Chapter 6

World oceans and coastal zones

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1 Introduction

Climate change will have significant impacts on the oceans of the world and the coastal zone, which will also play an important part in determining the nature and extent of climate change. Probably the most important aspects of climate change on the World Ocean and coastal zones will be the impact of sea-level rise on coastal residents and on marine ecosystems. These impacts are treated first, followed by the other impacts of climate change on the ocean and coastal zone.

The following assumptions were made in this report:

- carbon dioxide (CO_2) will double by 2050;
- other greenhouse trace gases will increase significantly;
- average world air temperature will increase by 1.5°-4.5°C;
- sea-level will rise by 0.3-0.5 m by 2050; up to about 1 m by 2100;
- there will possibly be an increase in solar ultraviolet-**B (UV-B)** radiation.

IPCC Working Group I scenarios were developed in parallel with the preparation of this report and are generally consistent with the assumptions of this report. However, a few of the cited studies with respect to sea-level rise have considered higher rates than those projected by Working Group I. This is useful information, given that there are important regional differences expected in sea-level rise because of such things as regional land subsidence, glacial rebound and oceanic currents (Mikolajewice et al., 1990), and the possibility of continuing natural processes such as polar ice sheet response to the last glaciation (NASA, 1990).

2 The socioeconomic and ecological impacts of sea-level rise and related climate change

2.1 Introduction

Future global warming could increase the rate at which sea-level has been rising by (i) warming and thereby expanding ocean water, (ii) melting mountain glaciers, and (iii) possibly causing polar ice sheets in Greenland and perhaps Antarctica to disintegrate. Current estimates are that sea-level will rise between 30-50 cm by the year 2050 and possibly up to 1 m by the year 2100 (Figure 6.1). Site-specific studies must add current trends in subsidence or emergence to these estimates. In addition, global warming may increase storm frequencies and intensities.

A rise in sea-level would (i) inundate and displace wetlands and lowlands, (ii) erode shorelines, (iii) exacerbate coastal storm flooding, (iv) increase the salinity of estuaries and threaten freshwater aquifers and otherwise impair water quality, (v) alter tidal ranges in rivers and bays, (vi) alter sediment deposition patterns, and (vii) decrease the amount of light reaching water bottoms (Figure 6.2).

Present population growth and development in areas subject to natural water-related hazards is itself a reason for concern. The foreseeable consequences of global warming and sea-level rise heighten concerns for countries and their citizens occupying these vulnerable areas. Other aspects of a countrys economic and social well-being may be adversely affected by fundamental changes to its fisheries and agriculture or its economic base in tourism. Also, in some countries, beaches and other coastal features provide important cultural values which may be threatened by sea-level rise. Further, there may be impacts on biodiversity as some small localised habitats are lost or move faster than the plants or animals which depend on them can adjust.

The present trend towards increasing deterioration of coastal areas through pollution, development and overuse (GESAMP, 1990) are also reducing the capacity of coastal systems to respond to and compensate for climate changes and sea-level rise.

After discussing the methodological limitations of existing knowledge, this chapter divides the impacts of sea-level rise into three categories:

(i) socioeconomic impacts (threatened populations in low-lying areas and island nations);

(ii) ecological impacts (alteration and degradation of the biophysical properties of beaches, estuaries, and wetlands);

(iii) physical aspects of shoreline retreat.

2.1.1 Methodological limitations

This chapter relies on previously published analyses that are based on a variety of sea-level scenarios. Many project a i m sea-level rise which Working Group I estimates will not be reached before the year 2100. There are far fewer studies which have looked at a rise of 0.5 m or less amount.

Because of inadequate data and the uncertainties regarding global warming, sea-level rise and future coastal development, the studies cited herein deal with possibilities, not forecasts. It is particularly difficult to assess the potential impacts consistently for all coastal regions.

Another problem facing all impact analyses is the need for baseline scenarios - in this case, what would happen without global warming (Stakhiv and Hanchey, 1989). Unfortunately, most sea-level rise studies (a notable exception is Gibbs, 1984), have ignored this issue and have generally assumed the current level of coastal development (eg Park et al., 1989; Delft, 1990a). The failure to consider future coastal development may have led these studies to underestimate the socioeconomic and environmental impacts of rising sea-level. Finally, there is little consistency regarding the probable response of society.

The purpose of this section is to assess the impacts of sea-level rise assuming (i) that people take rational but ad hoc actions and (ii) that governments take no organised response. Unfortunately, many of the studies cited do not follow this convention.

2.2 Socioeconomic impacts: threatened populations in low-lying areas and island countries

A simple measure of a country's vulnerability to sea-level rise is the proportion of its population and productive land that is within a few metres of present mean sea-level. A direct relationship exists between inundation (extended by the impacts of climate variability, storm surges, waves and erosion) and the viability of inhabited areas. Health, safety and food security are among the primary determinants of socioeconomic well-being. Threats to these attributes of well-being define a region's vulnerability. Not all countries are equally vulnerable and many will be only indirectly affected by sea-level rise, with limited impacts to a particular sector of the economy (eg fisheries, tourism) or affecting the mechanisms of trade and transportation (eg waterways, ports, inlets).

Coastal areas, particularly low-lying areas exposed to the open ocean are inherently hazardous, yet they have attracted people, industry and commerce. Every year lives are lost, tens of billions of dollars of damages are sustained, and hundreds of square kilometres of land are eroded. For most inhabitants who have a choice, the perceived benefits of living in this highly variable zone outweigh the risks and costs. Many are not so fortunate - they do not have the choices available to them. Thus, much of the dense coastal infrastructure in place today will probably be protected to the extent technically and economically feasible. Retreat would be more likely in less developed areas (Moser and Stakhiv, 1989; Dean et al., 1987; Barth and Titus, 1984).

Estimating monetary impacts is fairly straightforward; it is much harder to assign market values to non-monetary impacts (morbidity or mortality, ecosystem damage). Jansen (1990) reviewed methods of quantifying each. He discussed preventative policy measures, which are global and long term, and adaptive measures that can be more easily implemented nationally or locally. The few studies on economic assessment of sea-level rise estimate the engineering cost only.

Data on vulnerability to damage (altitudes of vulnerable areas, existing buildings and infrastructures) vary widely from country to country. The following sections examine the socioeconomic implications of inundation, erosion, agricultural losses, increased flooding and the impacts of water supply, water quality and infrastructures.

2.2.1 Inundation

The direct effect of inundation is the potentially large loss of inhabited areas, particularly in low-lying, flat deltaic and estuarine areas. Half of humanity inhabits the coastal regions around the globe, and large areas of highly vulnerable flood-prone sections are densely populated. A i m rise in sea-level could inundate 12-15% of Egypt's arable land (Broadus et.al., 1986) and 17% of Bangladesh (Commonwealth Secretariat, 1989). Large displacements of population would be likely in Indonesia and Vietnam. The United States would lose 20,000 km^2 kilometres of land, an area worth about $650 billion (Park et al., 1989; Yohe, 1990).

In extremely flat deltaic areas, a i m rise in sea-level would cause shores to retreat several kilometres, displacing hundreds of villages and depriving millions of people of their means of subsistence, ie their lands and natural resources. A group of experts convened by the Commonwealth Secretariat (1989) reported that the most vulnerable deltas include:

the Nile in Egypt, Ganges in Bangladesh, the Yangtze and Hwang Ho in China, the Mekong in Vietnam, the Irrawaddy in Burma, the Indus in Pakistan, the Niger in Nigeria, the Parana, Magdalena, Orinoco and Amazon in South America, the Mississippi in the US and the Po in Italy.

Many small island countries would lose a significant part of their land area with a sea-level rise of 1 m (Lewis, 1988). Coral atoll nations, such as Kiribati, Marshall Islands, Tokelau and Tuvalu, Cocos and Keeling Islands, are particularly vulnerable to inundation and erosion because they are generally below 3 m elevation and narrow, implying few possibilities for retreat. Coral reefs along many tropical coasts serve as natural breakwaters. Any sea-level rise will allow waves to over-top the reefs, increasing coastal vulnerability to erosion and storms, at least until reef growth can catch up with sea-level. The more rapid the rate of sea-level rise, the longer the period of vulnerability, and the greater the possibility that present reefs will be unable to catch up and that they will drown. Coral mining for building materials, and land reclamation on coral reef flats increase the risk of damage.

Some scientists (eg Parnell, 1989) have suggested that increased growth rate of coral reefs and more efficient sedimentation processes may offset some of the sea-level rise effects for atolls, at least for the next 50-100 years. Further research and study are clearly needed.

The 1190 small islands making up the Republic of the Maldives barely rise 2-4 m above sea-level (Small States Conference on Sea-level Rise, 1989.). A recent UNEP report on the republic (Pernetta and Sestini, 1989) illustrates the dilemma facing atoll countries. The Maldives already experience serious environmental degradation, primarily because of the high population density on the few inhabited islands within each atoll.

In a recent survey, Delft Hydraulics Laboratory (1990a, 1990b) attempted a first-order estimate of 181 coastal countries and territories. The study estimated that 345,335 km of low coast, 6400 km of urban waterfronts, 10,725 km of sandy beaches, and 1756 km^2 of harbour areas would have to be protected. Many of the island countries do not have the alternative of retreat and must either protect themselves or evacuate the islands. Table 6.1 shows the annual costs of preventing inundation and erosion as a percentage of the country's GNP. For ten countries, nine of which are islands, the estimate of annual costs would comprise greater than 5% of their GNP. Because the study assumed that all low land areas with population density greater than 10 inhabitants per km^2 would be protected, protection costs may be overstated. On the other hand, the total cost of sea-level rise may be underestimated because coastal areas are still being developed and the study did not consider the value of lost wetlands, dry land that would not be protected, or the cost of correcting problems due to increased flooding or saltwater intrusion.

2.2.2 Agricultural losses

Sea-level rise could decrease the agricultural productivity of many deltaic countries that can least afford the losses (Bangladesh, Egypt, China etc). The impacts on agriculture arise not only from direct loss of arable land to inundation, but also to the increased potential for erosion and increased coastal and riverine flooding. For example, about 20% of agricultural production could be lost, mainly rice, sugarcane and jute, as a result of the 1 m inundation of Bangladesh (UNEP, 1989). Similarly, about 15% of Egypt's agricultural production would be permanently lost. Thailand and China are regarded as being especially vulnerable to significant losses of productive deltaic agricultural land, as are Gambia, Senegal, Nigeria and Mozambique. Additional land could also be degraded by salinisation and flooding.

Differing interests may cause conflict and dispute over property rights and responsibilities. Farmers losing land to sea-level rise can get land only from others to compensate for their loss. Since vacant agricultural land is scarce, the result could be ruin for farmers hit by the effects of land loss. The problems can be tremendous in countries where large populations and areas are seriously hit.

2.2.3 Erosion and tourism

In many areas, the total shoreline retreat from rising sea-level would be greater than that due to inundation alone, because land well above sea-level could also erode. In the US, several studies have concluded that a 30 cm rise would eliminate the existing recreational beaches at most major resorts and threaten ocean-front property worth tens of millions of (US) dollars per kilometre of shoreline (Kana et al., 1984; Leatherman, 1985; Titus, 1986; 1990). The Miami and Perth IPCC coastal workshops suggested that sea-level rise would also threaten oceanside development in Portugal, Brazil, Nigeria, Thailand and most other nations with tourist beaches.

