on sediment supply from adjacent river catchments—which, if not provided, will result in substantial loss of such areas. Although Woodroffe (1993) has commented that research on coastal wetlands has concentrated upon reconstructing their development under conditions of sea-level rise during the Holocene, there also have been assessments of contemporary trends and processes and simulation modeling of environmental changes.

Historical studies of temperate salt marshes include those of Allen (1991) and Reed (1990), whereas Pethick (1993) and French (1993) have used current trends and numerical simulation, respectively. Pethick (1993) has shown that salt marshes in southeast England appear to be migrating inland along the estuary but that the natural changes are interrupted by the presence of flood embankments. The result is that loss of the seaward boundaries of these wetlands will continue without compensating landward migration—a process known as coastal squeeze in the United Kingdom. Wolff *et al*. (1993) have concluded that salt marshes have the ability to respond quickly to sea-level rise as long as sedimentation and internal biomass production processes keep pace and as long as the entire marsh can move to higher shore levels or further inland. Provided that it is not constrained by infrastructure, protection works, or other barriers, vertical accretion is likely to neutralize sea-level rise as long as sediment supply is sufficient and horizontal erosion is absent or can be compensated. If not, salt marshes will progressively decline and ultimately disappear. Pethick (1992) has also shown that salt marshes under stable sea level undergo cyclical changes to their seaward boundaries; infrequent high-magnitude storm events erode the edges, while intervening lower-magnitude events allow depositional recovery. An increase in the frequency of storm events as a response to sea-level rise would result in the replacement of such cyclical change by progressive erosion. The sensitivity of certain salt-marsh species to waterlogging and soil-chemical changes also could result in a change in species composition or the migration of vegetation zones (Reed, 1995).

Mangroves grow largely in tidal forests and are characterized by adaptations to unconsolidated, periodically inundated saline coastal habitats. They fringe about 25% of shorelines in the tropics and extend into the subtropics as far north as Bermuda and as far south as North Island, New Zealand. Studies on the effects of sea-level rise on tropical mangrove ecosystems have been primarily of historical nature (reviewed by Woodroffe, 1990; UNEP-UNESCO Task Team, 1993; Edwards, 1995). These studies have shown that extensive mangrove ecosystems became reestablished when sea level stabilized around 6,000 years BP. During the prior rise, mangroves probably survived as narrow coastal fringes, shifting landward with the migrating shoreline. Ellison and Stoddart (1991) and Ellison (1993) have indicated that mangroves in areas of low sediment input in both low-island and high-island settings appear to be unable to accrete vertically as fast as the projected rate of sea-level rise. However, recent evidence from the Florida Keys (Snedaker *et* *al.*, 1994) has shown that low-island mangroves may be resilient to rates of sea-level rise about twice those suggested as upper limits by Ellison and Stoddart (1991) from their study in Bermuda. It is also apparent that mangrove communities are more likely to survive in macrotidal, sediment-rich environments such as Northern Australia, where strong tidal currents redistribute sediment (Semeniuk, 1994; Woodroffe, 1995), than in microtidal sediment-starved environments such as around the Caribbean (Parkinson *et al.*, 1994).

If the rate of shoreline erosion increases, mangrove stands may tend to become compressed and suffer reductions in species diversity. On the other hand, extensive mangroves in deltaic settings with continuing large inputs of terrigenous sediment are likely to be more resilient to sea-level rise (Edwards, 1995). Thus, different responses can be envisaged in different mangrove settings. Additionally, certain species are likely to be more robust in the face of sea-level rise than others (Ellison and Stoddart, 1991; Aksornkaoe and Paphavasit, 1993).

It is now becoming increasingly clear, as Woodroffe (1993, 1994) and Edwards (1995) have observed, that coastal wetlands (marshes and mangroves) can undergo a number of responses to sea-level rise. Responses may be different in muddy, tide-dominated systems than in more organic systems, in areas of high or low tide range, and in areas of high or low sediment and freshwater input. Thus, the balance between accretion and submergence will be complex, and a range of morphological responses is likely for different coastal types and coastal settings. Although some marshes and mangroves may be under threat from sea-level rise over the next century, human impact has been the major threat up to the present and may be far more important locally than climate change in the long term (Bird, 1993a; WCC'93, 1994). In the case of mangroves, afforestation programs may be one way to compensate for natural or human-induced losses, although experiences in Bangladesh have indicated the difficulties in such a program (Saenger and Siddigi, 1993). There also is some evidence that coastal wetlands may experience loss due to short-term (decadal) acceleration in the rate of sea-level rise (Boesch *et al.*, 1994; Downs *et al.*, 1994).

Whereas mangroves are restricted to the intertidal zone, and salt marsh extends landward into supratidal areas, seagrasses extend subtidally to maximum depths of several tens of meters. Relatively little appears to have been published on the possible effects of climate change and sea-level rise on seagrasses (used here generically to include eelgrasses, turtlegrasses, etc.), although their biology and biogeography have been studied extensively (e.g., Larkum *et al.*, 1989; Mukai, 1993). Edwards (1995) has provided a brief but comprehensive analysis, noting the economic importance of seagrasses, and their ability to trap sediment, accrete vertically, stabilize unconsolidated sediment, slow water movement, and generally serve as natural coastal protection agents. Edwards (1995) has argued that intertidal and shallow seagrass beds (<5 m depth) are most likely to be affected by climate change, particularly by any sustained elevations in sea temperature or increases in freshwater runoff from land. However, the main threat to seagrass habitats is likely to come from increased anthropogenic disturbances, including dredging, overfishing, water pollution, and reclamation. In some parts of the world, seagrass beds are already severely threatened (Fortes, 1988), although elsewhere they have expanded due to eutrophication of estuarine waters.

9.4.5. Coral Reefs

Coral reefs are estimated to cover about 600,000 km^2 of the Earth's surface (Smith, 1978). They are dominated by calcifying organisms that are depositing about 0.6 to 0.9 Gt of calcium carbonate ($CaCO_3$) globally each year (Kinsey and Hopley, 1991). Intuitively, one would think that coral reefs—by precipitating $CaCO_3$ and sequestering carbon—would act as sinks for CO_2, but on the decade to century timescale this is not the case (Smith and Buddemeier, 1992). The calcification process actually generates CO_2 (Ware *et al.*, 1992), and over periods of decades reefs may contribute about 0.02 to 0.08 Gt C/yr as CO_2 to the atmosphere.

The effects of climate change on coral reefs, as well as nonclimatic anthropogenic disturbances, have recently been reviewed by Smith and Buddemeier (1992), Wilkinson and Buddemeier (1994) and Edwards (1995). The global climate-change effects of significance to coral reefs are likely to be increases in seawater temperature and sea-level rise; locally or regionally, changes in storm patterns and coastal currents, as well as changes in rainfall patterns, may have effects on coral communities—for example, through increases in sedimentation.

Coral reefs are particularly sensitive to increases in seawater temperature (Brown, 1987) and increased irradiance (Brown *et al.*, 1994). They respond to the combined effect of irradiance and temperature elevations by paling in color, or bleaching (Brown and Ogden, 1993). Corals do not generally bleach in response to rapid fluctuations in seawater temperature but rather to departures in temperature above their seasonal maximum. If the temperature elevation involves a substantial increase in seawater temperature (3–4°C) for an extended period (>6 months), considerable coral mortality can ensue (Brown and Suharsono, 1990). If, however, the temperature increase is only on the order of 1–2°C and for a limited period, bleached corals may recover but show reduced growth and impaired reproductive capabilities (Brown and Ogden, 1993).

Projected increases in seawater temperatures thus appear to be a major threat to coral reefs. In Indonesia, where severe bleaching took place as a result of seawater warming during an ENSO event in 1983, coral reefs have failed to show continued recovery beyond the initial recovery noted in 1988 (Brown and Suharsono, 1990). Such results have been mirrored in studies in the Galápagos and eastern Panama, where little recovery has been noted since major bleaching in 1982–1983. At sites in the East Pacific, reefs subsequently have shown rapid bioerosion from the destructive grazing activities of sea urchins, and destabilization of reef substrates is anticipated. Full community restoration probably will not occur for several hundred years (Glynn, 1993).

Reef accretion rates—calculated from community calcification rates, growth rates of calcifying organisms, and radiocarbon dating of cores through reefs—range from less than 1 mm/yr to a maximum slightly in excess of 10 mm/yr (Buddemeier and Smith, 1988; Hopley and Kinsey, 1988; Kinsey, 1991). A rate of 10 mm/yr is commonly taken as the consensus value for the maximum sustained vertical reef accretion rate (Buddemeier and Smith, 1988). The present best estimates for global sea-level rise over the next century (see Section 9.3) are well within the range of typical reef accretion rates. Even slowly accreting reef flats should, on average, be able to keep up with this rate of sea-level rise after a lag, provided that other factors such as increased seawater temperatures and damaging anthropogenic influences are not acting simultaneously (Edwards, 1995). Widespread warming of seawater, however, will clearly limit the accretion rates of coral reefs—as exemplified by the Panamanian reef, which before suffering 50% coral mortality as a result of sea-surface warming during an ENSO event was depositing about 10 tonnes $CaCO_3$/ha/yr and now is eroding at a rate of approximately 2.5 tonnes $CaCO_3$/yr, equivalent to vertical erosion of 6 mm/yr (Eakin, 1995).

