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EXECUTIVE SUMMARY

Global climate change will affect the physical, biological, and biogeochemical characteristics of the oceans and coasts, modifying their ecological structure, their functions, and the goods and services they provide. Large-scale impacts of global warming on the oceans will include:

- Increases in sea level and sea-surface temperature
- Decreases in sea-ice cover
- Changes in salinity, alkalinity, wave climate, and ocean circulation.

Feedbacks to the climate system will occur through changes in ocean mixing, deep water production, and coastal upwelling. Collectively, these changes will have profound impacts on the status, sustainability, productivity, and biodiversity of the coastal zone and marine ecosystems.

Scientists recently have recognized the persistence of multi-year climate-ocean regimes and shifts from one regime to another. Changes in recruitment patterns of fish populations and the spatial distribution of fish stocks have been linked to climate-ocean system variations such as the El Niño-Southern Oscillation (ENSO) and decadal-scale oscillations. Fluctuations in fish abundance increasingly are regarded as a biological response to medium-term climate-ocean variations, and not just as a result of overfishing and other anthropogenic factors. Of course, such factors can exacerbate natural fluctuations and damage fish stocks. Global warming will confound the impact of natural variation and fishing activity and make management more complex.

Growing recognition of the role of understanding the climate-ocean system in the management of fish stocks also is leading to new adaptive strategies that are based on the determination of stock resilience and acceptable removable percentages of fish. We need to know more about these interactions. Climate-ocean–related changes in the distribution of fish populations suggest that the sustainability of the fishing industries of many countries will depend on increasing flexibility in bilateral and multilateral fishing agreements, coupled with international stock assessments and management plans.

Marine mammals and seabirds are large consumers of fish and have been shown to be sensitive to inter-annual and longer term variability in oceanographic and atmospheric parameters. Several marine mammal and bird species, including polar bears and some seabirds, may be threatened by long-term climate change.

Marine aquaculture production has more than doubled since 1990 and is expected to continue its upward trend. However, aquaculture may be limited if key fish species used in feed production are negatively impacted by climate change. Increases in seawater temperature may directly impact aquaculture; such increases already have been associated with increases in diseases and algal blooms.

The adaptive capacities of marine and coastal ecosystems varies among species, sectors, and geographical regions. In the broader oceans, marine organisms will be relatively free to move to new geographical areas; organisms in enclosed seas and coastal zones are more constrained by the physical features of the shore, making natural adaptation more difficult.

Coastal zones are among the world's most diverse and productive environments. With global warming and sea-level rise, many coastal systems will experience:

- Increased levels of inundation and storm flooding
- Accelerated coastal erosion
- Seawater intrusion into fresh groundwater
- Encroachment of tidal waters into estuaries and river systems
- Elevated sea-surface and ground temperatures.

Tropical and subtropical coastlines, particularly in areas that are already under stress from human activities, are highly susceptible to global warming impacts. Particularly at risk are the large delta regions—especially in Asia, where vulnerability was recognized more than a decade ago and continues to increase. Mid-latitude temperate coasts often comprise coastal plains and barriers and soft sedimentary cliffs and bluffs that have been the subject of historical and model studies, virtually all of which confirm the high vulnerability of these coasts. High-latitude coastlines also are susceptible, although the impacts in these areas have been less studied. A combination of accelerated sea-level rise, increased melting of ground ice, decreased sea-ice cover, and associated more energetic wave conditions will have severe impacts on coastal landforms, settlements, and infrastructure.

Coastal areas also include complex ecosystems such as coral reefs, mangrove forests, and salt marshes. In such environments, the impact of accelerated sea-level rise will depend on vertical accretion rates and space for horizontal migration, which may be limited by the presence of infrastructure. Many mangrove forests are under stress from excessive exploitation, and salt marshes are under stress from reclamation. Many coral reefs already are degraded. In such situations, ecosystem resilience will be greatly reduced through human impacts as well as rising sea levels, increasing sea temperatures, and other climate-ocean–related changes, including prevailing wave activity and storm waves and surges.

Progress in evaluating the potential effects of climate change and sea-level rise on socioeconomic systems has not been as substantial as that relating to biogeophysical impacts. With reference to coastal zones, socioeconomic impacts have been considered in several ways, including:

- As a component of vulnerability assessment of natural systems
- With an emphasis on market-oriented or nonmarket-oriented approaches
- With a focus on costs for infrastructure and adaptation options.

Three coastal adaptation strategies have been identified previously: protect, accommodate, and retreat. In the past few years, structural shore-protection measures have been reevaluated, and there has been greater interest in managing coastal retreat. Enhancement of biophysical and socioeconomic resilience in coastal regions is increasingly regarded as a desirable adaptive strategy but appears not to be feasible in many of the world’s coastal zones. Additional insights can be gained by understanding adaptation to natural variability.

Although some countries and coastal communities have the adaptive capacity to minimize the impacts of climate change, others have fewer options; the consequences may be severe for them. Geographic and economic variability leads to inequity in the vulnerability of coastal communities and potentially in intergenerational access to food, water, and other resources. Techniques for the integration of biophysical and socioeconomic impact assessment and adaptation are developing slowly, while human population growth in many coastal regions is increasing socioeconomic vulnerability and decreasing the resilience of coastal ecosystems.

Integrated assessment and management of open marine and coastal ecosystems and a better understanding of their interaction with human development will be important components of successful adaptation to climate change. Also important will be integration of traditional practices into assessments of vulnerability and adaptation.

6.1. Introduction and Scope

The oceans cover 70% of the Earth's surface and play a vital role in the global environment. They regulate the Earth's climate and modulate global biogeochemical cycles. They are of significant socioeconomic value as suppliers of resources and products worth trillions of dollars each year (IPCC, 1998). Oceans function as areas of recreation and tourism, as a medium for transportation, as a repository of genetic and biological information, and as sinks for wastes. These functions are shared by the coastal margins of the oceans.

Approximately 20% of the world's human population live within 30 km of the sea, and nearly double that number live within the nearest 100 km of the coast (Cohen *et al*., 1997; Gommes *et al*., 1998). Nicholls and Mimura (1998) have estimated that 600 million people will occupy coastal floodplain land below the 1,000-year flood level by 2100.

Any changes associated with global warming should be considered against the background of natural variations, such as long-term variations caused by solar and tectonic factors, as well as short- and mid-term changes related to atmospheric and oceanic conditions. Climate change will affect the physical, biological, and biogeochemical characteristics of the oceans and coasts at different time and space scales, modifying their ecological structure and functions. These changes, in turn, will exert significant feedback on the climate system. The world's oceans already are under stress as a result of a combination of factors—such as increased population pressure in coastal areas, habitat destruction, and increased pollution from the atmosphere, from land-based sources, and from river inputs of nutrients and other contaminants (Izrael and Tsyban, 1983). These factors, along with increased UV-B radiation resulting from stratospheric ozone depletion, are expected to impair the resilience of some marine ecosystems to climate change.

This chapter reviews the potential impacts of climate change on the coastal zone, marine ecosystems, and marine fisheries. It provides an assessment of the latest scientific information on impacts and adaptation strategies that can be used to anticipate and reduce these impacts. Emphasis is placed on scientific work completed since 1995. This chapter builds on earlier IPCC reports but differs in several significant ways. First, the content of the present chapter was covered in three separate chapters in the Second Assessment Report (SAR: Chapter 8, Oceans; Chapter 9, Coastal Zones and Small Islands; Chapter 16, Fisheries) and in two chapters in the First Assessment Report (FAR: World Oceans and Coastal Zones, Working Group II; Coastal Zone Management, Working Group III). Second, in the *Special Report on Regional Impacts of Climate Change* (IPCC, 1998), impacts on the oceans and coasts were considered in each of the regional chapters; those on the Small Island States and the Arctic and Antarctic were of particular relevance to the present chapter. Third, whereas previous IPCC reports highlighted sea-level rise, vulnerability assessment, biogeophysical effects, and single-sector impacts, this chapter covers several other topics—including a range of methodologies; climate-change parameters; physical, biological, and socioeconomic sensitivities; and adaptation mechanisms. Additional and regionally specific coastal and marine details are included in the regional chapters of this Third Assessment Report (TAR).

6.2. State of Knowledge

In the past decade there has been considerable improvement in our knowledge of the impacts of climate change on coastal zones and marine ecosystems. This improvement has been far from uniform, either thematically or in regional coverage, and there are still substantial gaps in our understanding.

The First and Second Assessment Reports on ocean systems (Tsyban *et al*., 1990; Ittekkot *et al*., 1996) conclude that global warming will affect the oceans through changes in sea-surface temperature (SST), sea level, ice cover, ocean circulation, and wave climate. A review of the global ocean thermohaline circulation system—for which the term "ocean conveyor belt" has been coined (Broecker, 1994, 1997)—emphasizes the role of the global ocean as a climate regulator. Ittekkot *et al*. (1996) notes that the oceans also function as a major heat sink and form the largest reservoir of the two most important greenhouse gases [water vapor and carbon dioxide (CO_2)], as well as sustaining global biogeochemical cycles.

Climate-change impacts on the ocean system that were projected with confidence by Ittekkot *et al*. (1996) include SST-induced shifts in the geographic distribution of marine biota and changes in biodiversity, particularly in high latitudes; future improvement of navigation conditions in presently ice-infested waters; and sea-level changes resulting from thermal expansion and changes in terrestrial ice volume. Regional variations caused by dynamic processes in the atmosphere and ocean also were identified with some confidence. Less confident predictions include changes in the efficiency of carbon uptake through circulation and mixing effects on nutrient availability and primary productivity; changes in ocean uptake and storage capacity for greenhouse gases; and potential instability in the climate system caused by freshwater influx to the oceans and resultant weakening of the thermohaline circulation.

The SAR includes a comprehensive review of climate-change impacts on fisheries (Everett *et al.*, 1996). Principal impacts are believed to be compounded by overcapacity of fishing fleets, overfishing, and deterioration of aquatic habitats. The authors also note that the impacts of natural climate variability on the dynamics of fish stocks is being considered as an important component of stock management, although the nature and magnitude of that variability are not clear.

In the present report, we identify new information about the impacts of climate change that has accumulated since the SAR. We include assessments of impacts on fisheries, marine mammals, sea birds, aquaculture, and marine diseases. We show that more recent information identifies natural multi-year climate-ocean trends as an essential consideration in fisheries management and stewardship of marine ecosystems. We point out that separating the impacts of natural climate variability and regime shifts from those associated with long-term climate change will be important, although distinguishing between the two will be a difficult task.

The potential impacts of sea-level rise on coastal systems have been emphasized in recent years. Much less attention has been given to the effects of increases in air and sea-surface temperatures; and changes in wave climate, storminess, and tidal regimes. There are at least two reasons for this lack of attention. First, low-lying coastal areas such as deltas, coastal plains, and atoll islands are regarded as particularly vulnerable to small shifts in sea level. Second, global sea-level rise is regarded as one of the more certain outcomes of global warming and already is taking place. Over the past 100 years, global sea level has risen by an average of 1–2 mm yr^{-1}, and scientists anticipate that this rate will accelerate during the next few decades and into the 22nd century.

The FAR (Tsyban *et al.*, 1990) regards sea-level rise as the most important aspect of climate change at the coast and identifies seven key impacts:

1) Lowland inundation and wetland displacement
2) Shoreline erosion
3) More severe storm-surge flooding
4) Saltwater intrusion into estuaries and freshwater aquifers
5) Altered tidal range in rivers and bays
6) Changes in sedimentation patterns
7) Decreased light penetration to benthic organisms.

In the SAR, Bijlsma *et al.* (1996) acknowledge the importance of these impacts and further conclude, with high confidence, that natural coastal systems will respond dynamically to sea-level rise; responses will vary according to local conditions and climate; and salt marshes and mangroves may survive where vertical accretion equals sea-level rise—but built infrastructure limits the potential for landward migration of coastal habitats. That report also provides summaries of national and global vulnerability assessments, focusing on numbers of people, land areas, and assets at risk. Several coastal adaptation strategies are identified. The importance of resilience in coastal systems is hinted at and subsequently has become an important consideration in vulnerability analysis of sectors and geographical regions.

6.3 Marine Ecosystems

6.3.1. Habitat

The oceans have significant adaptive capacity to store heat and are the largest reservoir of water vapor and CO_2, although the storage capacity for CO_2 in the Southern Ocean recently has been questioned (Caldeira and Duffy, 2000). In the oceans, climate change will induce temperature changes and associated adjustments in ocean circulation, ice coverage, and sea level. Changes in the frequency of extreme events also may be expected. These changes, in turn, will affect marine ecosystem structure and functioning, with feedback to global biogeochemical cycles and the climate system.

Recent investigations have shown that there has been a general warming of a large part of the world ocean during the past 50 years (Levitus *et al.*, 2000). Analysis of historical SST data by Cane *et al.* (1997) shows an overall increase associated with land-based global temperature trends. Regional differences exist such that over the past century a cooling was observed in the eastern equatorial Pacific, combined with a strengthening of the zonal SST gradient.

Global mean sea-level has risen by about 0.1–0.2 mm yr^{-1} over the past 3,000 years and by 1–2 mm yr^{-1} since 1900, with a central value of 1.5 mm yr^{-1}. TAR WGI Chapter 11 projects that for the full range of the six illustrative scenarios in the IPCC's *Special Report on Emissions Scenarios,* sea level will rise by 0.09–0.88 m between 1990 and 2100. This range is similar to the total range of projections given in the SAR of 0.13–0.94 m. Higher mean sea level will increase the frequency of existing extreme levels associated with storm waves and surges.

The El Niño-Southern Oscillation is a natural part of the Earth's climate. A major issue is whether the intensity or frequency of ENSO events might change as a result of global warming. Timmermann *et al.* (1999) suggested an increased frequency of El Niño-like conditions under future greenhouse warming and stronger "cold events" in the tropical Pacific Ocean. Cooling has been observed in the eastern equatorial Pacific, not reproduced in most GCMs, and has been explained by an increase in upwelling from the strengthening of trade winds because of a uniform warming of the atmosphere (Cane *et al*., 1997). If temperature differences between the tropics and polar regions are reduced, however, a weakening of the atmospheric circulation patterns that cause upwelling could be expected.

In recent years there have been several studies of global ocean wind and wave climates (e.g., Young, 1999), but analyses of changes over the past few decades have been limited to a few regions. In the past 30 years there has been an increase in wave height over the whole of the North Atlantic, although scientists are not certain that global change is the cause of this phenomenon (Guley and Hasse, 1999). Similarly, analyses of wave buoy data along the entire west coast of North America demonstrate that the heights of storm-generated waves have increased significantly during the past 3 decades (Komar *et al*., 2000). On the U.S. east coast, analyses have shown that there has been no discernible long-term trend in the number and intensity of coastal storms during the past century, although there has been considerable interdecadal variation (Zhang *et al.*, 2000). The sensitivity of storm waves to a hypothetical sea-level rise and increase in wind strength recently has been modeled for Uruguay (Lorenzo and Teixeira, 1997).

Projected changes in tropical cyclone frequency and intensity remain inconclusive, although some studies have suggested that the maximum intensity of tropical cyclones may rise by 10–20% (Henderson-Sellars *et al.*, 1998; Knutson *et al.*, 1998). Walsh and Pittock (1998) and Walsh and Katzfey (2000) also suggest that once formed, tropical cyclone-like vortices might travel to higher latitudes and persist for longer as a result of increased SST.

Increased precipitation intensity in extreme events is suggested by climate models under doubled CO_2 for Europe (Jones *et al.*, 1997) and the United States (Mearns *et al*., 1995), and there is firm evidence that moisture in the atmosphere is increasing over China, the Caribbean region, and the western Pacific (Trenberth, 1999). Heavy rainfall increased during the 20th century in the United States (Karl and Knight, 1998), and there is evidence for increased precipitation rates in Japan and Australia (Iwashima and Yamamoto, 1993; Suppiah and Hennessy, 1998). Changes in the probability of heavy precipitation also are regarded as important indicators of climate change.

Globally, oceanic thermohaline circulation plays an important role in controlling the distribution of heat and greenhouse gases. This circulation is driven by differences in seawater temperature and salinity. There is some evidence that the global thermohaline circulation will weaken as a result of climate change, although views on this issue are still evolving.

