

Implications of Future Climate on The Ecosystems and Socio-Economic Structure in the Marine and Coastal Regions of the Intra-Americas Sea

George A. Maul¹
Task Team Chairman

ABSTRACT

Global climate change, and particularly the impact of human activities on Earth's biogeographical environment, is of enormous socio-economic and ecological importance. It is the regional effect of global change, however, that weighs most heavily on individual lives because of the complexity of local response to a world-wide phenomenon. This chapter summarizes the opinion of a Task Team of 29 experts concerning the implications of climate change on the Gulf of Mexico–Caribbean Sea–Bahamas–Bermuda–Guianas region, of a global 1.5°C temperature and 20 cm sea-level rise by the year 2025. For some ecosystems in the Intra-Americas Sea the effect of temperature rise is much more important than sea-level rise, and *vice versa* for others; for some neither is important; for others both are important. Of the 14 ecosystems considered, the most heavily impacted are expected to be deltas and beaches, both because of sea-level rise; neither are particularly vulnerable to a modest temperature rise. Estuaries, wetlands, lagoons and seagrass beds will all be moderately affected by both the 1.5°C and 20 cm scenarios. The other two very important ecosystems, mangroves and coral reefs, are expected to have a low-to-moderate vulnerability to climate change *per se*, but both are expected to experience extreme stress due to local anthropogenic activities such as deforestation, coastal development, runoff, overfishing and tourism. Seven socio-economic issues were also studied in the context of local response to global change; tourism and the influence of tropical storms are considered most important *vis a vis* levels of vulnerability. As with the ecosystems, some other socio-economic issues are more affected by sea-level rise (e.g., settlements and structures and cultural heritage) than temperature rise (which mostly affects coastal zones, public health and human migration). In addition to evaluating the effects of 1.5°C and 20 cm global rises, the Task Team discussed the potential local rates of temperature and sea-level rise and found that for the Intra-Americas Sea, less of a climate change is expected than for other areas of Earth, but that human population pressure will significantly stress the region's environment. Finally, we report on new computer-based decision-making tools for evaluating the effects

¹National Oceanic and Atmospheric Administration, and University of Miami/Cooperative Institute for Marine and Atmospheric Studies, Miami, FL 33149, USA

of climatic change, tools that will give decision-makers quantitative information upon which to base new policies for management.

1 INTRODUCTION

The history of modern civilization is inexorably related to Earth's climate. Climatic changes have influenced our literature, raised and toppled empires, altered our religious views, modified economies, forced mass migrations of both humans and animals, caused hunger and starvation; the list is nearly endless (e.g., Bryson and Murray, 1977). Yet in the quincennial year of the European discovery of the Caribbean Sea (but see Van Sertima, 1976; 1992), little more is known about climate in the region than what the early explorers told their sponsors. Assessing the impact of climate *change* then becomes a particularly challenging problem.

This study emphasizes the marine and coastal environment and addresses the implications of climatic change in the Intra-Americas Sea. As was the perspective of the early explorers, it is limited to a sailor's view of the coastline, reefs, passages, harbours, deltas, estuaries, and deep waters of the Caribbean Sea, the northeast coast of South America (excluding Brazil), the Gulf of Mexico and the Florida-Bahamas region of the western North Atlantic Ocean (Fig. 1.1). Nevertheless, such a perspective presents a formidable challenge involving meteorology, oceanography, geology, economics, sociology, medicine, law and ecology.

To address such challenges, the United Nations Environment Programme (UNEP) was founded in 1972, and within two years UNEP established its Regional Seas Programme. An action plan for the Caribbean Environment Programme was adopted in 1981, and five years later the Regional Coordinating Unit (RCU), in consultation with the Intergovernmental Oceanographic Commission (IOC) and its Subcommission for the Caribbean and Adjacent Regions (IOCARIBE), began addressing marine environmental issues from the RCU's new offices in Kingston, Jamaica. In concert with the recommendations of the World Meteorological Organization (WMO)/International Council of Scientific Unions (ICSU)/UNEP-sponsored meeting in Villach, Austria (WMO/ICSU/UNEP, 1985), the RCU extended its marine environmental interests to include questioning the impact of climate change in the region (UNEP, 1987). Similar programmes are active in five other marginal seas under the Regional Seas Programme.

There is little doubt that climate is changing, but there is an important difference in the climate change that is now understood to be taking place: human activity may be involved. The effects of such anthropogenic activity on the region are difficult to isolate from other natural oscillations in Earth's climate. Nevertheless, the arguments are accepted that regional climatic scenarios (Lamb, 1987) are valuable, with the understanding that they are *not* a prediction of future climate but an internally consistent view of a plausible climatic future. However, with the influence of human activity, there is even more uncertainty in developing climatic scenarios, and clearly a great deal of scientific research is still necessary. It is with these caveats, like the sailors 500 years ago, that we explore the uncharted seas of the implications of climate change.

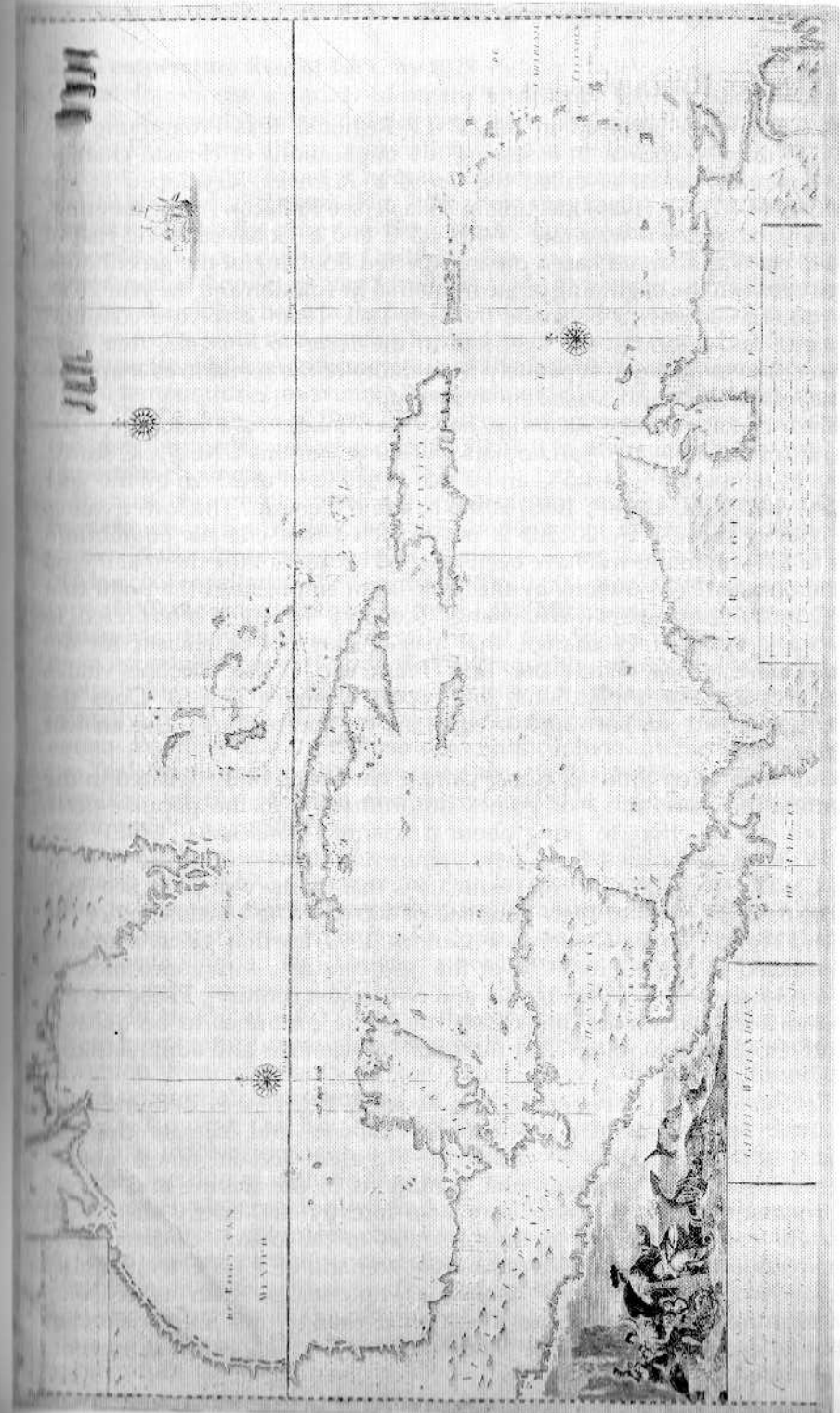


Fig. 1.1 Reproduction of early 18th century sea chart published by Gerard van Keulen. Translated from the French, the title reads: 'New Sea Chart of all THE COASTS OF AMERICA Showing all the Islands Bays and Rivers, as well as all the Rocks and Deepes, entirely composed from many Accounts of Very Experienced navigators by Jean Sikkema Master of Mathematics'. © 1991 Friends of the University of Miami Library; used by permission. See colour plates between pages 210 and 211.