Smith and Buddemeier (1992) have expected shifts in zonation and community structure associated with the interaction between wave-energy regime and sea level, although far too little is known about the physiological and physical constraints to reef growth (Spencer, 1995). Wilkinson and Buddemeier (1994) have shown that coral reefs have come through episodes of severe climate change in the past and have the necessary resilience to cope with current scenarios of climate change. However, coral reefs near land masses and near large population centers will come under greater human pressure in the future and are likely to be damaged beyond repair.

9.4.6. Coastal Biodiversity

Through the biogeophysical effects on coastal geomorphic and ecological systems described in Sections 9.4.1 through 9.4.5, climate change has the potential to significantly affect coastal biological diversity. It could cause changes in the population sizes and distributions of species, alter the species composition and geographical extent of habitats and ecosystems, and increase the rate of species extinction (Reid and Miller, 1989). Coral reefs have the highest biodiversity of any marine ecosystem, with enormous numbers of different species packed into small areas (Norris, 1993). Despite the known and potential value of reef communities and the threats to their health and vigor, the total biodiversity of coral reefs is not known, nor is the fraction of the diversity that is described versus undiscovered. Reaka-Kudla (1995) has estimated that there are about 91,000 described species of coral-reef taxa but argues that undocumented diversity is likely to be much higher. Nonetheless, coral-reef macrobiota represent about 4–5% of the described global biota, although they occupy less than 1% of the Earth's surface. Coral-reef biodiversity is centered around the archipelagos of the Philippines and Indonesia; diversity decreases away from this core. For example, the number of coral species in French Polynesia drops to less than 10% of that in the core area (Wilkinson and Buddemeier, 1994). Similar geographical variations in species richness occur in mangroves and tropical seagrasses (Woodroffe, 1990; Mukai, 1993).

In addition to marine systems such as coral reefs, coastal zones also comprise the adjacent terrestrial environments. Although scientists have long studied the interactions between marine and terrestrial systems and have seen the coastal zone as a discrete entity, it is poorly understood ecologically (Ray, 1991). Among all macroscopic organisms, there are 43 marine phyla and 28 terrestrial phyla; 90% of all known classes are marine (Reaka-Kudla, 1995). Ray (1991) has estimated that 80% of marine phyla occur in the coastal zone, which occupies only 8% of the Earth's surface, and argues that the marine portion of the coastal zone is the most biologically diverse realm on the planet. For example, of the 13,200 species of marine fish, almost 80% are coastal. Tropical coastal zones are particularly rich, with about 182,000 described species (Reaka-Kudla, 1995); they are about twice as rich as temperate coasts.

Coastal zones are sharply subdivided by gradients in geomorphic structure and habitat diversity; this enables them to perform many of the regulation functions and user and production functions outlined in Section 9.2.1. Ray (1991) has identified a nexus between physical processes and ecological pattern and diversity; he suggests that if global warming accelerates during the next few decades, the extent of coastal lagoons, marshes, and so forth will be affected and that these changes will strongly influence the fate of associated biota. In addition, intensive habitat modification on land and deterioration of coastal areas will clearly result in a decline of global biodiversity. Similarly, the capacity of species and ecosystems such as mangroves to shift their ranges and locations in response to climate change will be hindered by human land-use practices that have fragmented existing habitats. The establishment of nature reserves is seen as an option to arrest the decline of coastal biodiversity (Ray and Gregg, 1991; De Groot, 1992b).

9.5. Socioeconomic Impacts

Section 9.4 outlines how the coastal environment can be altered by climate change and sea-level rise; such alterations could have significant effects on functions and values in coastal zones and small islands. This section presents an overview of the related socioeconomic impacts and their evaluation, with an emphasis on the problems of sea-level rise. It highlights the particularly vulnerable situation of low-lying small islands and deltas. The emphasis on sea-level rise reflects a bias of existing studies. A discussion of the human activities in coastal zones that increase vulnerability to climate change also is included.

9.5.1. Pressures and Management Problems in Coastal Zones and Small Islands

During the twentieth century, urbanized coastal populations have been increasing because of the many economic opportunities and environmental amenities that coastal zones can provide. The need to protect and enhance the wealth-creation potential of coastal zones has led to widespread coastal construction and modification of natural coastal processes, resulting in losses of coastal habitats, changes in circulation and material flux, and reductions in biological productivity and biodiversity. These pressures are expected to increase substantially in the coming decades (WCC'93, 1994).

Of particular concern is the worldwide destruction and degradation of coral reefs, mangroves, sea grasses, and salt marshes—which, among other things, act as natural barriers against marine erosion processes. The natural response of salt marshes and mangroves to sea-level rise—an upward and landward migration of the intertidal profiles (see Section 9.4)—is inhibited by flood embankments and other human constructions. The result is that erosion of the seaward boundaries of these wetlands will continue without a compensating landward migration, leading to loss of wetland area. Deltaic processes also are being modified. In the United States, for example, the Mississippi River delta was roughly in a state of dynamic balance before the twentieth century, but since then human intervention in the form of large-scale engineering works, levees, dams, canals, and water diversions has effectively starved the wetlands of needed freshwater and sediments and radically altered wetland hydrology. Relative sea level is rising at a rate of up to 1 m per 100 years in this region; up to 100 km^2 of wetlands were lost each year during the 1970s, falling to 50 km^2/yr in the 1980s (Boesch *et al*., 1994). In Bangladesh, flood defense systems and/or human activities in the Ganges-Bramaputra-Meghna river system may have affected runoff, sediment flow, and deposition rates, with detrimental effects on coastlines, fisheries, and the frequency and severity of inland flooding (Warrick and Rahman, 1992; see also Ives and Messerli, 1989). Small island states (many of which are low-lying) face particularly severe threats, and pollution and mining of coral will further serve to inhibit the capabilities of these countries to respond to sea-level rise.

Human interference in the dynamic processes that affect coastal zones is not restricted to activities within the coastal zone itself. Activities upstream in catchment areas may also play a part. For example, effluent discharging from sewage plants and industrial plants and agricultural runoff can lead to eutrophication, and water-resource schemes (e.g., dams and irrigation systems) can restrict the supply of water, sediment, and nutrients to coastal systems. Sewage and siltation are among the most significant causes of coral-reef and other natural coastal system degradation in the Philippines, Singapore, Malaysia, Indonesia, Sri Lanka, the Pacific islands, Hawaii, the Persian Gulf, the Caribbean, parts of the South American coast, and Cuba (Lundin and Linden, 1993).

The message is clear: Climate-related changes such as accelerated sea-level rise and possibly altered patterns of storm frequency and intensity represent potential *additional* stresses on systems that are already under intense and growing pressure. In addition, there are complex interrelationships and feedbacks between human and environmental driving forces and impacts on the one hand and climate-induced changes and effects on the other. These relationships require considerably more study (Turner *et al*., 1995b).

9.5.2. Assessment of Impacts

Of direct relevance when analyzing socioeconomic impacts is the evaluation of the potential loss of environmental values. As discussed in Section 9.2, a coastal system can yield a number of different values related to the functions and services it provides. A range of methods is available to evaluate these (see Table 9-1).

Table 9-1: *Environmental evaluation methods showing—from left to right—increasing complexity and scale of analysis (adapted from Pearce and Turner, 1992).*

Least Complicated				*Most Complicated*
Financial Analysis	**Economic Cost-Benefit Analysis**	**Extended Cost-Benefit Analysis**	**Environmental Impact Assessment**	**Multi-Criteria Decision Methods**
• Financial profitability criterion • Private costs and revenues • Monetary valuation	• Economic efficiency criterion • Social costs and benefits • Monetary valuation	• Sustainable development principles • Economic efficiency and equity tradeoff environmental standards as constraints • Partial monetary valuation	• Quantification of a diverse set of effects on a common scale, but no evaluation	• Multiple decision criteria • Monetary and nonmonetary evaluation

The more comprehensive the technique, the greater the diversity of information that will be required and yielded to assist the appraisal of policy options from a societal perspective. Therefore, assessing the value of climate-change impacts is not a straightforward issue. More robust techniques are available for deriving use values than for non-use values. Moreover, monetary valuation is not always appropriate when cultural and heritage assets are threatened by climate change and sea-level rise. Small islands often are particularly threatened, including their distinct ways of life and possibly even their distinct cultures. The same applies to heritage and other culturally significant sites on the coast. The core project Land-Ocean Interactions in the Coastal Zone (LOICZ) of the International Geosphere-Biosphere Program (IGBP) (see also Sections 9.6.4 and 9.7) is currently preparing comprehensive guidelines for evaluating coastal functions and services.

Coastal zones and small islands support a range of socioeconomic sectoral activities that can be affected by climate change and sea-level rise. Most of these sectors are covered in separate chapters in this report. Table 9-2 reflects the results of these sectoral assessments as they pertain to direct impacts specifically related to climate change in coastal zones and small islands. The reader is referred to the chapters listed in the table for more detailed discussions of the impacts and vulnerability of each sector.