Sea ice covers about 11% of the ocean, depending on the season. It affects albedo, salinity, and ocean-atmosphere thermal exchange. The latter determines the intensity of convection in the ocean and, consequently, the mean time scale of deep-ocean processes affecting CO_2 uptake and storage. Projected changes in climate should produce large reductions in the extent, thickness, and duration of sea ice. Major areas that are now ice-bound throughout the year are likely to have lengthy periods during which waters are open and navigable. Observations in the northern hemisphere already have shown a significant decrease in spring and summer sea-ice extent by about 10–15% since the 1950s. It also has been suggested that the decline in ice volume is underestimated because of significant thinning of sea ice in the Arctic (Rothrock *et al.*, 1999). Evidence from whaling records implies a decline in Antarctic ice extent by as much as 25% between the mid-1950s and the early 1970s (de la Mare, 1997).

The foregoing physical responses in the ocean-climate system have implications for habitat and ecology in the oceans and coastal seas. Projected climate changes have the potential to become a major factor affecting marine living resources over the next few decades. The degree of the impact is likely to vary within a wide range, depending on the species and community characteristics and the regional specific conditions. Smith *et al.* (1999) review the sensitivity of marine ecosystems to climate change.

6.3.2. Biological Processes

Marine biota have an important role in shaping climate. Marine biological processes sequester CO_2 and remove carbon from surface waters to the ocean interior through the settling of organic particles and as ocean currents transport dissolved organic matter. This process, which is called the biological pump, reduces the total carbon content of the surface layers and increases it at depth. This process may be partially offset by biocalcification in reefs and organisms in the open ocean, which increases surface layer CO_2 by reducing bicarbonate alkalinity.

Projected global warming through the 21st century is likely to have an appreciable effect on biological processes and biodiversity in the ocean. A rise in temperature will result in acceleration of biodegradation and dispersal of global organic pollutants (petroleum and chlorinated hydrocarbons, for example). This process would promote their removal from the photic zone of the ocean, as has been demonstrated by Tsyban (1999a) for the Bering and Chukchi Seas.

Physiochemical and biological processes regulate uptake and storage of CO_2 by oceans. The Arctic Ocean, for instance, is an important CO_2 source in winter and sink in summer (Tsyban, 1999b). Climate change is expected to affect the processes that control the biogeochemical cycling of elements. Uptake and storage of CO_2 by the ocean via the biological pump therefore may change. Any changes that do occur are expected to feed back into the carbon cycle (Ittekkot *et al*., 1996).

Photosynthesis, the major process by which marine biota sequester CO_2, is thought to be controlled by the availability of nutrients and trace elements such as iron (de Baar *et al*., 1995; Behrenfeld *et al*., 1996; Coale *et al*., 1996; Falkowsky *et al*., 1998). Changes in freshwater runoff resulting from climate warming could affect the inputs of nutrients and iron to the ocean, thereby affecting CO_2 sequestration. Impacts are likely to be greatest in semi-enclosed seas and bays.

Climate change can cause shifts in the structure of biological communities in the upper ocean—for example, between coccoliths and diatoms. In the Ross Sea, diatoms (primarily *Nitzshia subcurvata*) dominate in highly stratified waters, whereas *Phaeocystis antarctica* dominate when waters are more deeply mixed (Arrigo *et al*., 1999). Such shifts alter the downward fluxes of organic carbon and consequently the efficiency of the biological pump.

6.3.3. Marine Carbon Dioxide Uptake

The oceans are estimated to have taken up approximately 30% (with great uncertainties) of CO_2 emissions arising from fossil-fuel use and tropical deforestation between 1980 and 1989, thereby slowing down the rate of greenhouse global warming (Ittekkot *et al*., 1996). An important process in the oceans is burial of organic carbon in marine sediments, which removes atmospheric CO_2 for prolonged time periods. Studies of the Southern Ocean by Caldeira and Duffy (2000) have shown high fluxes of anthropogenic CO_2 but very low storage. Model results imply that if global climate change reduces the density of surface waters in the Southern Ocean, isopycnal surfaces that now outcrop may become isolated from the atmosphere, which would tend to diminish Southern Ocean carbon uptake.

Using models of the effects of global warming on ocean circulation patterns, Sarmiento and Le Quéré (1996) analyzed the potential for changes in oceanic CO_2 uptake. They found that a weakening of the thermohaline circulation could reduce the ocean's ability to absorb CO_2 whereby, under a doubled-CO_2 scenario, oceanic uptake of CO_2 dropped by 30% (exclusive of biological effects) over a 350-year period. In simulations with biological effects under the same CO_2 conditions and time frame, they found that the oceanic uptake was reduced only by 14%. Confirmation that a collapse of global thermohaline circulation could greatly reduce the uptake of CO_2 by the ocean has been reported by Joos *et al.* (1999).

Sarmiento *et al*. (1998) modeled carbon sequestration in the ocean with increasing CO_2 levels and changing climate from 1765 to 2065. They found substantial changes in the marine carbon cycle, especially in the Southern Ocean, as a result of freshwater inputs and increased stratification, which in turn reduces the downward flux of carbon and the loss of heat to the atmosphere

6.3.4. Marine Fish

Climatic factors affect the biotic and abiotic elements that influence the numbers and distribution of fish species. Among the abiotic factors are water temperature, salinity, nutrients, sea level, current conditions, and amount of sea ice—all of which are likely to be affected by climate change. Biotic factors include food availability and the presence and species composition of competitors and predators. Clearly the relationship between climatic factors and the fish-carrying capacity of the marine environment is complicated, although water temperature can be used as a basis for forecasting the abundance and distribution of many species (Lehodey *et al*., 1997). Water temperature also can have a direct effect on spawning and survival of larvae and juveniles as well as on fish growth, by acting on physiological processes. Sea temperature also affects the biological production rate thus food availability in the ocean, which is a powerful regulator of fish abundance and distribution.

The question of large-scale, long-term fluctuations in the abundance of marine organisms, primarily those of considerable commercial importance, recently has gained attention. Research has shown that variations (with cycles of 10–60 years or more) in the biomass volume of marine organisms depend on sea temperature and climate (Ware, 1995). Examples include periodic fluctuations in the climate and hydrographic regime of the Barents Sea, which have been reflected in variations in commercial production over the past 100 years. Similarly, in the northwest Atlantic Ocean results of fishing for cod during a period of 300 years (1600–1900) showed a clear correlation between water temperature and catch, which also involved changes in the population structure of cod over cycles of 50–60 years. Shorter term variations in North Sea cod have been related to a combination of overfishing and warming over the past 10 years (O'Brien *et al*., 2000).

From 1987 to 1996, the world catch of all marine fishes averaged 74.5 Mt. From 1987 to 1993, catches were relatively stable, ranging between 71.6 and 75.9 Mt. There was a small increase over the period 1994–1996, ranging from 77.1 to 78.6 Mt (FAO, 1998). The 10 species with the largest landings represented 37.4% of the catch in 1996 and the next 10 species an additional 10.9%. Fluctuations in abundance of species representing the 10 largest landings often have been considered to result from overfishing and occasionally from a combination of ocean environment changes and fishing effects. However, there is increasing evidence to suggest that the impacts of climate variations are also having an important effect (O'Brien *et al.*, 2000).

The collapse of the Peruvian anchovy *(Engraulis ringens*) fishery from the mid-1970s to the mid-1980s was widely accepted as an example of overfishing and poor management. The increases in recent years, to catches slightly smaller than the large catches prior to the collapse, provide an example of the important impact of natural fluctuations and the difficulty of sorting out the impacts of fishing and climate-ocean-induced changes. Caddy and Rodhouse (1998) reported an increase in world cephalopod landings as world marine fish catches stabilized. These increases were believed to be related to reduced predation from overfishing of groundfish stocks, although warmer oceans were considered an important factor. These examples emphasize the importance of considering the ecosystem impacts of climate variations, as well as changes for individual species.

McGowan *et al.* (1998) show that there are large-scale biological responses in the ocean to climate variations. Off California, the climate-ocean regime shift in 1976–1977 (Ebbesmeyer *et al*., 1991) resulted in a reduced rate of supply of nutrients to a shallower mixing layer, decreasing productivity and zooplankton and causing reductions in kelp and sea birds. Although there is no question that fishing has impacts on the dynamics of fish populations, the recent evidence of climate-related impacts is beginning to confound past interpretations of fishing effects. McGowan *et al.* (1998) point out that the success of future fish stock assessments would depend, to a large extent, on the ability to predict the impacts of climate change on the dynamics of marine ecosystems. The assumption that marine ecosystems are stable is no longer acceptable, which raises questions about the definition of sustained yield (O'Brien *et al.,* 2000).

Weather impacts and seasonal rhythms have long been recognized by the global fishing industry, but decadal-scale regime changes have been acknowledged only recently as a factor in fish and ocean ecosystem dynamics. The concept of distinct states in climate-ocean environments, which after periods of persistence switch abruptly to other states, have been called regimes and regime shifts, respectively. More formally, regimes (Steele, 1996) can be defined as multi-year periods of linked recruitment patterns in fish populations or as a stable mean in physical

***Table 6-1**: Largest marine fisheries in 1996 (FAO, 1998).*

Species	**Landings (t)**	**% of Total**
Peruvian anchovy (*Engraulis ringens*)	8,864,000	11.3
Walleye pollock (*Theragra chalcogramma*)	4,533,000	5.8
Chilean Jack mackerel (*Trachurus murphyi*)	4,379,000	5.8
Atlantic herring (*Clupea harengus*)	2,331,000	3.0
Chub mackerel (*Scomber japonicus*)	2,168,000	2.8
Capelin (*Mallotus villosus*)	1,527,000	1.9
South American pilchard (*Sardinops sagax*)	1,494,000	1.9
Skipjack tuna (*Katsuwonus pelamis*)	1,480,000	1.9
Atlantic cod (*Gadus morhua*)	1,329,000	1.7
Largehead hairtail (*Trichiarus lepturus*)	1,275,000	1.6

data. A regime shift is a change in the mean of a data series. The existence of decadal-scale regimes in the environment has been documented (e.g., Gargett, 1997; Gu and Philander, 1997; Mantua *et al*., 1997). States even longer than the decadal-scale may exist (Ware, 1995; Marsh *et al*., 1999). Adkinson *et al.* (1996) and Beamish *et al.* (1997) have documented a large-scale response in fish populations to regimes and regime shifts for Pacific salmon.

Among the most important groups of marine fishes are herrings *(Clupea sp.*), sardines and pilchards *(Sardinops sp.*), and anchovies *(Engraulis sp.*) (see Table 6-1). These fish tend to be short-lived species that mature at an early age. Large fluctuations in abundance have been associated with changes in the climate-ocean environment, although it has not been possible to discover the mechanisms that link climate-ocean changes to recruitment (Cole and McGlade, 1998). One of the most convincing relationships of large-scale, synchronous responses in major fisheries resulting from changes in climate-ocean states exists for sardine *(Sardinops sp.*). The decadal variability in the Japanese sardine catch was synchronous with decadal-scale variability in the ocean and climate of the North Pacific; these phenomena also were synchronous with the fluctuations of sardine catches off Chile and California (Kawasaki, 1991; Hiyama *et al*., 1995) and with trends in Pacific salmon catches (Beamish *et al*., 1999) (see Box 6-1).

Fluctuations in the abundance and distribution of herring (*Clupea harengus*) and sardine (*Sadinella pilchardus*) in the North and Baltic Seas have been linked to variations of the North Atlantic Oscillation and the resulting strength and pattern of southwesterly winds (Alheit and Hagen, 1997).

Most fishing regime changes can be related directly to sea-temperature changes, but changes in other physical attributes also can have an impact. For instance, a decrease in wind stress off Tasmania that reduced large zooplankton production affected the density of Jack mackerel (*Trachurus declivis*), which eliminated the possibility of a commercially viable mackerel fishery (Harris *et al.*, 1992).

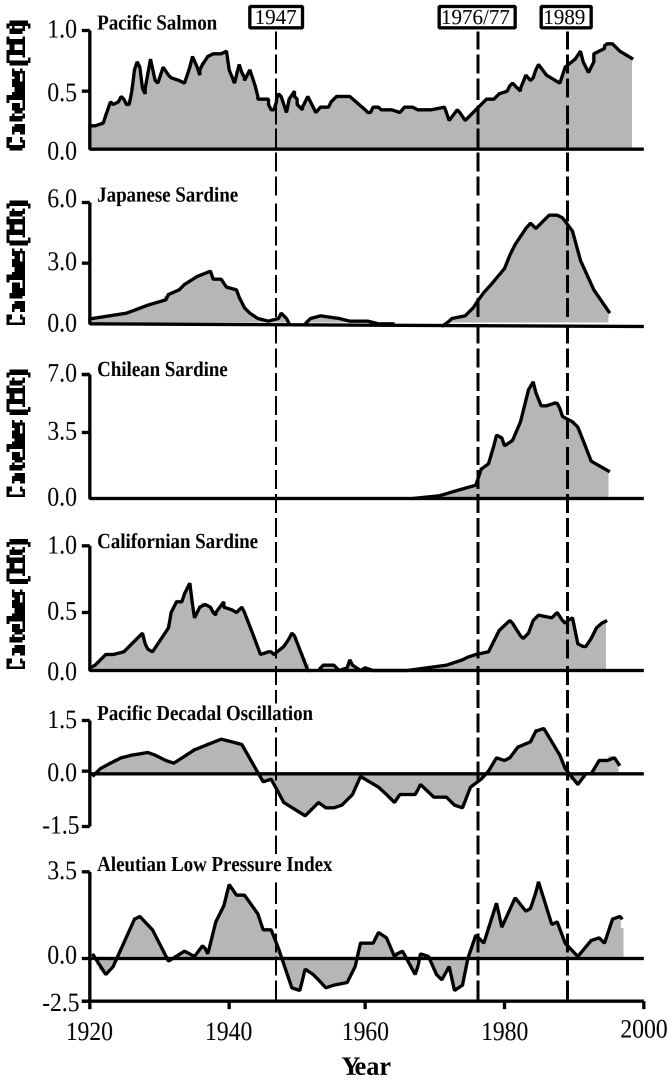
The aforementioned climate-related fluctuations in the Japanese sardine occurred at the same time as shifts in the migratory patterns of the northern bluefin tuna *(Thunnus thynnus*), with a higher proportion of bluefin remaining in the western Pacific when sardine abundance was high (Polovina, 1996). The migratory pattern of albacore tuna (*T. alalunga*) also was altered by decadal-scale climate changes (Kimura *et al*., 1997).

Nearly 70% of the world's annual tuna harvest comes from the Pacific Ocean. In 1996, Skipjack tuna *(Katsuwonus pelamis)* was the eighth-largest marine fishery in the world (see Table 6-1). Catches of skipjack are highest in the western equatorial Pacific warm pool; Lehodey *et al.* (1997) have shown that major spatial shifts in the skipjack population can be linked to large zonal displacements of the warm pool (see Box 6-2).

Welch *et al.* (1998) propose that continued warming of the North Pacific Ocean would compress the distributions of Sockeye salmon (*Oncorhynchus nerka*), essentially squeezing them out of the North Pacific and into the Bering Sea. Some modeling of future impacts of greenhouse gas increases, however, has shown an intensification of the Aleutian Low, which has been associated with mid-ocean cooling (Deser *et al*., 1996) and increased Pacific salmon production. The warmer surface waters could reduce growth if bioenergetic costs are higher and less food is available as a consequence of ocean habitat changes. The potential impact of climate change on Pacific salmon is expected to occur in freshwater and ocean situations (Hinch *et al*., 1995). This fact is important because production of more juveniles in hatcheries would not mitigate changes in the ocean carrying capacity for Pacific salmon. The most effective strategy to manage the impacts of climate change on Pacific salmon may be to ensure that wild salmon are preserved and protected, rather than to produce more salmon through artificial enhancement. It is possible that the variety of life history types and genetic traits of the wild stocks are inherent biological solutions to changing freshwater and marine habitats (Bisbal and McConnaha, 1998).

The potential deepening of the Aleutian Low and increase in the amplitude of the Pacific Decadal Oscillation would result in major changes in marine ecosystems (Mantua *et al*., 1997).

Box 6-1. Regimes and Regime Shifts: Salmon and Sardine Catch



As the figure to the left shows, catches (Mt) of Pacific salmon (*Oncorhynchus sp.*) and sardines (*Sardinops sp.*) fluctuate synchronously with large-scale climate-ocean changes in the North Pacific, as indicated by the Aleutian Low Pressure Index and SST as expressed in the Pacific Decadal Oscillation both of which are shown as a 5-year running average (data from Beamish *et al*., 1999, and Mantua *et al.*, 1997). Persistent states or regimes are separated by regime shifts, which occurred about 1947, 1976–1977, and 1989. These shifts are shown by the vertical dashed lines. The well-documented 1976–1977 regime shift has been associated with changing abundance trends of other marine organisms such as plankton. It also has been related to an abrupt change in the southernmost extent of sea ice in the Bering Sea, in turn affecting the distribution of Walleye pollock (*Theragra chalcogramma*) and Arctic cod (*Boreogadus saida*) (Wyllie-Echeverria and Wooster, 1998).