2.2.4 Increased potential of coastal flooding

Coastal storms can threaten human life, livestock, crops, structures and water supplies. As sea-level

Table 6.1 Survey of 1 m sea-level rise and protection costs. (Countries and territories ranked by estimated costs as per cent of GNP*)

No	Country or territory	Annual cost as % of GNP	Length low coast (km)	Beach length (km)
1	Maldives	34.33	1	25
2	Kiribati	18.79	0	0
3	Tuvalu	14.14	0	0
4	Tokelau	11.11	0	0
5	Anguilla	10.31	30	5
6	Guinea-Bissau	8.15	1240	0
7	Turks and Caicos	8.10	80	5
8	Marshall Island	7.24	0	0
9	Cocos (Keeling) Isl	5.82	1	0
10	Seychelles	5.51	1	25
11	Falkland Isl	4.75	1	0
12	French Guiana	2.96	540	0
13	Belize	2.93	500	0
14	Papua New Guinea	2.78	6400	0
15	Bahamas, the	2.67	400	200
16	Liberia	2.66	2200	0
17	Gambia, the	2.64	400	0
18	Mozambique	2.48	10015	25
19	St.Chr. and Nevis	2.33	40	10
20	Nieu	2.18	6	0
21	Guyana	2.12	1040	0
22	Suriname	1.94	2800	0
23	Sierra Leone	1.86	1835	0
24	Aruba	1.85	1	15
25	Pitcairn Island	1.71	0	0
26	Fiji	1.53	11	25
27	Sao Tome and Pr.	1.46	3	5
28	Nauru	1.25	3	0
29	British Virgin Isl	1.24	1	10
30	Tonga	1.14	4	0
31	Cayman Islands	1.04	1	25
32	Cook Islands	1.03	0	0
33	Equitorial Guinea	1.02	7	0
34	Antiqua and Barbuda	1.01	50	10
35	Sri Lanka	0.89	9770	30
36	Togo	0.87	300	20
37	St Lucia	0.82	25	10
38	Burma	0.77	7470	0
39	Benin	0.74	485	10
40	Micronesia, Fed. St.	0.73	0	0
41	New Zealand	0.70	14900	100
42	Palau	0.69	7	0
43	Grenada	o.67	6	5
44	Neth. Antilles	0.66	25	30
45	Senegal	0.65	1345	0
46	Ghana	0.64	2400	20
47	Somalia	0.62	700	0
48	Western Samoa	0.59	11	0
49	Madagascar	0.56	1190	0
50	St. Vincent and Gr.	0.55	7	5

* This estimate does not represent the total cost of sea-level rise, only the cost of erecting shore protection structures.

rises, these damages could increase substantially as the most densely populated areas landward of the present shoreline come under the direct influence of storm surges and wave attack. Sea-level could increase the risk of flooding for three reasons: (i) there would be a higher base upon which storm surges would build; if sea-level rises 1 m, an area flooded today with 50 cm of water every 20 years would then be flooded with 150 cm every 20 years; surges would penetrate further inland (Kana et al., 1984). (ii) beaches, sand dunes, coral reefs, marshes and mangroves currently protect many areas from direct wave attack; by removing these protective barriers, erosion would leave many areas more vulnerable; and (iii) sea-level rise would increase flooding from rainstorms and river surges owing to decreased drainage (Titus et al., 1987).

The higher base for storm surges would be particularly important in areas where hurricanes or severe storms are frequent, such as the southeastern US, the Indian subcontinent, the western Pacific and islands in the Caribbean Sea. Wynne (1989) estimates that even a 50 cm rise would cause areas in South Australia, flooded today only once per century, to be flooded every two years. In Japan, a i m rise would threaten an area of 1700 km^2 square kilometres in which 4 million people live (Mansfield and Nishioka, 1989).

Floods in Bangladesh would be worse for all of these reasons. In 1987, for example, flood crests of the Ganges and Brahmaputra rivers coincided in Bangladesh, inundating about one third of the country and forcing tens of millions of people from their homes. In addition, about ten million people live on land that lies within 1 m of mean sea-level near the coast. The coastal plains of Guyana, which also he at the high-tide level, are inhabited by 90% of the population. The coastal defence system has deteriorated and is vulnerable to sea-level rise. Finally, the Pacific and Indian Ocean atoll countries would be especially threatened by the increased flooding from a combination of sea-level rise and the possibility of the increased frequency and magnitude of coastal storms and cyclones (Emmanuel, 1988).

Other possible associated effects of global warming could also increase coastal flooding. In particular, increases in the frequency and magnitude of riverine floods and coastal storms could result from changing weather patterns, increased precipitation, and shifting of the seasonality of monsoons, snowmelt and other precipitation - runoff phenomena. The resultant wetter soils and increased flows could exacerbate flooding and result in the loss of agricultural productivity, as the soils stayed saturated for longer periods.

2.2.5 Water supply and quality

Sea-level rise would generally enable salt water to advance inland in both aquifers and estuaries. Particularly during droughts, the upstream migration of salt fronts in estuaries would threaten municipal and industrial freshwater intakes that draw water from tidal rivers for water supply. In the US, a 50 cm rise would enable salt water to advance 10-20 km upstream in the Delaware Estuary, threatening Philadelphia's municipal intake, as well as adjacent aquifers that are recharged by the (currently fresh) river water (Hull and Titus, 1986); New York (Miller et al., 1988), Southern California (Williams, 1989) and coastal cities throughout the world relying on freshwater intakes that draw water from tidal rivers would be similarly vulnerable.

Saltwater contamination of municipal water supplies could also occur more frequently than under historical drought periods. Even in areas where the General Circulation Models (GCM) predict a net increase of mean annual precipitation, the models also suggest a progressive increase in the frequency of droughts to the year 2050. Not only could municipal water supplies be contaminated more frequently, at the most critical times, groundwater aquifers could also be contaminated by saltwater intrusion. In addition, a good deal of agricultural irrigation water is withdrawn from the streams and rivers. Hence these supplies would also be adversely affected by extended periods of saltwater intrusion, also during the critical drought periods.

A particular concern facing atoll countries is the impact of sea-level rise on groundwater availability. Countries such as Kiribati, Marshall Islands, Tokelau and Tuvalu in the Pacific, and the Maldives, Cocos and Keeling Islands in the Indian Ocean depend on rainwater lenses that lie atop salt water. As sea-level rises, the thickness of the freshwater lens decreases, and hence the volume of fresh water decreases (Figure 6.3). Also sea-level rise would increase the likelihood of storm overwash of the islands, causing increased incidence of saltwater contamination of the freshwater lenses. Studies have also shown that as the atoll islands erode owing to increased sea-level rise and wave attack, a 20% reduction in the width of an island may cause a 50% loss of the volume of fresh water (Commonwealth Secretariat, 1989). Clearly, basic subsistence on these islands would be seriously impaired. If these changes are coupled with more frequently occurring droughts, the socioeconomic and ecological impacts could be devastating to these island countries.

Sea-level rise will impair estuarine water quality in other subtle ways, contributing to the degradation of in situ conditions for aquatic biota (eg increased temperature results in lower dissolved oxygen) and increasing the health risks of the population dependent on withdrawals of fresh water from the streams.

Increased precipitation and consequent riverine flooding, coupled with reduced interior drainage, could cause more frequent stormwater overloading of the municipal drainage and sewerage systems. The addition of large pulses of point source and non-point source pollution would contribute to general water quality degradation of riverine, estuarine and coastal waters. Less obvious are the potentially serious effects of the leaching of toxic and hazardous contaminants from countless hazardous waste sites, at least those in the US, that are located within the 100-year floodplain. Septic systems would fail and overflow more frequently as the soils remain waterlogged for extended periods. Moreover, if drainfields from septic tanks are less than 1.5 m above the watertable, they contaminate it; higher watertables would make this situation more commonplace. Finally, water bodies could stagnate, both because of higher temperatures and the decreased mixing and tidal flushing associated with deeper water (Park, 1990).

2.2.6' *Infrastructure*

Rising sea-level would expose coastal infrastructure to the combined impacts of waves, storm surges and erosion. In the US, about $100 billion could be required to protect tourist resorts and vulnerable urban areas from inundation and erosion alone. Modifications to stormwater and sewerage systems, ports and navigation channels, roads, bridges and water supply infrastructure could substantially increase this figure (Titus and Greene, 1989). Drainage improvements necessitated by a 1 m rise in sea-level for Miami International Airport alone, would cost about $US30 million (Miller, 1988). In Japan, the cost of modifying infrastructure for a 1 m rise in sea-level would be about $US20 billion (Mansfield and Nishioka, 1989).

Higher sea-levels would ease access to some shallow ports and through some sea-level canals.

2.3 Ecological impacts: alteration and degradation of the biophysical properties of beaches, coral reefs, estuaries and wetlands

2.3.1 *Wetlands*

Over two-thirds of fish caught for human consumption - as well as many birds and terrestrial animals depend on coastal marshes and swamps for part of their life cycles. Unlike most dry land, coastal wetlands can keep pace with a slow rate of sea-level rise. As Figure 6.4 shows, this ability has enabled the area of intertidal wetlands to increase several-fold with the slow rate of rise over the last few thousand years. However, if sea-level rises at a rate greater than the ability of wetlands to keep pace, the area of wetlands could decline by a similar amount; and when bulkheads and dikes protect adjacent dry land, there could be a complete loss (Titus et al., 1984; Titus, 1986, 1990).

Kana et al. (1988a and 1988b) surveyed the intertidal wetlands around Charleston, South Carolina, and Long Beach Island, NJ. In the Charleston site, they found that a 90 cm rise would inundate 50% of existing wetlands, although the net loss would be only 40% if wetlands are able to form inland. In the case of a 140 cm rise, they estimated that 90% of existing wetlands would be lost, but the net loss would be only 80% if the adjacent dryland areas are abandoned. In contrast, in the Long Beach Island site they found that a 90 cm rise would have little impact on total wetland acreage; the primary impact would be to convert the predominant high marsh to low marsh; a 140 cm rise, however, would drown 80% of the wetlands.

Park et al. (1986) used topographic maps to attain a first approximation of the impact of sea-level rise on US coastal wetlands. Their results suggested that a 1.4 m and 2.1 m rise in sea-level would inundate 47% and 80% (respectively) of US wetlands, but these losses could be reduced to 31% and 70% (respectively) if adjacent developed lowland were abandoned to the advancing sea.[1] However, Titus (1988) noted that interpolation of topographic maps inherently overestimates wetland elevations, and hence underestimates wetland loss. Therefore, Park et al. (1989) revised their regional study, this time using an unbiased procedure for estimating wetland elevations and using the lower estimate of a 1 m rise in sea-level. The revised results implied that such a rise would inundate 50-82% (95% confidence interval) of existing wetlands, but that the net loss would be reduced to 29-66% if only densely developed areas are protected.[2]

The applicability of these estimates for other countries is unknown. Because wetlands are found below the annual high tide, the most vulnerable areas would tend to be those in areas with small tidal ranges, such as the Mediterranean and Black seas,

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1. These results are reported in Titus, 1988, who did regional weighting to obtain national results.
2. These results are reported in Titus and Greene, 1989.

the Gulf of Mexico and estuaries with narrow openings to the sea. The least vulnerable would be those in areas with large tidal ranges, such as the Bay of Fundy.