Tourism also is of great importance to coastal zones and small islands, although it is not covered as a separate sector in this report. Tourism helps to support the economies of many coastal countries (Miller and Auyong, 1991). For many small islands in particular, tourism is the largest contributor to the country's GNP. Coastal tourism can be affected by climate change directly through coastal erosion and changes in weather patterns (e.g., storminess, precipitation, cloud cover). Indirect effects, however, may be just as important. Adverse impacts on freshwater supply and quality, human settlements, and human health will severely affect tourism, as will overdevelopment leading to environmental degradation.

Many efforts have been made in the last few years to assess the implications of climate change and associated sea-level rise on the coastal zone. As part of these efforts, the former Coastal Zone Management Subgroup of IPCC has published a methodology for assessing the vulnerability of coastal areas to sea-level rise (IPCC CZMS, 1991). The framework, called the Common Methodology, has been widely applied as the basis of vulnerability assessment studies. These studies have aimed to identify populations and resources at risk and the costs and feasibility of possible responses to adverse impacts. The vulnerability of many more coastal countries to sea-level rise has been reviewed using other approaches. Examples of assessments of the possible impacts and responses to sea-level rise and climate change can be found in Tobor and Ibe (1990), Parry *et al*. (1992), Bijlsma *et al*. (1993), Warrick *et al*. (1993), Ehler (1993), McLean and Mimura (1993), Qureshi and Hobbie (1994), O'Callahan (1994), WCC'93 (1995), and Nicholls and Leatherman (1995a). A series of studies on Pacific islands has been conducted by the South Pacific Regional Environment Programme, including Holthus *et al*. (1992), Aalbersberg and Hay (1993), McLean and D'Aubert (1993), and Nunn *et al*. (1994a, 1994b).

This section summarizes a number of these vulnerability case studies, with an emphasis on the strengths and weaknesses of those conducted using the Common Methodology or similar approaches.

9.5.2.1. Vulnerability Assessment and the IPCC Common Methodology

Vulnerability to impacts is a multidimensional concept, encompassing biogeophysical, socioeconomic, and political factors. The Common Methodology defines vulnerability as "the degree of incapability to cope with the consequences of climate change and accelerated sea-level rise" (IPCC CZMS, 1991). Therefore, analysis of the vulnerability of a coastal area or small island to climate change includes some notion of its *susceptibility* to the biogeophysical effects of climate change and sea-level rise (see Section 9.4), as well as of its natural *resilience*—which is greatly influenced by past, current, and future population and settlement patterns and rates of socioeconomic change. Susceptibility and resilience together determine the natural system's *sensitivity* to anticipated changes. Socioeconomic *vulnerability* is further determined by a country's technical, institutional, economic, and cultural capabilities to cope with or manage the

Table 9-2: *Qualitative synthesis of direct impacts of climate change and sea-level rise on a number of sectors in coastal zones and small islands, based on other chapters in this volume. Chapter numbers are in parentheses.*

	Climate-Related Events				
Impact Categories	Coastal Erosion	Flooding/ Inundation	Saltwater Intrusion	Sedimentation Changes	Storminess
Human Settlements (12)	✓	✓			✓
Agriculture (13)		✓	✓		✓
Freshwater Supply and Quality (14)		✓	✓		
Fisheries (16)	✓	✓	✓	✓	✓
Financial Services (17)	✓	✓			✓
Human Health (18)		✓			✓

anticipated biogeophysical effects and their consequent socioeconomic impacts (Turner *et al.*, 1995a).

The IPCC Common Methodology has aimed to identify "*the types of problems that a country will have to face and, if necessary, the types of assistance that are most needed to overcome these problems*." Assessments are to "*serve as preparatory studies, identifying priority regions and priority sectors and to provide a first reconnaissance and screening of possible measures*" (IPCC CZMS, 1991). Three boundary conditions and scenarios have been specified in the methodology: the impacts on the natural coastal systems, the impacts on socioeconomic developments, and the implications of possible response strategies for adaptation. The methodology includes consideration of the reference (or present) situation and a rise in sea level of 30 cm to 1 m by the year 2100. These scenarios approximate the low and high estimates of the 1990 IPCC Scientific Assessment. It considers socioeconomic developments by extrapolating 30 years from the present situation. The Common Methodology recommends considering a full range of adaptation options, including at least the extreme options of complete retreat and total protection. To simplify analysis, the method does not consider coastal evolution other than that caused by climate change, nor does it assess the effects of progressive adaptation at the local scale, such as the raising of dikes.

The Common Methodology has helped to focus the attention of many coastal nations on climate change and has contributed to long-term thinking about the coastal zone. On the other hand, a number of problems have been raised concerning the Common Methodology through the experiences of vulnerability assessment case studies (WCC'93, 1994):

- Many case studies have faced a shortage of accurate and complete data necessary for impact analysis. In particular, it often has proven difficult to determine accurately the impact zone in many countries due to the lack of basic data, such as the coastal topography.
- Many studies have found the use of a single global scenario of sea-level rise (1 m by 2100) inappropriate to their respective areas, often due to the lack of more detailed data on coastal elevations; most studies have ignored the spatial distribution of relative sea-level rise and other coastal implications of climate change, largely due to a lack of regional climate scenarios. Future vulnerability assessment would be greatly improved by the availability of regional scenarios for climate change and sea-level rise, including reference, low, and high scenarios.
- Although the Common Methodology has encouraged researchers to take into account the biogeophysical response of the coastal system to sea-level rise, lack of data and models for describing local coastal processes and responses have hindered detailed, quantitative impact assessment. Many case studies have carried out a simple first-order assessment by horizontally shifting the coastline landward by an amount corresponding with the sea-level rise scenario.
- While vulnerability profiles have yielded some useful relative guidance on potential impacts, the Common Methodology has been less effective in assessing the wide range of technical, institutional, economic, and cultural elements present in different localities.
- There has been concern that the methodology stresses a protection-orientated response, rather than considering a full range of adaptation options.
- Market-evaluation assessment frameworks have proved inappropriate in many subsistence economies and traditional land-tenure systems. More attention should be paid to broader socioeconomic evaluation techniques, which include traditional, aesthetic, and cultural values (see Box 9-2).

9.5.2.2. Vulnerability Assessment Case Studies

At least 23 country case studies have produced quantitative results that can be interpreted in terms of the IPCC Common

Box 9-2. Cultural Impacts and Alternative Assessments

Conventional impact evaluation techniques and indicators, such as GNP and population at loss, protection costs, and cost-benefit analysis, reflect only one (largely Western) approach for assessing potential damages from climate-related events. This has led to the development of alternative methodologies that seek to assess changes in culture, community, and habitat. In a study of coastal vulnerability and resilience to sea-level rise and climate change, Fiji is considered (Nunn *et al.*, 1994a). The methodology (Yamada *et al.*, 1995) computes a Sustainable Capacity Index based on the sum of ratings of vulnerability and resilience for many categories of cultural, social, agricultural, and industrial impacts at the local, regional, and national levels. Areas with higher concentrations of assets are judged to be more vulnerable, whereas areas with diversity and flexibility in the system—whether natural or managerial—tend to be viewed as more resilient in this analysis. The study has evaluated potential impacts to subsistence economies according to the view that communities in which people feed and clothe themselves with little cash exchange are more vulnerable but that subsistence economies in which staples can be replaced with other crops tend to be more resilient. In addition, cultural sites have been ranked according to the level of national interest in their preservation. The study concludes that subsistence economies and cultural assets are more vulnerable in Fiji and that conventional analyses of relatively high-lying islands such as Fiji would tend to underestimate the potential vulnerability of these areas, given that most people live in the low-lying coastal plain and the majority of cash and subsistence economic activities take place in the low-lying areas.

Methodology. Some results are summarized in Table 9-3, and these show considerable variation in possible impacts from country to country, reflecting that certain settings are more vulnerable than others. This conclusion is widely supported by all of the country studies that are available. Small islands, deltaic settings, and coastal ecosystems appear particularly vulnerable. In addition, developed sandy shores may be vulnerable because of the large investment and significant sand resources required to maintain beaches and protect adjoining infrastructure in the face of sea-level rise (Nicholls and Leatherman, 1995a).