The concepts of regimes, regime shifts, and natural trends in the abundance of animals indicates that it is important to assess the potential impact of global warming on decadal-scale processes as well as on species specific responses.

As ecosystems change, there may be impacts on the distribution and survival of fishes. Any changes in natural mortality would be associated with increased predation and other factors such as disease. Improved growth in the early life stages would improve survival, whereas decreased growth could facilitate increased mortality.

Sea temperature is an important regulator of fish behaviors. Wood and McDonald (1997) provide examples of how climate change could induce temperature responses in fish, but there are several areas where less certainty exists. The effect that global climate change will have on trends in the Aleutian Low Pressure system in the Pacific Ocean is an example. Although there are clear linkages between the intensity and position of the low and production trends of many of the commercially important fish species (Kawasaki *et al*., 1991; Polovina *et al*., 1995; Gargett, 1997; Mantua *et al.*, 1997; Francis *et al.*, 1998), a reduction in equator-to-pole temperature gradients would probably weaken winds and consequently reduce open-ocean upwelling. Important changes in species distributions in surface waters could result.

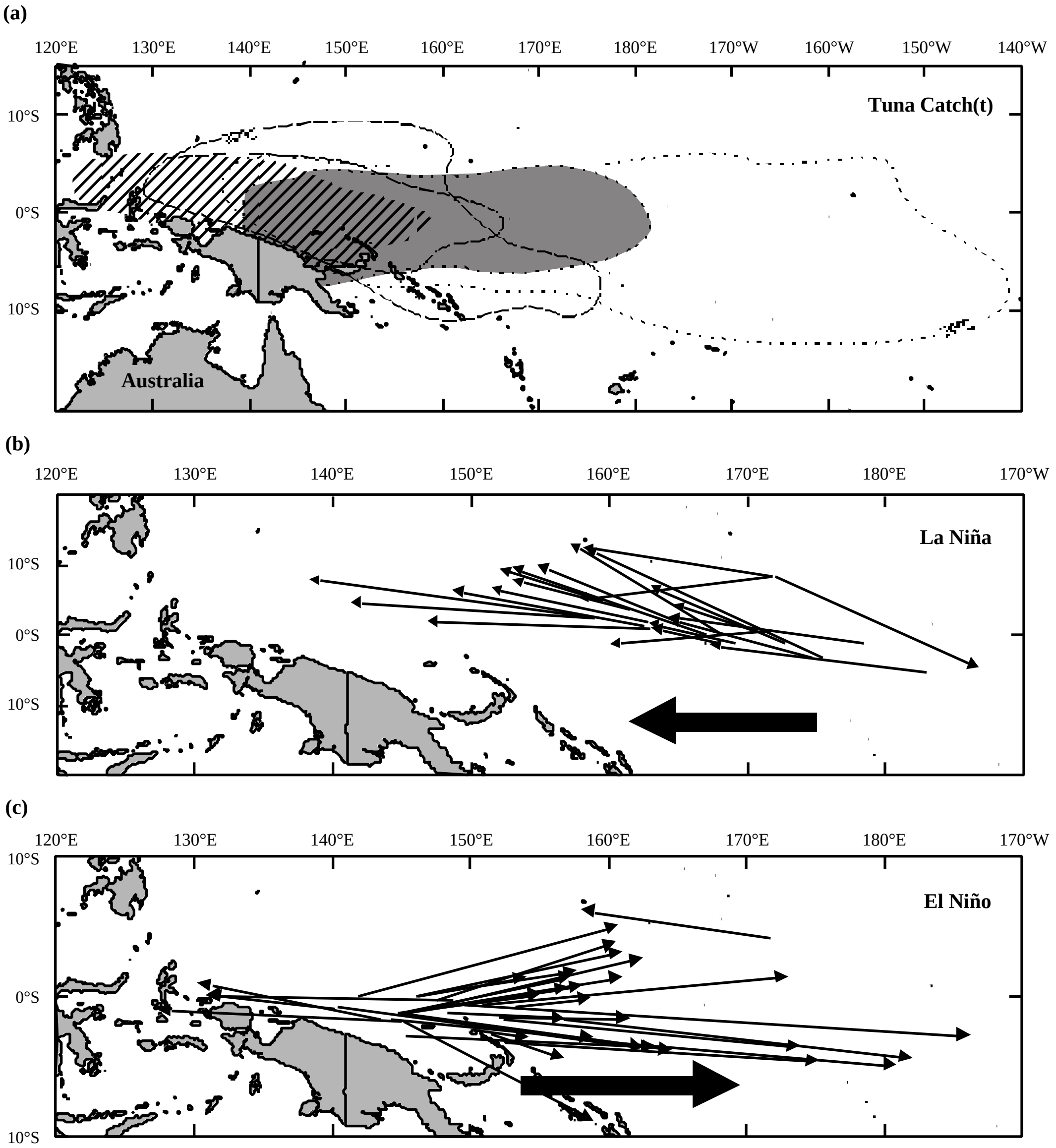
There is now a cautious acceptance that climate change will have major positive and negative impacts on the abundance and distribution of marine fish. Thus, the impacts of fishing and climate change will affect the dynamics of fish and shellfish such as abalone in Mexico (Shepherd *et al.*, 1998). Fishing impacts may be particularly harmful if natural declines in productivity occur without corresponding reductions in exploitation rates. Changes in fish distributions and the development of aquaculture may reduce the value of some species, however—as it has for wild Pacific salmon—and these changes may reduce fishing pressures in some areas.

Key to understanding the direction of change for world fisheries is the ability to incorporate decadal-scale variability into general circulation models (GCMs). Although progress has occurred, it still is not possible to assess regional responses to shifts in climate

Box 6-2. Tuna Migration and Climate Variability

Skipjack tuna (*Katsuwonus pelamis)* dominate the world's catch of tuna. The habitat supporting the densest concentrations of skipjack is the western equatorial Pacific warm pool, with SST of 29°C and warmer. Panel (a) clearly shows the association of skipjack tuna catch (shaded and cross-hatched areas indicate January–June catch of 200,000+ t) and mean SST [data from Lehodey *et al.* (1997)]. The figure also shows that the location of the warm pool is linked to ENSO and that it changes during El Niño and La Niña events. For instance, the catch area in the first half of 1989 (La Niña period), which is shown by cross-hatch, was centered around Palau and the Federated States of Micronesia; in the first half of 1992 (El Niño period), the center of abundance had shifted to the east, to the Marshall Islands and Kiribati (shown by shading).

Panels (b) and (c) indicate the scale of tuna migration during a La Niña period and an El Niño period, respectively. These figures were compiled from records of a large-scale skipjack tagging program carried out by the Secretariat of the Pacific Community (SPC). The illustrations are from Lehodey *et al.* (1997, 1998).



The close association of skipjack tuna catch and ENSO is evidence that climate variability profoundly affects the distribution pattern of tuna and resulting fishing opportunities. Scientists do not know how projected climate changes will affect the size and location of the warm pool in the western and central Pacific, but if more El Niño-like conditions occur an easterly shift in the center of tuna abundance may become more persistent.

trends, and it is unknown if a general warming will increase or decrease the frequency and intensity of decadal-scale changes in regions where national fisheries occur. Recent studies have not produced evidence to change the conclusion from the SAR (Everett *et al.,* 1996) that future saltwater fisheries production is likely to be about the same as at present, though changes in distribution could affect who catches a particular stock. However, if aquaculture becomes the major source of fish flesh and management of fisheries becomes more precautionary, the exploitation rate of wild marine fish may decrease in some areas.

6.3.5. Aquaculture

Marine aquaculture production more than doubled from 4.96 Mt in 1990 to 11.14 Mt in 1997. Similar trends were exhibited in freshwater aquaculture, with increases from 8.17 Mt in 1990 to 17.13 Mt in 1997, while yields from marine and freshwater fisheries remained relatively constant. The net result was that aquaculture production represented approximately 30% of total fish and shellfish production for human consumption in 1997. Aquaculture production is expected to continue its upward trend in the foreseeable future, although in many areas (such as in Thailand) there is a boom and bust pattern to aquaculture.

About 30% (29.5 Mt) of the world fish catch is used for nonhuman consumption, including the production of fishmeal and fish oils that are employed in agriculture, in aquaculture, and for industrial purposes. Fishmeal and fish oils are key diet components for aquaculture production; depending on the species being cultured, they may constitute more than 50% of the feed. Climate change could have dramatic impacts on fish production, which would affect the supply of fishmeal and fish oils. Unless alternative sources of protein are found, future aquaculture production could be limited by the supply of fishmeal or fish oils if stocks of species used in the production of fishmeal are negatively affected by climate change and live-fish production. The precise impacts on future aquaculture production also will depend in part on other competing uses for fishmeal and fish oils. Usage of other sources of protein or developments in synthetic oils for industrial applications could reduce demands on fishmeal and fish oils, thereby reducing potential impacts on aquaculture.

Climate change is expected to have physical and ecosystem impacts in the freshwater and marine environments in which aquaculture is situated. Water and air temperatures in mid- to high latitudes are expected to rise, with a consequent lengthening of the growing season for cultured fish and shellfish. These changes could have beneficial impacts with respect to growth rate and feed conversion efficiency (Lehtonen, 1996). However, increased water temperatures and other associated physical changes, such as shifts in dissolved oxygen levels, have been linked to increases in the intensity and frequency of disease outbreaks and may result in more frequent algal blooms in coastal areas (Kent and Poppe, 1998). Any increases in the intensity and frequency of extreme climatic events such as storms, floods, and droughts will negatively impact aquaculture production and may result in significant infrastructure damage. Sea-level rise can be expected to have a negative effect on pond walls and defenses.

Elevated temperatures of coastal waters also could lead to increased production of aquaculture species by expanding their range. These species could be cultivated in higher latitudes as well as in existing aquafarms as a result of a longer warm season during which water temperature will be near optimal. A decrease in sea-ice cover could widen the geographical boundaries, allowing cultivation of commercially valuable species in areas hitherto not suitable for such developments.

6.3.6. Ocean Ranching

Ocean ranching is used to increase the production of several fish species. The primary difference between ocean ranching and aquaculture is that in ocean ranching the fish are cultured for only a portion of their life cycle and then released prior to maturity. The cultured fish are then captured as "common property" in a variety of fisheries. These cultured or "enhanced" fish interact with the wild fish in the ecosystem and compete for the finite food and habitat resources available (often referred to as "carrying capacity"). Climate change will alter carrying capacity, but the impacts associated with ocean ranching or stock enhancement activities also need to be considered when examining overall changes to the ecosystem.

Although the precise impacts are species-dependent, the addition of billions of enhanced fish into the marine ecosystem may have significant consequences from genetic and ecological perspectives. In the Pacific, for example, large numbers of salmon are released from hatcheries in Russia, Japan, Canada, and the United States (Mahnken *et al*., 1998). Beamish *et al.* (1997) estimate that 83% of the catch of chum salmon by all countries is from hatchery production. If climate change increases SST and reduces winter wind mixing in the upper layers of the ocean, the feeding areas for salmon may be less productive because of increased surface layer stability. Reductions in overall production and catches of salmon—and likely other species—would result (Gargett, 1997).

6.3.7. Marine Mammals and Seabirds

Marine mammals and seabirds are sensitive indicators of changes in ocean environments. Springer (1998) concluded that synchrony in extreme fluctuations of abundance of marine birds and mammals across the North Pacific and Western Arctic were a response to physical changes, including climate warming. The linkages with climate change were compelling enough for Springer to suggest that fluctuations in marine bird and mammal populations in the North Pacific are entirely related to climate variations and change.

The climate variations beginning in the 1990s and associated with El Niño conditions (Trenberth and Hoar, 1996), in combination with overfishing, have been linked to behavioral changes in killer whales. These changes drastically reduced sea otter abundance along the Aleutian Islands, which in turn changed the ecology of the kelp forests (Estes *et al*., 1998). The changes in prey resulting from persistent changes in climate appear to be one of the important impacts of a changing climate on the marine mammals that feed from the top of the food chain.

Climate change also may have an effect on access to prey among marine mammals. For instance, extended ice-free seasons in the Arctic could prolong the fasting of polar bears *(Ursus maritimus*), with possible implications for the seal population (Stirling *et al*., 1999). Reduced ice cover and access to seals would limit hunting success by polar bears and foxes, with resulting reductions in bear and fox populations. This dynamic could have negative effects on the lifestyle, food, and health standards of some indigenous peoples (Hansell *et al*., 1998). Because global climate change is likely to have profound impacts on sea-ice extent and duration, it is in this habitat where the initial impacts on marine mammals may be first evident. Reductions in sea ice have been predicted to alter the seasonal distributions, geographic ranges, migration patterns, nutritional status, reproductive success, and ultimately the abundance of Arctic marine mammals (Tynan and DeMaster, 1997). Studies recognizing multi-year to decadal variability in marine biotic systems include Mullin (1998) on zooplankton over 5 decades in the eastern Pacific (with connections to El Niño), and Tunberg and Nelson (1998) on soft bottom macrobenthic communities in the northeast Atlantic (with connections to the North Atlantic Oscillation). Sagarin *et al*. (1999) have argued that changes in the distribution of intertidal macroinvertebrates on rocky shores in California over the past 60 years have been caused by climate change.

Seabirds are an integral part of marine ecosystems, where they may consume vast amounts of fish. It has been estimated that seabirds consume 600,000 t yr^{-1} of food in the North Atlantic (Hunt and Furness, 1996). Modeling studies have shown that in several marine ecosystems, seabirds eat 20–30% of the annual pelagic fish production. The dependence on some species of fish, particularly during breeding, and their large abundance make seabirds a good indicator of ecosystem change. Where changes in breeding success or mortality occur, however, distinguishing the climate impact from fishing impacts can be difficult (Duffy and Schneider, 1994). Very few decadal-scale studies of seabirds are available to assess the impacts of long-term variations in climate, however.

In general, seabirds have evolved to adapt to weather patterns (Butler *et al*., 1997). The ability of a species to alter its migration strategy appears to be important to survival in a changing climate. Food resources appear to be critical to general survival, especially for young seabirds. Dolman and Sutherland (1994) proposed that feeding rate affects the ability of individuals to survive winter. The change in marine ecosystem described by Roemmich and McGowan (1995) was associated with a mortality resulting in a 40% decline in seabird abundance within the California current system from 1987 to 1994 (Veit *et al*., 1996). The decline was largely related to a dramatic (90%) decline of sooty shearwaters *(Puffinus girseus),* but the response in the ecosystem was not characterized only by declines. There was a northward movement of some species, and in offshore waters the abundance of the most common species, Leach's storm petrels *(Oceanodroma leucorhoa),* increased over the same period. The authors were careful to note that the changes in abundance they described could not be related directly to population dynamics because of complex migratory patterns and the size of the habitat.

Such changes are evidence of the sensitivity of seabirds to climate-ocean changes and that survival and distribution impacts will occur as climates shift. The anomalous cold surface waters that occurred in the northwest Atlantic in the early 1990s changed the fish species composition in the surface waters on the Newfoundland shelf. These changes were readily detected in the diets of northern gannet *(Sula bassana)*. The sensitivity of the distribution patterns of the pelagic prey of fish-feeding and plankton-feeding seabirds imply to Montevecchi and Myers (1997) that small changes in the ocean environment resulting from climate changes could affect seabird reproductive success. Changes in fish-feeding seabird abundance in the eastern Bering Sea are related to the abundance of juvenile pollock (Springer, 1992). It has been argued that long lifespans and genetic variation within populations enable seabirds to survive adverse short-term environmental events, as evidenced by the response to El Niño and La Niña events in the tropical Pacific (Ribic *et al*., 1997). However, small populations tied to restricted habitat, such as the Galapagos Penguin (*Spheniscus mendiculus*), may be threatened by long-term climate warming (Boersma, 1998).

6.3.8. Diseases and Toxicity

Changes in precipitation, pH, water temperature, wind, dissolved CO_2, and salinity can affect water quality in estuarine and marine waters. Some marine disease organisms and algal species are strongly influenced by one or more of these factors (Anderson *et al*., 1998). In the past few decades there has been an increase in reports of diseases affecting closely monitored marine organisms, such as coral and seagrasses, particularly in the Caribbean and temperate oceans. The worldwide increase in coral bleaching in 1997–1998 was coincident with high water temperatures associated with El Niño, but Harvell *et al.* (1999) suggest that the demise of some corals might have been accelerated by opportunistic infections affecting the temperature-stressed reef systems. Talge *et al*. (1995) report a new disease in reef-dwelling foraminifera, with implications for coastal sedimentation.