2 TERMS OF REFERENCE

Each Task Team involved in the UNEP Regional Seas Programme has used a common format in assessing the implications of climate change. The common format is called the *Terms of Reference*, developed at the WMO/ICSU/UNEP (1985) meeting in Villach (see Preface). At the meeting, an *equilibrium* global warming of 1.5–4.5°C and a global sea-level rise of 20–140 cm was adapted based on an expected doubling of the greenhouse gases between the beginning of the Industrial Revolution and the year 2030. The determinations to be made by each Task Team involve a common scenario, and although not specified in the *Terms of Reference*, this Task Team chose to question separately the validity of the scenario as it applies to the local marine and coastal environment.

Many climate-change scenarios have been made, as a reading of the references in Lamb (1987) and others will show. For this UNEP/IOC study, a rise in temperature of 1.5°C and a rise in sea level of 20 cm by the year 2025 (WMO/ICSU/UNEP, 1985) is the baseline scenario. The lower values are chosen because by 2025 it is not expected that climatic equilibrium due to CO₂-doubling will have been reached because of the thermal inertia of the oceans. Deliberations by the Task Team emphasized the point that 1.5°C and 20 cm are a *global-change* scenario, which is interpreted to mean a global average change, that may or may not be realistic for the Intra-Americas Sea. While the Task Team used these baseline values in addressing the implications, one report (Chapter 9) asks 'Does the historical record support such predictions for the region?'. The answer is ambiguous.

Since 1985, projections of future climate have been hotly debated in the scientific literature and (sometimes unfortunately) in the popular press as well. In an effort to bring about a scientific consensus, UNEP and the WMO co-sponsored the Intergovernmental Panel on Climate Change (IPCC). The 'best' IPCC (1990a) estimate is that by the year 2100, sea level will rise 50 cm, with a 'high' estimate of 100 cm. The conclusions of the Second World Climate Conference (Geneva, 1990) are that 'global warming is predicted to reach 2 to 5°C over the next century . . . accompanied by sea-level rise of 65 ± 35 cm by the end of the next century'. These are not contradictory statements, but clearly the issue continues to be debated (Maul, 1992), and requires close attention by scientists and administrators alike.

The last issue in interpreting the *Terms of Reference* is defining how the Task Team understands the terms 'climate' and 'climate change'. *Climate* is understood to be limited to the multi-decadal time-averaged meteorological and oceanographic conditions of the marine and coastal environment; although agriculture and forestry are briefly discussed, they are only considered in their relation to the ocean. *Climate change* is understood to mean the decadal-scale scenario of a 1.5°C temperature rise and a 20 cm sea-level rise; short time-scales, such as seasonal and high-frequency aspects of interannual change, are not considered, although certain aspects of El Niño-Southern Oscillation (ENSO) events are explored.

3.1 Temperature Rise of 1.5°C by 2025

Climatologists use a variety of means to describe Earth's past climate. In the US National Academy of Science report *Understanding Climatic Change* (NAS, 1975), a wealth of information is given on the subject. To illustrate current knowledge about temperature change, temperature records for the last 10,000 and 1000 years (Fig. 1.2), show that Earth's temperatures have varied significantly since the 15th century European discoveries of North America. In fact, when the Caribbean Sea was discovered, Europe was in a cold period known as the 'Little Ice Age'. At present, Earth's climate is warmer than it has been in the last 1000 years, but by no means is it as warm as it was in several past epochs, as the longer records (last 1,000,000 years) indicate. So while an interpretation of the last 100 years shows increasing global temperatures on average (Hansen and Lebedeff, 1988; lower panel in Fig. 1.2), the decades of 1940–1970 had declining temperatures. Translating the global records such as shown in Fig. 1.2 to the regional level was one important challenge for the Task Team.

Fortunately, geochemists are constructing climatic histories of the Intra-Americas Sea region, and are showing that much of the variability shown in the upper panel of Fig. 1.2 applies to the Caribbean Sea and Gulf of Mexico. Hodell *et al.* (1991) published a 10,000-year history of oxygen isotope ($\delta^{18}O$) measurements taken from Lake Miragoane, Haiti (not shown), which has many of the characteristics of this 'global' temperature curve; most especially they conclude that $\delta^{18}O$ roughly follows the Milankovitch orbitally induced insolation curve. But they note that superimposed on the orbitally forced climate trend (cooling for the next 5000 years) are abrupt events resulting from non-linear ocean-atmosphere interactions. So while the Task Team debated the 'historical record' (last ~150 years), they were cognizant of the progress and uncertainties in applying global-change arguments to a specific region.

Does the historical record support the WMO/ICSU/UNEP (1985) scenario of a 1.5°C temperature rise in the region by the year 2025? Data to assess a rise of sea-surface temperature were considered scarce, so Hanson and Maul (Chapter 9) decided to analyse air temperature at Key West, Florida. The 136-year record gives evidence that a warming has occurred between 1890–1950, but the last 30 years or so have been relatively steady at +0.3°C above the long-term mean; a similar analysis of air temperature from ship reports in the Straits of Florida shows no deviation from constancy of the mean. Gray (Chapter 5) found that the maximum air temperatures in Jamaica and in Trinidad and Tobago increased during the last 10 years, but that evaporation had decreased (which is inconsistent with a temperature increase); it is unclear if these changes are due to climatic change or to other factors. Aparicio (Chapter 6) reports an air-temperature trend of +0.1°C per decade in Venezuela, but other data from volunteer observing ships in the central Caribbean Sea suggest sea-surface temperatures have been decreasing since 1950. Linear extrapolation of these case studies leads one to see some suggestion of an air temperature rise in the region, but that 1.5°C seems to be too high; less than 1.0°C rise by 2025 appears to be a more plausible picture of our future temperature.

2.2 Sea-Level Rise of 20 cm by 2025

As with questioning the validity of the global temperature change for the region, the Task Team looked into the historical sea-level record to put the WMO/ICSU/UNEP (1985) scenario into perspective. The remarkably slow rate of sea-level rise in South Florida and in Jamaica during the last 3200 years (only about 0.04 cm/yr; Fig. 1.3) allowed many shorelines to stabilize or to expand, and many shallow marine environments to build. However, since the early 1930s, sea-level records from many sites around Florida show much faster rates of sea-level rise, very similar to the rate during the period 3200–5500 years ago, when there was a rapid retreat of the shoreline. The data in Fig. 1.3 gave the Task Team a benchmark against which to judge the WMO/ICSU/UNEP global scenario of 50 cm rise per 100 years.

Does the modern historical record of the Intra-Americas Sea support the WMO/ICSU/UNEP (1985) scenario of a 20 cm sea-level rise by the year 2025? To answer this question, the highest quality (revised local reference)

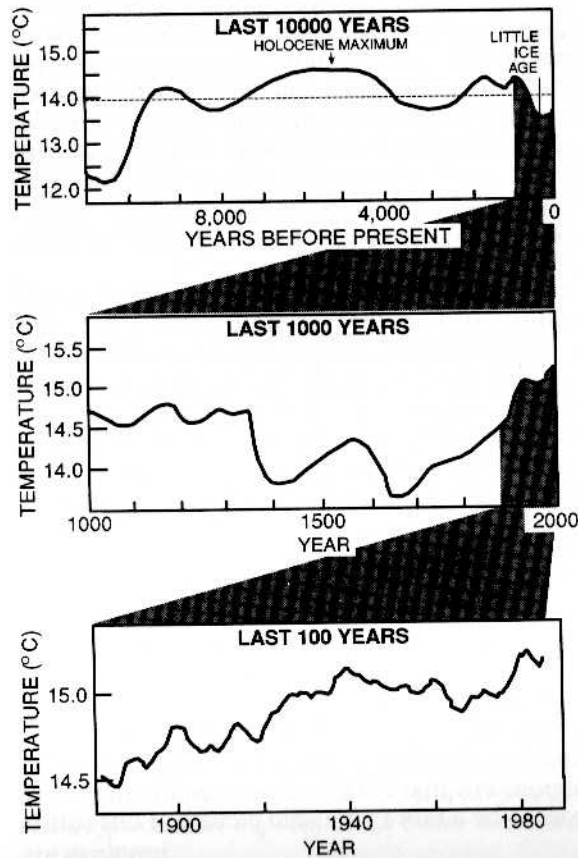


Fig. 1.2 Temperature change for the last 10,000 years and 1000 years based on records in Europe (upper two panels; redrawn from IPCC, 1990a), and a global estimate (lower panel; from Hansen and Lebedeff, 1988). Temperature scale for upper two panels is only approximate and is chosen to be in agreement with the record for the last 100 years which is based on direct observations. Maul (1992) discusses urbanization effects in Hanson and Lebedeff (1988) and gives references related to the issue (*cf.* Wigley and Santer, Chapter 2; Gallegos *et al.*, Fig. 3.5).