Several caveats are in order so that the following impact estimates can be put into proper perspective (following Section 9.5.2.1). First, the impacts presented assume a 1-m rise in sea level by 2100—which is the high estimate of the IPCC90 business-as-usual sea-level rise scenario—and no other climate change. The latest scientific information, however, suggests a lower global mean sea-level rise (see Section 9.3.1.1). For a number of nations, the impacts of a 50-cm or smaller rise have been examined, including Argentina (Dennis *et al*., 1995a), parts of north China (Han *et al*., 1993), Japan (Mimura *et al*., 1994), Nigeria (G.T. French *et al*., 1995), Senegal (Dennis *et*

Table 9-3: *Synthesized results of country case studies. Results are for existing development and a 1-m rise in sea level. People affected, capital value at loss, land at loss, and wetland at loss assume no measures (i.e., no human response), whereas adaptation assumes protection except in areas with low population density. All costs have been adjusted to 1990 US$ (adapted from Nicholls, 1995).*

	People Affected		**Capital Value at Loss**		**Land at Loss**		**Wetland at Loss**	**Adaptation/ Protection Costs**	
Country/Source	# people (1000s)	% Total	Million US$[1]	% GNP	km^2	% Total	km^2	Million US$[1]	% GNP
Antigua[2] (Cambers, 1994)	38	50	–	–	5	1.0	3	71	0.32
Argentina (Dennis *et al*., 1995a)	–	–	>5000[7]	>5	3400	0.1	1100	>1800	>0.02
Bangladesh (Huq *et al*., 1995; Bangladesh Government, 1993)	71000	60	–	–	25000	17.5	5800	>1000[9]	>0.06
Belize (Pernetta and Elder, 1993)	70	35	–	–	1900	8.4	–	–	–
Benin[3] (Adam, 1995)	1350	25	118	12	230	0.2	85	>400[10]	>0.41
China (Bilan, 1993; Han *et al*., 1995a)	72000	7	–	–	35000	–	–	–	–
Egypt (Delft Hydraulics *et al*., 1992)	4700	9	59000	204	5800	1.0	–	13100[11]	0.45
Guyana (Kahn and Sturm, 1993)	600	80	4000	1115	2400	1.1	500	200	0.26
India (Pachauri, 1994)	7100[6]	1	–	–	5800	0.4	–	–	–
Japan (Mimura *et al*., 1993)	15400	15	849000	72	2300	0.6	–	>156000	>0.12
Kiribati[2] (Woodroffe and McLean, 1992)	9	100	2	8	4	12.5	–	3	0.10
Malaysia (Midun and Lee, 1995)	–	–	–	–	7000	2.1	6000	–	–
Marshall Islands[2] (Holthus *et al*., 1992)	20	100	160	324	9	80	–	>360	>7.04
Mauritius[4] (Jogoo, 1994)	3	<1	–	–	5	0.3	–	–	–
The Netherlands (Peerbolte *et al*., 1991)	10000	67	186000	69	2165	5.9	642	12300	0.05
Nigeria (G.T. French *et al*., 1995)	3200[6]	4	17000[7]	52	18600	2.0	16000	>1400	>0.04
Poland (Pluijm *et al*., 1992)	240	1	22000	24	1700	0.5	36	1400	0.02
Senegal (Dennis *et al*., 1995b)	110[6]	>1	>500[7]	>12	6100	3.1	6000	>1000	>0.21
St. Kitts–Nevis[2] (Cambers, 1994)	–	–	–	–	1	1.4	1	50	2.65
Tonga[2] (Fifita *et al*., 1994)	30	47	–	–	7	2.9	–	–	–
United States (Titus *et al*., 1991)	–	–	–	–	31600[8]	0.3	17000	>156000	>0.03
Uruguay (Volonté and Nicholls, 1995)[5]	13[6]	<1	1700[7]	26	96	0.1	23	>1000	>0.12
Venezuela (Volonté and Arismendi, 1995)	56[6]	<1	330[7]	1	5700	0.6	5600	>1600	>0.03

[1]Costs have been adjusted to reflect 1990 US$.
[2]Minimum estimates—incomplete national coverage.
[3]Precise year for financial values not given—assumed to be 1992.
[4]Results are linearly interpolated from results for a 2-m sea-level rise scenario.
[5]See also review in Nicholls and Leatherman (1995a).
[6]Minimum estimates—number reflects estimated people displaced.
[7]Minimum estimates—capital value at loss does not include ports.
[8]Best estimate is that 20,000 km^2 of dry land are lost, but about 5,400 km^2 are converted to coastal wetlands.
[9]Adaptation only provides protection against a 1-in-20 year event.
[10]Adaptation costs are linearly extrapolated from a 0.5-m sea-level rise scenario.
[11]Adaptation costs include 30-year development scenarios.

al., 1995b), parts of the United Kingdom (Turner *et al*., 1995a), the United States (Titus *et al*., 1991), Uruguay (Volonté and Nicholls, 1995), and Venezuela (Volonté and Arismendi, 1995). Second, all of the country studies have assumed that the socioeconomic situation is constant until 2100. This is unrealistic and ignores the rapid coastal development that is occurring with little regard for existing problems, let alone tomorrow's (WCC'93, 1994). However, the mere threat of extensive loss of land and other assets may stimulate macroeconomic effects within national economies. Some assets may be relocated and others may be adapted to reduce the damage implications of climate change. On the other hand, the damage-cost estimates may represent underestimates because they neglect some nonmarket asset values and factors such as the cost of resettlement of coastal populations that cannot be easily protected. Finally, it has been assumed that the rise in sea level will be a slow, gradual process, which may not be the case for all regions. Scientific uncertainties are compounded by the socioeconomic adaptation uncertainties referred to above and by the fact that economic cost estimates are very sensitive to changes in discount rates.

Despite these limitations, these studies have offered some important insights into potential impacts and possible responses to climate change and sea-level rise. Many of the vulnerability assessments emphasize the severe nature of existing coastal problems such as beach erosion, waterlogging, and pollution (e.g., El-Raey *et al*., 1995; Han *et al*., 1995b). For many small islands, population pressure and urbanization, coastal pollution, and overexploitation of resources already are critical problems. For deltas and estuaries, changes in sediment supply and distribution are often already causing significant changes in the coastal zone. This reinforces the message that climate change will act on coastal systems that are already under stress.

In addition to accelerated sea-level rise, there is widespread concern about the coastal implications of other aspects of climate change such as changing rainfall and runoff in the catchment area, as well as the effects of changes in storminess and storm surges (e.g., Warrick *et al*., 1993; McLean and Mimura, 1993). One quantitative vulnerability assessment study exists; it shows that in The Netherlands the costs of avoiding damage related to an adverse 10% change in the direction and intensity of storms may be worse than those of a 60-cm rise in sea level (Peerbolte *et al*., 1991). This storm-change scenario is arbitrary, but shows that concern is justified and that there is a need for more widespread analysis.

All of the 23 national case studies shown in Table 9-3 project land loss as the sum of dry-land and wetland loss, assuming no protective measures are taken. The estimated losses range from 0.05% of the national land area in Uruguay (Volonté and Nicholls, 1995) to more than 12% of Tarawa, Kiribati (Woodroffe and McLean, 1992); more than 17% of Bangladesh (Huq *et al*., 1995); and 80% of Majuro atoll, Marshall Islands (Holthus *et al*., 1992). From fifteen case studies, 63,000 km^2 of wetlands are estimated to be lost. Most of these assessments are based on first-order analyses, and key parameters such as limiting vertical accretion rates and potential for wetland migration often are poorly defined (Nicholls, 1995). The study of the United States has considered wetland migration, estimating that a 50-cm rise in sea level would erode or inundate 38% to 61% of existing coastal wetlands. Assuming that dikes or bulkheads were not built to impede inland migration, new wetland formation on formerly upland areas would reduce the total loss to 17% to 43% (Titus *et al*., 1991). Therefore, wetland migration is not projected to compensate for losses, even under the most ideal circumstances. Many studies, however, have found that direct human reclamation of wetlands for a range of purposes at present is a much bigger threat than sea-level rise (Nicholls and Leatherman, 1995a).

Fifteen case studies have provided estimates of undiscounted capital value potentially at loss, assuming no protection. Nearly half of the studies have concluded that capital value at loss could exceed 50% of present GNP, illustrating the concentration of infrastructure and economic activity in the coastal zones of many of the countries studied. To counter these impacts, adaptation would be expected (see Section 9.6). Table 9-3 stresses the cost of total protection rather than other possible adaptation options, which may have lower costs. Assuming that costs will accrue uniformly over 100 years, the annual protection costs—as a percentage of present GNP—are highest for the Marshall Islands at 7% (Holthus *et al*., 1992) and St. Kitts-Nevis at 2.7% (Cambers, 1994). This supports the conclusion that some small islands have a high vulnerability to sea-level rise. However, Kiribati has a similar setting to the Marshall Islands, yet the estimates of protection costs are much smaller, at 0.1% of present GNP (Woodroffe and McLean, 1992). This reflects important differences in assumptions about the meaning of total protection. In Kiribati, local engineers have selected existing low-technology, low-cost gabions to protect the atoll, whereas in the Marshall Islands large and expensive sea walls have been utilized to determine the costs. This comparison shows one of the weaknesses of the Common Methodology and the need to assess a wider range of response options in future vulnerability assessment studies.

In many locations, beaches are likely to require nourishment to protect tourist infrastructure because existing urban and tourist infrastructure could be damaged and destroyed. The amount of sand required to maintain a beach in the face of long-term sea-level rise is uncertain (Stive *et al*., 1991); in some case studies, the costs of beach nourishment could dominate basic response costs if countries invest in such an adaptation option (Dennis *et al*., 1995b; Nicholls and Leatherman, 1995a; Volonté and Nicholls, 1995). There is also the question of the availability of sufficient sand resources. The usual source is suitable-grade nearshore deposits, if available. However, the implication of the removal of such deposits must be carefully considered in terms of its effect on the coastal sediment budget and the nearshore wave climate.