ENSO cycles and increased water temperatures have been correlated with Dermo disease (caused by the protozoan parasite *Perkinsus marinus*) and MSX (multinucleated spore unknown) disease in oysters along the U.S. Atlantic and Gulf coasts. In addition to affecting marine hosts, several viruses, protozoa, and bacteria affected by climatic factors can affect people, by direct contact or by seafood consumption. Many of the reported cases of water-borne diseases involve gastrointestinal illnesses; some can be fatal in infants, elderly people, and people with weakened immune systems (ASM, 1998).

The bacterium *Vibrio vulnificus*, which is found in oysters and is potentially lethal to humans with immune-system deficiencies, becomes more abundant as water temperature increases (Lipp and Rose, 1997). The incidence and severity of cholera (*Vibrio cholerae*) epidemics associated with marine plankton also has been linked with prolonged elevated water temperature. Annual epidemics of cholera in Bangladesh have been correlated with increased SST and sea-surface height (Harvell *et al.*, 1999).

6.4. Coastal Systems

6.4.1. General Considerations

Coastal environments occupy one of the most dynamic interfaces on Earth, at the boundary between land and sea, and they support some of the most diverse and productive habitats. These habitats include natural ecosystems, in addition to important managed ecosystems, economic sectors, and major urban centers. The existence of many coastal ecosystems is dependent on the land-sea connection or arises directly from it (e.g., deltas and estuaries). Coastal ecosystems can encompass a wide range of environmental conditions over short distances, particularly of salinity (from fresh to hypersaline) and energy (from sheltered wetlands to energetic wave-washed shorelines). At a much coarser geographical scale, there is a spectrum of climate types—from tropical to polar—with concomitant broad-scale differences in biogeophysical processes and features. Coastal environments, settlements, and infrastructure are exposed to land-sourced and marine hazards such as storms (including tropical cyclones), associated waves and storm surges, tsunamis, river flooding, shoreline erosion, and influx of biohazards such as algal blooms and pollutants. All of these factors need to be recognized in assessing climate-change impacts in the coastal zone.

A summary of potential impacts appears in Box 6-3. Note, however, that owing to the great diversity of coastal environments; regional and local differences in projected relative sea level and climate changes; and differences in the resilience and adaptive capacity of ecosystems, sectors, and countries, the impacts summarized here will be highly variable in time and space and will not necessarily be negative in all situations.

Box 6-3. Potential Impacts of Climate Change and Sea-Level Rise on Coastal Systems

Biophysical impacts can include the following:

- Increased coastal erosion
- Inhibition of primary production processes
- More extensive coastal inundation
- Higher storm-surge flooding
- Landward intrusion of seawater in estuaries and aquifers
- Changes in surface water quality and groundwater characteristics
- Changes in the distribution of pathogenic microorganisms
- Higher SSTs
- Reduced sea-ice cover.

Related socioeconomic impacts can include the following:

- Increased loss of property and coastal habitats
- Increased flood risk and potential loss of life
- Damage to coastal protection works and other infrastructure
- Increased disease risk
- Loss of renewable and subsistence resources
- Loss of tourism, recreation, and transportation functions
- Loss of nonmonetary cultural resources and values
- Impacts on agriculture and aquaculture through decline in soil and water quality.

Some natural features of the shore zone provide significant coastal protection, including coral reefs (the most extensive, massive, and effective coastal protection structures in the world); sand and gravel beaches, which function as wave energy sinks; and barrier beaches, which act as natural breakwaters. Coastal dunes form natural buffers and sand repositories, from which sand may be extracted during storms without major shoreline retreat; coastal vegetation often absorbs wind or wave energy, retarding shoreline erosion. Even the value of salt marsh as a sea defense (King and Lester, 1995) and mangroves as a sediment trap (Solomon and Forbes, 1999) have been recognized. These functions of natural coastal systems contribute to resilience, as discussed in Section 6.6.2.

Bijlsma *et al.* (1996) and the various regional reports in IPCC (1998) identify the areas of greatest sensitivity to accelerated sea-level rise. These areas comprised low-elevation coral atolls and reef islands, as well as low-lying deltaic, coastal plain, and barrier coasts, including sandy beaches, coastal wetlands, estuaries, and lagoons. To this list can be added coarse gravel beaches and barriers, especially if sediment-starved; cliffed coasts in unlithified deposits, particularly where the proportion of sand and gravel is limited; and ice-rich cliffed coasts in high latitudes. Bold and rock-dominated coasts are relatively less vulnerable but often include coastal reentrants with beaches, estuaries, or deltas, which may represent areas of localized vulnerability. On such coasts, wave runup and overtopping can be a factor that threatens infrastructure situated well above mean sea level (Forbes, 1996).

It is important to recognize that vulnerable coastal types in many parts of the world already are experiencing relative sea-level rise, from a combination of subsidence and the global component of sea-level rise identified to date. Submergence rates of 2.5 mm yr^{-1} or more are not uncommon, and higher rates apply locally, such as in parts of China (Ren, 1994), the United States (Dean, 1990), Canada (Shaw *et al*., 1998a), and Argentina (Codignotto, 1997). Although this sea-level rise implies enhanced vulnerability, it also provides a basis for assessing coastal response to various rates of relative sea-level rise, where similar coastal types, boundary conditions, and system properties can be identified. Numerous studies along the U.S. Atlantic coast, where relative sea level is rising at rates of 2–4 mm yr^{-1}, have demonstrated common patterns of barrier beach retreat by washover and ephemeral inlet processes (Leatherman *et al.*, 2000). More rapid retreat is recorded in delta-margin settings characterized by rapid subsidence (e.g., Stone and McBride, 1998).

In addition to submergence, seawater intrusion into freshwater aquifers in deltaic and nondeltaic areas is an increasing problem with rising sea level (Moore, 1999). This intrusion has been documented in diverse environments such as the arid Israeli coast, the humid Thailand coast, the Chinese Yangtze Delta, the Vietnamese Mekong Delta, and low-lying atolls (e.g., Melloul and Goldberg, 1997; Chen and Stanley, 1998; Singh and Gupta, 1999).

Although some low, sediment-starved, gravel barrier beaches show rapid retreat under rising sea level, this process is highly nonlinear and in some cases is more closely related to storm event frequency and severity (Forbes *et al.,* 1997a). The response of coasts to storm-related sea-level variations around the North Sea has not been determined, although past increases in the winter means of high water levels of the order of 1–2 mm yr^{-1} have taken place (Langenberg *et al.*, 1999).

6.4.2. Beaches, Barriers, and Cliff Coasts

Sandy coasts shaped and maintained primarily by wave and tidal processes occupy about 20% of the global coastline (Bird, 1993). A smaller proportion consists of gravel and cobble-boulder beaches and related landforms, occurring in tectonically active and high-relief regions and in mid- to high-latitude areas of former glaciation. Coral rubble beaches and islands are common in low-latitude reefal areas. Any analysis of climate-change impacts on the coastal zone should include beaches and barriers of sand and/or gravel as well as coastal cliffs and bluffs.

Over the past 100 years or so, about 70% of the world’s sandy shorelines have been retreating, about 20–30% have been stable, and less than 10% have been advancing. Bird (1993) argues that with global warming and sea-level rise there will be tendencies for currently eroding shorelines to erode further, stable shorelines to begin to erode, and accreting shorelines to wane or stabilize. Local changes in coastal conditions and particularly in sediment supply may modify these tendencies, although Nicholls (1998) has indicated that accelerated sea-level rise in coming decades makes general erosion of sandy shores more likely.

Previous discussions of shoreline response to climate change have considered the well-known simple relations between sea-level rise and shoreline retreat of Bruun (1962). This two-dimensional model assumes maintenance of an equilibrium nearshore profile in the cross-shore direction as sea level rises. Some papers have supported this approach for long-term shoreline adjustment (Mimura and Nobuoka, 1996; Leatherman *et al.*, 2000); others have suggested various refinements (Komar, 1998a). Although the model’s basic assumptions are rarely satisfied in the real world (Bruun, 1988; Eitner, 1996; Trenhaile, 1997), its heuristic appeal and simplicity have led to extensive use in coastal vulnerability assessments for estimating shoreline retreat under rising sea levels, with varying degrees of qualification (Richmond *et al*., 1997; Lanfredi *et al*., 1998; Stewart *et al.*, 1998). Erroneous results can be expected in many situations, particularly where equilibrium profile development is inhibited, such as by the presence of reefs or rock outcrops in the nearshore (Riggs *et al.*, 1995). Moreover, Kaplin and Selivanov (1995) have argued that the applicability of the Bruun Rule, based on an equilibrium approach, will diminish under possible future acceleration of sea-level rise.

Few models of shoreline response incorporate large-scale impacts of sea-level rise coupled to changes in sediment availability. Efforts to address this shortcoming have been pioneered by Cowell and Thom (1994) for sandy barrier-dune complexes and Forbes *et al.* (1995) for gravel barriers. Although these parametric models incorporate sediment supply as well as sea-level change, they are still in the early stages of development and are useful primarily to indicate general patterns of response. A multifaceted approach is needed to incorporate other factors such as longshore and cross-shore variability in shore-zone morphology, sediment supply, texture and composition, nonlinear shore-zone response to storms and storm sequences (Forbes *et al*., 1995), tectonic history of the site, and the presence or absence of biotic protection such as mangroves or other strand vegetation.

Impact assessment, adaptation actions, and other management decisions must consider all of these factors within a coastal systems context. Temporal variation in storminess and wind climate can produce significant coastal adjustments (Forbes *et al*., 1997a). Another important component of analysis involves historical trends of shoreline change, including variability caused by storms or other anomalous events (Douglas *et al*., 1998; Gorman *et al*., 1998). This analysis can provide essential baseline data to enable comparisons in the future, albeit prior to anticipated climate-change impacts.

Field studies and numerical simulation of long-term gravel barrier evolution in formerly glaciated bays of eastern Canada (Forbes *et al*., 1995) have revealed how sediment supply from coastal cliffs may be positively correlated with the rate of relative sea-level rise. In this case, rising relative sea level favors barrier progradation, but the system switches to erosional retreat when the rate of sea-level rise diminishes, cliff erosion ceases, and no new sediment is supplied to the beach. Along the South American coast, El Niño events are linked to higher-than-average precipitation causing increased sediment discharge to the Peruvian coast, leading to the formation of gravel beach-ridge sequences at several sites (Sandweiss *et al*., 1998).

In assessing coastal response to sea-level rise, the relevant sedimentary system may be defined in terms of large-scale coastal cells, bounded by headlands or equivalent transitions—typically one to several tens of kilometers in length and up to hundreds of kilometers in some places (Wijnberg and Terwindt, 1995). Within such cells, coastal orientation in relation to dominant storm wind and wave approach direction can be very important (Héquette *et al.*, 1995; Short *et al.*, 2000), and sediment redistribution may lead to varying rates and/or directions of shoreline migration between zones of sediment erosion and deposition.

Changes in wave or storm patterns may occur under climate change (Schubert *et al.,* 1998). In the North Atlantic, a multi-decadal trend of increased wave height is observed, but the cause is poorly understood and the impacts are unclear. Changing atmospheric forcing also has been suggested as a process contributing to increases in mean water level along the North Sea coast, independent of eustatic and isostatic contributions to relative sea level. Changes in large-scale ocean-atmospheric circulation and climate regimes such as ENSO and the Pacific Decadal Oscillation have implications for coastal beach and barrier stability (see Box 6-4).

Erosion of unlithified cliffs is promoted by rising sea levels but may be constrained or enhanced by geotechnical properties and other antecedent conditions (Shaw *et al*., 1998a; Wilcock *et al.,* 1998). Bray and Hooke (1997) review the possible effects of sea-level rise on soft-rock cliffs over a 50- to 100-year planning scale. They evaluate different methods of analyzing historical recession rates and provide simple predictive models to estimate cliff sensitivity to sea-level rise in southern England. Historical observations of cliff erosion under an accelerating sea level suggest, however, that the results of such methods must be interpreted carefully.

If El Niño-like conditions become more prevalent (Timmermann *et al*., 1999), increases in the rate of cliff erosion may occur along the Pacific coasts of North and South America (Kaminsky *et al*., 1998; Komar, 1998a,b). For example, El Niño events raise sea level along the California coast and are marked by the presence of larger than average, and more damaging, waves and increased precipitation. These conditions and the changed direction of wave attack combine to increase sea-cliff erosion on the central California coast, particularly on southerly or southwesterly facing cliffs. An increase in El Niño-like conditions with global warming would very likely increase sea-cliff erosion along this section of coast and endanger infrastructure and property (Storlazzi and Griggs, 2000).

6.4.3. Deltaic Coasts

In addition to increasing erosion, many of the world's low-lying coastal regions will be exposed to potential inundation. Deltas that are deteriorating as a result of sediment starvation, subsidence, and other stresses are particularly susceptible to accelerated inundation, shoreline recession, wetland deterioration, and interior land loss (Biljsma *et al.*, 1996; Day *et al*., 1997).

River deltas are among the most valuable, heavily populated, and vulnerable coastal systems in the world. Deltas develop where rivers deposit more sediment at the shore than can be carried away by waves. Deltas are particularly at risk from climate change—partly because of natural processes and partly because of human-induced stresses. Deltaic deposits naturally dewater and compact as a result of sedimentary loading. When compaction is combined with isostatic loading or other tectonic effects, rates of subsidence can reach 20 mm yr^{-1} (Alam, 1996). Human activities such as draining for agricultural development; levee building to prevent flooding; and channelization, damming, and diking of rivers to impede sediment transfers have made deltas more vulnerable to sea-level rise. Examples of sediment starvation include the Rhone and Ebro deltas (Jimenez and Sanchez-Arcilla, 1997) and polder projects in the Ganges-Brahmaputra (Jelgersma, 1996). Sediment transport by the Nile, Indus, and Ebro Rivers has been reduced by 95% and in the Mississippi by half in the past 200 years, mostly since 1950 (Day *et al*., 1997). Further stress has been caused by subsurface fluid withdrawals and draining of wetland soils. In the Bangkok area of the Chao Phraya delta, groundwater extraction during 1960–1994 increased average relative sea-level rise by 17 mm yr^{-1} (Sabhasri and Suwarnarat, 1996). Similar severe land subsidence has been experienced in the Old Huange and Changjiang deltas of China (Chen, 1998; Chen and Stanley, 1998). In the latter case, groundwater removal was curtailed, leading to a reduction in subsidence rates.

Where local rates of subsidence and relative sea-level rise are not balanced by sediment accumulation, flooding and marine processes will dominate. Indeed, Sanchez-Arcilla and Jimenez (1997) suggest that in the case of largely regulated deltas, the main impacts of climate change will be marine-related because impacts related to catchment areas will be severely damped by river regulation and management policies. In such cases, significant land loss on the outer delta can result from wave erosion; prominent examples include the Nile (Stanley and Warne, 1998), Mackenzie (Shaw *et al*., 1998b), and Ganges (Umitsu, 1997). In South America, large portions of the Amazon, Orinoco, and Paraná/Plata deltas will be affected if sea-level rise accelerates as projected (Canziani *et al*., 1998). If vertical accretion rates resulting from sediment delivery and *in situ* organic matter production do not keep pace with sea-level rise, waterlogging of wetland soils will lead to death of emergent vegetation, a rapid loss of elevation because of decomposition of the belowground root mass, and, ultimately, submergence and erosion of the substrate (Cahoon and Lynch, 1997).

In some situations, saltwater intrusion into freshwater aquifers also is a potentially major problem, as demonstrated by a three-scenario climate change and sea-level rise model study of the Nile delta (Sherif and Singh, 1999). In other places, saltwater intrusion is already taking place (Mulrenna and Woodroffe, 1998). In the Yangtze delta, one consequence of saltwater incursion will be that during dry seasons shortages of freshwater for agriculture are likely to be more pronounced and agricultural yields seriously reduced particularly around Shanghai (Chen and Zong, 1999).

6.4.4. Coastal Wetlands

An estimate by Nicholls *et al.* (1999) suggests that by the 2080s, sea-level rise could cause the loss of as much as 22% of the world's coastal wetlands. Although there would be significant regional variations (Michener *et al.,* 1997), such losses would reinforce other adverse trends of wetland loss resulting primarily from direct human action—estimated by DETR (1999) to be

Box 6-4. Changes in Wave Climate, Storm Waves, and Surges

Over the long term, beaches and coastal barriers are adjusted in plan shape, profile morphology, and geographical position to factors such as sediment type and availability; wave climate, including prevailing wave energy and direction; and episodic storm waves and storm surge events. Few studies have been made of potential changes in prevailing ocean wave heights and directions as a consequence of climate change and sea-level rise, even though such changes can be expected. Similarly, changes in the magnitude of storm waves and surges with a higher sea level can be expected to reach to higher elevations on land than at present, as well as to extend further inland. Changes cannot be expected to be uniform, however, and impacts will vary locally and regionally.