A recent global survey of coastal wetlands and mangrove swamps was conducted by the Netherlands (Rijkswaterstaat, 1990). This survey, which did not include data from the US, Canada, Australia and New Zealand, shows that, in the aggregate, there are about 730,000 km^2 of coastal wetlands, plus another 165,000 km^2 of mangroves. Eight countries out of 120 surveyed - Mexico, Brazil, Argentina, Cuba, Indonesia, Papua-New Guinea, Vietnam and Malaysia - possess slightly more than half of the world's coastal wetlands. They found through their survey that about 88% of the total coastal wetlands areas of the world are situated in regions with a population density of less than 10 inhabitants/km^2. They reason that these areas are unlikely to be protected by 'hard' coastal structures because of unfavourable economics, and thus, the land uses upland of the wetlands pose no barriers to the landward migration and transition of wetland types as sea-level rises. At most, 5-10% of wetlands by area would be lost to hard coastal structures with a rise of 1 m given the current level of coastal development. This conclusion is similar to that of Park et al. (1989). Thus, most wetland loss would be due to inundation, not coastal structures. Nevertheless, several authors have cautioned that current rates of coastal development could lead to much greater proportion of the coast being developed, with a corresponding increase in wetland loss due to structures preventing the inland migration of coastal ecosystems (Everett and Pastula, 1990; Titus, 1990).

Coastal areas place an added problem of the presence of hazardous waste sites, the flooding of which could have serious environmental consequences. In the US, about 1100 active hazardous waste sites, and possibly as many closed or abandoned sites, are located within areas that have a probability of flooding once every 100 years (Flynn et al., 1984). Increased flooding could exacerbate the problem of hazardous waste entering the environment.

2.3.2 Background: importance of wetlands

Coastal tidal wetlands are very important to the functioning of estuarine and near-shore ecosystems. In Europe and the US, a large proportion of coastal wetlands has been lost to development - and a relatively high percentage continues to be lost annually through a combination of subsidence and sediment starvation caused by dams and dikes that restrict natural sedimentation. About 18,000 square km^2 of coastal wetlands remain in the US (Office of Technology Assessment, 1984).

Wetlands are vital to the ecology and economy of coastal areas. Their biological productivity is equal to or exceeds that of any other natural or agricultural system, (Teal, 1962; Ryzkowski, 1984). Wetlands support resident and migratory birds, coastal animals which use them for habitats and forage, and they are vital to the well-being of many species of fish and shellfish. Over half the species of commercially important fish in the southeastern US use salt marshes as nursery grounds. The value of marshes as habitat for various life-cycle stages of countless species may be their most important function. Wetlands also serve as sinks for pollutants and provide a degree of protection from floods, storms and high tides. Based on these functions, marshes have an estimated present worth to society of as much as $US13,600/ha (Thurman, 1983).

Coastal wetlands and estuaries are important to many species. If sea-level rise is too rapid, natural succession of the coastal ecology would not take place and could lead to disruption in the life cycles of many species. In the near term, production of fisheries could rise as marshes flood, die and decompose, thus improving fisheries habitat in some cases and providing more nutrients. Additional nutrients would become available from leaching of soils and peat which would flood more frequently. This temporary increase in productivity appears to be happening now in the southeastern US where sea-level rise is compounded by land subsidence (Zimmerman et al., 1989). However, this temporary benefit for fisheries may be balanced by negative impacts on birds and other wildlife as the habitat area is decreased. In the longer term, by 2050 the overall impact on fisheries and wildlife will probably be negative.

For example, in coastal Louisiana, US, brackish marshes are deteriorating because of high rate of sea-level rise (due to subsidence) and saltwater intrusion. Recent increases in juvenile shrimp in the fishery may be the result of a short-term increase in nursery area due to increased tidal penetration into the marshes. If this is so, then the increasing trend of shrimp production may be reversed if wetland deterioration continues (Condrey, 1989).

2.3.3 Redistribution of wetlands

An accelerated rise in sea-level could result in a substantial redistribution of coastal wetlands types. Salt, brackish and fresh marshes as well as mangrove and other swamps would be successively lost to inundation and erosion; others would transform and adapt to the new hydrologic and hydraulic regime or would migrate inland through adjacent lowlands not impeded by protective structures. The value of these wetlands as habitat for wildlife could be impaired during the transitional period and their biodiversity may decrease (Davis, 1985). Sedimentation and peat formation have allowed many wetlands to keep pace with sea-level rise in the last few thousand years, which has enabled the area of wetlands to increase in most parts of the world, as illustrated in Figure 6.3. However, if the sea-level rises more rapidly than the wetland vertical accretion rate, there could be a corresponding net loss of wetlands. Kearney and Stevenson (1985) found that in some areas, any acceleration of sea-level rise would induce a net loss of wetlands; in contrast, Park et al. (1986, 1989) assumed that wetland accretion in most areas could keep pace with an acceleration of 1 or 2 mm per year. The literature provides no evidence, however, that wetlands could generally keep pace with a relative sea-level rise of 1 cm per year, which would be reached by the year 2100 even in the 50 cm scenario. In fact, such a rate would be as great as the rate attained during the disintegration of the continental ice sheets at the end of the Pleistocene, which drowned barrier islands and associated features on the continental shelves (Peltier, 1988).

Owing to the combination of climatic changes, it is expected that specific ecological communities within coastal ecosystems will not only move inland, wherever humankind does not intervene, but will generally move poleward.

2.3.4 *Changes in nutrients and chemicals*

Particularly for a large rise in sea-level, biogeochemical cycles will be altered by saltwater inundation of land not submerged in millennia. Increases in nitrogen and phosphorous concentrations can be expected as well as the release into the marine environment of pesticides and toxic substances resident in the ground.

2.3.5 *Other ecological impacts of sea-level rise*

There are several ecological impacts of sea-level rise beyond those in wetland areas. Many species of sea turdes are recognised throughout the world as threatened with extinction. (Everett and Pastula, 1990). As nesting beaches are lost, either by sea-level rise or by human development, additional significant stresses will be placed on turtle populations. In addition, dune ecosystems are also important to many species of birds and other animals as nesting and foraging areas. Many marine mammals rely on beach zones for critical parts of their life cycle. Sea-level rise approaching the 1 m worst-case scenario may inundate some important haulout or put these mammals into conflict with human uses; however, in most cases animals are expected to adapt. On the other hand coral reef communities have a limited capacity to adjust to sea-level rise: whereas the corals appear to have accommodated to historic sea-level change rates, it is unclear whether they can adjust as readily under rates approaching the worst-case scenario.

In addition, a rapid rate of sea-level rise may threaten coral reefs which fringe coral atolls and provide the material sustenance for them. They may not be able to keep up with the sea-level rise, thus causing their ecological structure to change as they become flooded.

2.4 Physical aspects of shoreline retreat: inundation, erosion and recession of barrier islands, coral reefs and other shorelines

2.4.1 *Background*

The primary direct physical effect of sea-level rise is inundation. Inundation increases the rate of shoreline recession or retreat by raising the mean water level upon which the tides, waves and storm surges can attack the beaches, bluffs, embayments and barrier islands of the world's coastlines. Historically, submergence has accounted for a relatively small portion of net shoreline recession along exposed sedimentary coasts (Hands, 1976). That is, most sandy shorelines worldwide have retreated during the past century because of the erosion associated with the regional storm and wave climate (Bird, 1976). Locally, human interference with the coastal sediment transport regime has accelerated erosion problems, as jetties and groins have impeded littoral transport processes. On a global scale, however, human interference cannot be considered a primary cause of erosion since retreat also occurs on sparsely populated and little-developed sandy coasts (Bird, 1976). Less than 10% of the length of the world's sandy shoreline has progressed, more than 60% has regressed, and the balance (30%) has been relatively stable or has shown no consistent trend during the past century (Bird, 1976).

The slope of the beach foreshore is the controlling variable of shoreline recession: steep-sloped shorelines will experience relatively little horizontal displacement with each increment of sea-level rise. Gently sloping shores will undergo much greater recession and flooding for the same increment of sea-level rise (National Research Council, 1987).

For example, the deltaic coast of Louisiana in the Gulf Coast region of the US has been receding at a rate of 4.2 m/yr (May et al., 1983). This is associated with a relative rise of sea-level (caused mostly by subsidence) of about 1 cm/yr. Along sand beaches, the general rule of thumb for the relationship of average beach recession to sea-level rise is about 100:1, ie a shoreline recession of 100 m for a 1 m rise in sea-level (National Research Council, 1987).

It is essential to understand the effects of sea-level rise on coastal physical processes, for these processes will not only determine the overall physiographic and geomorphological features of the coast, but also their interaction with man-made structures designed to stabilise the shoreline. Our ability to predict these processes under contemporary slow rising sea-level remains rudimentary, even though a considerable amount of empirical and theoretical coastal engineering research has been accomplished (National Research Council, 1987).

2.4.2 Global projections of inundation and recession

The recent Dutch study (Delft Hydraulics Laboratory, 1990b), estimated the total shoreline length that would be inundated or otherwise affected by a rise in sea-level of 1 m. Low coasts were defined as those with a coastal zone broader than 25 km below the 100 m contour. In addition, the Dutch reasoned that only coastal areas with a population density greater than 10 inhabitants/km^2 could be considered vulnerable to the combined threat of inundation, flooding and erosion. Over 345,000 km of low coast in 181 countries were identified and surveyed on the basis of these assumptions, along with 10,700 km of barrier island beaches and major recreational oceanic beaches. The Dutch used Leatherman's (1988) estimates for the length of sandy shorelines in the US. Of the 11,000 km of sandy shoreline in the US, some 3000 km were considered to require some form of stabilisation.

According to the US Army Corps of Engineers' National Shoreline Study (1971), there are approximately 51,000 km of shoreline in the conterminous US (excludes Alaska which has about 75,000 km and Hawaii). Of the 51,000 km, about 24,500 km (nearly 50%) were considered erosional, but only 3000 km were considered to be critical enough for protective action. Currently, only about 1000 km are protected by some form of 'soft' (eg periodic beach nourishment) or 'hard' structural measures. These figures are presented as a rough indicator of the current degree of protection that is considered economically feasible for a country.

2.4.3 Shoreline erosion and stabilisation

As was demonstrated by the Dutch worldwide survey of coastal inundation, low coasts of variable sedimentary composition and morphology dominate the statistics. They consist of sandy, rocky or muddy substrates, supporting various types of vegetation such as marshes, mangroves and meadows. Erosion processes are variable and as a result are difficult to predict. Apart from direct inundation, and the impacts on human safety and agricultural productivity, there is the perpetual issue of barrier island stabilisation from the erosive forces of wind, waves and storm surges.

Because of human habitation on inherently hazardous shores, primarily for recreation and aesthetic enjoyment, society has taken actions to stabilise these highly mobile shores through various protective measures that include periodic beach nourishment, groins, breakwaters, bulkheads and riprap. One of the most important aspects of shoreline management is the stabilisation of inlets and navigation channels that are needed for recreational boats as well as for commercial navigation, including fishing fleets.

Barrier islands and classical sandy coast-lines apparently account for a very small proportion of the total shoreline subject to inundation due to projected sea-level rise according to the Dutch survey. Much of the research and literature on shoreline stabilisation issues deal with the highly mobile, dynamic processes associated with these beaches. There is still considerable debate in the literature regarding the origin and fate of barrier beaches under conditions of sea-level rise. The general consensus is that in response to sea-level rise, barrier islands tend to migrate landward as storms wash sand from the ocean side to the bay side. This overwash process may enable barrier islands to keep pace with an accelerated sea-level rise (Leatherman, 1982). However, there is also a belief that these barrier islands will either disintegrate or will merge with the mainland, if the rate of sea-level rise is rapid.

The lagoons and embayments behind barrier islands and spits provide natural sheltered harbour. In their natural conditions, the tidal inlets between barrier islands migrate along the shoreline, whereas when stabilised by jetties, they are fixed in position to provide the essential and reliable navigation channels (National Research Council, 1987). In some bays and inlets, the tidal transport of sediment creates shallow delta, depositing the sediment load either on the seaward side of the bay entrance (on the ebb-tide) or on the bay side (on the floodtide). Consequently, as sea-level rises, the volume of these shoals will increase correspondingly, and the elevation of these deltas will grow in elevation to keep up with the rising sea-level.

