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Ecosystem and Socioeconomic Response to Future Climatic Conditions in the Marine and Coastal Regions of the Caribbean Sea, Gulf of Mexico, Bahamas, and the Northeast Coast of South America

[Prepared by: George A. Maul, Chairman
UNEP/IOC Task Team
on Implications of Climatic Changes in the Wider Caribbean Region.]

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ABSTRACT

Global climate change, and particularly the impact of human activities on Earth's biogeographical environment, is of enormous socioeconomic 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 report summarizes the opinion of a Task Team of 23 experts concerning the implications of climate change in the Intra-Americas Sea (Gulf of Mexico - Caribbean Sea -Bahamas - Bermuda - Guianas), of a global 1.5°C temperature and 20 cm sea level rise by the year 2025. For some ecosystems in the region, 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 socioeconomic 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 socioeconomic 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 climatic 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 of climatic change, tools that will give decision makers quantitative information upon which to base new policies for management.

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; Lamb, 1982). Yet in the year of the quincentennial of the European discovery of the Caribbean Sea (*cf.* Van Sertima, 1976, 1992 for discussions on African and Chinese visits ca. 1000 B.C.), precious little more is known about climate in the region than what the early European explorers told their sponsors. Assessing the impact of climate *change* then becomes a particularly challenging problem.

The area of concern encompasses the marginal or semi-enclosed seas of the tropical and subtropical western North Atlantic Ocean: the Caribbean Sea, the northeast coast of South America (excluding Brazil), the Gulf of Mexico, the Bahamas, and (biogeographic ally) Bermuda. This area is called the "Wider Caribbean Region" by the United Nations Environment Programme (UNEP) and is also called the "Caribbean Sea and Adjacent Regions" by the Intergovernmental Oceanographic Commission (IOC) of UNESCO and its Subcommission IOCARIBE. Early oceanographers mistakenly called it the "American Mediterranean," but the author prefers the term "Intra-Americas Sea" to emphasize its unique and *interrelated* geography, climate, and culture.

This study emphasizes the marine and coastal environment and addresses the implications of climatic change in the Intra-Americas Sea and its environs. To facilitate understanding the technical terms of this report, a glossary (abbreviated from Maul and Baig, 1993) is included as an appendix. As was the perspective of the early European and African explorers, the report is limited to a sailor's view of the coastline, reefs, passages, harbors, deltas, estuaries, and deep waters of this semi-enclosed sea (Figure 1). Nevertheless, such a perspective presents a formidable challenge involving meteorology, oceanography, geology, economics, sociology, medicine, law and ecology.

To address such challenges, UNEP was founded in 1972, and within two years established its Regional Seas Programme. An action plan for the Caribbean Environment Programme was adopted in 198 1, and five years later the Regional Coordinating Unit (RCU), in consultation with the IOC and 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 1985 meeting in Villach, Austria (WMO/ICSU/UNEP, 1986), 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.

Climate in marginal seas such as the Intra-Americas Sea is linked to the global system by the air and water that flows over or through the region. The global system is driven by incoming solar radiation and outgoing Earth radiation; Figure 2 is a sketch of the radiative balance and the interactions with components of the system. The role of the air and ocean is to distribute the heat received from the sun, principally from the warm equatorial regions where there is an excess of heat to the poles where there is a deficit. Warm ocean surface currents pass through the Intra-Americas Sea, eventually loosing heat to the atmosphere as they travel toward Europe where they sink and return as deep water flowing into the South Atlantic at about 1500-4500 m depth along the eastern margin of the Bahamas and Caribbean Sea. Figure 2 also shows some of the principal mechanisms involved in the global system such as solar radiation, clouds, greenhouse gases (principally H_2O water vapor, and CO_2, carbon dioxide), ice, volcanos, river runoff, land type (forests, deserts, cultivation, *etc.*), and the thermodynamic effects of heat exchange between water, land, ice, and the atmosphere. Human intervention enters the global system through increasing the amount of greenhouse gases (mostly through the respiration of civilization, *i.e.* $C0_2$ production, methane, and CFC's) changing of land features (*i.e.* deforestation, construction, agriculture), and affecting the quantity and quality of riverine inputs.