The following case studies illustrate these points and highlight variations in prevailing storm wave/surge trends, differences in attribution and in the nature of past and potential coastal erosion and accretion impacts.

Changes in wind generated ocean waves in North Atlantic Ocean
Over the past 30 years, visual estimates from merchant ships and instrumental records suggest that significant wave height increases of 0.1–0.3 m have occurred over the whole of the North Atlantic except the west and central subtropics. The coastal response to this change in wave climate has not been documented.
Sources: WASA Group (1998); Guley and Hasse (1999).

Changes in extreme storm surges off Western Europe: The recent record
Storm surge activity in the Irish Sea and North Sea during the 1960s and 1970s reached levels unprecedented since the 1900s. These levels were followed by a sharp decline in the 1980s, taking the number of surges back to the levels of decades before the 1960s. Changes in pressure conditions could be a manifestation of shifts in storm tracks. Changes are part of natural variability on decadal time scales rather than long-term climate change resulting from anthropogenic influences.
Source: Holt (1999).

Changes in waves and storm activity off Western Europe with climate change
A high-resolution climate change experiment mimicking global warming resulted in a weak increase in storm activity and extreme wave heights in the Bay of Biscay and the North Sea; waves and storm action decreased slightly along the Norwegian coast. A weak increase in storm surges in the North Sea can be expected.
Source: WASA Group (1998).

Beach rotation and the Southern Oscillation in eastern Australia
Beach profiles measured at monthly intervals along Narrabeen Beach (Sydney) from 1976 to 1999 suggest a cyclic beach oscillation, with two cycles over the 23-year period; the profiles also suggest that the beach is rotating in a cyclic pattern around a central point. These changes have been related to ENSO. When the Southern Oscillation Index (SOI) is positive, there is a greater prevalence of east to northerly waves; these waves help build out the southern beach. When the SOI is negative, southerly waves dominate the wave climate, leading to a northerly shift of sand, thus feeding beach accretion in the north while the south end of the beach is eroded. If more El Niño-like conditions prevail in the future, a net change in shoreline position can be expected.
Source: Short et al. (2000).

Venice and the northern Adriatic coast: reduction in storm surges as a result of recent climate change?
Coastal flooding and damaging storm surges generated by the *bora* and other easterly winds affect the northern Adriatic Sea. Analysis of wind records from Trieste (1957–1996) show a decline in frequency of such winds. This decline may be caused in part by interdecadal variability, though their persistence suggests that it may be a consequence of recent global warming and less frequent drifts of polar cold air toward middle latitudes.
Source: Pirazzoli and Tomasin (1999).

Sensitivity of storm waves in Montevideo (Uruguay) to future climate change
Outputs from a simple storm wave generation model that uses real-time wind data for the 1980s have been compared with simulations representing a 10% higher wind strength and a 1-m sea-level rise. Under this scenario, storm waves would increase in height; their angle of incidence would remain unchanged.
Source: Lorenzo and Teixeira (1997).

about 40% of 1990 values by the 2080s. Stabilization scenarios developed by DETR (1999) show a large reduction in wetland losses—to 6–7%, compared with unmitigated emissions (13%). Two main types of tidal wetland—mangrove forest and salt marsh—are considered here, although serious impacts on other coastal vegetation types, including subtidal seagrasses, can be expected (Short and Neckles, 1999).

Mangrove forests often are associated with tropical and subtropical deltas, but they also occur in low- to mid-latitude lagoon and estuary margins, fringing shorelines from Bermuda in the north to northern New Zealand in the south. Mangroves have important ecological and socioeconomic functions, particularly in relation to seafood production, as a source of wood products, as nutrient sinks, and for shoreline protection (Rönnbäck, 1999). Moreover, different kinds of mangrove provide different goods and services (Ewel *et al*., 1998). The function and conservation status of mangroves has been considered in special issues of two journals, introduced by Field *et al*. (1998) and Saenger (1998).

Many mangrove forests are being exploited and some are being destroyed, reducing resilience to accommodate future sea-level rise. In Thailand, 50% of mangrove has been lost in the past 35 years (Aksornkoae, 1993); yet with greatly increased sediment supply to the coastal zone in some places, mangrove colonization has expanded seaward in suitable habitats (Panapitukkul *et al*., 1998). As for other shore types, this example emphasizes the importance of sediment flux in determining mangrove response to sea-level rise. Ellison and Stoddart (1991), Ellison (1993), and Parkinson *et al.* (1994) suggest that mangrove accretion in low- and high-island settings with low sediment supply may not be able to keep up with future sea-level rise, whereas Snedaker *et al.* (1994) suggest that low-island mangroves may be able to accommodate much higher rates of sea-level rise. This ability may depend on stand composition and status (e.g., Ewel *et al*., 1998; Farnsworth, 1998) and other factors, such as tidal range and sediment supply (Woodroffe, 1995, 1999; Miyagi *et al*., 1999). In some protected coastal settings, inundation of low-lying coastal land may promote progressive expansion of mangroves with sea-level rise (Richmond *et al*., 1997). In contrast, Alleng (1998) predicts the complete collapse of a mangrove wetland in Jamaica under rapid sea-level rise.

The response of tidal marshes to sea-level rise is similarly affected by organic and inorganic sediment supply and the nature of the backshore environment (Brinson *et al*., 1995; Nuttle *et al*., 1997). In general, tidal marsh accretion tracks sea-level rise and fluctuations in the rate of sea-level rise (e.g., van de Plassche *et al*., 1998, 1999; Varekamp and Thomas, 1998). Marsh accretion also reflects marsh growth effects (Varekamp *et al*., 1999). Bricker-Urso *et al.* (1989) estimate a maximum sustainable accretion rate of 16 mm yr^{-1} in salt marshes of Rhode Island (assuming that vertical accretion rates are controlled mainly by *in situ* production of organic matter); this rate is an order of magnitude higher than rates reported by others. Orson *et al.* (1998) also emphasizes the effects of variability between marsh species types.

Temporal and spatial variability in rates of relative sea-level rise also is important. Stumpf and Haines (1998) report rates of >10 mm yr^{-1} in the Gulf of Mexico over several years, where the long-term mean rate of relative sea-level rise is 2 mm yr^{-1} or less. Forbes *et al.* (1997b) report multi-year fluctuations in sea-level rise at Halifax, Nova Scotia, of as much as 10 mm yr^{-1} and occasionally higher, superimposed on a long-term mean of 3.6 $mmyr^{-1}$. Thus, short-term fluctuations in sea-level rise may approach the maximum limit of accretion, although the drowning of marsh surfaces is unlikely to be a major concern. Higher local rates of sea-level change have been recorded over the past 100 years or so in a few places, one of which is the Caspian Sea. Here, the response of riparian vegetation to the sea-level fall in the early part of the 20th century was a rapid seaward progression of vegetation. This progression ceased with the rise in Caspian sea level averaging 120 mm yr^{-1} from 1978 to 1996, but it did not result in a similar rapid regression of vegetation. Instead, the vegetation consolidated its position, which has been partly explained by the wide flooding tolerance of the major emergent plant species, with floating vegetation increasing in extent with more favorable (higher water level) conditions (Baldina *et al.*, 1999).

In some areas, the current rate of marsh elevation gain is insufficient to offset relative sea-level rise. For instance, model results from a wetland elevation model designed to predict the effect of an increasing rate of sea-level rise on wetland sustainability in Venice Lagoon revealed that for a 0.48-m rise in the next 100 years, only one site could maintain its elevation relative to sea level; for a 0.15-m rise, seven sites remained stable (Day *et al.*, 1999).

Maintenance of productive marsh area also depends on horizontal controls discussed by Nuttle *et al.* (1997) and Cahoon *et al.* (1998). For example, in settings with sufficient sediment influx, the wetland may expand toward the estuary, while also expanding landward if the backshore slope is sufficiently low and not backed by fixed infrastructure (Brinson *et al.*, 1995). If sediment supply is low, however, marsh front erosion may occur (Dionne, 1986).

Although determining the threshold for such erosion is difficult, this erosion is regarded as a negative impact on many wetlands, particularly those constrained by artificial structures on the landward side. Nicholls and Branson (1998) use the term “coastal squeeze” to describe the progressive loss and inundation of coastal habitats and natural features located between coastal defenses and rising sea levels. They believe that intertidal habitats will continue to disappear progressively, with adverse consequences for coastal biological productivity, biodiversity, and amenity value. Where sediment influx is insufficient to sustain progradation, there is potential for significant loss of coastal wetlands. After considering two “what if” climate change scenarios, Mortsch (1998) found that key wetlands around the Great Lakes of Canada-USA are at risk—particularly those that are impeded from adapting to the new water-level conditions by artificial structures or geomorphic conditions.

6.4.5. Tropical Reef Coasts

Coral reefs occur in a variety of fringing, barrier, and atoll settings throughout the tropical and subtropical world. Coral reefs constitute important and productive sources of biodiversity; they harbor more than 25% of all known marine fish (Bryant *et al*., 1998), as well as a total species diversity containing more phyla than rainforests (Sale, 1999). Reefs also represent a significant source of food for many coastal communities (Wilkinson *et al*., 1999). Coral reefs serve important functions as atoll island foundations, coastal protection structures, and sources of beach sand; they have economic value for tourism (which is increasingly important for many national economies) and support emerging opportunities in biotechnology. Moberg and Folke (1999) have published a comprehensive list of goods and ecological services provided by coral reef ecosystems.

The total areal extent of living coral reefs has been estimated at about 255,000 km^2 (Spalding and Grenfell, 1997). As much as 58% (rising locally to >80% in southeast Asia) are considered at risk from human activities, such as industrial development and pollution, tourism and urbanization, agricultural runoff, sewage pollution, increased sedimentation, overfishing, coral mining, and land reclamation (Bryant *et al*., 1998), as well as predation and disease (e.g., Antonius, 1995; Richardson *et al*., 1998). In the past these local factors, together with episodic natural events such as storms, were regarded as the primary cause of degradation of coral reefs. Now, Brown (1997), Hoegh-Guldberg (1999), and Wilkinson (1999), for instance, invoke global factors, including global climate change, as a cause of coral reef degradation.

Previous IPCC assessments have concluded that the threat of sea-level rise to coral reefs (as opposed to reef islands) is minor (Bijlsma *et al*., 1996; Nurse *et al*., 1998). This conclusion is based on projected rates of global sea-level rise from Warrick *et al.* (1996) on the order of 2–9 mm yr^{-1} over the next 100 years. Reef accretion at these rates has not been widely documented, largely because most reefs have been growing horizontally under stable or falling sea levels in recent years (Wilkinson and Buddemeier, 1994). Schlager (1999) reports an approximate upper limit of vertical reef growth during the Holocene of 10 mm yr^{-1}, suggesting that healthy reef flats are able to keep pace with projected sea-level rise. The situation is less clear for the large numbers of degraded reefs in densely populated regions of south and southeast Asia, eastern Africa, and the Caribbean (Bryant *et al*., 1998), as well as those close to population centers in the Pacific (Zann, 1994).

Positive trends of SSThave been recorded in much of the tropical ocean over the past several decades, and SST is projected to rise by 1–2°C by 2100. Many coral reefs occur at or close to temperature tolerance thresholds (Goreau, 1992; Hanaki *et al*., 1998), and Brown (1997) has argued that steadily rising SST will create progressively more hostile conditions for many reefs. This effect, along with decreased $CaCO_3$ saturation state (as CO_2 levels rise), represent two of the most serious threats to reefs in the 21st century (Hoegh-Guldberg, 1999; Kleypas *et al.*, 1999). Several authors regard an increase in coral bleaching as a likely result of global warming. However, Kushmaro *et al.* (1998) cite references that indicate it is not yet possible to determine conclusively that bleaching episodes and the consequent damage to reefs are caused by global climate change. Corals bleach (i.e., pale in color) because of physiological shock in response to abrupt changes in temperature, salinity, and turbidity. This paling represents a loss of symbiotic algae, which make essential contributions to coral nutrition and clarification. Bleaching often may be temporary, with corals regaining color once stressful environmental conditions ameliorate. Brown *et al.* (2000) indicate that some corals in the Indian Ocean, Pacific Ocean, and Caribbean Sea are known to bleach on an annual basis in response to seasonal variations in temperature and irradiance. Major bleaching events can occur when SSTs exceed seasonal maximums by >1°C (Brown *et al*., 1996). Mortality for small excursions of temperature is variable and, in some cases, apparently depth-related (Phongsuwan, 1998); surviving coral has reduced growth and reproductive capacity. More extensive mortality accompanies temperature anomalies of 3°C or more over several months (Brown and Suharsono, 1990). Hoegh-Guldberg (1999) found that major episodes of coral bleaching over the past 20 years were associated with major El Niño events, when seasonal maximum temperatures were exceeded by at least 1°C.

Corals weakened by other stresses may be more susceptible to bleaching (Glynn, 1996; Brown, 1997), although Goreau (1992) found in Jamaica that anthropogenically stressed areas had lower bleaching frequencies. More frequent and extensive bleaching decreases live coral cover, leading to reduced species diversity (Goreau, 1992; Edinger *et al*., 1998) and greater susceptibility to other threats (e.g., pathogens and emergent diseases as addressed by Kushmaro *et al*., 1996, 1998; Aronson *et al*., 2000). In the short term, this bleaching may set back reef communities to early successional stages characterized by noncalcifying benthos such as algae, soft corals, and sponges (Done, 1999). Reefs affected by coral bleaching may become dominated by physically resilient hemispherical corals because branching corals are more susceptible to elevated SST, leading to a decrease in coral and habitat diversity (Brown and Suharsono, 1990). Differential susceptibility to bleaching among coral taxa has been reported during the large-scale event in 1998 on the Great Barrier Reef (Marshall and Baird, 2000).

The 1998 bleaching event was unprecedented in severity over large areas of the world, especially the Indian Ocean. This event is interpreted by Wilkinson *et al.* (1999) as ENSO-related and could provide a valuable indicator of the potential effects of global climate change. However, the 1998 intense warming in the western Indian Ocean has been associated with shifts in the Indian dipole rather than ENSO.

Attempts to predict bleaching have met with variable success. Winter *et al*. (1998) compared a 30-year record of SST at La Parguera, Puerto Rico, with coral bleaching events at the same location but could not forecast coral bleaching frequency from the temperature record. On the other hand, analyses of recent sea temperature anomalies, based on satellite data, have been used to predict the mass coral bleaching extent during 1997–1998 (Hoegh-Guldberg, 1999).

Recently it has been suggested that a doubling of CO_2 levels could reduce reef calcification, but this effect is very difficult to predict (Gattuso *et al*., 1999). Kleypas *et al*. (1999) argue that such effects could be noticed by 2100 because of the decreased availability of $CaCO_3$ to corals. In combination with potentially more frequent bleaching episodes, reduced calcification could impede a reef's ability to grow vertically in pace with sea-level rise.

The implications for reef-bound coasts in terms of sediment supply, shore protection, and living resources may be complex, either positive or negative, and are difficult to predict at a global scale. However, there have been suggestions that fishing yields will be reduced as reef viability decreases, leading to reduced yields of protein for dependent human populations, and that the effects of reducing the productivity of reef ecosystems on birds and marine mammals are expected to be substantial (Hoegh-Guldberg, 1999).

6.4.6. High-Latitude Coasts

High-latitude coasts are highly susceptible to a combination of climate change impacts in addition to sea-level rise, particularly where developed in ice-bonded but otherwise unlithified sediments. In this context, atmospheric warming affects ground-surface temperatures and thaw, as well as SST and sea ice.

Ground temperatures determine the presence of perennially frozen ground (permafrost), which often contains large volumes of excess ice that may occur in the form of massive ice. The seasonal cycle of ground and nearshore seawater temperatures determines the depth of the seasonally active thaw layer in high-latitude beaches and the nearshore, with implications for limiting beach scour during storms (Nairn *et al*., 1998). Deepening of the active layer (Vyalov *et al*., 1998) also can lead to melting of near-surface massive ice and may trigger additional coastal slope failure (Dallimore *et al*., 1996; Shaw *et al*., 1998b).