The shoreline stabilisation implications for the downdrift beaches are clear. Ebbtide deltas will become ever greater barriers to downdrift longshore transport of sediment, causing greater erosion downstream of the inlets. Unless there are sand bypass technologies available, the rate of erosion would be greater than that expected by sea-level rise (National Research Council, 1987).

The costs of navigation channel and tidal inlet maintenance, through dredging, sand bypassing, and construction ofjetties, will increase at a greater than linear rate. This is because some of the sediments are polluted and the costs of dredged material disposal have increased sharply over the past decade as a result of a variety of stringent environment regulations in many developed countries.

2.4.4 Examples of sea-level rise impacts on particular regions

The Mediterranean The Mediterranean region has about 46,000 km of coastline, 75% of which is found in four countries - Greece, Yugoslavia, Italy and Turkey (Telegersma and Sestini, 1989). More than 50% of the coast is rocky, the rest being considered sedimentary (Baric, 1989). Tourism comprises a large part of the economy of these countries: over 100 million visitors annually in 1984. Tourism associated with beaches and recreational navigation would be most adversely affected in the European Mediterranean, because many of the beaches are small pockets fringed by rocky coastlines.

Venice, Italy Since 1890, relative mean sea-level in Venice has risen by about 25 cm. The mean number of floodings has increased over that period from 10/yr to 40/yr (Sbavaglia et al., 1989). In terms of damaging effects, the increased flooding is equivalent to increasing the frequency of 'normal' floods, as well as that of rare floods, although no statistical evidence has shown that the frequency of storms has increased. Further rises in sea-level will only exacerbate the problem.

Egypt A i m rise in sea-level would extend inland over 30 km south of the city of Alexandria, which is a highly industrialised city. Furthermore, erosion and accretion patterns along the Mediterranean coast of Egypt would change significantly, affecting the important tourist, recreational and economically developed areas (El Raey, 1989).

Poland Poland has a 493 km long coast on the Baltic sea, which consists of alternating cliffed (105 km) and barrier beaches (373 km). The coast is relatively low lying. Almost 3000 km^2 lies below an elevation of +2 m (mean sea-level), with a total population of 405,000 in this low-lying zone that would be seriously threatened by a 1 m rise in sea-level (Rotnicki and Borowka, 1989). The recession rate is estimated to be 2.3 m/year.

In the Odra River valley, a sea-level rise of 0.5 m will have a direct impact on a floodplain 3-4 km wide and extending 50 km upstream, and a corresponding increase in the salinity of surface and groundwater. (Rotnicki and Borowka, 1989).

Ivory Coast The Ivory Coast has 550 km of low barrier beach shoreline which is fringed with 350 km of lagoon covering about 1200 km^2. Approximately 3 million people out of a total population of 10 million live along the coast and derive their livelihood there. A large portion of the sandy shorelines is being eroded at a rate of 1-2 m/year (Kaba et al., 1989). Increased sea-level will accelerate the shoreline recession rate.

Ghana The Ghanaian coastline stretches for approximately 550 km and suffers from severe erosion, which would be accelerated by sea-level rise. Many towns and villages have been retreating from the large rate of coastal recession. Flooding has been a major problem for many of the villages, disrupting daily life and the means of subsistence which is dependent on agriculture and fisheries.

Argentina The Argentine coasts exhibit a diversity of coastal geomorphic features, with different tidal and wave regimes. Of the 5000 km of coastline, especially severe erosion occurs in the Province of Buenos Aires, with a coastline of 1800 km and 40% of the country's population. Coastal floods are severe on the shores of the Rio de la Plata. Coastal recession in some sections of the shore exceed 5 m/yr (Schnack et al., 1989) and is expected to continue.

Guiana Coast, South America The Guiana coast (Guyana, Surinam and French Guiana) can be designated as a low-lying chenier plain, much of which would be inundated by a sea-level rise of 30 cm. More than 90% of the population of the Guiana coast lives in the coastal plain. A i m rise in sea-level would cause the coastline to retreat 2-5 km, causing large-scale disruption in urban and agricultural areas (Daniel, 1989).

Australia Australia's coastline is dominated by sedimentary deposits composed of sand (16,000 km^2)

and mud (6500 km^2). In addition, there are hundreds of deltas, bays, estuaries and offshore islands that would be vulnerable to rising sea-levels (Prime Minister's Science Council, 1989). Australia's Great Barrier Reef and the reef complexes of western Australia are active coral communities which could be threatened by the rate of sea-level rise in the high scenario.

China A im rise would flood or destroy most salterns and seawater breeding farms. Reconstruction will require 5000 km^2 of land. Nearly half of the Pearl River Delta would be inundated, along with the more developed areas of the Yangtze and Yellow Rivers. There will also be other widespread impacts on housing, transport, and food and water supply (Ruqiu, 1990).

Soviet Union The Soviet Union is a nation with a great diversity of coasts and there are varying directions and amounts of vertical movement of local land masses. Thus, even though the overall amount of change for the nation is an increase of 1-2 mm per year (similar to that observed for the world), the local impacts will vary considerably. This is particularly so because there are periodic changes in sea-level of 5, 7, 10, 12, 20 and 22 years for different areas of the Soviet Union, thus compounding the impacts on areas that are in a natural period of increasing sea-level (Goskomgidromet, 1990).

3 The ecological and socioeconomic impacts of climate change on the world ocean

3.1 Introduction

The earth's climate is directly influenced by the ocean-atmosphere system. The two continuously interact. The World Ocean plays a deciding role in the turnover of water and $C0_2$ as well as in the biogeochemical cycling of all the most important biogenic elements.

Because of this, the predicted global climate warming (for the middle of the next century) will have an appreciable effect on the state of the World Ocean and, consequently, on the nature of its effects on human kind. The magnitude and direction of such an effect may differ significantly between the open ocean and coastal zones. Possible physiochemical, ecological and socioeconomic consequences will be determined by the specific character of the function of marine ecosystems, their regional peculiarities and their role in the world and national economies.

A whole complex of scientific methods and approaches is necessary to assess the impact of global climate warming on the World Ocean. Data from the GCMs of the coupled ocean-atmosphere system, and the global CO_2 cycle, results of palaeooceanographic investigations, analog comparisons, analysis of ecological observations and economic estimates were used in this report.

An analysis was conducted of possible changes in the physiochemical parameters of the ocean environment and their influence on the biological and ecological characteristics of marine ecosystems on global and regional scales.

Socioeconomic consequences were assessed on the basis of the expected changes in the state of fisheries in the open ocean and coastal zones using historic analogs.

As a whole, comprehensive assessment of the effect of global warming of the World Ocean and its coastal zones will contribute to forecasting the development of human civilisation in new climatic conditions, as well as planning the system of adaptive options.

3.2 Impact on physiochemical processes

3.2.1 Impact of global warming on the heat budget and water circulation of the World Ocean

A key problem in forecasting possible changes in all fundamental natural processes under changed climatic conditions is assessing the impact of global warming on the heat budget and water circulation of the World Ocean. Because changes in the composition and circulation of the atmosphere affect the processes occurring in the ocean and, vice versa, it is necessary to consider the function of the ocean-atmosphere system in conditions of the development of the greenhouse effect to resolve this problem.

One of the most promising methods to investigate the sensitivity of the climatic system to the gaseous composition of the atmosphere is the performance of numerical experiments with the use of the numerical GCMs of the coupled ocean/atmosphere system (Manabe and Stouffer, 1980; Schlesinger, 1986). Using these models, it is possible to predict a change in the temperature regime of the lower atmosphere and the surface layer of the oceans.

Among the coupled ocean-atmosphere GCMs, those of the Oregon State University (US) (Ghan, 1982; Schlesinger and Mitchell, 1987), the Goddard Institute for Space Studies (US) (Hansen et al., 1983, 1988), the Geophysical Fluid Dynamics Laboratory of NOAA (Princeton, US) (Manabe and Wetherald, 1980, 1987) and the National Center for Atmospheric Research (US) (Washington and Meehl, 1989) include most of the principal factors influencing the coupled circulation processes.

The basic parameters studied in all these models are: sea surface temperature, average surface wind speed, solar radiation flux, total cloudiness, sea-level pressure and evaporation. In each model, the ocean is considered as a simple mixed layer; ice cover and its melting are also included. However, none of the published coupled ocean-atmosphere GCMs has a satisfactory treatment of sea ice or deep ocean circulation. A chronic problem in these models has been a too large ice extent and too weak thermohaline circulation in the northern North Atlantic and its connection to the Arctic Ocean (Bryan, 1986; Washington and Meehl, 1989). In their present state of development, the global climate models are unable to capture some of the possible feedbacks that may occur in the ice-ocean system as a response to atmospheric warming.

Results of numerical experiments with these GCMs show a good qualitative agreement in the basic trends for thermal budgets of ocean and atmosphere under conditions of doubled atmospheric $C0_2$. However, significant differences exist in the quantitative estimates. According to these calculations, the warming of the lower atmosphere by 1.3°-4.2°C should be expected, with a more intensive warming on the land than on the ocean. Comparable sea surface temperature increases will vary from 0.2° to 2.5°C. Increased precipitation should also be expected, especially on the eastern edges of the continents. Analysis of the seasonal dynamics of the temperature field for all four models has pointed to the maximum warming occurring in winter in arctic and antarctic regions.

The predicted warming trend in arctic and subarctic regions is significant. An intensive warming in polar latitudes will reduce the meridional (north, south) gradients of sea surface temperature and, consequently, will lead to a decrease in the trade wind intensity and in the power of ocean currents (Mitchell, 1988). This, in turn, could lead to a reduction in the area and intensity of ocean upwelling, such as in the equatorial eastern tropical Pacific.

On the other hand, GCMs predict that increases in temperature gradients between the strongly heated land mass and the cooler ocean can drive a competing mechanism by intensifying the along-shore wind stress on the ocean surface. This process would be accompanied by acceleration of coastal upwelling This is confirmed by present-day natural observations of upwelling dynamics (Bakun, 1990). These data from widely separated areas of the world suggest that the equator-ward along-shore wind stress has been increasing during the respective upwelling seasons of the past 40 years.

It is likely that both upwelling mechanisms could take place under conditions of global warming, but the dominance of one or the other mechanisms will be determined by the proximity to land (eg eastern boundary current regimes) or the open ocean (eg the North Pacific Equatorial Counter-current). Upwelling is likely to intensify in coastal regions, whereas oceanic upwelling may weaken. These subtle, but large-scale, changes have profound impacts upon the fisheries as well as on the climate of the immediate coastal zone.

Apart from the impact on the water circulation in the World Ocean, a warming in arctic and antarctic regions may have a significant influence on the state of the earth's cryosphere (glaciers and shelf and sea ice). Such changes will in turn further affect the global climate. First, sea ice, covering 11% of the world's ocean surface, affects internal ocean and ocean-atmosphere thermal exchange. These factors determine the intensity of convection in the ocean which characterises the mean time scale of processes occurring in deep ocean layers (for example, $C0_2$ uptake). Therefore, changes in the extent of sea ice will have an effect on atmospheric circulation and temperature. Also, open ocean waters absorb much more solar radiation than do those which are ice covered (Walsh, 1983). Second, even small changes in the earth's cryosphere could lead to a noticeable deviation of global sea-level from its recent average value. The predicted warming for the Arctic will lead to significant reduction in sea-ice extent around Svalbard, and along the north Siberian and Canadian arctic coasts. At the same time the projected rise in temperature for the period up to the middle of the 21st century is not expected to lead to a significant decrease in the amount of ice volume in the massive ice caps of Greenland and Antarctica. In fact, a recent study in the Northern Hemisphere has shown that despite a small increase in mean annual temperature, the extent of ice has increased in the most recent decade (Bryan et al., 1988). The predicted rise of temperature by 4°-5°C by the middle of the 21st century (Mitchell, 1988) might lead to acceleration of the ice flow from the continent into the ocean in west Antarctica and lead to decrease in ice cover in the Arctic (Budyko and Izrael, 1987). Owing to melting sea ice in the Arctic, freshening of surface waters in the North Atlantic would occur, interfering with bottom water formation. This process might affect the northward heat flux and cross-equatorial heat transfer (the so-called 'conveyor belt' (Broecker et al., 1985)), which could cause a shift in global ocean circulation (Broecker and Peng, 1990; Bryan, 1986). The consequences of such major changes in ocean circulation would be enormous in terms of regional climate and biochemical cycling. A major international program, the World Ocean Circulation Experiment (WOCE), is now under way to study this question.