data on file with the Permanent Service for Mean Sea Level (PSMSL) were studied by Hanson and Maul (Chapter 9) for the Intra-Americas Sea, and from Venezuelan records by Aparicio (Chapter 6) for the southern Caribbean Sea. For the longest records, Hanson and Maul found that sea level is rising on average at about 0.36 cm/yr (± 0.25 cm/yr) over the last 30 years, but due to complicated tectonic activity, subsidence, and petroleum/groundwater extraction, the values ranged from +1.0 cm/yr in Texas (rising sea level) to -0.3 cm/yr in Mexico (falling sea level). At Key West, Florida, a site of tectonic stability, the rise is 0.22 cm/yr (± 0.01 cm/yr), based on the years 1913–1986. More important perhaps, is that sea-level rise due to temperature/salinity changes in the upper 1000 m of the water column east of Abaco Island, the Bahamas, for 1950–1987 was +0.14 cm/yr (Chapter 9), and there is no evidence of acceleration in the rate of rise. So, as with the temperature scenario, a lower value, perhaps 10 cm by 2025, may be a more plausible regional value, but the high spatial variability makes a regional average nearly meaningless; site-specific values are required for realistic assessments.

Gallegos *et al.* (Chapter 3) and Mercado *et al.* (Chapter 4) cautiously advise that many more long records are required in order to sort out the decadal and longer wave motions in the relative sea-level record.

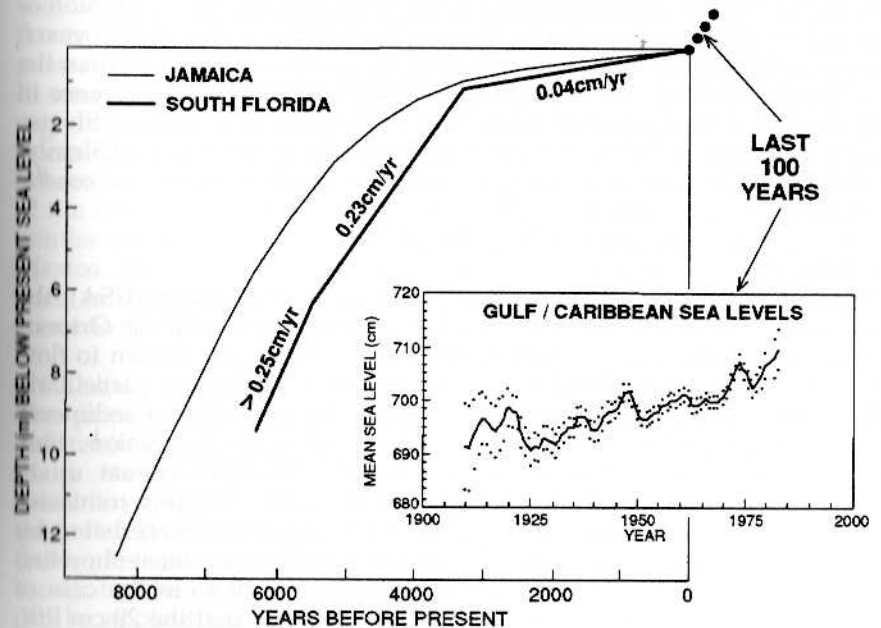


Fig. 1.3 Sea-level change based on geological records taken in south Florida by Wanless *et al.*, 1988, and from Jamaica by Digerfeldt and Hendry, 1987. The relative rise of 36 cm per 100 years shown in the inset is based on direct observations at all PSMSL (Pugh *et al.*, 1987) RLR sea-level stations in the region; dots show range of standard error of the mean. The shoreline retreat associated with sea-level rise occurs in storm-driven steps and is often not immediately seen as beach erosion or lowland inundation.

The physics of the very lowest frequencies in oceanic circulation are not well understood. Circulation, the three-dimensional movement of water with time, is affected by geological activity, the wind field, Rossby waves, periodic behaviour of the Sverdrup balance, interbasin modes of oscillation, and so forth. Progress in numerical modelling will give the resolution to determine submesoscale features and subdecadal oscillations (Mercado *et al.*, Chapter 4), but it may be 10 years before such calculations are possible. To further complicate the issue, Chao (1991) argues that sea level has fallen by about 7 cm in the last 100 years due to the building of reservoirs for irrigation and water control. In the interim, thoughtful extrapolation of the PSMSL observations, in concert with careful monitoring and a vigorous modelling activity, will give the most plausible estimates of future sea level.

3 EFFECTS OF SEA-LEVEL CHANGES ON COASTAL ECOSYSTEMS

The first task in the *Terms of Reference* (*q.v.* Preface) is to examine the possible effects of the sea-level changes on the coastal ecosystems (*cf.* IPCC, 1990b). Gable (Chapter 10) gives an overview of the ecosystems in the region, and *Oceanus* (1987/88) is an issue devoted to Caribbean Sea marine science. The variable of interest in this section is relative sea-level (RSL) rise, that is the net effect of tectonic uplift or subsidence plus expansion or contraction of the water column. During the Holocene (last 10,000 years) in Jamaica for example (Hendry, Chapter 7), sea-level rise is less than the 0.5 cm/yr implied by the assumptions at the International Conference in Villach, and in the last 3000 years before the present century, RSL rise has been almost nil (Fig. 1.3). All other things being equal, 0.5 cm/yr (20 cm between 1985 and 2025) is expected to place stress on coastal ecosystems.

3.1 Deltas

In the region there are four major river deltas: the Mississippi (USA), the Rio Grande (Mexico/USA), the Magdalena (Colombia) and the Orinoco (Venezuela); in addition, waters of the Amazon River are known to flow into the Caribbean Sea (Muller-Karger, Chapter 8). Deltas are particularly vulnerable to erosion enhanced by sea-level rise because the sediments are unconsolidated muds subject to subsidence and compaction. One might expect, according to the Bruun Rule, a shoreline retreat up to several metres horizontally for each centimetre RSL rise; this translates into thousands of hectares of lost land. The problem is exacerbated by potential increased storm activity (Gray, Chapter 5), since most shoreline erosion occurs during storms, and by subsidence such as in the case of Louisiana. However, Mercado *et al.* (Chapter 4) argue that the 20 cm RSL rise scenario will be of no practical consequence on storm-surge modelling, as far as it might calculate increased surge heights. Delta benthic systems, particularly seagrass beds, would be most affected or destroyed by the expected RSL rise. In contradistinction, RSL near the Orinoco Delta may be falling, but more measurements are needed to document this preliminary result.

3.2 Estuaries

The RSL effect on estuaries, as with deltas and many other geomorphological features, must be considered on a case-by-case basis in order to make meaningful impact assessments in the region (Vicente *et al.*, Chapter 11). Because of local uplift, the following areas are expected to have reduced increase in RSL due to climate change: east coasts of the Cayman Islands; north coast of Jamaica; southeast coast of Cuba; north coast of Bahia, the southwest coast of Haiti; Barbados; north coast of the Dominican Republic; and the southwestern Gulf of Mexico (see Fig. 10.2 for locations). In addition to the subsidence experienced in deltas, other areas experiencing downwarping include: the Maracaibo region of Venezuela; the entire northern Gulf of Mexico from Texas to Alabama; the estuary of Port au Prince; and the western Gulf of Honduras. Coastal lagoons, salinas and estuaries (transient environments that owe their existence to sea-level rise), depending on their location, could suffer from saline intrusion. Lagoons, however, should be able to support their usual nurseries; salinas on the other hand (Vicente *et al.*, Chapter 11), could be flooded over continuously and change their economic value.

3.3 Wetlands

The ability of a wetland to sustain vertical growth is a balance between sedimentation and RSL rise. In the tectonically complicated Intra-Americas Sea, no single definitive statement is possible, but in the last 5000 years, many wetlands have been able to keep pace with rising sea level. In areas with marked subsidence, particularly if there is canalization of organic silts and clays away from the wetland into the marine environment (Hendry, Chapter 7), wetlands will be submerged and lost to productivity. Where wetlands are bounded by steep-sided basins, as is the case in many of the islands, it is unlikely that they will be replaced as sea-level rises; on gentler island and continental floodplains, such as the northern Gulf of Mexico, the problem may be less severe. Loss of some wetland economies such as shellfish industries is expected to occur with the 20 cm RSL rise scenario (Snedaker, Chapter 12).