Rapid coastal retreat already is common along ice-rich coasts of the Beaufort Sea in northwestern Canada (e.g., Dallimore *et al*., 1996), the United States, and the Russian Arctic (e.g., Are, 1998). Where communities are located in ice-rich terrain along the shore, warmer temperatures combined with increased shoreline erosion can have a very severe impact. For example, at Tuktoyaktuk—the main community, port, and offshore supply base on the Canadian Beaufort sea coast—many structures are located over massive ice along eroding shore (Wolfe *et al*., 1998).

Coastal recession rates along the Arctic coast also are controlled by wave energy during the short open-water season. An early study based on historical records of shoreline recession, combined with hindcast waves derived from measured wind and observed ice distributions, showed that coastal recession rates at several sites are correlated with open-water fetch, storminess, and wave energy. Using estimates of less extensive ice distribution under a doubled-CO_2 atmosphere, Solomon *et al.* (1994) were able to demonstrate an increase in coastal erosion rates to a mean value comparable to the maximum observed rates under present climate conditions. In the Canadian Arctic Archipelago region, where many fine-grained (mud and sand) shorelines and deltas now experience almost zero wave energy (e.g., Forbes and Taylor, 1994), any increase in open water will lead to rapid reworking and potentially substantial shoreline retreat.

Sea ice may erode the seabed in the nearshore zone, but it also may supply shoreface sediments to the nearshore and beach (Reimnitz *et al*., 1990; Héquette *et al*., 1995). Thinner ice or later freeze-up resulting from climate warming may lead to changes in nearshore ice dynamics and associated sediment transport. Warmer temperatures and associated changes in winter sea-ice distribution at mid-latitudes are expected to have a negative impact on coastal stability. Rapidly eroding sandy coasts in the southern Gulf of St. Lawrence are partially protected in winter by development of an icefoot and nearshore ice complex. The strongest storms and most persistent onshore winds occur in winter, partially overlapping the ice season. Severe erosion in recent years has been linked to warmer winters with late freeze-up—an anticipated outcome of greenhouse warming (Forbes *et al*., 1997b).

6.5. Socioeconomic Impacts of Climate Change

In the past decade, some progress has been made in evaluating potential socioeconomic impacts of climate change and sea-level rise on coastal and marine systems. This progress, however, has not been as substantial as that relating to biogeophysical impacts; nor has it been especially comprehensive (Turner *et al*., 1995, 1996). To date, emphasis has been in three areas. First, research has focused on the coastal zone itself (we are not aware of any studies of the socioeconomic impact of climate change on open-ocean marine ecosystems). Second, there has been an emphasis on the potential socioeconomic impact of sea-level rise but little on any other climate change variables. Third, emphasis has been on economic effects, not on impacts on social and cultural systems. These emphases are evident in the following review, in which we consider socioeconomic impacts initially as a component of the methodology for vulnerability assessment and then through economic cost-benefit analyses of coastal zones in general and infrastructure developments in particular. In these cases, "benefits" derive from the inclusion of adaptation options—primarily shore protection—into the analyses to derive some net cost. Finally, we consider attempts that have been made to "value" natural systems, as well as the potential social and cultural impacts of climate change.

6.5.1. Socioeconomic Impacts as Part of Vulnerability Assessment

In the SAR, Bijlsma *et al.* (1996) reviewed several country case studies that had applied the IPCC Common Methodology for assessing the vulnerability of coastal areas to sea-level rise. These case studies offered important insights into potential impacts and possible responses. Many of the assessments emphasized the severe nature of existing coastal problems such as beach erosion, inundation, and pollution, as well as the effects of climate change acting on coastal systems that already are under stress.

The Common Methodology defined *vulnerability* as a country's degree of capability to cope with the consequences of climate change and accelerated sea-level rise. The methodology of seven consecutive analytical steps allowed for identification of coastal populations and resources at risk and the costs and feasibility of possible responses to adverse impacts. The SAR also identified the strengths and weaknesses of the Common Methodology. More recently, Klein and Nicholls (1999) have evaluated the IPCC's approach and results, concluding that the Common Methodology has contributed to understanding the consequences of sea-level rise and encouraged long-term thinking about coastal zones. They went on to develop a new conceptual framework for coastal vulnerability assessment that identifies the main components of the natural system and the socioeconomic system, as well as the linkages between them and climate change and other change variables. This framework is outlined in Box 6-5.

In the SAR, data on socioeconomic impacts were derived from country and global vulnerability assessment studies. Figures for several countries were given relating to the population affected, capital value at loss, and adaptation/protection costs (Bijlsma *et al*., 1996, Table 9-3). For the coastal zone, the authors concluded that:

- There will be negative impacts on several sectors, including tourism, freshwater quality and supply, fisheries and aquaculture, agriculture, human settlements, financial services, and human health.
- The number of people potentially affected by storm-surge flooding is expected to double (or triple) in the next century, ignoring potential adaptation and population growth.
- Protection of low-lying island states and nations with large deltaic areas is likely to be very costly.
- Adaptation to sea-level rise and climate change will involve important tradeoffs, which may include environmental, economic, social, and cultural values.

Since the SAR, there have been several summaries of the socioeconomic results of the vulnerability assessment studies, presenting data at local, regional, and global levels. Examples include case studies of Poland and Estonia (Kont *et al*., 1997; Zeider, 1997), the Philippines (Perez *et al*., 1999), Bangladesh (Ali, 1999), Egypt (El-Raey *et al*., 1999), and The Gambia and Abidjan (Jallow *et al*., 1999), as well as the regional analyses and global synthesis of Nicholls and Mimura (1998). The initial global vulnerability assessment has been revised on the basis of scenarios for global sea-level rise derived from the Hadley Centre's HadCM2 ensemble simulations and HadCM3 simulations for GHG-only forcing (Nicholls *et al*., 1999). This assessment indicated that by the 2080s, the potential number of people flooded by storm surge in a typical year will be more than five times higher than today (using a sea-level rise of 0.38 m from 1990 to 2080) and that between 13 million and 88 million people could be affected even if evolving protection is included. Broadly similar results are given in the study undertaken by DETR (1999). However, they note that the flood impacts of sea-level rise are reduced by emissions scenarios that lead to stabilization of CO_2. By the 2080s, the annual number of people flooded is estimated to be 34 million under the 750-ppm scenario and 19 million under the 550-ppm scenario.

Klein and Nicholls (1999) have categorized the potential socioeconomic impacts of sea-level rise as follows

- Direct loss of economic, ecological, cultural, and subsistence values through loss of land, infrastructure, and coastal habitats
- Increased flood risk of people, land, and infrastructure and the aforementioned values
- Other impacts related to changes in water management, salinity, and biological activities.

They also developed a methodology that has not yet been applied in any case studies.

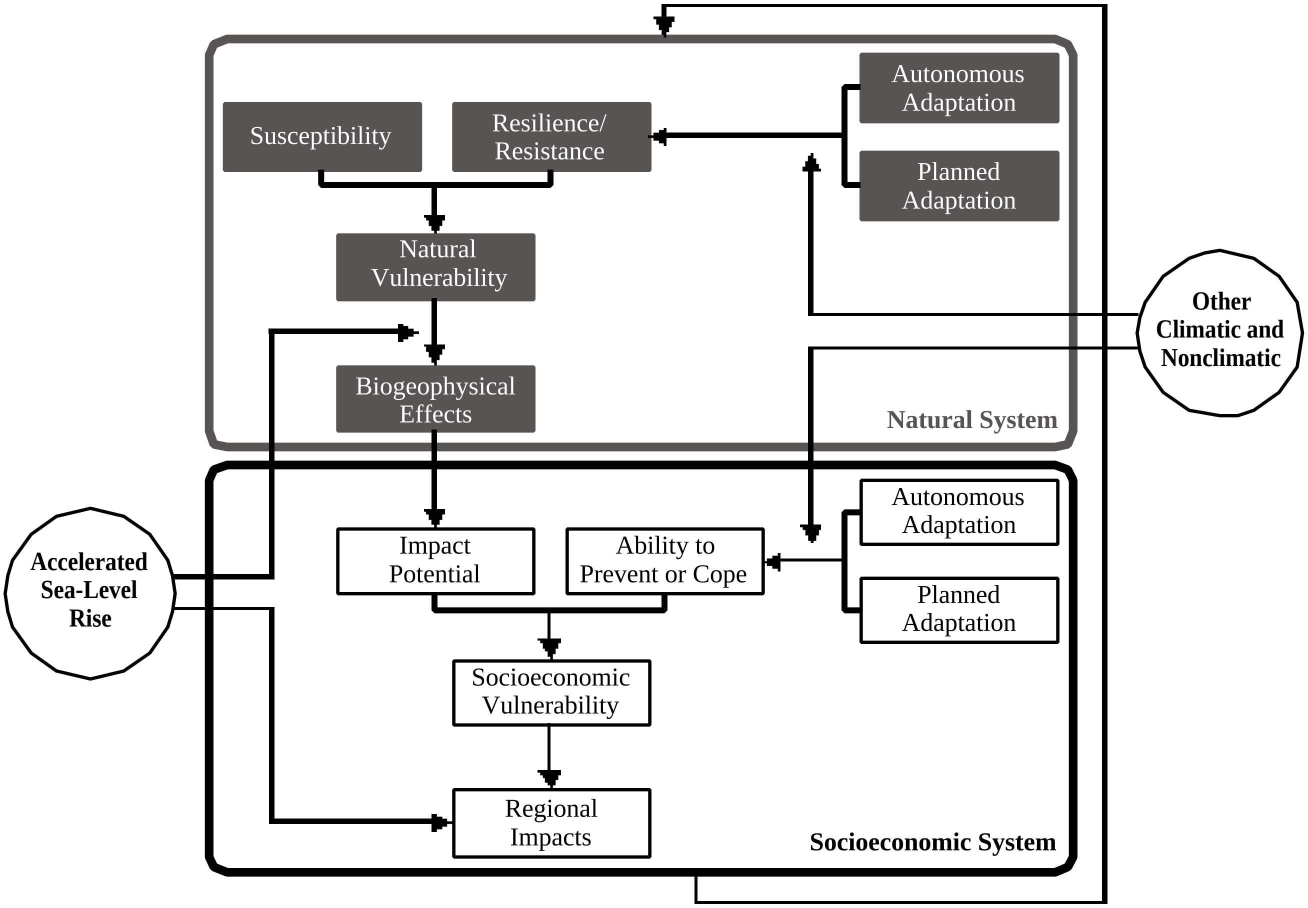
6.5.2. *Economic Costs of Sea-Level Rise*

In the early 1990s, several studies examined the cost of sea-level rise in the United States, based on uniform national response strategies of holding back the sea (Titus *et al.,* 1992) or not holding back the sea (Yohe, 1990). A series of nationwide studies in other countries (see Bijlsma *et al.,* 1996) followed much the same approach. Turner *et al.* (1995) attempted to assess the cost of sea-level rise in general. Yohe *et al.* (1996) analyzed the economic cost of sea-level rise for developed property in the United States. They conclude that their cumulative figure of US$20.4 billion (1990 US$) cumulative is much lower than earlier estimates because those estimates had not considered offsetting factors, such as the cost-reducing potential of natural, market-based, adaptation measures or the efficiency of discrete decisions to protect (or not to protect) small tracts of property on the basis of individual economic merit. In most analyses, those "offsetting factors," or adaptations, are shore protection works. The expected economic cost of protection or abandonment in the United States also has been assessed (Yohe and Schlesinger, 1998).

Saizar (1997) assesses the potential impacts of a 0.5-m sea-level rise on the coast of Montevideo, Uruguay. Given no adaptive response, the cost of such a rise is estimated to be US$23 million, with a shoreline recession of 56 m and loss of only 6.8 ha of land. Olivo (1997) determined the potential economic impacts of a sea-level rise of 0.5 m on the coast of Venezuela. At six study sites, he identified land and infrastructure at risk—such

Box 6-5. Conceptual Framework for Coastal Vulnerability Assessment

In the scheme illustrated below, analysis of coastal vulnerability starts with a notion of the natural system's *susceptibility* to the biogeophysical effects of sea-level rise and its capacity to cope with these effects (*resilience* and *resistance*). Susceptibility reflects the coastal system's potential to be affected by sea-level rise; resilience and resistance determine the system's robustness or ability to continue functioning in the face of possible disturbance. Together, these factors determine the *natural vulnerability* of the coastal zone.



Resilience and resistance are functions of the natural system's capacity for *autonomous adaptation*, which represents the coastal system's natural adaptive response. Resilience and resistance often are affected by human activities, which need not only be negative: *Planned adaptation* can reduce natural vulnerability by enhancing the system's resilience and resistance, thereby adding to the effectiveness of autonomous adaptation.

The biogeophysical effects of sea-level rise impose a range of potential socioeconomic impacts. This *impact potential* is the socioeconomic equivalent of susceptibility; it is dependent on human influences. S*ocioeconomic vulnerability* is determined by the impact potential and society's technical, institutional, economic, and cultural ability to prevent or cope with these impacts. As with the natural system's resilience and resistance, the potential for *autonomous adaptation* and *planned adaptation* determines this ability to prevent or cope.

Dynamic interaction takes place between natural and socioeconomic systems. Instead of being considered as two independent systems, they are increasingly regarded as developing in a co-evolutionary way, as shown by the feedback loop from the socioeconomic system to the natural system.

Sources: Klein and Nicholls (1999); Mimura and Harasawa (2000).

as oil infrastructure, urban areas, and tourist infrastructure—and, after evaluating four scenarios, concludes that Venezuela cannot afford the costs of sea-level rise, either in terms of land and infrastructure lost under a no-protection policy or in terms of the costs involved in any of three protection policies. In Poland, Zeider (1997) estimates the total cost of land-at-loss at US$30 billion; the cost of full protection for the 2,200 km of coast would be US$6 billion.

Several different methods have been used to estimate economic costs. Yohe and Neumann (1997) focus attention on the cost-benefit procedures applied by coastal planners to evaluate shoreline protection projects in relation to sea-level rise. They develop three alternative adaptive responses to the inundation threat from climate-induced sea-level rise: cost-benefit with adaptation foresight (CBWAF), cost-benefit absent adaptation (CBAA), and protection guaranteed (PG). On economic grounds, CBWAF became the preferred option; CBAA conforms most closely with the routine application of existing procedures. “Adaptation foresight” in Yohe and Neumann’s cost-benefit procedures assumes that erosion resulting from sea-level rise is a gradual process and that storm impacts do not change as sea level rises. West and Dowlatabadi (1999) suggest, however, that although a rise in sea level may be gradual and predictable, the effects of storms on coastal shorelines and structures are often stochastic and uncertain, in part because of sea-level rise effects.

Sea-level rise can increase the damage caused by storms because mean water level (the base level for storm effects) is higher, waves can attack higher on the shore profile, and coastal erosion often is accelerated, bringing structures nearer the shoreline and potentially removing protection offered by dunes and other protective features. The Heinz Center (2000) estimates that roughly 1,500 homes in the United States will be lost to coastal erosion each year for several decades, at a cost to property owners of US$530 million yr^{-1}. Most of the losses over the next 60 years will be in low-lying areas that also are subject to flooding, although some damage will be along eroding bluffs or cliffs. West *et al.* (2001) estimate that the increase in storm damage because of sea-level rise increases the direct damages of sea-level rise from erosion of the shoreline by 5%, but storm damage could be as much as 20% of other sea-level rise damages. They also developed a method for evaluating the effects of investor decisions to repair storm damage on the net economic impacts of rising sea level in the United States. Neumann *et al.* (2000) have estimated that a 0.5-m sea-level rise by 2100 could cause cumulative impacts to U.S. coastal property of US$20 billion to US$150 billion and that more extensive damage could result if climate change increases storm frequency or intensity.

Morisugi *et al.* (1995) attempt to evaluate the household damage cost in Japan from increased storm surges and the potential benefit generated by countermeasures, using a microeconomic approach. In this approach, household utility is expressed as a function of disaster occurrence probability, income, and other variables, and the change of utility level from sea-level rise and/or countermeasures is translated into monetary terms. For a 0.5-m sea-level rise, the damage cost without countermeasures in Japan would be about US$3.4 billion yr^{-1}, based on the comparison of the utility level between no sea-level rise and a 0.5-m sea-level rise without countermeasures. When the utility level is calculated for the case with countermeasures, the damage cost is reduced to about –US$1.3 billion yr^{-1}, which means that a benefit is created. Therefore, the benefit created by countermeasures for a 0.5-m sea-level rise, which is defined as the decrease of damage cost, would be about US$4.7 billion yr^{-1} at the national level. Because the annual expense for countermeasures is estimated to be about US$1.9 billion yr^{-1} (Mimura *et al.*, 1998), the countermeasures are still beneficial after expenses are considered. This and other examples given here suggest that more robust assessments of the economic impacts of sea-level rise are possible and that they can improve the quality of adaptation strategies.