3.2.2 Changes in the carbon cycle

The predicted increase of CO_2 in the atmosphere by the middle of the next century could lead to disturbances in the global carbon cycle and, as a consequence, could have strong feedback to the earth's climate system. To assess the impact of such an anthropogenic increase of CO_2 in the atmosphere and of resultant changes in the global carbon cycling on the World Ocean, it is necessary to improve our understanding of the cause-and-effect relationship of past natural CO_2 variations.

Measurements of gases trapped in polar ice cores (Barnola et al., 1987) convincingly demonstrated that the concentration of atmospheric CO_2 was subject to several dramatic natural changes which paralleled and possibly slightly preceded the major climatic fluctuations. Since the ocean contains about 60 atmospheric carbon units (Sundquist and Broecker, 1985) such changes, to a great extent, must be tied to the ocean. The 'biological pump' transfers CO_2 across the thermocline into deep water via photosynthetic marine organisms which incorporate gaseous CO_2 into carbonaceous compounds. The combined variations in the 'biological pump' process and in the chemistry and physical circulations of the ocean, could provide the dominant forcing of the observed changes in atmospheric CO_2 (Siegenthaler and Wenk, 1984). In this context, numerous models have been proposed and examined (Sundquist and Broecker, 1985; Meir-Reimer and Hasselmann, 1987; Mix, 1989).

One important result of such model experiments, using data from ocean palaeoproductivity estimates, is that changes in coastal and equatorial upwelling may in part control atmospheric CO_2 (Sarntheim et al., 1988; Flohn, 1982). Recent studies have shown that this factor alone cannot explain the whole amplitude of natural variations and that a major role for controlling atmospheric CO_2 levels is played by the ocean alkalinity which determines the solubility of CO_2 in ocean water. Alkalinity variations appear to be triggered by changes in deep water formation in the high-latitude North Atlantic (Boyle, 1988; Broecker and Peng, 1990).

According to Takahashi's estimates of CO_2 source/sink regions in the World Ocean (Takahashi, 1989) the most intense source of CO_2 is the equatorial Pacific and the most intense sink is the subantarctic belt, 40°-55° S. Coastal and equatorial upwelling regions are carbon sinks because of their productivity, but are net sources of CO_2 due to outgassing of CO_2-enriched waters, which overpowers the carbon transfer by productivity.

Furthermore, increased dissolution of carbonates due to the acidification of sea water by an increase of CO_2 would lead to higher alkalinity and therefore higher CO_2 uptake capacity of the ocean (Boyle, 1988). Enhanced burial of organic matter in ocean sediments due to increased nutrients influx would promote the sequestering of CO_2 from the atmosphere (Siegenthaler, 1989). Lastly, arctic/subarctic seas are also significant sink areas for anthropogenic CO_2 (Roots, 1989).

Expected changes in the carbonate system and in the transport of particulate organic carbon from surface into deep ocean layers will greatly affect the marine biota. For example, recent results have suggested that the dissolution rate of shells of some mussels may be significantly higher than hitherto assumed (Betzer et al., 1984).

In conclusion it should be noted that increasing CO_2 in the atmosphere could lead to disturbances in the global carbon cycling. The direction and magnitude of such changes will be determined to some extent by the functioning of upwelling ecosystems and changes in oceanic carbonate systems under the conditions of global warming.

A major international program, the Joint Global Ocean Flux Study (JGOFS) has been set up under the auspices of the ICSU-sponsored Scientific Committee on Oceanic Research (SCOR) for the decade 1990-99. Its main purpose is to investigate the flux of carbon in the ocean and the extent to which the oceans may affect climate change by exchanging CO_2 with the atmosphere.

3.2.3 Changes in nutrients

In highly industrialised regions, such as the North Atlantic community, increased discharge of anthropogenic gases and aerosols containing compounds of nitrogen, phosporous and sulphur into the atmosphere, results in increased fluxes of these substances from the atmosphere into the ocean (Oppenheimer, 1989). This process could be of great importance for nitrogen and sulphur, the atmospheric inputs of which to the photic zone of the ocean (at least for the Sargasso Sea and the equatorial Pacific) are comparable to diffusive convectional inputs (Duce, 1986). Marine biota may respond to these changes in nitrogen and sulphur contents with increased productivity, especially in impacted areas of the ocean. Such processes are already observed in the North Sea (Lancelot et al., 1987).

Sea-level rise, followed by flooding and erosion of soil, could lead to substantial increases in the flow of nitrogen, phosphorous and sulphur into the coastal zones, creating the potential for severe eutrophication. The consequence will be an acceleration of biochemical cycling of all biogenic elements (Oppenheimer, 1989). In turn, the increased cycling could cause a rise in the productivity of adjacent nutrient-poor ecosystems, particularly the so-called 'oceanic deserts'. However, whether or not nutrient supplies and productivity would actually increase as a result of increased wetland and sediment erosion from sea-level rise appears to be dependent on regional conditions. For example, in the Beaufort Sea, eroding peat from the tundra may be an important source of organic carbon for the coastal food chain, but in warmer water, such as the gulf of Mexico, where the biodegration and nutrient recycling rates are higher, the eroding nutrient and organics may not provide a significant contribution to the overall flux of materials. Rather, the relationship of increased fishery yield with wetland degradation in warmer waters may be more plausibly related to increased wetland-saltwater interface, affecting habitat dimensions (Condrey, 1989). This phenomenon has been observed, at least for the short term, in the Gulf of Mexico (Zimmerman et al., 1989). Oxygen depletion also occurs in association with increased eutrophication, especially in estuarine and deltaic regions adversely impacting all higher life forms.

If, as suggested by GCMs, some mid-latitude continental areas will become more arid, then fewer nutrients would flow through river systems to estuarine areas (Glantz, 1989) although the reduction in nutrient may not be proportional to reduction in precipitation and river discharge. Loss of nutrients could have an adverse effect on fish populations and decreased river discharge would affect some organisms which depend on fresh discharges for spawning. River systems of this type might include the Mississippi (US) and the Nile (Egypt) (Condrey, 1989,). On the other hand, precipitation and runoff are expected to increase in'most high-latitude continental areas, thereby increasing the volume of nutrients delivered to subpolar continental shelf areas.

The reduction or displacement of salt marshes and littoral zones as a result of sea-level rise could lead to a sustained loss or disturbances of habitats of marine plants which synthesise dimethylsulphide (DMS) (Holligan and Kirst, 1989). DMS is the most important component of the global sulphur cycles and could be a major source of cloud condensation nuclei over the oceans (Charlson et al., 1987; Griffin, 1988) with consequent influences on global albedo and climate.

The subgroup takes note of the discussions on the feasibility of fertilising the oceans with iron which would be carried to appropriate iron-deficient zones by vessels. The idea is to increase primary production, leading to removal of some CO_2 from the atmosphere and is based on the work of Martin (1990). We urge full consideration of ecosystem impacts and strong caution in these discussions.

3.2.4 Changes in contaminants

A rise of temperature will result in the acceleration of biodégradation of global organic pollutants (petroleum and chlorinated hydrocarbons etc). This process would promote their removal from the photic zone of the ocean (Izrael et al., 1990; Tanabe, 1985) On the other hand, sorption of these compounds on suspended matter may decrease as a result of higher temperature, which will lead to less deposition of these pollutants in the bottom sediments (Pierce et al., 1974). As a consequence, it could increase the 'residence time' of the pollutants in ecosystems.

The increase of UV-B radiation intensity (as a result of depletion of the atmospheric ozone layer) will increase the intensity of photochemical processes, particularly at the air/sea interface (Zika, 1989). This factor would accelerate the photo-destruction of polychlorinated biphenyls (PCB) and polyaromatic hydrocarbons (PAH) and, as a consequence, reduce this type of pollution in sea water (Doskey and Andren, 1987). But at the same time, increased penetration of solar UV-B radiation itself can have widespread adverse effects on life in the open ocean and wetlands. (US EPA, 1987).

The increased concentration of atmospheric CO_2 could probably cause some acidification of surface waters (Wilson and Mitchell, 1987). The process will not influence the behaviour of organic hydrophobic contaminants, but it could be rather significant for ionogenic compounds. The assciated decline in pH could enable the enhanced penetration of organic ionogenic compounds through cell membranes and, correspondingly, the increased accumulation of pollutants in hydrobionts (Landner, 1989). Furthermore, the enhanced acidity may decrease the stability of the complexes of heavy metals with humic substances (Paxeus, 1985; Mantoura and

Riley, 1975). The process may be accompanied by an increased toxic impact on marine organisms (Sunda and Lewis, 1978; Sedlacek et al., 1983).

3.3 Ecological impacts

Physical-chemical parameters are the primary determinants of the distribution of marine habitats, communities, and ecosystems. A change in these parameters (described above) will have broad impacts on basic ecological structures and processes. These changes will, in turn, cause impacts on marine and coastal resources.

3.3.1 Changes in habitats

The predicted temperature rise of surface waters and a change in the ocean circulation would substantially impact on the structure and location of marine habitats. However, marine organisms, as a rule, have rather high genetic and behavioural plasticity, allowing them to adapt to constantly changing environmental conditions. This property is a basis for the relative stability of zoogeographical patterns under the conditions of natural climate variations (Odum, 1986).

Under the present scenario for anthropogenically-influenced climate change, a general global warming is postulated, causing poleward spreading and deepening of warm oceanic waters. The response of biological communities will, in general, reflect poleward translocation to new optimal habitat. However, some life forms that are relatively immobile or are genetically less adaptable may be threatened with extinction if the rates in the worst-case scenario are realised (Sharp, 1989).

Global warming could have especially strong impacts on the regions of sub-polar fronts (Roots, 1989) where the temperature increase in deep water could lead to a substantial redistribution of both pelagic and benthic communities, including commercially important fish species. At the same time, a similar temperature rise in tropical latitudes would not affect greatly the functioning of marine organisms.

However, the distribution of biological populations, as well as their abundance, appears often to be more related to the dynamic physical processes that control various patterns in the ecosystem than to the direct effects of temperature itself (Bakun, 1990). For example, recent empirical results (Cury and Roy, 1989) indicate that reproductive success of pelagic fishes in upwelling regions mostly depends on wind stress.

As a result of changes in the ocean and coastal zone, there may be impacts on biodiversity. In the open ocean, the effects on biodiversity will likely be less than those expected in the estuaries and wetlands. The oceanic ecosystems will be relatively free to move to new geographic areas while the near-shore ecosystems are more constrained by the physical features of the shore. With regard to the coastal ocean, the effects of changing freshwater inputs as a result of changing precipitation patterns, and the consequent impact on estuarine habitats, circulation, and nutrient and sediment supply warrant consideration. It is important to keep in mind the dynamics of shelf-water masses are influenced by meteorological forcing in addition to upwelling, as classically defined. In warm temperate and sub-tropical regions (eg the southeast US and Gulf of Mexico) cross-shelf transport, associated with frontal passages, is important to the transport offshore of eggs and larvae of estuarine-dependent species of fish and crustaceans. Thus, meteorological forcing influences shelf-water mass stability and advection, which in turn has important biological and geochemical consequences.