3.4 Coastal Plains

The primary effect on coastal plains will be increased flooding during storms (from raised sea level and/or from heavy rainfall). Unfortunately many storm-surge models differ markedly in their predictions (the variability in their predictions being several orders of magnitude larger than the 20 cm scenario; Mercado *et al.*, Chapter 4). Shore migration (both erosion and accretion) will vary depending on the substrate, and sandy beaches will be more affected than rocky coasts. No single rule can be applied for the region as a whole, but modelling on a local scale is required to account for differences such as tectonic displacement, beach structure, offshore bottom topography, and storm frequency and magnitude. The concentration of human population in the poorly drained low-lying coastal plains is a source of concern in many countries. Special attention should be paid to areas where subsidence is evident, as it will exacerbate the flooding problem. Port au Prince, Haiti, Puerto Cortes, Honduras and the Galveston-centred area of the US Texas–Louisiana

coast, are coastal plain areas most vulnerable to flooding from sea-level rise and storms.

3.5 Coral Reefs

The second largest coral reef system in the world dominates the offshore area of the western Caribbean Sea (Milliman, Chapter 13), and all areas except the northern Gulf of Mexico coast have extensive reef systems. Growth of individual coral organisms is estimated between 1–20 cm/yr (Vicente *et al.*, Chapter 11), and reef growth rates as a whole are known to be up to 1.5 cm/yr (Hendry, Chapter 7). Not all reefs accumulate at these rates, but if they did, they could keep pace with the rise in RSL of 20 cm by 2025 if other factors do not alter growth conditions. Environmental stress on the reefs from other variables (storms, sedimentation, disease, rainfall, radiation, turbidity, overfishing, mass mortality in algal grazers, etc.) may prevent some reefs from keeping pace with rising RSL, resulting in alteration of the nearshore hydrodynamics. The issue is further complicated by consideration of the type of reef, coastal geomorphology, reef depth and ecological state of the reef in question. Accurate predictions on the effect of RSL rise may be possible in reefs that have already been physically and biologically monitored, such as in Panama, Jamaica, and Puerto Rico.

3.6 Mangroves

Mangrove forests are a unique feature of protected coastal shorelines of the tropics and subtropics; their root systems (prop roots and pneumatophores) stabilize the sediment, dampen wave energy, provide habitat shelter for numerous organisms, and form the base of the nearshore marine foodweb (Vicente *et al.*, Chapter 11). The five species comprising the mangrove flora of the Intra-Americas Sea occupy an area of approximately 3.2 million hectares, or some 15% of the estimated world area of mangrove of 22 million hectares. Within the region, the best developed mangrove forests are associated with areas of high precipitation and upstream land runoff. Because mangroves grow best in moderately saline environments where the rate of peat production exceeds the anaerobic decomposition of peat by seawater sulphate-reducing microorganisms, it is postulated that mangroves can keep pace with RSL in rain-fed humid areas, but may be overstepped and abandoned in more arid areas particularly if inland retreat is not possible. Thus, in terms of global climate change, future changes in patterns of precipitation and catchment runoff may be more important than RSL (Snedaker, Chapter 12). Notwithstanding the current high rate of regional mangrove loss by overcutting, land clearing and habitat conversion, global climate change is a minor factor in consideration of the fate of this regionally important coastal habitat.

3.7 Seagrass Beds

Seagrasses are a benthic environment throughout the region that are important in stabilizing bottom sediments (Hendry, Chapter 7), serve as nurseries for juveniles, and for providing surfaces upon which many organisms attach. A 20 cm RSL rise *per se* is not expected to seriously affect the six common species (Vicente *et al.*, Chapter 11), but if there are other

changes, such as in the quality of light, influence of herbivores, substrate, wave energy, or bottom slope, the beds may be impacted.

3.8 Fisheries

The impact of sea-level rise on fisheries is not expected to be great unless turbidity increases due to erosion from higher water or river runoff (Muller-Karger, Chapter 8). Turbidity increase could have a negative impact on fisheries particularly during the early life history stage (W. Richards, NOAA/NMFS, pers. comm.). Estuarine-dependent species in areas such as Mississippi, the Florida Everglades, Guyana and the Orinoco Delta, may be particularly vulnerable to sea-level rise, especially if salinity changes are involved. These ecosystems are also particularly vulnerable to increases in the discharge by rivers of pollutants, which may accumulate, and eventually become harmful to humans and other animals in the foodweb.

4 EFFECTS OF TEMPERATURE ELEVATIONS ON ECOSYSTEMS

As discussed above, there is considerable question if trace gas-induced temperature elevation can be seen in the records at Key West, Venezuela, Jamaica or in Trinidad and Tobago. Temperature change, however, is only one aspect of the meteorology that will effect terrestrial and aquatic ecosystems. Hanson and Maul (Chapter 9) find no evidence for changes in precipitation at Key West during the last 101 years; Aparicio (Chapter 6) finds none along the southern Caribbean Sea; Muller-Karger (Chapter 8) does not detect trends in precipitation over the Mississippi, Orinoco, or Amazon drainage basins during the past 50–100 years. In the northern Caribbean Sea, Gray (Chapter 5) finds hints of decreased rainfall in the last 20 years, which is possibly associated with decreased hurricane activity. An increase of 1.5°C in sea-surface temperature could increase the number of hurricanes by as much as 40% (Shapiro, 1982), and the maximum wind speed by 8%; there is, however, a considerable uncertainty in these figures (40% increase means on average $+1.6 \pm 1.2$ hurricanes per year). Many other factors are important in hurricane analysis, and it may be that the storm-formation location and track are more important than changes in strength or frequency.

In the sense that Lamb (1987) develops climate-change scenarios as plausible future events, Gray (Chapter 5) assumes the following (*cf.* Gallegos *et al.*, Chapter 3; Aparicio, Chapter 6): rainfall will continue to decrease, air temperatures will continue to rise, surface wind speed and evaporation will continue to increase. Caution must be exercised in applying these changes as anything other than persistence forecasting. It is unknown, for example, if the decreased frequency of large hurricanes over the last two decades is really a long-term trend, if it is random, or part of some cycle as yet not understood. Hurricanes are an important contributor of rainfall; is the decrease in precipitation merely a reflection of fewer large storms? Increased temperature may affect the drag of wind on water, but Mercado *et al.* (Chapter 4) and Hendry (Chapter 7) see no clear indication of a significant change in storm surges or waves associated with elevated temperature. Clearly, however, any change in wind and precipitation patterns will impact the discharge of major rivers and the

dispersal patterns of their water and its suspended/dissolved constituents (Muller-Karger, Chapter 8). With these thoughts in mind, the second item in the *Terms of Reference* (*q.v.* Preface), 'effects of temperature elevation on the ecosystem, including on economically important species' is considered (*cf.* IPCC, 1990b).

4.1 Agricultural Resources

Saline intrusion is expected to have more impact on agriculture in the coastal plains than elevated temperature, particularly on rice production along the Guyana coast. Soil erosion probably will increase, but poor management practices are probably more contributive than temperature elevation and saline intrusion. Vicente *et al.* (Chapter 11) argue that it is unlikely that inland and hilly forests will be affected much by increased temperature, although Gray (Chapter 5) warns of increased erosion due to increased winds and decreased precipitation. However, warmer temperatures could be a significant factor in forest fires, particularly if precipitation decreases. Human settlements are unlikely to be affected significantly by 1.5°C weather changes, except where RSL is important (Alm *et al.*, Chapter 15).

4.2 Coastal Systems

In the tropics, marine organisms live closer to their maximum thermal tolerance than those in more temperate climates. Although the 1.5°C temperature-rise scenario would raise the summertime mean temperature to 30.5°C over much of the region, most migratory organisms are expected to be able to tolerate such a change. Some corals will be affected (for example, the 1983 and 1987 bleaching events), but it is expected that other environmental stresses will be more important (Milliman, Chapter 13). Littoral-supralittoral organisms, such as mangroves, are adapted to withstand high temperature, and unless the 1.5°C increase affects the reproductive cycle, the temperature elevation will probably cause unmeasurable results (Snedaker, Chapter 12). Similarly, only seagrass beds already located in thermal stress situations (*i.e.*, in shallow lagoons or near power plant effluents) are expected to become negatively affected by the projected WMO/ICSU/UNEP (1985) temperature rise.