6.5.3. Impacts on Coastal Infrastructure

A large portion of the human population now lives in coastal areas, and the rate of population growth in these areas is higher than average (Cohen *et al*., 1997; Gommes *et al*., 1998). Many large cities are located near the coast (e.g., Tokyo, Shanghai, Jakarta, Bombay, New York), and Nicholls and Mimura (1998) have argued that the future of the subsiding megacities in Asia, particularly those on deltas, is among the most challenging issues relating to sea-level rise. People in developed coastal areas rely heavily on infrastructure to obtain economic, social, and cultural benefits from the sea and to ensure their safety against natural hazards such as high waves, storm surges, and tsunamis. Their well-being is supported by systems of infrastructure that include transportation facilities, energy supply systems, disaster prevention facilities, and resorts in coastal areas. Significant impacts of climate change and sea-level rise on these facilities would have serious consequences (see Chapter 7). This analysis applies not only in highly developed nations but in many developing economies and small island states (Nunn and Mimura, 1997). The vulnerability of waste facilities, septic systems, water quality and supply, and roads is a particular concern in many places (Solomon and Forbes, 1999).

Mimura *et al.* (1998) summarize Japanese studies on the impacts on infrastructure. Several studies suggested that disaster prevention facilities such as coastal dikes, water gates, and drainage systems and coastal protection structures such as seawalls, breakwaters, and groins will become less functional because of sea-level rise and may lose their stability. A common concern relates to the bearing capacity of the soil foundation for structures. For instance, the increased water table resulting from sea-level rise decreases the bearing capacity of the soil foundation and increases the possibility of liquefaction, which results in higher instability of coastal infrastructures to earthquakes (Shaw *et al*., 1998a). In the United Kingdom, sea defenses and shore protection works around 4,300 km of coast cost approximately US$500 million yr^{-1} to maintain at present—a figure that Turner *et al.* (1998) suggest will continue to rise in the future.

Port facilities are another type of infrastructure that will be affected by climate change and sea-level rise. Higher sea level probably will decrease the effectiveness of breakwaters against wave forces, and wharves may have to be raised to avoid inundation. When such effects are anticipated, countermeasures can be implemented to maintain function and stability. Therefore, the real impacts will occur as an additional expenditure to reinforce the infrastructure. The total expenditure to keep the present level of functions and stability for about 1,000 Japanese ports is estimated to be US$110 billion for a 1-m sea-level rise (Mimura *et al*., 1998).

6.5.4. Socioeconomic Impacts and Natural Systems

Turner *et al*. (1995) assert that relationships between the physical impacts of climate change and socioeconomic implications in the coastal zone have not been fully encompassed in recent work. This statement remains valid to date. Some attempts have been made to express the value of coastal features that are normally regarded as nonmarket goods (Costanza *et al*., 1997; Alexander *et al*., 1998). Several assessments of mangrove and reef ecosystems have highlighted their economic value on the basis of ecosystem goods and services, as well as natural capital value (e.g., Moberg and Folke, 1999).

Estimates of the monetary value of wetlands and information about attitudes toward wetland conservation can be used in policy decisions (e.g., Söderqvist, 2000). “Use” and “non-use” values may be determined (Stein *et al.*, 2000). For example, Rönnbäck (1999) suggests that mangrove systems alone account for US$800–16,000 ha^{-1} in seafood production. Streever *et al.* (1998) sought public attitudes and values for wetland conservation in New South Wales, Australia, and found that a conservative estimate of the aggregate value of these wetlands, based on willingness-to-pay criteria, was US$30 million yr^{-1} for the next 5 years. They also refer to an earlier study on the value of marketable fish in mangrove habitats of Moreton Bay, Queensland, estimated at more than US$6,000 ha^{-1} yr^{-1} (Marton, 1990). Stein *et al.* (2000) have developed a framework for crediting and debiting wetland values that they suggest provides an ecologically effective and economically efficient means to fulfill compensatory mitigation requirements for impacts to aquatic resources.

Climate change impacts on natural systems can have profound effects on socioeconomic systems (Harvey *et al*., 1999). One example cited by Wilkinson *et al.* (1999) is the 1998 coral bleaching event in the Indian Ocean. This event was unprecedented in severity; mortality rates reached as high as 90% in many shallow reefs, such as in the Maldives and the Seychelles. Such severe impacts are expected to have long-term socioeconomic consequences as a result of changed fish species mix and decreased fish stocks and negative effects on tourism as a result of degraded reefs. Degradation of reefs also will lead to diminished natural protection of coastal infrastructure against high waves and storm surges on low-lying atolls. Wilkinson *et al.* (1999) estimate the costs of the 1998 bleaching event to be between US$706 million (optimistic) and US$8,190 million (pessimistic) over the next 20 years. The Maldives and the Seychelles are identified as particularly affected, because of their heavy reliance on tourism and fishery.

Some economic impacts of marine diseases and harmful algal blooms influenced by climate variations have been evaluated since the SAR. An outbreak in 1997 of the toxic dinoflagellate *Pfiesteria piscida*, which has been associated with increased nutrients and SSTs, caused large fish kills on the U.S. Atlantic coast that resulted in public avoidance and economic losses estimated at US$60 million (CHGE, 1999). A persistent brown tide bloom in the Peconic Estuary system of New York blocked light and depleted oxygen in the water column, severely affecting seagrass beds and reducing the value of the Peconic Bay scallop fishery by approximately 80% (CHGE, 1999). Harmful algal blooms associated with increased SSTand the influx of nutrients into an estuary can result in economic harm through shellfish closures, impacts on tourism, reduction of estuarine primary productivity, deterioration of fishery habitat (e.g., seagrass beds), and mortality of fish and shellfish.

6.5.5. Social and Cultural Impacts

In some coastal societies, the significance of cultural values is equal to or even greater than that of economic values. Thus, some methodologies have been developed that include traditional social characteristics, traditional knowledge, subsistence economy, close ties of people to customary land tenure, and the fact that these factors are intrinsic components of the coastal zone (e.g., Kay and Hay, 1993). As such, they must be taken into account in certain contexts, including many South Pacific island countries (e.g., Yamada *et al.*, 1995; Solomon and Forbes, 1999) and indigenous communities in northern high latitudes (e.g., Peters, 1999), among other examples.

Patterns of human development and social organization in a community are important determinants of the vulnerability of people and social institutions to sea-level rise and other coastal hazards. This observation does not mean that all people in a community share equal vulnerability; pre-event social factors determine how certain categories of people will be affected (Heinz Center, 1999). Poverty is directly correlated with the incidence of disease outbreaks (CHGE, 1999) and the vulnerability of coastal residents to coastal hazards (Heinz Center, 1999).

Examples of inequitable vulnerability to coastal hazards include population shifts in Pacific island nations such as Tonga and Kiribati. In Tonga, people moving from outer islands to the main island of Tongatapu were forced to settle in low-lying areas, including the old dumping site, where they were proportionally more vulnerable to flooding and disease (Fifita *et al.*, 1992). Storm-surge flooding in Bangladesh has caused very high mortality in the coastal population (e.g., at least 225,000 in November 1970 and 138,000 in April 1991), with the highest mortality among the old and weak (Burton *et al.*, 1993). Land that is subject to flooding—at least 15% of the

Bangladesh land area—is disproportionately occupied by people living a marginal existence with few options or resources for adaptation.

El-Raey *et al.* (1997, 1999) studied the effects of a 0.5-m sea-level rise on the Nile delta. In addition to economic costs from loss of agricultural land and date palms, they identify social and cultural impacts. Under a no-protection policy, El-Raey *et al.* (1997) predict that the population would suffer from the loss of residential shelter (32% of urban areas flooded) and employment (33.7% of jobs lost). In addition, a substantial number of monuments and historic sites would be lost (52%).

6.6. Adaptation

6.6.1. Evolution of Coastal Adaptation Options

In the SAR, Biljsma *et al.* (1996) identified three possible coastal response options:

- *Protect,* which aims to protect the land from the sea so that existing land uses can continue, by constructing hard structures (e.g., seawalls) as well as using soft measures (e.g., beach nourishment)
- *Accommodate,* which implies that people continue to occupy the land but make some adjustments (e.g., elevating buildings on piles, growing flood- or salt-tolerant crops)
- *Retreat,* which involves no attempt to protect the land from the sea; in an extreme case, the coastal area is abandoned.

An evaluation of such strategies was regarded as a crucial component of the vulnerability assessment Common Methodology. Klein and Nicholls (1999) argue, however, that as far as adaptation is concerned, that methodology has been less effective in assessing the wide range of technical, institutional, economic, and cultural elements in different localities. Indeed, they indicated that there has been concern that the methodology emphasizes a protection-oriented response rather than consideration of the full range of adaptation options.

Klein *et al.* (2000) develop a methodology that seeks to address some of these comments. They argue that successful coastal adaptation embraces more than just selecting one of the technical options to respond to sea-level rise; it is a more complex and iterative process, with a series of policy cycles. Four steps can be distinguished in the process of coastal adaptation:

1) Information collection and awareness raising
2) Planning and design
3) Implementation
4) Monitoring and evaluation.

In reality, however, adaptive responses often are undertaken reactively rather in a step-wise, planned, and anticipatory fashion.

The process of coastal adaptation can be conceptualized by showing that climate change and/or climate variability, together with other stresses on the coastal environment, produce actual and potential impacts. These impacts trigger efforts of mitigation, to remove the cause of the impacts, or adaptation to modify the impacts. Bijlsma *et al.* (1996) noted that climate-related changes represent potential additional stresses on systems that already are under pressure. Climate change generally will exacerbate existing problems such as coastal flooding, erosion, saltwater intrusion, and degradation of ecosystems. At the same time, nonclimate stresses can be an important cause of increasing coastal vulnerability to climate change and variability. Given such interactive effects, adaptation options to be most effective should be incorporated with policies in other areas, such as disaster mitigation plans, land-use plans, and watershed resource plans. In other words, adaptation options are best addressed when they are incorporated in integrated coastal management and sustainable development plans.

Policy criteria and coastal development objectives condition the process of adaptation. Other critical influences include values, awareness, and factors such as historical legacies, institutions, and laws. There is growing recognition of the need for researchers, policymakers, residents, and other key stakeholders to work together to establish a framework for adaptation that is integrated within current coastal management processes and practices and takes a broader view of the subject. Collaborative efforts of this kind can support a process of shared learning and joint problem solving, thereby enabling better understanding, anticipation of, and response to climate change. Cash and Moser (2000) identify some of the deficiencies in integrating science and policy. They suggest the following guidelines for meeting the challenge: Use “boundary organizations” that can link researchers and decisionmakers at various scales, capitalize on particular scale-specific capabilities, and develop adaptive assessment and management strategies through long-term iterative processes of integrated assessment and management.

6.6.2. Resilience and Vulnerability

In the context of climate change and coastal management, vulnerability is now a familiar concept. On the other hand, the concept of coastal resilience is less well known but has become much more important in recent years (Box 6-5). Coastal resilience has ecological, morphological, and socioeconomic components, each of which represents another aspect of the coastal system’s adaptive capacity to external disturbances. We have identified several natural features that contribute to resilience of the shore-zone by providing ecological buffers, including coral reefs, salt marsh, and mangrove forest and morphological protection in the form of sand and gravel beaches, barriers, and coastal dunes.

Socioeconomic resilience is the capability of a society to prevent or cope with the impacts of climate change and sea-level rise, including technical, institutional, economic, and cultural ability (as indicated in Box 6-5). Enhancing this resilience is equivalent to reducing the risk of the impacts on society. This resilience can be strengthened mainly by decreasing the probability of occurrence of hazard (managed retreat or protection); avoiding or reducing its potential effects (accommodation or protection), and facilitating recovery from the damages when impacts occur. Among these options, managed retreat has gained some prominence in the past 2 decades (see Box 6-6); Clark (1998) has argued that flood insurance is an appropriate management strategy to enhance coastal resilience in the UK.

Technological capacity is a component of social and economic resilience, although adaptation strategies may involve more than engineering measures. Technological options can be implemented efficiently only in an appropriate economic, institutional, legal, and sociocultural context. A list of technologies that could be effective for adaptation appears in Klein *et al.* (2000). Indigenous (traditional) technologies should be considered as an option to increase resilience and, to be effective, must fit in with traditional social structures (Veitayaki, 1998; Nunn *et al.*, 1999).

Enhancing coastal resilience in these ways increasingly is regarded as an appropriate way to prepare for uncertain future changes, while maintaining opportunities for coastal development (although some tradeoffs are involved, and the political discourse is challenging). In short, enhancing resilience is a potentially powerful adaptive measure.

6.6.3. Adaptation in the Coastal Zone

The purpose of adaptation is to reduce the net cost of climate change and sea-level rise, whether those costs apply to an economic sector, an ecosystem, or a country. A simple schematic of the objective of adaptation appears in Figure 6-1.

Adaptation within natural systems has been considered a possibility only recently; it results in part from considerations of coastal resilience. An example is provided by coral reefs. Applying the two types of adaptation discussed in Box 6-5, Pittock (1999) suggests that "autonomous adaptation" is what reefs would do by themselves, whereas "planned adaptation" involves conscious human interference to assist in the persistence of some desirable characteristics of the coral reef system. The first type of adaptation may involve more rapid growth of coral, changes in species composition, or evolution of particular species in response to changed temperatures or other conditions. Planned adaptation might involve "seeding" of particular reefs with species adapted to higher temperatures or attempts to limit increased sediment, pollutant, or freshwater flow onto reefs. For reef communities that presently are under stress and are likely to be particularly vulnerable to climate change, the design of managed (or planned) adaptation should involve an evaluation of the extent of autonomous adaptation that can be expected given the current and probable future status of the reef system.

Box 6-6. Adaptation through Managed Retreat

Managed retreat generally is designed to avoid hazards and prevent ecosystems from being squeezed between development and the advancing sea. The most common mechanisms for managed retreat are *setbacks* that require new development to be a minimum distance from the shore, *density restrictions* that limit development, and *rolling easement* policies that allow development on the condition that it be removed to enable wetlands to migrate landward (Titus, 1998). These strategies may all become elements of an integrated coastal management policy. Setback could be considered a managed retreat strategy, particularly in cases in which the setback line is shifted inland as the shoreline recedes. Other measures of managed retreat can include conditional phased-out development, withdrawal of government subsidies, and denial of flood insurance.

Examples of managed retreat and related measures as adaptation to sea-level rise include the following:

- ***Canada:*** New Brunswick completed remapping of the entire coast of the province to delineate the landward limit of coastal features. Setback for new development is defined from this limit. Some other provinces have adopted a variety of setback policies, based on estimates of future coastal retreat.
- ***Barbados:*** A national statute establishes a minimum building setback along sandy coasts of 30 m from mean high-water mark; along coastal cliffs the setback is 10 m from the undercut portion of the cliff.
- ***Aruba and Antigua:*** Setback established at 50 m inland from high-water mark.
- ***Sri Lanka:*** Setback areas and *no-build zones* identified in Coastal Zone Management Plan. Minimum setbacks of 60 m from line of mean sea level are regarded as good planning practice.
- ***United Kingdom:*** House of Commons in 1998 endorsed the concept of *managed realignment* as the preferred long-term strategy for coastal defense in some areas.
- ***United States:*** The states of Maine, Massachusetts, Rhode Island, and South Carolina have implemented various forms of *rolling easement* policies to ensure that wetlands and beaches can migrate inland as sea level rises.
- ***Australia:*** Several states have coastal setback and minimum elevation policies, including those to accommodate potential sea-level rise and storm surge. In South Australia, setbacks take into account the100-year erosional trend plus the effect of a 0.3-m sea-level rise to 2050. Building sites should be above storm-surge flood level for the 100-year return interval.

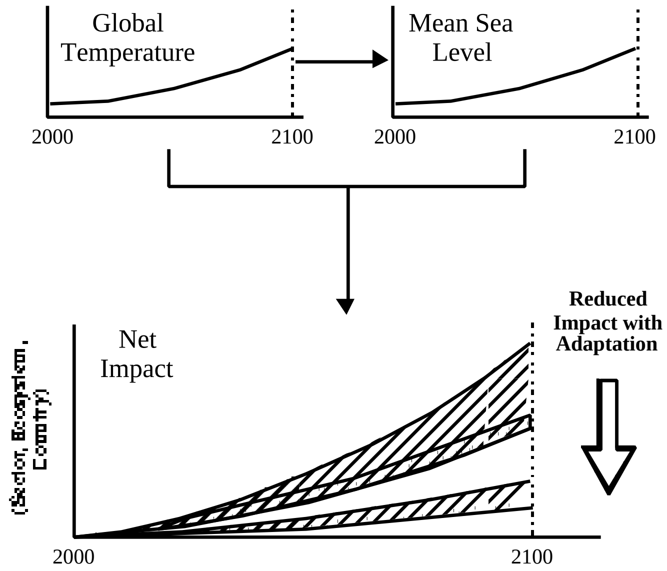


Figure 6-1: The role of adaptation in reducing potential impacts in the coastal zone from global temperature increase and sea-level rise to the year 2100. The bottom panel is a schematic that shows the increasing cost or loss to an economic sector, ecosytem, or country. The area shown by cross-hatch indicates the range of possible impacts and how net impact can be reduced with adaptation. Stipple within the cross-hatched areas indicates the importance of sector, ecosystem, or country resilience as a component of net impact.