In many industrialized countries, the main potential loss from sea-level rise seems to be coastal wetlands, as well as sandy beaches in some countries (e.g., Mimura *et al*., 1994).

Box 9-3. The Vulnerable Situation of Small Islands

Many small island countries could lose a significant part of their land area with a sea-level rise of 50 cm to 1 m. The Maldives, for example, have average elevations of 1 to 1.5 m above existing sea level (Pernetta, 1992). Although bio-geophysical processes may counter land losses (see Section 9.4), the threat of submergence and erosion remains; this could convert many small islands to sandbars and significantly reduce the usable dry land on the larger, more populated islands. Saltwater intrusion and loss of the freshwater lens may be an equally binding constraint on human habitation in some islands, particularly smaller atolls (Leatherman, 1994).

The available case studies have shown that small islands—most particularly, coral atolls such as the Marshall Islands (Holthus *et al*., 1992)—are heavily oriented toward coastal activities and hence are vulnerable to sea-level rise (e.g., Cambers, 1994; Fifita *et al*., 1994). At the same time, their relatively small economies may make the costs of adaptation prohibitive. In global terms, the population of small islands is relatively small, but a number of distinct societies and cultures are threatened with drastic changes in lifestyle and possibly forced abandonment from ancestral homelands if sea level rises significantly (Roy and Connell, 1991).

Even the less-vulnerable small islands would suffer significant economic effects from the loss of beach tourism and recreation areas because of sea-level rise and, possibly, more storms leading to increased beach and reef erosion. In 1988, among the Caribbean islands, income from tourism as a percentage of GNP was 69% for Antigua and Barbuda and 53% for the Bahamas; for a dozen other Caribbean islands, tourism revenues make up more than 10% of the GNP (Hameed, 1993). The Indian Ocean islands of the Seychelles and the Maldives also have seen a steady growth in tourism. In 1991, total receipts from tourism generated foreign exchange earnings of $94 million in the Maldives. This represented some 74% of the country's total foreign exchange earnings. Since 1985, tourism has been the single biggest contributor to the GNP of the Maldives. Tourism to developing countries has increased significantly in recent years, and small island developing states have experienced a particularly rapid increase. Tourist numbers to Mauritius, for example, have increased from 1,800 visitors in 1968 to 180,000 in 1988 (UNEP, 1991).

Given accelerated sea-level rise, first-order estimates suggest that substantial investment would be required in some developing countries in order to protect urban areas and maintain related activities such as beach tourism. Nine small island states appear in the list of countries facing the highest coastal protection costs as a percentage of their GNP. The global average percentage required annually for coastal protection is 0.037%; however, for many small islands it is significantly higher—up to 34% for the Maldives (OECD, 1991). To explore the full range of potential responses, more comprehensive assessment of the available adaptation options in these vulnerable settings is urgently required.

However, a change in the frequency, intensity, or distribution of extreme weather events could have implications for urban areas and related capital assets in countries such as Japan, Australia, the United States, and some countries bordering the North Sea.

From the above it is clear that all coastal zones of the world are vulnerable to the range of possible impacts from sea-level rise and other climate-induced impacts, although to different degrees. Studies using other approaches than the Common Methodology support this conclusion. Small island developing states are often judged to be among the most vulnerable countries. In Box 9-3, case material is presented for small islands, centering chiefly on threats to small economies dominated by tourism.

9.5.2.3. Global Vulnerability Assessment

In addition to local and country vulnerability assessments, a Global Vulnerability Assessment (GVA), which provides a worldwide estimate of the socioeconomic and ecological implications of accelerated sea-level rise (Hoozemans *et al*., 1993) has been conducted, using the same scenarios as the Common Methodology. The GVA has provided estimates of the following impacts: *population at risk*, the average number of people per year subject to flooding by storm surge on a global scale; *wetlands at loss*, the ecologically valuable coastal wetland area under serious threat of loss on a global scale; and *rice production at change*, the changes in coastal rice yields as a result of less-favorable conditions due to sea-level rise in South, Southeast, and East Asia.

Recently, an extension of the GVA has been prepared using a more refined approach to estimate flooding probabilities (Baarse, 1995). Sea-level rise scenarios of both 50 cm and 1 m have been considered. The data sets available for global-scale analysis are limited, and important assumptions are necessary with regard to storm-surge probability and population distribution. Also, increases in wave height and wave run-up have not been taken into account in these analyses, and neither have socioeconomic changes such as population growth. Therefore, the results of both studies must be considered as first-order estimates.

Some conclusions drawn from Hoozemans *et al*. (1993) and Baarse (1995) include:

- Presently, some 200 million people are estimated to live below the "maximum" storm-surge level (the once-per-1000-years storm-surge level). Based on this population estimate, as well as on first-order estimates of storm-surge probabilities and existing levels of protection, 46 million people are estimated to experience flooding due to storm surge in an average year under present conditions. Most of these people live in the developing world.
- The present number of people at risk will double if sea level rises 50 cm (92 million people/yr) and almost triple if it rises 1 m (118 million people/yr).
- The average number of people who will experience coastal flooding more than once per year will increase considerably under both scenarios (80–90% of the respective populations at risk). This estimate underlines that many people will have to adapt to sea-level rise by moving to higher ground, increasing protection efforts or other adaptation options (see Section 9.6).
- Because of regional differences in storm-surge regimes, the increase of flood risk due to sea-level rise is greater than average for the Asian region (especially the Indian Ocean coast), the south Mediterranean coast, the African Atlantic and Indian Ocean coasts, Caribbean coasts, and many of the small islands.
- All over the world, coastal wetlands are presently being lost at an increasingly rapid rate, averaging 0.5–1.5% per year. These losses are closely connected with human activities such as shoreline protection, blocking of sediment sources, and development activities such as land reclamation, aquaculture development, and oil, gas, and water extraction.
- Sea-level rise would increase the rate of net coastal wetland loss. Losses of coastal wetlands of international importance are expected to be greater than average for the coasts of the United States, the Mediterranean Sea, the African Atlantic coast, the coast of East Asia, and the Australian and Papua New Guinean coast.
- Approximately 85% of the world's rice production takes place in South, Southeast, and East Asia. About 10% of this production is located in areas that are considered to be vulnerable to sea-level rise, thereby endangering the food supply of more than 200 million people.
- Less-favorable hydraulic conditions may cause lower rice production yields if no adaptive measures are taken, especially in the large deltas of Vietnam, Bangladesh, and Myanmar.

In summary, the GVA confirms that sea-level rise will have global impacts and reinforces the need for more refined vulnerability assessments at regional and local scales.

9.5.2.4. Overview of Impact Assessment

Vulnerability assessment has demonstrated that certain settings are more vulnerable to sea-level rise, including small islands (particularly coral atolls), nations with large deltaic areas, coastal wetlands, and developed sandy shores. However, vulnerability assessment has been less successful in assessing the range of response options to deal with the problems of climate change. Therefore, vulnerability analysis has further utility for countries and areas where none has yet been carried out or where only preliminary studies are available. Even in many areas with a completed vulnerability assessment, an assessment of additional sea-level rise scenarios, scenarios of other impacts of climate change, and a wider range of response options remains necessary. This entails a greater emphasis on local conditions and careful evaluation of progressive adaptation options.

Problems and deficiencies with the Common Methodology have been indicated in several papers in O'Callahan (1994) and McLean and Mimura (1993) [e.g., Kay and Waterman (1993)], and recommendations have been made for integrating vulnerability assessments into the process of coastal zone management (WCC'93, 1994). In order to continue vulnerability assessment studies in a more complete form, approaches should be developed that more readily meet biogeophysical, socioeconomic, and cultural conditions, as well as governmental and jurisdictional arrangements (e.g., Yamada *et al*., 1995). Common approaches or frameworks that are tailored to the geographic circumstances and needs of each nation should be consistent with the IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptation (Carter *et al*., 1994) and need to take into account and correct the weaknesses found with the Common Methodology (McLean and Mimura, 1993; WCC'93, 1994).

9.6. Response Strategies

There is no doubt that the threat of climate change and sea-level rise has focused attention on coastal zones and small islands and awakened awareness of the vulnerability of the world's coastal regions in general—and to low-lying coasts, tidal deltas, and small islands in particular. IPCC CZMS (1990, 1992) have distinguished three groups of response strategies: (planned) retreat, accommodate, and protect. The first involves strategic retreat from or the prevention of future major developments in coastal areas that may be impacted. The second includes adaptive responses such as elevation of buildings, modification of drainage systems, and land-use changes. Both strategies are based on the premise that increases in land loss and coastal flooding will be allowed to occur and that some coastal functions and values will change or be lost. On the other hand, these strategies help to maintain the dynamic nature of coastal ecosystems and thus allow them to adapt naturally. The third strategy involves defensive measures and seeks to maintain shorelines at their present position by either building or strengthening protective structures or by artificially nourishing or maintaining beaches and dunes. This strategy could involve the loss of natural functions and values.