4.3 Fisheries

The blue, clear waters of the region are relatively nutrient-poor, and most of the fisheries are concentrated on Campeche Bank and along the northern coast of the Gulf of Mexico, at the Mosquito Bank off Honduras and Nicaragua in the Caribbean Sea, and in the Gulf of Paria and the coastal waters of the Atlantic Ocean off Surinam, Guyana and French Guiana (Gable, Chapter 10). It is not expected that a modest increase in temperature will significantly affect the fisheries except in some shallow lagoons where hypersalinity may affect productivity, particularly if juveniles have a critical dependence on salinity or temperature. Increased alongshore winds, however, could lead to increased coastal upwelling along some continental coasts (Aparicio, Chapter 6) or other circulation changes (Gallegos *et al.*, Chapter 3), and thus to increased productivity (*cf.* Vicente *et al.*, Chapter 11).

Tropical fish eggs hatch very quickly (12-48 hours), and development is associated with temperature. Just as 'cold snaps' can be devastating, so can 'hot snaps', particularly during early juvenile stages. Extrema in temperature are usually averaged out in climate analysis, but with increased temperature, the likelihood of 'hot snaps' increases; the 1987 Caribbean Sea coral bleaching event was attributed to 'hot snaps' by some researchers (Milliman, Chapter 13). The complexities of the ecosystem could be greatly affected by slight temperature changes. It is unknown, for example, why fish stocks either decline or increase by orders of magnitude, except due to early life history events caused directly by the physical environment or indirectly through complex chains in ecosystem dynamics. Temperature effects on tropical fisheries remains an important and unanswered question, although there is some evidence of fish migration associated with increased coastal temperatures.

5 POSSIBLE SOCIO-ECONOMIC CHANGES

Climate change will have socio-economic impacts on both the micro-economic or localized level, and on the macro-economic or economy-wide level (*cf.* IPCC, 1990c). The complexity of these interactions is

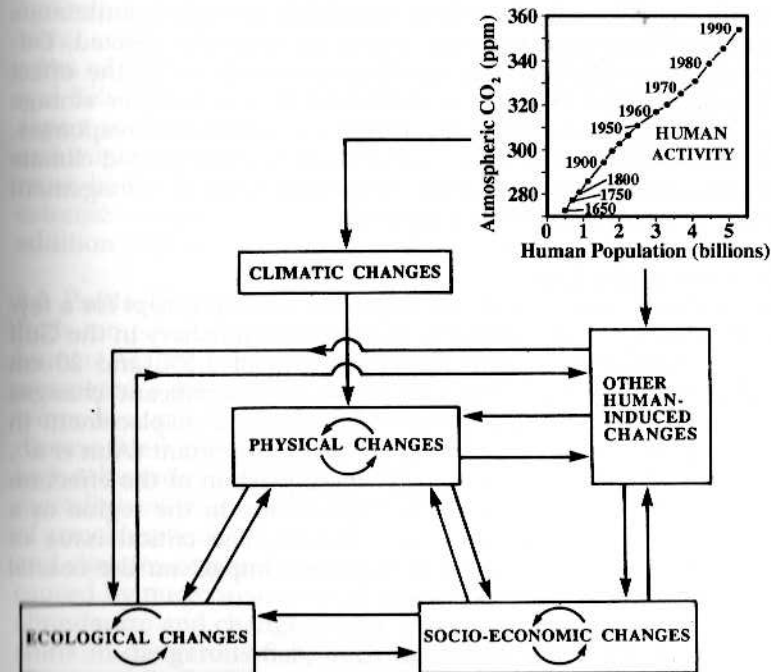


Fig. 1.4 Pathways in socio-economic aspects of the climate change problem (from Alm *et al.*, 1988; population vs. CO₂ (1650–1990 AD) from Idso, 1989). The full complexities are further discussed in Chapters 15 and 16, but the interested reader is also referred to IPCC (1990b) for impact assessments and IPCC (1990c) for response strategies.

summarized in Fig. 1.4, showing the numerous pathways possible in complex social systems (*cf.* Alm *et al.*, Chapter 15; Engelen *et al.*, Chapter 16) and showing that the generic effect of human activity is the strongly linear relation between human population and atmospheric CO₂ concentration (Idso, 1989). The smaller or the more coastal-oriented an economy is, the greater will be the impact of sea-level rise. The Intra-Americas Sea, with its many small island-based economies such as fishing and/or tourism, is particularly vulnerable to the physical changes associated with changing climate. Some climatic changes will benefit certain sectors of an economy (rising RSL may benefit the construction industry), while being detrimental to others (beach erosion may cause a loss in tourism). A climate change-induced benefit to the construction industry reflects a *transfer* of benefits and costs rather than the *creation* of new benefits and costs. The net sum of costs and benefits must be assessed on an individual basis because it is the true cost due to climate change only that is of interest (Engelen *et al.* Chapter 16).

5.1 Agriculture and Forestry

Islands usually have small, coastal aquifers, and sea-level rise will impact water quality in aquifers that have hydrological continuity with the sea. Loss of agricultural land in low-lying coastal plains will be a minor, but perceptible impact, particularly in those areas where saline intrusion affects the water supply, such as on the leeward side of small mountainous islands; continental areas are not expected to be seriously affected. Differing permeability in aquifers can cause great variability in the effect of rising RSL. Relocation of wells, construction of weirs, water storage schemes and barging of water are all possible socio-economic responses. In regards to forestry, as noted in an earlier section, the expected climate change impact is anticipated to be small compared to proper management policies on the industries and people involved.

5.2 Fisheries and Coastal Zones

Most fishing in the coastal zone in the region is artisanal except for a few larger industries such as shrimping and the menhaden fishery in the Gulf of Mexico. The WMO/ICSU/UNEP (1985) scenario of 1.5°C and 20 cm increases by 2025 are not expected to create any significant changes in the fisheries, although to the artisanal fisherman, a displacement in traditional fishing sites may be perceived as being important (Alm *et al.*, Chapter 15). There does remain an unanswered question of the effect on fisheries of extreme temperature events. Aquaculture in the region as a whole is considered undeveloped at the present. The critical issue of shoreline migration, which is the most important impact on the coastal zone, is discussed in the following sections.

5.3 Tourism

The single most important industry in the region is tourism, especially in Florida, the Bahamas, Cuba, Jamaica and the Lesser Antilles. Of all the possible climate change impacts that affect tourism, none is so clearly demonstrated as beach erosion (*q.v.* Hendry, Chapter 7). Shoreline migration will create new areas of economic benefit as new

beaches are built, but the protection, replenishment and stabilization of existing beaches, at least until major existing tourist investments are amortized, represent a major socio-economic impact. It is difficult to estimate the impact of climate-induced sea-level rise, in addition to the erosion associated with the relentless interaction of the sea on the coast, that is not associated with climate change; in addition, certain sand-mining practices (such as in Trinidad and Tobago) are already considered important. A temperature rise of 1.5°C locally is probably of little consequence, but the scenario of a global 1.5°C rise probably means much higher temperatures at mid-latitudes (where most tourists come from), thus reducing the attractiveness of a warmer climate for vacationing. Indirect socio-economic effects on tourism due to increasing pollution, coral-reef mortality and storm damage are also involved.

5.4 Settlements and Structures

Up to a certain point, structures will be worth building to protect settlements and facilities. Navigation and port facilities normally have to be reconstructed and maintained, so the socio-economic impact of a 20 cm sea-level rise is not considered serious (Alm *et al.*, Chapter 15). Some nearshore roads, seawalls and bridges will have to be increasingly repaired, and if the RSL rise is augmented by increased storm activity, the impacts will be serious, particularly in countries with marginal economies. As with agriculture in low-lying lands that depend on well water, many municipal water supplies and drainage and sewage systems, will have to be modified; areas of particular concern in this regard are the coastal cities of Guyana and Belize (Vicente *et al.*, Chapter 11). The most damaging socio-economic aspect is climate change coupled with population growth (see Fig. 15.2) and migration to coastal cities. Often the population growth is into areas most likely to be impacted by water-level changes, and in periods of extreme weather events, serious public health impacts are probable in addition to physical danger (Hardin, 1971).

5.5 Public Health

Both temperature and sea-level rises are expected to have an effect on human health; temperature because many diseases and acute effects are associated with elevated temperatures, and with water levels because water is a principal agent for many diseases and organisms that carry disease (de Sylva, Chapter 14). If higher temperatures are coupled with higher humidity as Gray expects (Chapter 5), heat-related health stress and mortality will increase. Human health changes are related to a wide variety of considerations including: mortality and morbidity related to weather and climate; extreme weather events; airborne materials; seasonal diseases caused by microorganisms; parasitic diseases; nutrition; water quality and abundance; and changes in the marine environment including population shifts in dangerous fish, such as sharks, and toxic organisms (de Sylva, Chapter 14). Socio-economic effects relate not only to increased spread of tropical diseases and their associated shift in costs and benefits to the health industry, but also to potential losses in other industries due to health-related absenteeism. It is anticipated that transfer of costs and benefits will be associated with climatic change to public health in the

region, but that the health-care delivery systems will keep pace with the climate-related aspects to the year 2025; whether or not the systems are capable of coping with other social changes is uncertain.