In summary, global warming may cause considerable changes in the structure and distribution of marine habitats, thereby greatly impacting on the structure and operation of world fisheries.

3.3.2 Changes in production/destruction processes and biosedimentation

To assess possible consequences of the effect of global warming on the productivity of oceanic ecosystems, it should be taken into account that 45% of the annual primary production of organic matter in the World Ocean is synthesised in the upwelling zones and high-latitude regions, and 20% is in near-shore waters (Koblents-Mishke et al., 1970; Sarnthein et al., 1988). Hence, the productivity of the global ocean in the new climatic conditions would be first of all determined by the changes in functioning of the ecosystems of those highly productive regions.

Current forecasts of the possible changes in ocean productivity are mainly based on the outputs of GCMs and the result of palaeoclimatic reconstructions.

GCM outputs indicate that climate warming causes a decrease in meridional temperature gradients (Schlesinger, 1986; Mitchell, 1988), as well as a general weakening of oceanic upwelling. Numerous palaeoclimate studies have estimated past productivity that tends to confirm the GCM results. According to these studies, the productivity of oceanic upwelling regions during glacial periods was much higher than during interglacial periods (Sarntheim et al., 1987; Sarntheim et al., 1989; Lapenis et al., 1990). All of these studies indicate that global warming should be accompanied by a fall of productivity in upwelling regions and, thus, a decrease in total productivity of the global ocean (Budyko and Izrael, 1987; Lapenis et al., 1990).

The mechanisms just discussed deal primarily with the open reaches of the global ocean. However, as previously noted in Section 3.2.2, the predicted intensification of the coastal upwellings would tend to enhance primary organic production in these systems. But whether this increased primary production would be channelled to trophic components that society particularly values is unclear. There has been little clear demonstration that increased primary production actually promotes reproductive success and population growth of commercial fishes. (Bakun, 1990). Consequently, conclusions about compensatory changes in total ocean productivity under the present scenario cannot be made on existing information.

Apart from tropical and mid-latitude regions where productivity is mainly determined only by the contents of nutrients, the basic limiting factors in polar and subpolar regions are light and temperature. A rise of mean temperature of high latitudes will lead to an increase in the duration of the growing period and ultimately in the bioproductivity of these regions.

However, the predicted rise of water temperature will be accompanied by an increase in the rate of degradation of organic matter, especially in subpolar waters as well as in shelf waters and the surface layer of the boreal zones by 1.1 to 1.3 times (Odum, 1986; Izrael and Tsyban, 1989).

Biodégradation rates in the surface layers in low latitudes are determined by the inflow of organic matter from sub-polar regions through meridional transport of intermediate and deep waters. In this connection, elevated temperatures are expected to increase biodégradation rates. However, the overall amount of low-latitude biodégradation may not be changed significantly.

According to Suess (1980) the amount and the rate of biosedimental flux would increase with an increase in productivity. So, taking into consideration the predicted changes in production/destruction processes the enhanced biosedimental flux is expected in the coastal upwelling zone (Bakun, 1990). At the same time, increased production in subpolar regions does not appear to be accompanied by raising of the biosedimental flux due to intensive microbial degradation.

Increased anthropogenic pollution in the global oceans is expected to affect the rate of production of organic matter. According to the estimates, the quantity of the contaminants in the photic zone of the ocean would have increased by 25-30% by the middle of the next century (Izrael and Tsyban, 1989). Besides, the warming of the sea water followed by the acceleration of chemical reactions could lead to the strengthening of toxicity of the contaminants to marine biota. This process would negatively affect the productivity of oceanic ecosystems (Tsyban et al., 1985; Patin 1979).

In conclusion, it should be noted that primary production does not necessarily equate with fishery production. Nevertheless, under conditions of global warming, changes in the centres of primary production could lead to changes in the distribution patterns of commercially important fish stocks and the recruitment of fish resources.

3.3.3 The role of ice in supporting polar ecosystems

Ice plays a major role in the development and sustenance of arctic and subarctic ecosystems: (i) it plays a significant role in the growth of marine algae (the primary source of food for the marine ecosystem), (ii) it creates a productive environment at the ice/water interface, allowing plants to grow and, in turn, supporting abundant and diverse communities, and (iii) it supports organisms which form a link in the transfer of energy between primary production (algae and phytoplankton) and fish, sea birds and mammals.

One of the possible consequences of global warming would be to reduce the extent and persistence of sea ice, affecting the production regimes and ecosystems accordingly. For example, the absence of summer ice over the continental shelves of the Arctic Ocean would radically increase the productivity of affected areas, given an adequate supply of nutrients.

Polar mammals use ice in particular ways to support their feeding and reproduction needs. For example, the range of polar bears is determined by the maximum seasonal extent of sea ice in any one year and clearly, without ice, the very existence of polar bears and also some seals would be threatened. Similarly, a reduction in ice would be expected to have a significant effect upon the feeding, breeding and resting activity of penguins and walruses and they would be very vulnerable to hunting and predatory pressures. If ice is reduced, other animals, such as the otter, would move into new territories. It is not clear how the migratory patterns of animals, such as whales which follow the ice edge, would be affected by changes in ice distribution.

Changes to water temperature and wind regimes as a result of global warming would also probably affect the distribution and characteristics of polynyas (ice-free areas) which are so vital to the polar ecosystems. Also, changes in the extent and duration of ice, combined with changes in characteristics of currents, for example the Circumpolar Current in southern latitudes, may affect distribution, mass and harvesting of krill. Krill is an important link in the food chain of southern ocean fauna and an economically important fishery. It is important to understand how and where the Southern Ocean productivity will change under global warming processes.

3.3.4 Regional aspects of the problem (the Bering Sea as an example)

It is predicted that high latitudes would be profoundly influenced by global warming (Roots, 1989). There could be marked changes in the functioning of sea ecosystems. Thus, it is necessary to summarise the results of modern ecological observations of the state of sub-polar and polar ecosystems with the aim of having an earlier understanding of the effects of global warming.

The Soviet-American long-term research study (Programme 'Bering Sea', Project 'Comprehensive Analysis of the Environment') has produced a large amount of information about the functioning of the subarctic ecosystem of the Bering Sea.

Under conditions of global warming in the region of the Bering Sea, according to the predictions of GCMs, the shift of the sea surface isotherms towards the North Pole could occur (warming by 0.5°C for a decade could be followed by the shift of more than 50 km) (Hansen et al., 1988). Such a temperature shift would lead to an increase in the area and duration of the ice-free season, which would in turn increase the growing season (Roots, 1989), thereby further enhancing the productivity of the Bering Sea ecosystem.

According to current estimates, the mean value of primary production in the Bering Sea is 0.65 g C/m^2 per day reaching in some areas 7 g C/m^2 per day, (Izrael et al., 1986; Whitledge et al., 1988; McRoy and Goering, 1976). With the expected creation of more favourable conditions for marine biota, the mean value of primary production could rise to 0.75-0.90 g/Cm^2 per day. Taking into account that, at present, the mean value of the microbial degradation of organic substances in the Bering Sea is 0.3 g C/m^3 per year (Izrael et al., 1986; Whitledge et al., 1988), the predicted intensification of these processes under conditions of global warming in subpolar regions could lead to raising the magnitude up to 0.35-0.50 g C/m^3 per year.

The expected acceleration of the microbial and photochemical processes, followed by the increase of the destruction of organic contaminants, could cause some decrease of the anthropogenic pollution of the ecosystem (Izrael et al., 1990).

The acceleration of the production/degradation processes would lead to the intensification of the biogenic sedimentation. Also, some increase in biosedimental flux would be possible. It is estimated that 1.6 x $10^8$1 C per year is deposited in sediments of the Bering Sea (Izrael et al., 1986). This could be taken as a minimum one of the carbon flux fiom atmosphere to the seawater, since 53 x 10^8 t C per year is estimated as the general flux of carbon from the atmosphere into the World Ocean (Odum, 1986). These results confirm the importance of subarctic ecosystems for global biogeochemical carbon cycling.

One of the most important consequences of the global warming could be the shift of the subarctic front into the Bering Sea, which would lead to abrupt changes in habitats of pelagic and benthic communities, including many valuable fish species. Because the Bering Sea is an important fisheries region for several countries, where annually 3 x 10^6 t of fish is caught (Wilimovski, 1974), it is necessary to foresee the possible negative consequences of a warming climate in this region for the distribution and recruitment of the main commercially important species and for marine mammals and birds. The creation of forecasts for living marine resources under conditions of global warming would promote development of effective systems of adaptive options.

3.4 Palaeoecological studies and El Nino analogs

GCMs still lack the specificity to predict ocean currents and upwelling accurately. However, the palaeosedimentary record is available through analysis of sediment cores and can demonstrate how ecosystems changed in the past when the earth was warmer. This could improve understanding of the cause-and-effect relationships and possible feedback loops during times of rapid climate change.

Recent investigations of palaeo-productivity of the World Ocean, based on organic carbon accumulation rates (Sarnthein et al., 1987) have shown that the basic spatial distribution patterns of ocean productivity persisted through glacial and interglacial times. However, the ocean in glacial times was characterised by a more polarised productivity pattern than today, that is, by more productive upwelling cells and a slightly less productive ocean. This regime induced a bulk increase in the global carbon transfer to the deep ocean by about 2-4 GtC/yr and led, via an enhanced $CaCO_3$ dissolution and alkalinity in the deep ocean, to a significant extraction of CO_2 from the surface and intermediate waters and the atmosphere.

According to data from empirical palaeoproductivity curves from the east Atlantic (Sarnthein et al., 1988), this increase, to a large extent, was linked to enhanced carbon export from pulsating plankton blooms and resulted from a strong intensifying of oceanic upwelling in middle and low latitudes. It is confirmed by other palaeoecological analyses of zonal sea surface anomalies that show the average intensity of wind-driven coastal upwelling along the northeast Atlantic continental margin increased by at least 50% during the last Glacial Maximum (Lapenis et al., 1990; Sarnthein et al., 1987).

The interglacial reduction in bioproductivity of upwelling regions is one of the main factors leading to both the simultaneous rise in atmosphere CO_2 as recorded in ice cores and, with a delay of more than 1000 years, to a large-scale gradual CO_2 depletion of the deep ocean. This conclusion is based on the benthic carbon isotope record of CO_2. The decrease in new production matches a clear 13C depletion of organic matter, possibly recording an end of extreme nutrient utilisation in upwelling cells (Sarnthein et al., 1988). Based on these results and prognostic estimates of GCMs, Lapenis et al. (1990) predict a decrease in productivity of upwelling zones and, consequently, of the whole ocean under conditions of global warming.

In the Pacific Ocean the El Nino phenomenon is the dominant interannual climate signal. Thus, it has immense consequences in the Pacific and also in other parts of the world. Consequently it is important to know what will happen to this dominant short-term phenomenon under the postulated conditions of long-term global warming. El Nino is an oscillatory ocean-atmosphere interaction process, which exhibits maxima recurring at intervals of 2-10 years with extremes occurring at about 30 years. It is caused by disturbances in the global atmospheric circulation system. The spreading of warm waters from the north to the south along the coast of South America is accompanied by a rise of sea surface temperature of 5°-8°C, strengthening of water mass stratification and, consequently, by a sharp weakening of the intensity of coastal upwelling. These processes lead to mass development of the organisms of 'red tides' (dinoflagellates and symbiotic bacteria), changes in the series structure of the phytoplanktonic community, a sharp reduction of productivity in the coastal zone, mass mortality of fish and birds feeding on them, as well as to secondary contamination of the ecosystem with organic matter. Economic damage for the region is estimated at hundreds of millions of dollars.