As discussed in Section 9.5, vulnerability assessment of various forms provides a range of procedures for a first overview of the consequences of climate change to coastal nations. These procedures also include guidance to a survey of response strategies and a country's capacity to implement those strategies in the context of management and planning of coastal areas. For the majority of coastal nations surveyed, the typical problems posed by sea-level rise (i.e., increased coastal erosion, inundation, flooding, saltwater intrusion) are not uniformly threatening. This does not imply that serious problems will not arise—only that there may be feasible, cost-effective adaptation options.

From Section 9.5, four major areas of concern regarding sea-level rise have emerged: inundation and increased flooding of low-lying islands, inundation and increased flooding of large parts of densely populated deltaic areas, loss of coastal wetlands, and erosion of developed sandy coasts. Each of these areas may require different options to reduce or prevent the prospective adverse impacts associated with biogeophysical changes caused by climate change and sea-level rise. In addition, strategies to reduce the vulnerability of coastal zones and small islands to climate change and sea-level rise should not be seen independently of the resolution of short-term problems arising primarily from human activities. Effective adaptation to climate change and sea-level rise therefore requires a flexible coastal management strategy at all timescales, that incorporates and integrates both short-term and long-term goals.

Although one may argue that there is still a considerable amount of time to implement a response strategy, present-day coastal development often adversely influences the effectiveness of long-term adaptation options (WCC'93, 1994). Moreover, considerable time lags are often involved between the planning and implementation of adaptation options (Vellinga and Leatherman, 1989). The World Coast Conference therefore has concluded that strengthening planning and management capabilities for coastal areas should be delayed no further (WCC'93, 1993, 1994).

Assessing the full social costs of adaptation to climate change is a complicated, often controversial, issue, for which a range of techniques will be required. Apart from estimates of protection costs for a number of countries (see also Table 9-3), this chapter does not offer a comprehensive assessment of these full social costs. This has been done in Chapter 6, *The Social Costs of Climate Change: Greenhouse Damage and the Benefits of Control*, and Chapter 7, *A Generic Assessment of Response Options*, of the IPCC Working Group III volume, which also discuss the techniques available for assessing adaptation costs. A number of cost–benefit studies have been undertaken that attempt to determine optimal response strategies in the face of sea-level rise. Studies include Titus (1991), Nijkamp (1991), Fankhauser (1995), and Turner *et al*. (1995a).

9.6.1. Adaptation Options

There is a wide array of adaptation options that can be employed to retreat, accommodate, and protect. Table 9-4 outlines the options within these three strategies, as listed in the IPCC First Assessment Report (IPCC, 1990).

Box 9-4. Approaches to Coastal Adaptation to Climate Change: Two Examples

West and Central Africa: The coastal nations of West and Central Africa (e.g., Senegal, Gambia, Sierra Leone, Nigeria, Cameroon, Gabon, Angola) have mostly low-lying lagoonal, erosive coasts—and hence are likely to be threatened by sea-level rise, particularly since most of the countries in this area have major, rapidly expanding cities on the coast (Tobor and Ibe, 1990; Adam, 1995; Dennis *et al*., 1995b; G.T. French *et al*., 1995). Ibe (1990) has found that large-scale protective engineering measures are impractical in the region because of the high costs to those countries. Instead, low-cost, low-technology, but effective measures—such as permeable nonconcrete floating breakwaters; artificial raising of beach elevations; installation of riprap; timber groins; and so forth—are considered to be more sensible. Ibe (1990) has noted that "fortunately, outside the urbanized centers, the coasts are almost in pristine condition and largely uninhabited. Where coasts are deemed highly vulnerable, total ban of new development is absolutely necessary."

The Netherlands: The Dutch Impacts of Sea-Level Rise on Society (ISOS) study has assessed consequences and the possible responses for water management and flood protection in the Netherlands (Peerbolte *et al*., 1991). Various scenarios of climate change have been considered, including sea-level rise, changes in river discharges, and changes in storm patterns (i.e., wind direction, storm frequency and intensity). Possible adaptation options, including investments in infrastructure and soft measures such as beach and dune nourishment, have been evaluated and optimized in time for the different sets of scenarios. If sea level were to rise by 60 cm over the next century, $3.5 billion would have to be spent on raising dikes and other safety infrastructure, $500 million on preserving the dune areas, $900 million on adapting flood-prone residential and industrial areas and harbors, and $800 million on adapting water-management facilities. An unfavorable change in storm pattern alone would have the same magnitude of impacts. The occurrence of sea-level rise in combination with the implementation of protective measures will further lead to losses of wetland and intertidal area. These losses cannot be prevented by any realistic additional measures.

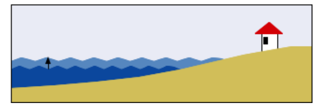
Table 9-4: *Response strategies to sea-level rise (IPCC, 1990).*

Present Situation

(Planned) Retreat

Emphasis on abandonment of land and structures in highly vulnerable areas and resettlement of inhabitants

- Preventing development in areas near the coast
- Conditional phased-out development
- Withdrawal of government subsidies



Accommodate

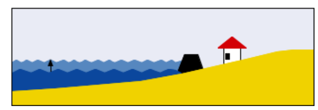
Emphasis on conservation of ecosystems harmonized with the continued occupancy and use of vulnerable areas and adaptive management responses

- Advanced planning to avoid worst impacts
- Modification of land use, building codes
- Protection of threatened ecosystems
- Strict regulation of hazard zones
- Hazard insurance

Protect

Emphasis on defense of vulnerable areas, population centers, economic activities, and natural resources

- Hard structural options
  - Dikes, levees, and floodwalls
  - Sea walls, revetments, and bulkheads
  - Groins
  - Detached breakwaters
  - Floodgates and tidal barriers
  - Saltwater intrusion barriers
- Soft structural options
  - Periodic beach nourishment (beach fill)
  - Dune restoration
  - Wetland creation
  - Littoral drift replenishment
  - Afforestation



Traditionally, the emphasis has been on engineering responses to coastal erosion and protection against flooding, with action often being triggered in response to an extreme event. Now the range of options has expanded to include nonstructural adaptation consisting primarily of zoning, building codes, land-use regulation, and flood-damage insurance, with more emphasis on a precautionary approach. Two different approaches to adaptation to anticipated climate change are discussed in Box 9-4.

IPCC CZMS (1990) has identified the environmental, economic, cultural, legal, and institutional implications of the three response strategies. Vulnerability assessments have since made clear that the extreme options of retreat and full protection highlight the negative effects and overestimate the potential costs and losses from climate change and sea-level rise. Yet adaptation options in low-lying island states (e.g., the Marshall Islands, the Maldives) and for nations with large deltaic areas (e.g., Bangladesh, Nigeria, Egypt, China), which have been identified as especially vulnerable, are problematic because the options have not been fully evaluated but appear limited and potentially very costly. Even without climate change and associated sea-level rise, these nations will continue to experience rapidly increasing vulnerability to natural coastal hazards due to high rates of population growth, increased demands, continued unsustainable exploitation of resources in the coastal zone, and development in upstream catchment areas. Continued natural and possible anthropogenic subsidence (relative sea-level rise) of large river deltas will increase the risk from storm surges. Strategies must be devised to reduce the economic damages and social hazards well before climate change and associated sea-level rise become a significant factor (Han *et al*., 1995b; Boesch *et al*., 1994). For these situations, conventional adaptation options will have to be enacted as a first step, while innovative or radical solutions—for example, controlled flooding and sedimentation to harness the natural capability of a delta to respond to sea-level rise—are examined for their effectiveness, environmental impact, social acceptability, and economic efficiency.

Heavily populated areas are primary candidates for structural protection measures such as dikes, sea walls, breakwaters, and beach groins. Because these are expensive options, the use of economic evaluation principles—especially risk assessment and benefit-cost analysis—can provide useful tools in deciding whether to protect or retreat, as well as where such infrastructure investments ought to be placed in order to maximize national or regional social and economic welfare (Carter *et al*., 1994).

Some of the more detailed recent studies of response strategies to sea-level rise have been accomplished for coastal urban areas. In all instances, the problems of sea-level rise are considered to be serious. Many examples can be found in Frassetto (1991) and Nicholls and Leatherman (1995a), including Venice, Hamburg, London, Osaka, St. Petersburg, Shanghai, Hong Kong, Lagos, Alexandria, Recife, and Tianjin. However, Devine (1992) has argued that the shantytown areas found in many coastal cities may be particularly vulnerable to climate change, and adaptation options are uncertain. Chapter 12 further discusses impacts of and adaptation options to climate change in human settlements, including coastal cities.

Kitajima *et al*. (1993) have undertaken a comprehensive analysis of the range of likely structural measures that would be required to respond to a 1-m sea-level rise at 1,100 Japanese ports, harbors, and neighboring areas, as well as their estimated costs. The cumulative undiscounted costs have been estimated at $92 billion. Of that sum, about $63 billion is for raising port facilities and $29 billion is for adjoining shore protection structures (e.g., breakwaters, jetties, embankments). This cost estimate covers about 25% of Japan's coastline; other residential areas would also have to be protected, if that were the most cost-effective option. Further costs would be incurred to maintain existing standards of protection for populated areas as sea level rises (Mimura *et al*., 1994). For a rise of 1 m, total costs would exceed $150 million. Further, natural shores could be largely lost from Japan's coast. It should be noted that, on an average annual basis, the costs constitute a small fraction of the GNP.