6 MOST VULNERABLE AREAS OR SYSTEMS

In order to determine areas or systems which appear to be most vulnerable to changes in sea-level and temperature (*q.v.* *Terms of Reference*; IPCC 1990b), and their impact on ecological and socio-economic structure and activities, three broad topics are addressed: (1) physical processes; (2) ecological aspects; and (3) socio-economic issues. Much of the material in the following sections is drawn from notes and recommendations made during the deliberations of these three working groups of the Task Team.

It was clear that detailed information on the wide variety of areas or systems most vulnerable to climate change in the region could not be prepared without additional substantial effort and support. In order to ultimately provide such detail, the consensus was the following:

- Strengthen existing institutions rather than creating new ones.
- Improve communication and information exchange particularly through the use of electronic media and 'personal computer' technology.
- Reduce uncertainties in the regional impact of the global 1.5°C/20cm scenario by data generation, case studies, and modelling, obtaining probability estimates on sea-level rise and other climate change.
- Continue the interdisciplinary interaction of the Task Team in order to provide *quantitative* information to member states.

The latter point of quantifying results, based on the best physical or economic models, is considered the penultimate goal of this joint UNEP/IOC programme.

6.1 Physical Processes

Climate change involves much more than RSL rise and temperature increase; precipitation, evaporation, humidity, wind velocity, storm cloudiness, insolation, ocean currents, waves, mixing, riverine input etc., are all important variables. In order to strengthen quantitative information transfer to states, regional climate models nested in couple ocean-atmosphere global circulation models are needed, along with vigorous, stable, long-term *in situ* verification programme, couple with an active multidisciplinary research effort which should include examination of the historical, geological and archeological records in order to supplement direct measurements. Understanding future shoreline migration is arguably the first priority based on current information, but if precipitation changes (for example) are markedly underestimated the impact on agriculture and coastal ecosystems could be far more important. To this end, participation in efforts such as the World Climate Programme, with significant international visibility by scientists from the region, is absolutely necessary to improve the physical basis upon which quantitative information is provided to ecologists, sociologists, economists, politicians and managers.

6.2 Ecological Aspects

Identification of the most vulnerable ecosystems requires more of a microscale approach than the mesoscale thinking required of the physical processes discussed above. Preparation of a regional map with a classification scheme showing areas and ecosystems most vulnerable to climate change is a massive, but necessary undertaking. Seagrass beds, coral reefs, mangroves (particularly the black mangrove) and coastal lagoons are probably the most critical habitats to be mapped. Associated with the critical habitats are species that utilize them as feeding and/or nursery grounds. Of vital concern to these critical habitats are climate-related impacts from the sewage and toxic wastes of nearby human population centres and agricultural regions. Conversely, impacts of saline intrusion on local fresh-water supplies and inundation of seaside population centres, particularly during storms, are critical concerns to local residents; high population-density islands such as Barbados, and cities with rapidly rising RSL such as Galveston, Port au Prince, Puerto Cortes, New Orleans and Cartagena, are particularly vulnerable.

6.3 Socio-Economic Issues

Before effective socio-economic responses to climatic changes can be initiated, there is a need to reduce significantly the degree of uncertainty about the likelihood, extent and direction of such changes. The most vulnerable 'system' in the socio-economic and health sectors is the credibility of those making impact assessments. Governments and institutions will revert to procrastination as the most viable response to weak forecasting, rather than to improving information development and dissemination, risk spreading and diversification, or to reducing levels of fixed commitments. Some states, Costa Rica for example, have already established new building set-back laws for construction along the coasts; others, Florida for example, have locally opted for massive beach replenishment programmes. Most small island states, which numerically constitute a substantial fraction of governing units, do not have the financial resources nor the technical expertise to develop appropriate socio-economic responses to climate change; it is for this reason that initial efforts in socio-economic numerical modelling are directed to small islands (Engelen *et al.*, Chapter 16). Probably the greatest single socio-economic scenario that individual governments must prepare for is a significant international migration of populations from highly vulnerable locales to areas where safety and the quality of life is deemed to be better. To prepare for such future change, a catalogue of institutional responses needs to be developed along with specification of conditions under which those responses should be implemented.

6.4 Synthesis

H.L. Mencken once said 'For every complex problem there is a solution that is simple, neat, and wrong.' With this caveat in mind, an attempt to synthesize much of the implications of climatic changes in the region is given in Table I.1. Three subjective levels of vulnerability to rises in sea level and temperature are chosen and assigned to the ecosystems and socio-economic topics outlined in the *Terms of Reference* (*q.v.* Preface).

While on a site-specific scale many of the estimated impact levels will be different, on a regional scale vulnerability to most climatic changes *per se* is judged low to moderate. However, due to other pressures on the marine environment, and to human efforts to deal with the effects of these pressures, the vulnerability of society to climatic changes increases. In many cases the future impacts on society of non-climatic factors may far exceed those due to climatic changes. It is important, therefore, for policy considerations, to view this synthesis in a proper context, which is, climatic changes will exacerbate environmental changes already ongoing and documented in other studies.

Table 1.1 Implications of climatic changes in the Intra-Americas Sea.*

Terms of Reference	(a) RSL 20 cm	(b) SST 1.5°C
Ecosystem	Level of vulnerability**	
Deltas	H	L
Estuaries	M	M
Wetlands	M	M
Coastal plains	M	L
Coral reefs	L	M
Lagoons	M	M
Mangroves	M	L
Seagrass beds	M	M
Fisheries	L	M
Agriculture	L	L
Forests	L	M
Rivers	L	M
Coastal lakes	L	L
Beaches	H	L
Socio-economic issues		
Coastal zones	L	M
Tourism	H	M
Settlements and structures	M	L
Public health	L	M
Tropical storms	L	H
Human migration	L	M
Cultural heritage	M	L

Notes

*These levels of vulnerability reflect only the WMO/ICSU/UNEP (1985) climate scenario detailed in the *Terms of Reference* (q.v. Preface), and must be considered as issues that exacerbate other problems such as population pressure, pollution, subsidence, coastal erosion, construction, warfare, etc.

** (L) Low impact, (M) Moderate impact, (H) High impact.

7 MODELS OF FUTURE CLIMATE

In Chapter 2, Wigley and Santer give a very detailed discussion of the possible future climate of the Intra-Americas Sea (*cf.* IPCC, 1990a). They compare the results of four numerical models that predict future surface air temperature change and precipitation change for each of the four seasons. Each model calculates the effect on temperature and rainfall of doubling all the greenhouse gases, expressed as doubled CO₂ (2×CO₂). All four numerical models are *global* models, but Wigley and Santer only report the *regional* results of interest herein. Fig. 1.5 from Wigley and Santer (*pers. comm.*) shows the model results for annual mean temperature and annual mean precipitation. Results from atmospheric General Circulation Models (GCMs) for future climate on a regional scale must be interpreted very cautiously because of the limitations in numerically simulating such a complex problem as climate. Cautiously then, the range of annual average *modelled* temperature change (Fig. 1.5a) and annual average *modelled* precipitation change (Fig. 1.5b), are discussed below.

The annual average temperature change caused by effective CO₂-doubling shows a fairly consistent result in each GCM: an increase of 2–4°C is calculated. Details of increased annual average temperature change are different from GCM to GCM, but in general the continental boundaries of the Intra-Americas Sea are modelled to have higher annual average temperatures than the islands. Annual average precipitation changes due to effective CO₂-doubling also shows significant variability between GCMs, but each model shows that the zero contour (in millimetres per day), which runs through the centre of the Caribbean Sea, is the dominate feature of the calculation. Precipitation in the region is strongly influenced by tropical storms, however, which are not in these GCMs.