Furthermore, evidence is mounting for teleconnections between El Nino and worldwide climate anomalies having the same characteristic periodicities (Glantz, 1984). These climate anomalies can be traced in all kinds of global palaeo-climate records, such as: varied sediments, coral records and tree ring cores.

Studies using ocean/atmosphere models, the low cadmium content in 400-year-old coral records (Shen et at., 1987) and tree ring analyses (Michaelson, 1989) indicate that the frequency and intensity of El Nino events since the little ice age (AD 1500-1850) were not too much different from those experienced in modern times. Hence, one can speculate that such frequency and intensity of El Nino phenomena will continue over the next 100 years regardless of the trend in global warming (Enfield, 1988).

3.5 Impacts on fisheries

Climate change is one of the most important factors affecting fisheries. The level of the impact varies widely and depends on attributes of the species as well as on their regional specificity.

Each population within a species is adapted to a hydrodynamic structure of specific temporal and spatial features. Changes in the ocean circulation may lead to the loss of certain populations, or the establishment of new ones, at the periphery of the species' area of distribution, in addition to changes in the location and absolute abundance of the population inside the boundaries of the species distribution areas (Troadec, 1989).

One useful approach to identify possible impacts is the method of historical analogs. It might be instructive to consider the biological consequences according to the decadal scale of warming that occurred during the first half of the present century. One of the most obvious consequences of that warming was the penetration of tropical and subtropical marine organisms into the temperate latitudes and the penetration of boreal organisms into the higher latitudes. This penetration was observed both in the North Pacific and North Atlantic; but warming impacts on the abundance of commercially important species can be either positive or negative, even for the same species, depending on region. For example, in the 1940s and 1950s, increased water temperature coincided with the largest year of biomass of Atlanto-Scandinavian herring, while at the same time the North Sea herring biomass fell to very low levels.

More recent fishery investigations in the North Atlantic have revealed clear climatic influences on growth, distribution and recruitment of commercially important fish stocks. For example, the 'seventies anomaly' (Rapp, 1984) brought about considerable impact on several fish stocks. This anomaly which started off East Greenland in the 1960s, propagated around Greenland and Labrador and into the North Atlantic Current, and reached the Barents Sea in 1979-80 (Dickson et al., 1984). In the late 1960s, this anomaly gave rise to extremely low temperatures in North Icelandic waters and was the probable reason for the change in summer distribution of the Atlanto-Scandinavian herring.

While these observations and others show consequences of fluctuations within a few years, it is likely that the impacts of a far more permanent change in temperature will be even more profound. A temperature rise of about 2°C may have substantial impact on the distribution, growth and reproduction of the fish stocks. The commercially very important fish stocks may take new spawning areas and their distribution patterns may change considerably.

In the Bering Sea, an increase was observed in pollock stocks in the 1970s and early 1980s. The high level of pollock stocks has been sustained despite the high levels of exploitation. This shows that the impact of climate may be manifested to a lesser degree in high productivity regions in the temperate and high latitudes such as the Bering Sea, than in less productive regions. Above all, in the most productive upwelling areas, the abundance of commercially important fish has remained at relatively stable levels (except for collapse of Peruvian anchovy in 1972-73).

Mariculture will also be affected by climatic change. Increasing near-shore temperatures resulting from the greenhouse effect could result in increased production of species in established higher latitude farming operations because of the prolonged availability of temperatures near to those optimum for growth. Cultivation of new species of temperate and subtropical origin could conceivably result as well. Finally a decrease in ice cover could substantially expand the geographic limits for potentially viable commercial operations for species such as salmonids, oysters and scallops (Frank et al., 1988). However, a significant increase in summer seawater temperatures in the Marlborough Sound in New Zealand, for example, may have serious implications for the salmon farming industry as these are already near the maximum for the successful cultivation of salmonids (New Zealand, 1989). For wild northern salmon, however, the strong homing instinct will prevent populations from southern areas which are warming up, from moving northward and they may finally disappear from different river systems as conditions become too severe for survival.

The impact of UV-B radiation is of concern because commercial and recreational species reside, during their very early life stages, in wetlands or in neuston, and/or feed on near-surface plankton during some life stage of their existence. Although most sea water may be relatively opaque to UV-B radiation, fish eggs and larvae that float close to the surface, as well as near-surface phytoplankton, zooplankton, corals and wetland plants, could be exposed to levels which will cause genetic abnormalities or direct mortality. Recent investigations have shown that UV-B radiation exposure could have a lethal effect on several marine species, including anchovy, shrimp, and crab larvae (Hunter et al., 1979). In connection with the expected increase in the intensity of UV-B radiation, there is a need for the full assessment of such effects on a population-wide basis for a number of vulnerable species.

3.6 Socioeconomic impacts

Changes in climate will alter the species composition and productivity of marine ecosystems supporting major fisheries. As a first approximation of the ability of societies to cope with changes in abundance and distribution of marine resources, one can look at the socioeconomic impacts of such changes in the recent past. Commonly cited examples of such changes include the collapse of the Peruvian anchoveta, the Californian sardine, the Alaskan King Crab, or the expansion of such fisheries as the Bering Sea pollock and the Chilean sardine. These provide important information about how societies have dealt with major changes (favourable as well as adverse) in fishery resources availability in the recent past. For example, as fish stocks have declined because of a combination of less favourable environmental conditions and overfishing, industries have often made the problem worse by continuing heavy fishing pressure, thus accelerating the collapse of the fishery. Frequently, industries as well as governments have been unwilling to accept the advice of scientists and take meaningful action to protect fish stocks. It is likely that global warming will produce collapses of some fisheries and expansions of others. The likelihood of collapse may be aggravated by inadequate management due to insufficient authority, unwillingness to act or lack of knowledge.

Fishery management is affected by shortcomings in the institutions for allocating scarce fish and by limited understanding of fish reproductive strategies with regard to environmental variability. If uncertainty with regard to the abundance of fish in the future is going to increase, regulatory institutions will have more difficulty in adapting. Many stocks will remain overexploited which is already the major cause of variability. On the other hand, improvement in the fishery management institutions will reduce variability as well as the adverse effects of equivalent changes due to global warming. There is progress on understanding fish and their environment. If the direction of potential changes in ocean circulation could be known, useful assumptions could be made on the likely changes in fish stock abundance and, hence, on fisheries management (Troadec, 1989). As an example of the interaction of fisheries, their environment and fishery management, the onset of a major El Niño event in 1972 coupled with overexploitation and apparent recruitment failure caused the Peruvian fishing industry to suffer a severe crisis in the following years (Caviedes, 1989; Barker and Chavez, 1986).

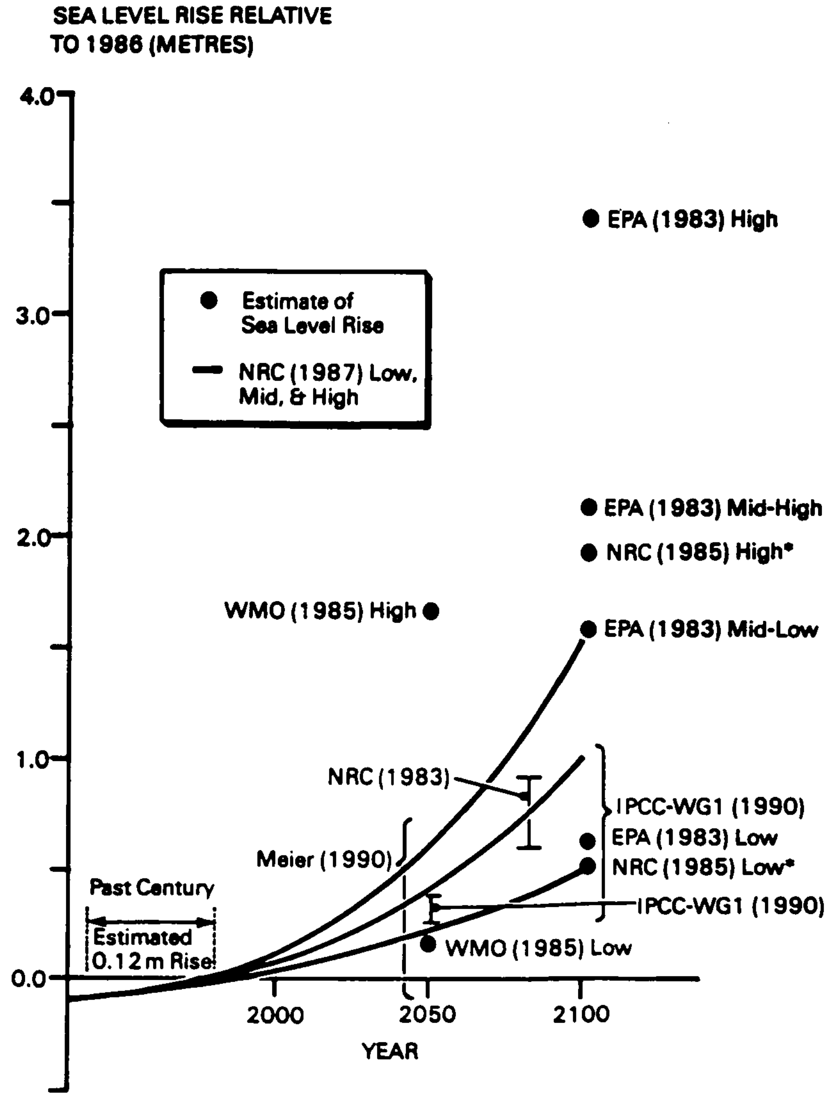
A major adverse impact occurs in societies having economies which are narrowly dependent on fishery resources and which are incapable of diversifying to other activities. This often is the case in developing countries bordered by major upwelling regions (eg Mauritania, Namibia, Peru, Somalia) (Troadec, 1989).

In general, societies have not coped well with changes in biological productivity, regardless of causes (natural or anthropogenic) (Glantz et al., 1987). Case studies of societal response provide insight into how people and their governments can better prepare for regional changes in distribution and abundance that might accompany global warming. If, in the face of climate change, it is desired to maintain fisheries at levels matching society's needs, higher levels of international collaboration might be needed, for which there, is no global analog from the past.

3.7 Impacts on navigation and territorial policies

At present, the northern ice-bound land borders of North America, Europe and Asia are highly sensitive national defence zones for all countries with Arctic territory. Security adjustments will be necessary if these coastal areas become navigable. National sovereignty issues regarding international fishing, hydroelectric power development, and freshwater transfers may be significantly altered. In the south polar region, warming may have implications for the future of the Antarctic Treaty which presently holds a number of territorial claims in abeyance. The possibility of climate-induced changes in access and prospects for resource development may result in altered national positions and competing claims. It is also recognised that the incidence of sea ice should decrease, providing benefits to navigation. Small sea-level rises may also **be** beneficial to port operations by enabling ships to **be** loaded to greater draught and still clear restricted channels. Transportation aspects are treated in Chapter **5.**

Figure 6.1 Estimates of future sea-level rise



Glacial Volume Estimate of NRC (1985) Augmented With Thermal Expansion Estimates of NRC (1983)

SOURCES:

Environmental Protection Agency, Projecting Future Sea Level Rise, 1983.

National Research Council, Responding to Changes in Sea Level: Engineering Implications, 1987.