Some adaptation measures handle uncertainty better than others. For example, beach nourishment can be implemented as relative sea level rises and therefore is more flexible than a dike or seawall; expansion of the latter may require removal or addition of structures. Any move from "hard" (e.g., seawall) to "soft" (e.g., beach nourishment) shore protection measures must be accompanied, however, by a much better understanding of coastal processes that prevail in the area (Leafe *et al.*, 1998). Rolling easements are more robust than setbacks (Titus, 1998) but may be impractical for market or cultural reasons. Maddrell (1996) found that over time scales of 35 and 100 years, managed coastal retreat is the most cost-effective adaptation option in reducing flood risks and protection costs for nuclear power facilities on the shingle foreland at Dungeness, UK. Flood insurance can discourage a flexible response if rates are kept artificially low or fixed at the time of initial construction, as they are in the United States (Crowell *et al*., 1999).

Reevaluations of the efficacy of hard shore protection schemes as a long-term response to climate change and sea-level rise are increasingly being undertaken. Chao and Hobbs (1997) have considered the role of decision analysis of shore protection under climate change uncertainty; Pope (1997) has suggested several ways of responding to coastal erosion and flooding that have relevance in the context of climate change. Documented changes in tidal characteristics as a result of the construction of sea dikes and seawalls also have implications for shore protection in the face of rising sea level. Several alternatives to seawalls have been suggested as adaptation measures to reduce coastal erosion and saltwater intrusion from rising sea levels in Shanghai, including improving drainage quality and channel capacity, increasing pumping facilities to reduce the water table, constructing a barrier across the mouth of the river, and developing new crops that are tolerant of a higher groundwater table (Chen and Zong, 1999).

It also should be noted, however, that Doornkamp (1998) has argued that in some situations past management decisions about human activities in the coastal zone (including flood defenses, occupance of flood-prone lands, extraction of groundwater and natural gas) have had an impact on relative land and sea levels and have done more to increase the risk of coastal flooding than damage that can be assigned to global warming to date.

6.6.4. Adaptation in Marine Ecosystems

Adaptation of the fishing industry to climate change is closely connected with investigations of the consequences of the effect of climatic anomalies and climate change scenarios. Because the effects of changes in climate factors will have different consequences for various species, development of special measures aimed at adaptation of the fish industry is regional in character and falls into the category of important socioeconomic problems.

Possible adverse effects of climate change can be aggravated by an inadequate utilization of fish reserves. For example, if a fish stock decreases as a result of the combined effect of climate change and overfishing, and the commercial catch remains high, species abundance may decrease dramatically and the commercial catch may become unprofitable. In such circumstances, some measures may need to be taken to protect fish reserves, such as the precautionary measures suggested by O'Brien *et al.* (2000) to give the North Sea cod fishery a chance to rebuild. Several sustainability indicators of marine capture species are discussed in Garcia and Staples (2000). Aquaculture also can be regarded as an adaptation; though to be an ecologically sustainable industry, it must emphasize an integrated approach to management (Carvalho and Clarke, 1998). Another adaptation is fish stock enhancement through ocean ranching (see Section 6.3.6).

Fish reserves rank among the most important economic resources in many countries. Approximately 95% of the world catch falls within the 200-mile economic zones of maritime states. Environmental impacts in those zones as a consequence of climate change could affect the catch volume and national economies. It should be noted that gains and losses at different levels of social organization can occur not only as a consequence of climate change but also as a result of human society's responses to this change. In some regions, for instance, special measures may be taken to promote adaptation and to reduce the negative consequences of climate change—which adds another dimension to fish management.

Adaptation measures that are relevant to the fishing industry may include the following:

- Establishment of national and international fishery management institutions that will be able to manage expected changes
- Expansion of aquaculture as a way of meeting increasing demand for seafoods of an increasing world population
- Support for innovative research and integrated management of fisheries within coastal and open marine ecosystems
- Improvement and development of an integrated monitoring system in the most productive areas, aimed at obtaining systematic information on hydrophysical, hydrochemical, and hydrobiological processes
- Organization of data banks on the results of integrated ecological monitoring to identify anthropogenic changes, including climate change, and predict fish productivity
- Modification and improvement of the technology of the fishing industry and management of the fish trade as required to adapt to climate change
- Organization of marine biosphere reserves and protected areas for the habitat of marine mammals
- Use of emerging predictive information related to natural climate variability (e.g., ENSO) to support fishery management and planning.

Adoption of some adaptation options to the potential impacts of climate change is not a panacea, however. Fish often are transboundary resources in that they may cross international and state boundaries in their oceanic migrations. In the case of Pacific salmon, for instance, problems have arisen in the agreement between the United States and Canada that are attributable in part to the effects of large-scale climate fluctuations (see Box 6-1). Miller (2000) suggests that the Pacific salmon case demonstrates that it may not be a simple matter for the fishing industry or governments to respond effectively to climate change. She concludes that adaptation is difficult when a resource is exploited by multiple competing users who possess incomplete information about the resource. If their incentives to cooperate are disrupted by the impacts of climate variation, dysfunctional breakdown in management rather than efficient adaptation may occur (Miller, 2000).

6.7. Synthesis and Integration

This chapter is concerned with two closely related but geographically different environments. The oceans—which cover more than 70% of the Earth's surface—are open, expansive, and spatially continuous. By contrast, coastal zones are long, narrow, and discontinuous. As a result, climate change impacts on marine ecosystems may be accommodated more readily in the open ocean (e.g., by migration) than in coastal regions, where mobility is restricted, there are more environmental constraints, and human impacts may be more severe. The potential biological and physical impacts of climate change and sea-level rise vary considerably between the oceans and coastal regions. The least vulnerable coastal and marine ecosystems have low exposure or high resilience to the impacts. Similarly, coastal communities and marine-based economic sectors that have low exposure or high adaptive capacity will be least affected. Countries, communities, and individuals in the higher range of economic well-being have access to technology, insurance, construction capital, transportation, communication, social support systems, and other assets that enhance their adaptive capacity. Those that do not have access have limited adaptive capacity. Unequal access to adaptation options, therefore unequal vulnerability, are attributable largely to different socioeconomic conditions. Poor adaptation or "maladaptation" also may lead to increased impacts and vulnerability in the future, with implications for intergenerational equity. These concepts are summarized in Figure 6-2.

Whereas the estimated costs of sea-level rise and other climate-related impacts in developed countries typically are limited to

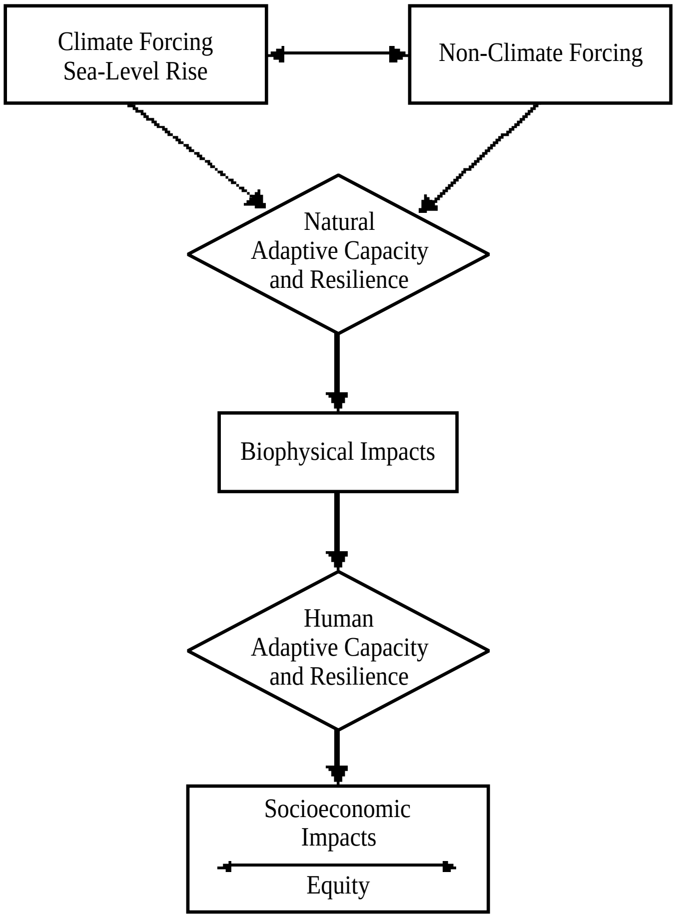


Figure 6-2: The role of natural and human adaptive capacity and resilience on the socioeconomic impacts of climate change following climate forcing, sea-level rise, and nonclimate forcing. The equity arrow in the bottom box indicates that impacts will not be uniform and that there will be wide inequalities, depending on socioeconomic conditions.

property losses, the reported outcomes of coastal floods in developing countries often include disease and loss of life. Vulnerability assessments in the developing world often do not consider the costs of business interruptions and failures, social disruption and dislocation, health care, evacuation, or relocation. A full accounting of the economic costs associated with lost, diminished, or disrupted lives would require estimates of the economic productivity losses they represent. Because this level of cost accounting is rare in developing countries, inequities may be significantly underestimated.

Turner *et al.* (1996) note that coastal zones are under increasing stress because of an interrelated set of planning failures, including information, economic market, and policy intervention failures. Moreover, moves toward integrated coastal management are urgently required to guide the co-evolution of natural and human systems. Acknowledging that forecasts of sea-level rise have been scaled down, they note that (1) much uncertainty remains over, for example, combined storm-surge and other events; and (2) within the socioeconomic analyses of the problem, resource valuations have been only partial at best and have failed to incorporate sensitivity analysis in terms of the discount rates utilized. They suggest that these factors would indicate an underestimation of potential damage costs and conclude that a precautionary approach is justified, based on the need to act ahead of adequate information acquisition and use economically efficient resource pricing and proactive coastal planning.

More recently, Turner *et al.* (1998) have aimed to elicit the main forces influencing the development of coastal areas and the means available to assess present use and manage future exploitation of the coastal zone. Their way of analyzing coastal change and resource management is through the pressure-state-impact-responses (P-S-I-R) conceptual framework. They analyze a variety of pressures and trends (including climate change, population changes, port development, marine aggregate extraction, and pollution). In the P-S-I-R framework, all of these factors are examined in the context of sustainable use of coastal resources and on the basis of an interdisciplinary ecological economics approach.

Several changes that might be expected to accelerate with global warming in the future already are detected in some regions and systems. Examples include global sea-level rise, increases in SST, and regional decreases in sea-ice cover. Impacts associated with these changes have included shoreline erosion, wetland loss, seawater intrusion into freshwater lenses, and some impacts on coral reefs. These impacts provide contemporary analogs for potential impacts in the future, recognizing that future changes and impacts may be of greater magnitude than those experienced so far and that changes and impacts may become more geographically widespread, including expansion into new areas that have not experienced such conditions previously. The contemporary environment gives us some insights into potential ecosystem impacts, some idea of costs, and some experience with potentially useful adaptation strategies.

We have found very few studies that indicate benefits of climate change and sea-level rise in coastal and marine systems. Recent studies, however, point to possible economic benefits from adaptation measures. Such benefits are likely to be restricted, particularly in the areas most at risk—including a large number of developing countries. Furthermore, the extent of impacts in those regions and the range of potentially effective adaptation measures remain poorly defined. Although there is growing acceptance of the need for integrated management strategies, progress has been slow in implementing these concepts in many jurisdictions. Part of the reason is limited development of understanding and tools for integrated assessment and management needs, involving various levels and aspects of integration, each of which may be difficult to implement. For instance, integration between the different disciplines involved in coastal and marine impact and adaptation analysis has been identified as a key issue by Capobianco *et al.* (1999). This and other integration needs are summarized in Box 6-7.

Some progress has been made since the SAR in developing and refining methodologies for assessing impacts of sea-level rise. Environments under particular threat include deltas, low coastal plains, coastal barriers, heavily utilized seas, tropical reefs and mangroves, and high-latitude coasts where impacts from warming may occur sooner or more rapidly.

Some topic areas rarely have been addressed, however. For instance, only a few case studies attempt to integrate potential impacts of sea-level rise and increased precipitation and runoff in coastal watersheds in assessing coastal vulnerability. Techniques for similar integration between biophysical and socioeconomic impacts are developing slowly, while human development and population growth in many regions have increased socioeconomic vulnerability and decreased the resilience of coastal ecosystems. Few studies provide details or any quantitative measures. We believe that integrated assessment and management of open marine and coastal ecosystems and a better understanding of their interaction with human development could lead to improvements in the quality of sustainable development strategies.

Global climate change will affect the biogeophysical characteristics of the oceans and coasts, modifying their ecological structure and affecting their ability to sustain coastal residents and communities. Impacts in the coastal zone will reflect local geological, ecological, and socioeconomic conditions within a broader regional or global context. Shorelines are inherently dynamic, responding to short- and long-term variability and trends in sea level, wave energy, sediment supply, and other forcing. Coastal communities—particularly on low-lying deltas, atolls, and reef islands—face threats of inundation, increased flooding, and saltwater intrusion, with impacts on health and safety, water supply, artisanal fisheries, agriculture, aquaculture, property, transportation links, and other infrastructure. In some coastal areas, particularly in developed nations, a shift in emphasis toward managed retreat appears to have gained momentum. Enhancement of biophysical and socioeconomic resilience in coastal regions increasingly is regarded as a cost-effective and

Box 6-7 Integration forAssessment and Management of Marine and Coastal Systems

Integration of marine, terrestrial, and coastal processes and a better understanding of their interactions with human development could lead to substantial improvements in the quality of adaptation strategies. Integration must take place in several areas, including the following:

- ***Subject/topic-area integration*** (e.g., climate-change related stresses plus non-climate stresses; biophysical and socioeconomic susceptibility, resilience, vulnerability, impacts)
- ***Geographical/spatial integration*** (e.g., linkages between terrestrial, coastal, and oceanic systems and feedbacks; global, regional, local scales)
- ***Methodological integration*** (e.g., integrating physical, social, and economic models)
- ***Integrated implications*** (e.g., for sustainable development, intergenerational equity and ethics)
- ***Integration of science, impacts, and policy*.**

Estuaries as an example of the need for integration
Changes in salinity, temperature, sea level, tides, and freshwater inflows to estuaries are considered likely consequences of climate change on estuarine systems. Estuaries are among the world's most-stressed ecosystems because of their close proximity to areas of population growth and development. Understanding of regional differences in the physical drivers that will cause changes in estuarine ecosystems and their ecological functions is limited. Uncertainty also exists regarding changes to dissolved carbon, nutrient delivery and pollutant loading, and their interactions. For example, intensive forestry and agriculture that may be implemented as some regions adapt to climatic change could increase the transport of nutrients such as nitrogen and phosphorus to estuaries. Linkage of hydrological models for surface waters with ocean-atmosphere models is needed to integrate marine and terrestrial ecosystem change. Estuaries illustrate the need for vertical integration among the foregoing subject areas and issues, spatial scales, and methodological approaches, with implications for habitation and use of coastal environments and ecosystems.

desirable adaptive strategy. Growing recognition of the role of the climate-ocean system in the management of fish stocks is leading to new adaptive strategies that are based on determination of accepable removable percentages in relation to climate change and stock resilience.

Vulnerability to climate change and sea-level rise has been documented for a variety of coastal settings via common methodologies developed in the early 1990s; these assessments have confirmed the spatial and temporal variability of coastal vulnerability at national and regional levels. New conceptual frameworks include biophysical and socioeconomic impacts and highlight adaptation and resilience as components of vulnerability. Recent advances include models to evaluate economic costs and benefits that incorporate market and nonmarket values. Sustainable approaches to integrated coastal management can now include new financial accounting approaches that include ecological services and traditional cultural values. Nevertheless, adaptive choices will be conditioned by policy criteria and development objectives, requiring researchers and policymakers to work toward a commonly acceptable framework for adaptation.

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