Adaptation can exploit the fact that coastal infrastructure is not static. There is a turnover of many coastal facilities through major rehabilitation, construction, and technological changes in ports, harbors, and urbanized areas, averaging roughly 25–30 years. Therefore, there will be recurring opportunities to adapt to sea-level rise, especially if the rate is relatively slow and construction and maintenance plans can be taken into account in land-use planning, management, and engineering design criteria (Stakhiv *et al*., 1991; Yim, 1995). Moreover, experience with allowances for accelerated sea-level rise is limited but growing (e.g., Nicholls and Leatherman, 1995b). The interaction of different aspects of climate change should be considered. For instance, given the likelihood of both sea-level rise and a decrease in the return period of intense rainfall events (see Section 9.3), more consideration of future drainage capacity requirements in low-lying coastal areas may be prudent (Titus *et al*., 1987; Nicholls *et al*., 1995).

Some structural examples of proactive adaptation include:

- In the early 1990s, design standards for new seawalls in The Netherlands and eastern England were raised 66 cm and 25 cm, respectively, to allow for accelerated sea-level rise. This has been in response to the IPCC90 best estimate for future sea-level rise; the different magnitudes reflect a 100-year and 50-year planning horizon, respectively.
- The Massachusetts Water Resources Authority has included an additional 46 cm of height in the Deer Island sewage treatment plant. This is a safety factor to maintain gravity-based flows under higher sea levels without the additional costs of pumping.
- In Hong Kong, the West Kowloon reclamation is being built 80 cm above earlier design levels to allow for sea-level rise and/or unanticipated subsidence (Yim, 1995). In this case, costs have increased by less than 1%; future reclamations are expected to be similarly raised, and existing reclamations may be raised as part of the redevelopment cycle.

Enlarged setbacks to allow for expected shoreline recession, most notably in some states in Australia (Caton and Eliot, 1993), would enable planned retreat to accommodate climate change impacts. A variant on fixed setbacks is presumed mobility—whereby coastal residents are allowed to live at the shore but give up their right to protect the shore if it retreats in response to climate change or other causes (Titus, 1991). To counter the coastal squeeze of wetlands and maintain their habitat and flood-buffering functions, managed retreat on estuarine shorelines is increasingly favored in the United Kingdom (Burd, 1995). This involves setting back the line of actively maintained defense to a new line inland of the original and promoting the creation of intertidal habitat on the land between the old and new defenses.

9.6.2. Implementation Considerations

To date, the assessment of possible response strategies has focused mainly on protection. There is a need to better identify the full range of options within the adaptive response strategies: protect, accommodate, and retreat. Identifying the most appropriate options and their relative costs and implementing these options while taking into account contemporary conditions as well as future problems such as climate change and sea-level rise will be a great challenge in both developing and industrialized countries. The range of options will vary among and within countries, and different socioeconomic sectors may prefer competing adaptation options for the same areas. Experience shows that intersectoral conflicts are a major barrier to improved coastal management (WCC'93, 1994). In the present context, they could also be a major barrier to adaptation to climate change. An appropriate mechanism for coastal

Box 9-5. Integrated Coastal Zone Management

ICZM involves comprehensive assessment, setting of objectives, planning, and management of coastal systems and resources, while taking into account traditional, cultural, and historical perspectives and conflicting interests and uses. It is an iterative and evolutionary process for achieving sustainable development by developing and implementing a continuous management capability that can respond to changing conditions, including the effects of climate change. ICZM includes the following:

- Integration of programs and plans for economic development, environmental quality management, and land use
- Integration of programs for sectors such as food production (including agriculture and fishing), energy, transportation, water resources, waste disposal, and tourism
- Integration of all the tasks of coastal management—from planning and analysis through implementation, operation and maintenance, monitoring, and evaluation—performed continuously over time
- Integration of responsibilities for various tasks of management among levels of government—local, state/provincial, regional, national, international—and between the public and private sectors
- Integration of available resources for management (i.e., personnel, funds, materials, equipment)
- Integration among disciplines [e.g., sciences such as ecology, geomorphology, marine biology; economics; engineering (technology); political science (institutions); and law].

planning under these varying conditions is integrated coastal zone management (ICZM) (see Box 9-5).

There is no single recipe for ICZM; rather it constitutes a portfolio of sociocultural dimensions and structural, legal, financial, economic, and institutional measures. There are many approaches as well as diverse institutional arrangements that can be tailored to the particular culture and style of governance. Yet a number of essential prerequisites can be identified (WCC'93, 1994). The first of these is the need for *initial leadership* for the planning process. The initiative may consist of a centrally led "top-down" approach, a community-based "bottom-up" approach, or something in between. The second necessary element of ICZM is the provision of *institutional arrangements*. This may involve creating new institutions but more commonly will involve improving horizontal and vertical linkages between existing ones. Third, *technical capacity* (both technological and human capacities) is necessary for compiling inventories in the planning phase and during the implementation of the program, and for monitoring the changes. The final necessary element of ICZM is *management instruments*. These include tools ranging from directive to incentive-based, all with the aim of encouraging stakeholders to comply with the goals and objectives of the given ICZM program.

At both UNCED and at the World Coast Conference, ICZM has been recognized as the most appropriate process to deal with current and long-term coastal problems, including degradation of coastal water quality, habitat loss, depletion of coastal resources, changes in hydrological cycles, and, in the longer run, adaptation to sea-level rise and other effects of climate change.

The goal of ICZM is not only to address current and future coastal problems but also to enable coastal societies to benefit from a more efficient and effective way of handling coastal development. Most coastal areas are called on to provide multiple products and services. As demands on coastal resources continue to grow with increasing population and economic development, conflicts could become more common and apparent. ICZM should resolve these conflicts and implement decisions on the mix of uses that best serve the needs of society now and in the future. Also, ICZM is important in the context of the increasingly expressed concern for sustainable development. Sustainable use of any natural resource can be achieved only by having in place a set of integrated management tasks that are financed and carried out continuously (WCC'93, 1994).

There is a persuasive case for taking action about climate change now—to institute or expand ICZM and thus comply with the precautionary approach. Although the time lag between planning and investment in integrated (cross-sectoral) management is longer than that for single-sector management, the returns are significantly greater. A proactive approach to ICZM, in order to enhance the resilience of natural coastal systems and reduce vulnerability, would be beneficial from both an environmental and an economic perspective (Jansen *et al.*, 1995). In addition to reducing vulnerability and enhancing the resilience of developed coastal regions, such initiatives also can encompass the large lengths of shorelines that are presently undeveloped but may be subject to significant pressures in the coming decades. By acting now, future development may be designed to be sustainable and to accommodate the potential impacts of climate change and sea-level rise.

9.6.3. Constraints to Implementation

It is important for governments and policymakers to recognize that although a particular response strategy may appear initially to be appropriate, there are constraining factors that can determine how successfully that option can be implemented (SDSIDS, 1994).

The applicability of any option must be evaluated against (among other things) a background of a country's technology and human resources capability, financial resources, cultural and social acceptability, and the political and legal framework. This is not to suggest that these constraints are insurmountable but that decisionmakers must be realistic when considering the range of options available to them.

9.6.3.1. Technology and Human Resources Capability

For many countries, scarcity of (or lack of access to) appropriate technology and trained personnel will impose limits on the adaptation options realistically available. For example, the design, implementation, and maintenance of "state-of-the-art" civil works may be beyond the immediate reach of many developing nations unless there is technical assistance to provide the required technology and human skills. This is highlighted in vulnerability assessments for a number of countries, such as Tonga (Fifita *et al*., 1994), Bangladesh (Khan *et al*., 1994), and Belize (Pernetta and Elder, 1993).

Specifically in the case of protection and accommodation, there will be a need for ongoing maintenance and periodic replacement and upgrade. These activities will also require access to the relevant technology and skills to remain effective.

9.6.3.2. Financial Limitations

The implementation of any adaptation option—whether retreat, accommodate, or protect—will necessitate certain financial commitments from governments, although the level of required funding may vary widely from one option to another. In the case of planned retreat, substantial infrastructure would have to be rebuilt and settlements relocated to less-vulnerable areas, at high reinvestment costs. Adjustment strategies might entail acceptance of less-than-ideal circumstances, while simultaneously increasing the costs of reducing flood risks. Protection strategies almost always involve "hard" engineering structures, which are costly both to construct and to maintain. In the Maldives, for example, the present costs of shoreline protection are close to $13,000 per m; in Senegal, Benin, Antigua, Egypt, Guyana, the Marshall Islands, St. Kitts-Nevis, and Uruguay, maintenance of the existing shoreline against a 1-m rise in sea level could require substantial funding compared with the nation's GNP (Nicholls, 1995). However, it should be noted that national responses to climate change will more likely comprise a variable combination of planned retreat, accommodation, and protection; hence, lower-cost responses probably are available in some areas (e.g., Turner *et al*., 1995a; Volonté and Nicholls, 1995).