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Intergovernmental Panel on Climate Change — Working Group I, 1990 Meier, M.F. 1990 'Reduced Rise in Sea Level': *Nature*

Figure 6.2 Physical consequences of climate change

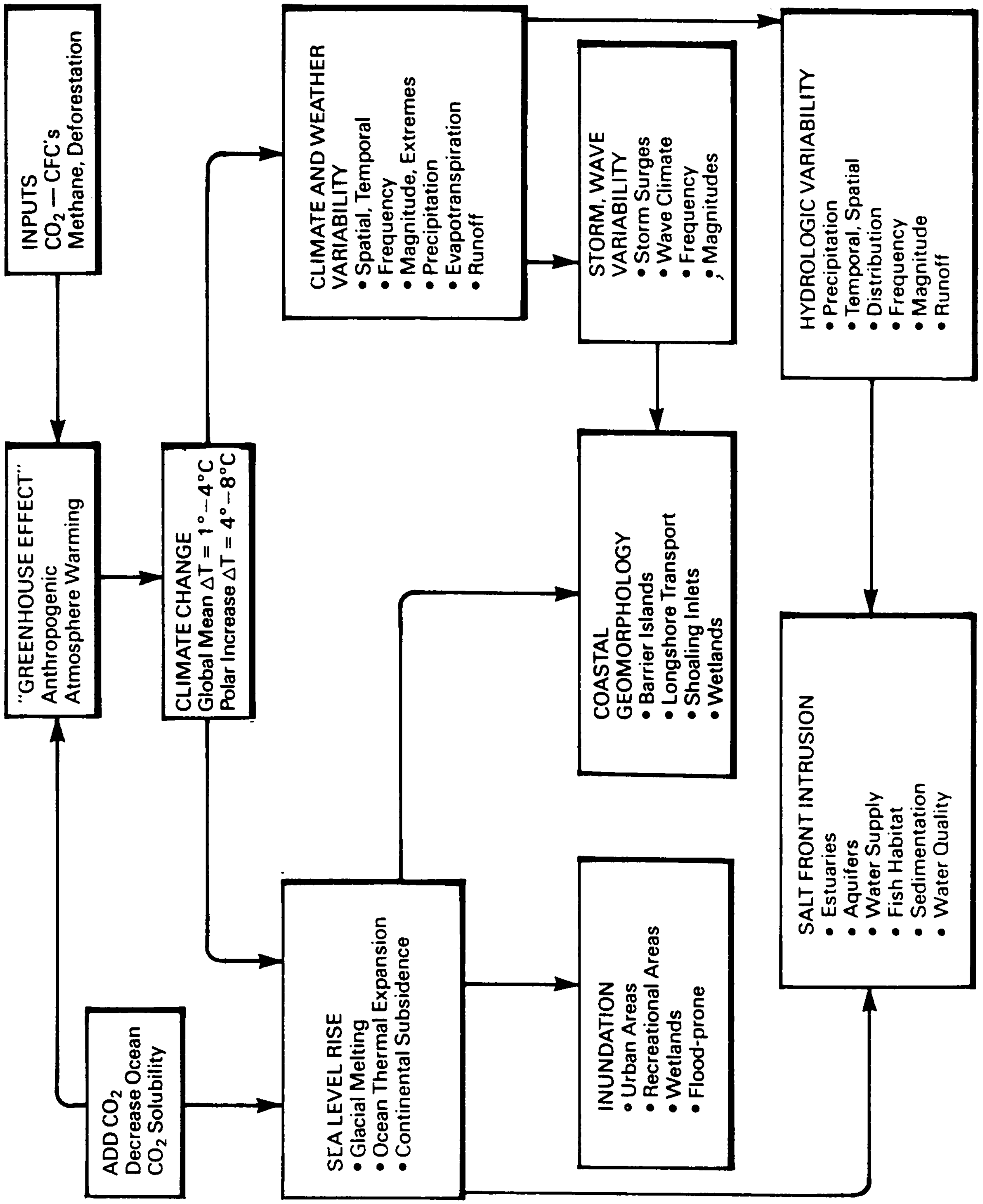
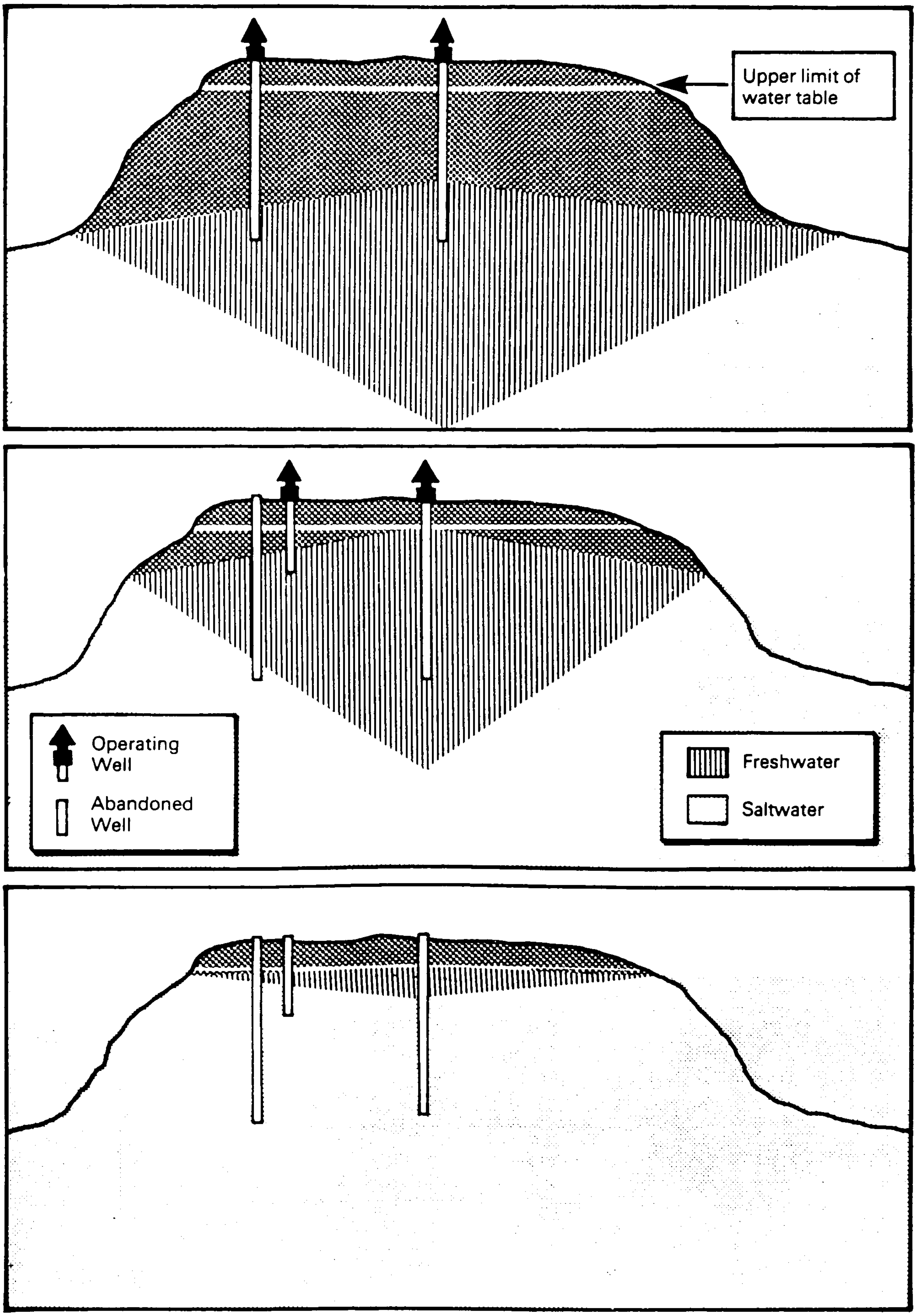
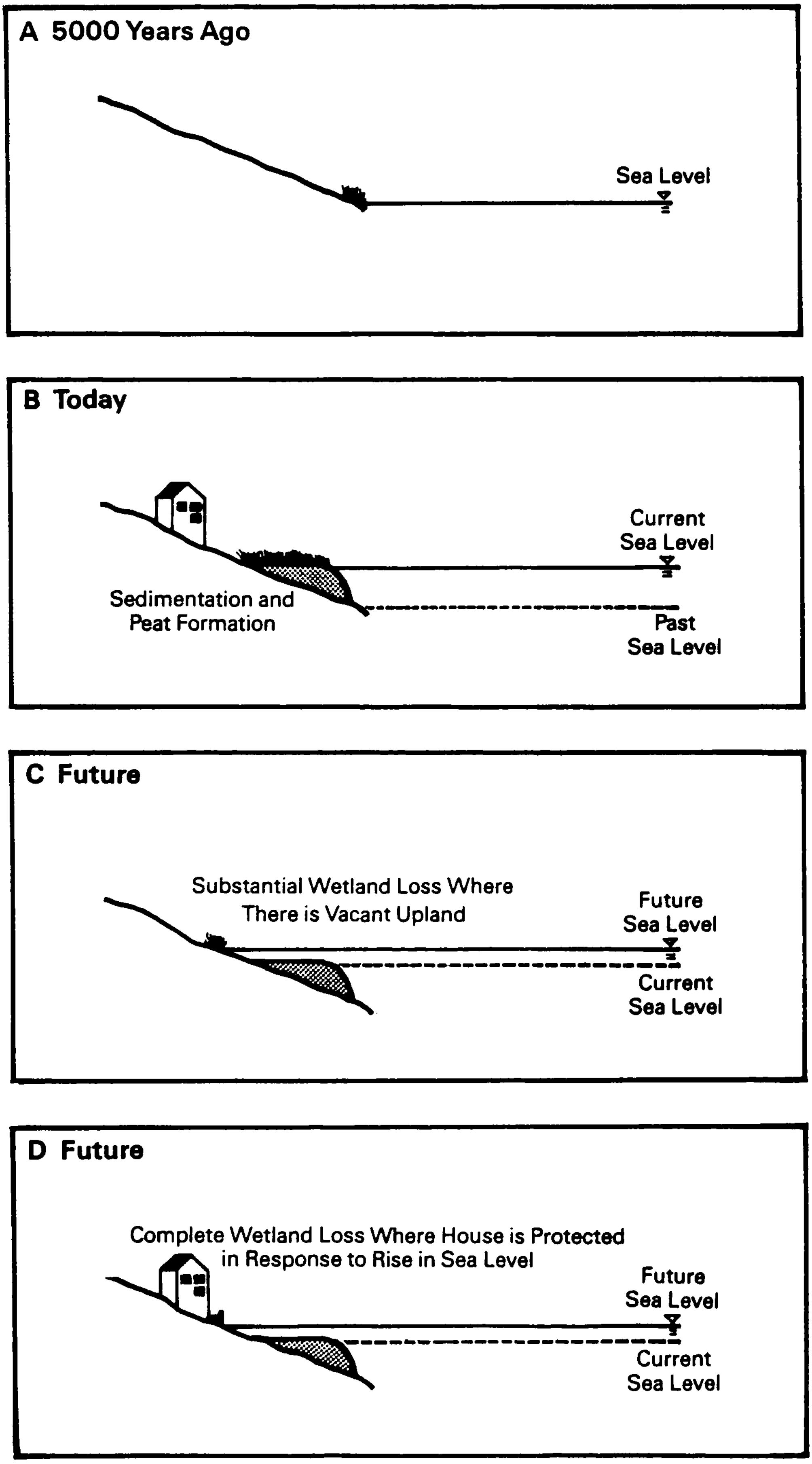


Figure 6.3 Impacts of sea-level rise on groundwater tables



Source: IPCC 1990 Miami Conference

Figure 6.4 Evolution of a marsh as sea-level rises



Source: Titus (1986)

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