Although the results shown in Fig. 1.5 vary considerably between GCMs, the general conclusion is in agreement with the WMO/ICSU/UNEP (1985) scenario of rising temperature. Climate, however, is the sum of many geophysical factors, the greenhouse gases only being one of them, and there may be competing factors (particularly on a regional scale) that can modify these modelled results. Human activities such as massive deforestation can alter the balance of factors that add up to Earth's climate, and the prudent observer will interpret the results shown in Fig. 1.5. cautiously

An alternative method of considering future climate is the scenario modelling (Lamb, 1987) discussed earlier. In Chapter 3, oceanographer Gallegos and his colleagues have applied the scenario model to the Intra-Americas Sea. As with Wigley and Santer (Chapter 2), Gallegos *et al.* have focused in on seasonal variability as potentially having a greater short-term implication than the mean (annual) changes. Based on analysis of actual data they foresee larger seasonal fluctuations than at present, a result not dissimilar from the numerical model results. Gallegos *et al.* carry the results of their scenario modelling further, and give indications of the effect of increased intra-season variability on the region's marine waters. They foresee that a few consecutive hot summers have the potential to: readjust coastal sea level, which may affect the fresh-water balance in coastal ecosystems; modify the location and magnitude of shoreline

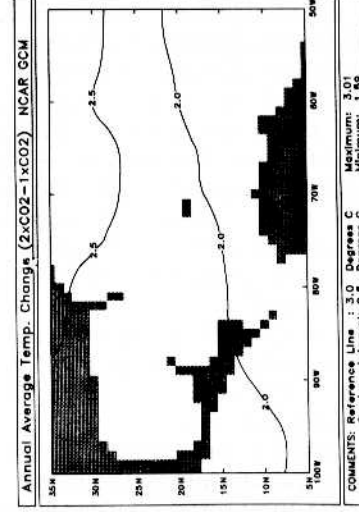
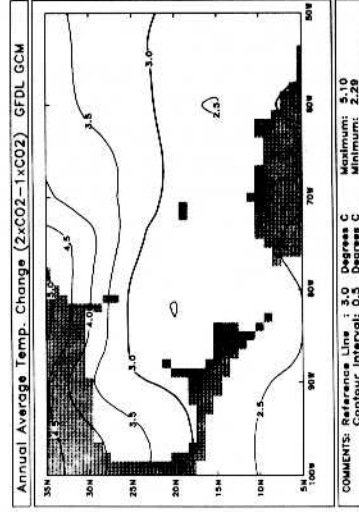
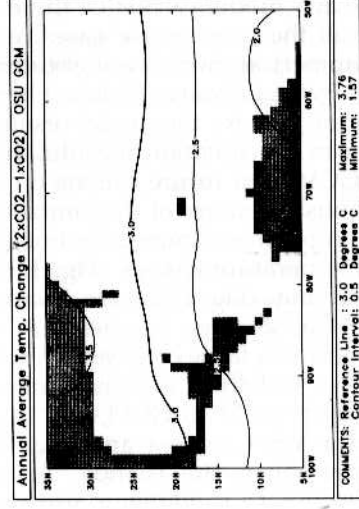
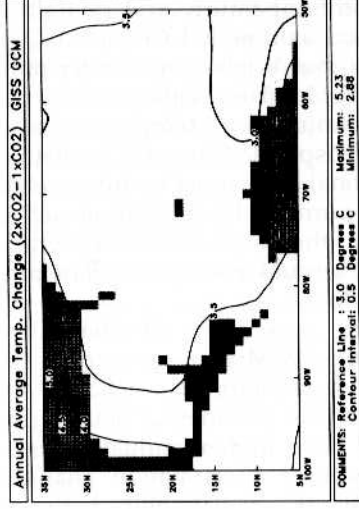


Fig. 1.5a Annual average temperature change due to effective CO₂-doubling from GCMs of the Geophysical Fluid Dynamics Laboratory (GFDL), Goddard Institute for Space Studies (GISS), Oregon State University (OSU), and the National Center for Atmospheric Research (NCAR). Maps courtesy of Wigley and Santer (cf. Chapter 2).

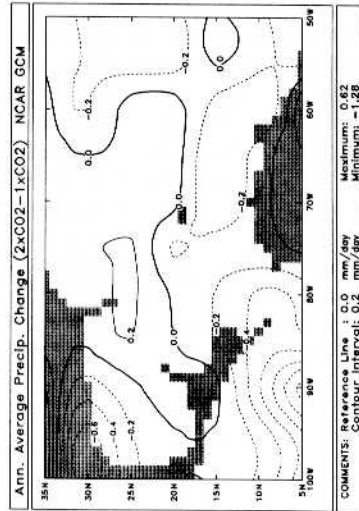
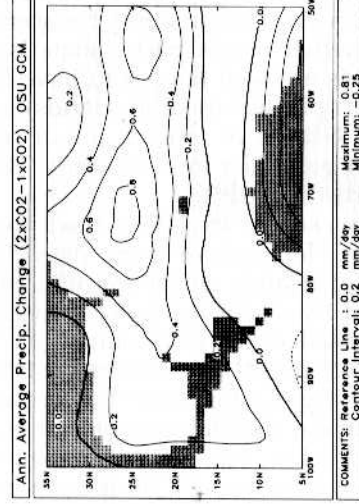
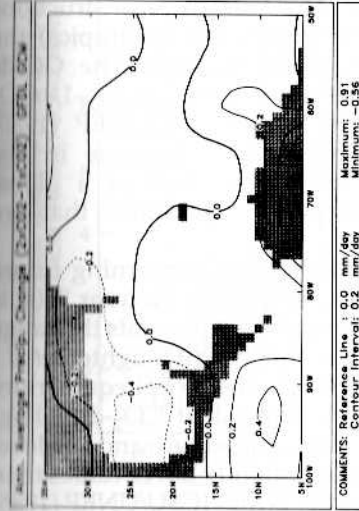
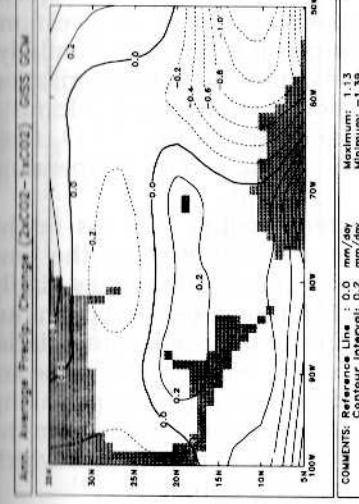


Fig. 1.5b Annual average precipitation change due to effective CO₂-doubling from GCMs of the Geophysical Fluid Dynamics Laboratory (GFDL), Goddard Institute for Space Studies (GISS), Oregon State University (OSU), and the National Center for Atmospheric Research (NCAR). Maps courtesy of Wigley and Santer (cf. Chapter 2).

migration; alter patterns of economically important marine species; cause sufficient changes in surface currents to effect marine transportation and contingency plans for spills of hazardous substances; and reorder air-sea interaction which may shift local weather patterns such as precipitation.

When comparing results from GCMs and from scenario models (cf. Chapters 2 and 3), there are caveats that must be considered. As eloquent as Lamb's (1987) arguments for scenario models are, there are questions as to whether or not past climate is a harbinger of the future. Similarly, the GCMs are well known to have limitations, and the parameterization of certain physics (notably clouds) and unmodelled effects of volcanism (AGU, 1992) are of concern in our confidence of the $2\times\text{CO}_2-1\times\text{CO}_2$ forecasts. Of particular importance is 'How is the global surface temperature change distributed?'

MacCracken *et al.* (1990) have explored temperature patterns in the Northern Hemisphere using paleoclimate reconstructions from the time periods of relative global warmth. MacCracken (pers. comm.) has kindly provided two such reconstructions: the mid-Holocene (6000 ybp) minus the latter half of the 19th century (*q.v.* Fig. 1.2) and the Eemian interglacial optimum (125,000 ybp) minus the latter half of the 19th century; these are shown in Fig. 1.6 for winter (lower panel) and summer (upper panel) along with a similar meridional profile of predicted temperature change from the four GCMs (*q.v.* Fig. 1.5a). For the tropical/subtropical region with which this report is concerned, there are some remarkable differences.

All three profiles show that the surface temperature change will be larger at high latitudes, a pattern consistent with all IPCC forecasts (Houghton *et al.*, 1992). However, both the Holocene and the Eemian reconstructions show that south of about 35°N (i.e., in the tropics and subtropics) the temperature was cooler during periods of global warmth. The GCMs show quite the opposite: warming at all latitudes with $2\times\text{CO}_2-1\times\text{CO}_2$ predictions. Readers are reminded that the WMO/ICSU/UNEP (1985) scenario with which we are dealing is for a 1.5°C increase in the regions surrounding the Intra-Americas Sea that is part of a global 1.5°C increase. Fig. 1.6 leaves us with important questions that are unresolved.