Clearly, any combination of response strategies will be largely influenced by monetary considerations, necessitating both short-term investment and a commitment to longer-term maintenance and replacement costs. Many developing countries will find it especially difficult to meet such costs and will increasingly have to turn to donor countries and international agencies for assistance. In Kiribati, for instance, it has been demonstrated that implementation of protection measures especially will almost certainly require external assistance (Abete, 1993). Lack of adequate financial resources will also circumscribe a country's capacity to "purchase" appropriate technology and human skills required for the implementation of various options. Countries should therefore consider designing efficient, least-cost response plans, based on some realistic assessment of what their economies will be able to sustain (WCC'93, 1994).

9.6.3.3. Cultural and Social Acceptability

Although certain options may be technically and financially possible in a given set of circumstances, they may, at the same time, be culturally and socially disruptive. In some societies, resettlement, for example, would lead to dislocation of social and cultural groups and might even involve the loss of cultural norms and values and the assimilation of new ones. Additionally, an option involving planned retreat could mean the loss of access to communally owned resources and land entitlements, which might undermine the entire economic, social, and cultural base of some communities. Other adaptive measures, such as the construction of "hard" engineering structures, could cause the partial or total elimination of access to traditional fishing, hunting, and culturally important sites.

9.6.3.4. Political and Legal Framework

The extent to which a given response strategy can be successfully employed may well be influenced by political and legal considerations (Freestone and Pethick, 1990). Retreat options, for example, might prove infeasible given the policy and legal structures of the "receiving" area. Where international resettlement is indicated, these issues can become even more complex—as demonstrated by the plight of refugees worldwide. Further, some options will be incompatible with existing systems of land tenure and ownership and in some societies would necessitate a fundamental change in arrangements prior to implementation to avoid violating certain rights. Failing this, governments could be called upon to provide substantial compensation to communities for loss of property and resource-use rights.

Strategies that lead to coastal land loss might also have an undesirable impact on a country's Exclusive Economic Zone (e.g., Aparicio-Castro *et al*., 1990). This could lead to international legal disputes concerning ownership and use of resources. In those circumstances, such options might not only be considered legally unacceptable but politically infeasible as well.

9.6.4. Overcoming the Constraints

As a step toward overcoming these constraints, the World Coast Conference was organized with the objective of bringing together coastal experts and policymakers to identify actions that can be taken to strengthen capabilities for progressive sustainable development and integrated coastal zone management. The conference participants acknowledged that there is an urgent need for coastal states to strengthen their capabilities, in particular with regard to the exchange of information, education and training; the development of concepts and tools; research, monitoring, and evaluation; and funding (WCC'93, 1993). The following are examples of measures that could improve capabilities for developing, implementing, and strengthening national programs for ICZM (WCC'93, 1993):

- Multidisciplinary studies and assessments to determine the potential importance of the coastal zone and its vulnerabilities, particularly those that limit its ability to achieve sustainable development
- An institutional body or mechanism to investigate the need and potential benefits and costs of developing an ICZM program
- A long-term and effective body or mechanism to prepare, recommend, and coordinate the implementation of a permanent ICZM program
- A continuing monitoring and assessment program to collect data, assess results, and identify the need for change or improvement
- An ongoing research program, including an investigation of the potential effects of global climate change, to improve the analytical foundation for the decisionmaking process
- A policy to increase the availability and accessibility of information to all interested parties
- Active support for local initiatives, exchange of practical and indigenous experiences, and enhancement of public participation
- Education, training, and public-awareness efforts to increase the constituency for ICZM
- Coordination of financial support for relevant activities and investigation of innovative sources for additional support.

Effective ICZM can be achieved by coordination among national, regional, and international organizations and institutions. This will help to avoid unnecessary duplication and develop the concepts, tools, and networks needed to facilitate the development and implementation of national programs, which is a complex process that can be accelerated and enhanced through international cooperation. Regional approaches can complement and strengthen activities at the national and international levels.

Various international initiatives have been undertaken to encourage and facilitate coordination and cooperation in both policy and research. Several United Nations organizations and other international governmental and nongovernmental organizations have developed programs aimed at strengthening ICZM capabilities at different levels. An overview of these activities is presented in WCC'93 (1994). In 1993, the IGBP launched its core project LOICZ, which aims to stimulate interdisciplinary scientific coastal research in the context of global change (Pernetta and Milliman, 1995).

Clearly, the wide range of uncertainty in human and natural variables that will affect ICZM emphasizes the need for continued research and monitoring. The results of scientific research and information from monitoring activities need to be integrated into policy development, planning, and decisionmaking throughout the ICZM process.

9.7. Research and Monitoring Needs

Although much has been achieved since the IPCC First Assessment in 1990, this chapter shows that the understanding of the likely consequences of climate change and sea-level rise is still imperfect. This situation can be improved only through a sustained research and monitoring effort, requiring a major commitment of resources at the national, regional, and global levels. The potential problems of small islands, deltas, coastal wetlands, and developed sandy coasts deserve particular attention as part of these efforts. Coastal zones and small islands illustrate the fundamental need for better coupling of research and models from the natural sciences and the social sciences to provide improved analytical capability and information to decisionmakers. An emphasis on understanding the impacts of climate change at the local and regional scales is essential.

There are a number of critical issues and priorities in ongoing research and monitoring, as initiated by IPCC CZMS (1990, 1992), that should be continued over the next few years to enable better decisionmaking concerning the possible impacts of climate change in coastal zones and small islands:

- Development of improved biogeophysical classifications and frameworks of coastal types for climate-change analysis, including the influence of human activities (IGBP-LOICZ has taken an important step in this direction)
- Investigations of geomorphological and biological responses of coastal types and critical ecosystems to climate change and sea-level rise, with specific attention to the response of seagrass to climate change as well as potential changes in sediment budgets
- Improved methodologies for incorporating existing, high-quality historical and geological coastal-change data into response models for climate change
- Improved coastal-processes data (especially in developing countries), based on instrumentation (tide gauges, current meters, wave recorders, etc.), as well as improved capacity to interpret and analyze the data
- Improved databases for vulnerability assessment and adaptation planning on coastal socioeconomic trends, such as population changes and resource utilization and valuation, taking into consideration differences in sociocultural characteristics of countries and ethnic groups

- Extension of new and existing vulnerability assessment studies to include a range of local scenarios of sea-level rise (rather than a single scenario), other possible impacts of climate change such as changing storminess or precipitation, and an assessment of the range of possible adaptation strategies
- Continued education and training relevant to vulnerability assessment and integrated coastal zone management, employing, as far as practicable, standardized methodologies and frameworks.

Some ongoing initiatives have already been undertaken to address these priorities. For example, the Intergovernmental Oceanographic Commission (IOC) coordinates a Global Sea Level Observing System (GLOSS). However, there still are many gaps, and the system requires increased international support and coordination. IGBP-LOICZ aims to stimulate interdisciplinary scientific coastal research in the context of global change. Focus 2 of LOICZ aims to investigate coastal biogeomorphological interactions under different global-change scenarios. It focuses on the interaction between major ecosystem types with the sedimentary environment and aims to assess the implications of ecosystem perturbations on coastal stability with a rise in sea level. Focus 4 is especially relevant for integrated coastal zone management because it addresses the socioeconomic impacts of global change on coastal zones and aims to investigate how improved strategies for the management of coastal resources can be developed.

New initiatives also are required, as has been recognized by participants of the World Coast Conference (WCC'93, 1994). Increased efforts are needed mainly in the social sciences and adaptation to climate change, including the development of:

- Integrated coastal-response models, which seek to combine the interactions of biogeophysical, socioeconomic, and climate-change factors, incorporating the knowledge and technologies of traditional societies and local peoples
- Methods to quantify the benefits of integrated coastal zone management
- A broad framework for the analysis, planning, and management of coastal zones in the context of climate change, recognizing the co-evolution of natural and social systems.

Such a framework would encourage nations in the formulation and implementation of ICZM strategies and programs that are appropriate to climate change and fully take into account the existing environmental, social, cultural, political, governance, and economic contexts. This would help to fulfill the recommendations made by IPCC CZMS (1990).

To facilitate these goals, an international conference to share experience on coastal impacts and adaptation to climate change might be useful, building on the success of earlier meetings of the IPCC Coastal Zone Management Subgroup and the World Coast Conference. Particular targets for such a conference could include:

- An updated assessment of coastal vulnerability to climate change
- Examples of biogeophysical/socioeconomic integration in coastal research and coastal management
- Testing of the framework for ICZM via case studies in a range of countries or regions.

These activities could assist coastal nations in meeting their obligations under Agenda 21 of UNCED.

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This chapter is only one small step on the road to global sustainable coastal development and could not have been written if many earlier steps had not been taken. For many decades, scientists and policymakers from all over the world have devoted themselves to coastal research and management; the list of references below reflects only a minor part of their efforts. Hence, the authors would like to thank every person and institution who has contributed to the increased understanding of coastal systems and the growing awareness of the importance of their healthy functioning. Special thanks are due to the contributors and reviewers of this chapter and to Mark Naber and Willem Storm (National Institute for Coastal and Marine Management, The Netherlands), who prepared the figures.

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