Lest there remain ambivalence in the reader's mind concerning future climate, a global forecast of temperature and sea level to the year 2100 is given in Fig. 1.7. The stippled area for each projection represents the range of uncertainty in the 'best guess' IPCC scenario for 1992 (Houghton *et al.*, 1992) as calculated by Wigley and Raper (1992) for the global equilibrium temperature change ($\Delta T_{2x}=2.5^\circ\text{C}$) due to the equivalent CO_2 -doubling. Based on the revised IPCC estimates, the global temperature and sea level will be 2.5°C and 48 cm higher in 2100 than today, slightly lower values than in the IPCC (1990a) estimates. With respect to the WMO/ICSU/UNEP (1985) scenario dealt with herein (1.5°C and 20 cm by 2025 respectively), Fig. 1.7 suggests that the 1.5°C temperature rise is most likely to occur *c.* 2060, and the 20 cm sea-level rise *c.* 2050. Although the range of uncertainty is much larger at 2100 than at 2050, there is little doubt in the Wigley and Raper (1992) calculation that by the middle of the next century, a warmer Earth is expected, but forecasting the ΔT_{2x} scenario on a regional basis is fraught with additional uncertainty.

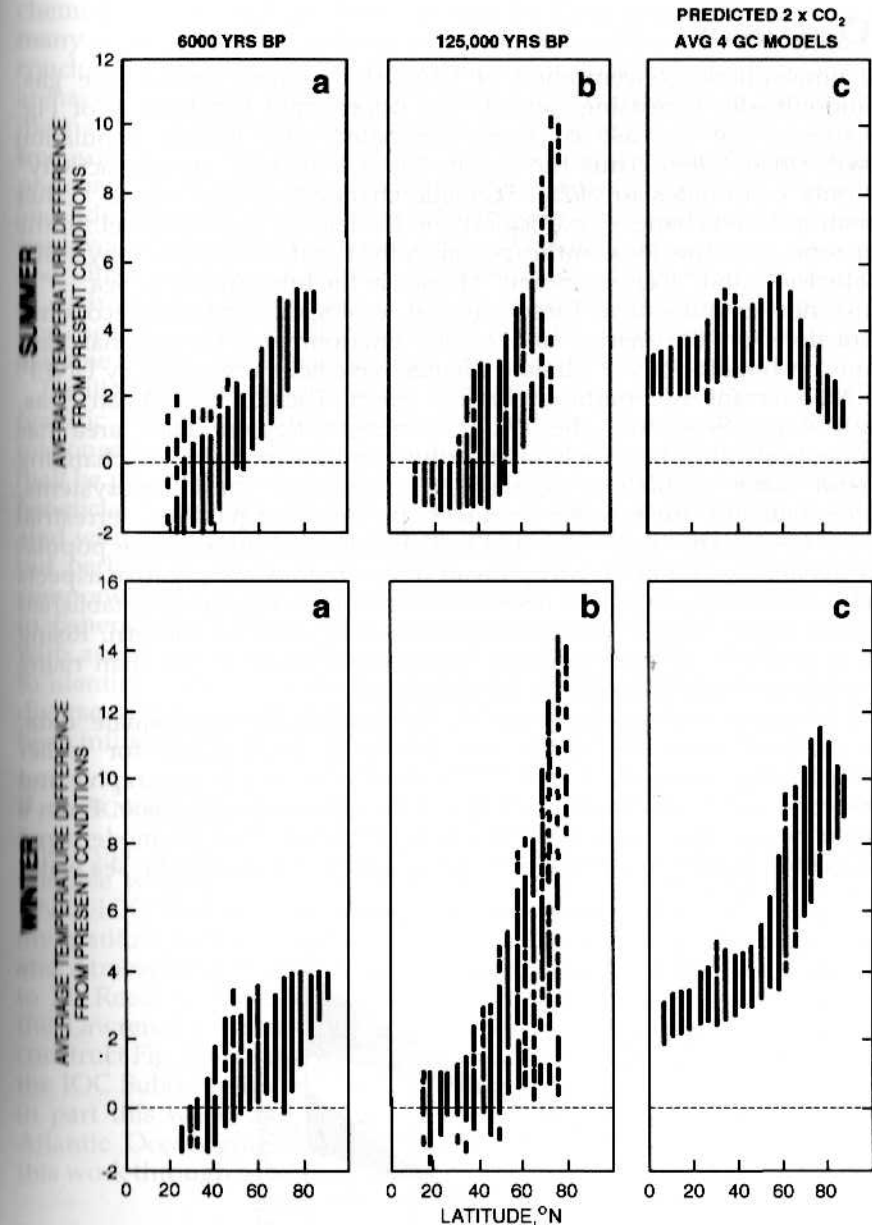


Fig. 1.6 Paleoclimate and greenhouse model comparisons of the meridional profile of seasonal average surface temperature in the Northern Hemisphere. (a) Holocene minus latter half of the 19th century; (b) Eemian minus latter half of the 19th century; (c) average predicted from four GCMs of $2\times\text{CO}_2-1\times\text{CO}_2$. From MacCracken (pers. comm.) following an analysis in MacCracken *et al.* (1990).

8 CONCLUSION

The atmospheric concentration of CO₂, the primary greenhouse gas, is undoubtedly increasing, and as the upper right hand panel of Fig. 1.4 shows, the increase is clearly associated with human population growth (Idso, 1989). Thus the box in Fig. 1.4 marked "human activity" not only contributes to global "climatic changes", it also causes "other human-induced changes" particularly on the local or regional level. In the near term, it is this local anthropogenic effect that dominates "physical", "ecological", and "socio-economic" change in the Intra-Americas Sea.

In order to understand these physical, ecological, and socio-economic interactions on the marine and coastal environment, six regional Task Teams on Implications of Climate Change have been organized by UNEP: the Mediterranean, Southeast Pacific, South Pacific, East Asian Seas, South Asian Seas, and the Wider Caribbean Region. Each area has unique problems, but each shares the common concern of changing air and water circulation, coastal geomorphology, coastal ecosystems, soil degradation, fresh-water resources, precipitation patterns, terrestrial ecosystems, coastal industries and settlements, and littoral zone population dynamics. The underlying thread often emphasizes negative aspects of climate change; this isn't necessarily universal. Whenever established patterns are disturbed, vested interests tend to exhibit a concern. Rising RSL is probably of more concern in the Intra-Americas Sea than rising temperature, but it is too early to be definitive.

Of primary concern, however, is the availability of adequate data. The sea-level network, which was briefly in good repair for earlier regional programmes such as BOMEX (the Barbados Oceanographic and Meteorological Experiment) in 1969, is now marginally adequate. From a climate perspective, a sea-level observing network must be modernized and include marine meteorological data, geodetic levelling data, sea water

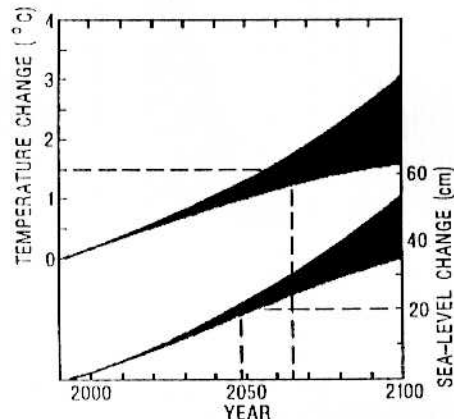


Fig. 1.7 Global temperature (upper curves) and sea-level (lower curves) projections for the various IPCC 1992 scenarios. A range of projections within each stippled area are calculated for the 'best-guess' sets of ice-melt and climate models. Redrawn from Wigley and Raper (1992), the projections only show the anthropogenic component of a future climate, with natural variability superimposed on them.

chemistry data, and ancillary site-specific information. Because of the many short records of sea level and weather, and the difficulty of making conclusions based on them, a concurrent programme of geological, archaeological, and historical data analysis is considered a cost-effective means of strengthening those conclusions. There must also be rapid and free exchange of the observations, a basin-wide commitment to common problems, a responsibility to calibrate and intercompare measurements, and adequate sustained funding. Establishing and *maintaining* a modern sea-level/weather observing network is absolutely necessary to document and ultimately forecast climate-change impacts. Of particular importance in such an observing system is the ability to record extrema in precipitation, sea level, and in temperature of both the water and air; it is in the extreme events that climate-change impact may be most noticeable.

Finally, we choose not to argue for wholly negative impacts. There is a realistic expectation that certain positive benefits may accrue; the local response to global change is simply not predictable at this time. What may be perceived as negative to one sector of society in the region may be beneficial to another. Two examples: (1) a change in precipitation associated with a temperature rise may allow the introduction of different crops but perhaps at the sacrifice of others; (2) an increase in the alongshore component of the wind could increase coastal upwelling and be a benefit to fisheries, yet it may be a cause for concern to agronomists dealing with aerial erosion. A truly challenging and interesting problem will be to identify and explore the legal and institutional implications under the diverse systems and governments which characterize a region that has been influenced by so many native, African, and European cultures.

9 ACKNOWLEDGEMENTS

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Part 2

Modelling climate change