Figure 1. Reproduction of an early 18th century sea chart published by Gerard van Keulen.

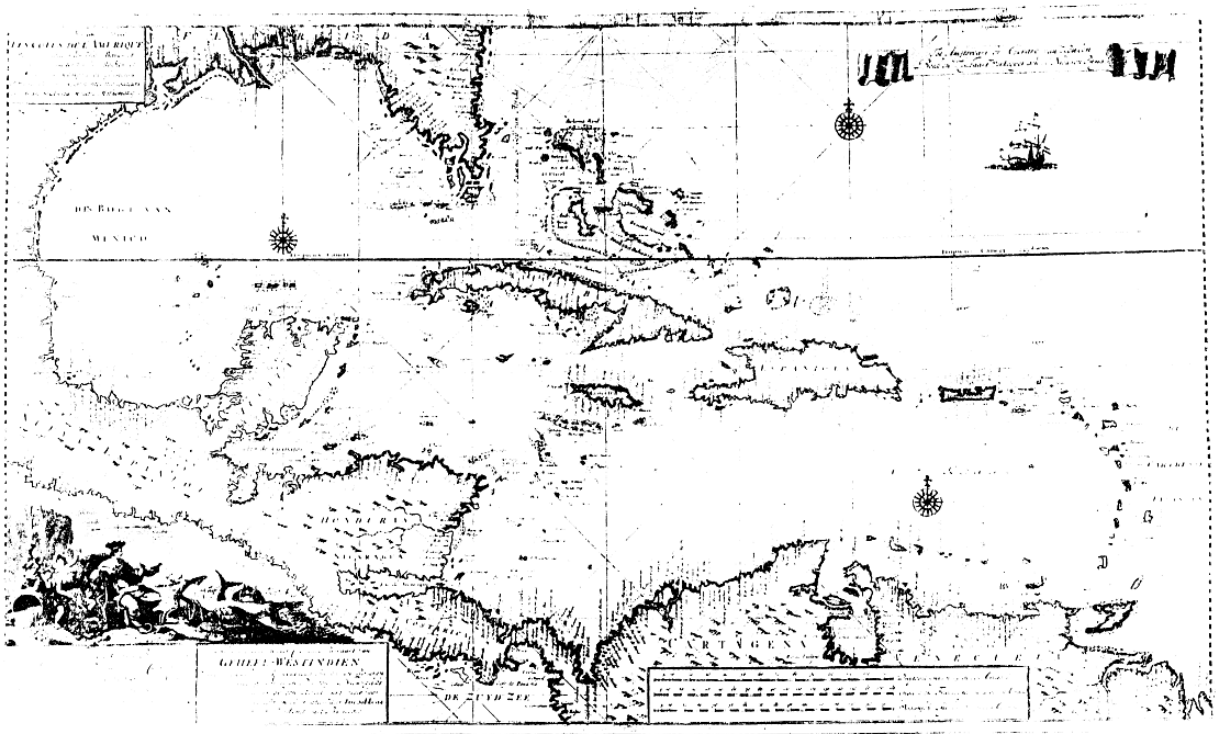

Figure 1. Reproduction of an early 18th century sea chart published by Gerard van Keulen. Translated from the French, the title reads: "New Sea Chart of all THE COASTS OF AMERICA Showing all the Islands Bays, and Rivers, as well as the Rocks and Deeps, entirely composed from many Accounts of Very Experienced navigators by Jean Sikkena Master of Mathematics." © 1991 Friends of the University of Miami Library, used by permission.

Figure 2. Schematic illustration of the components of the coupled atmosphere-ice-land-ocean climate system.

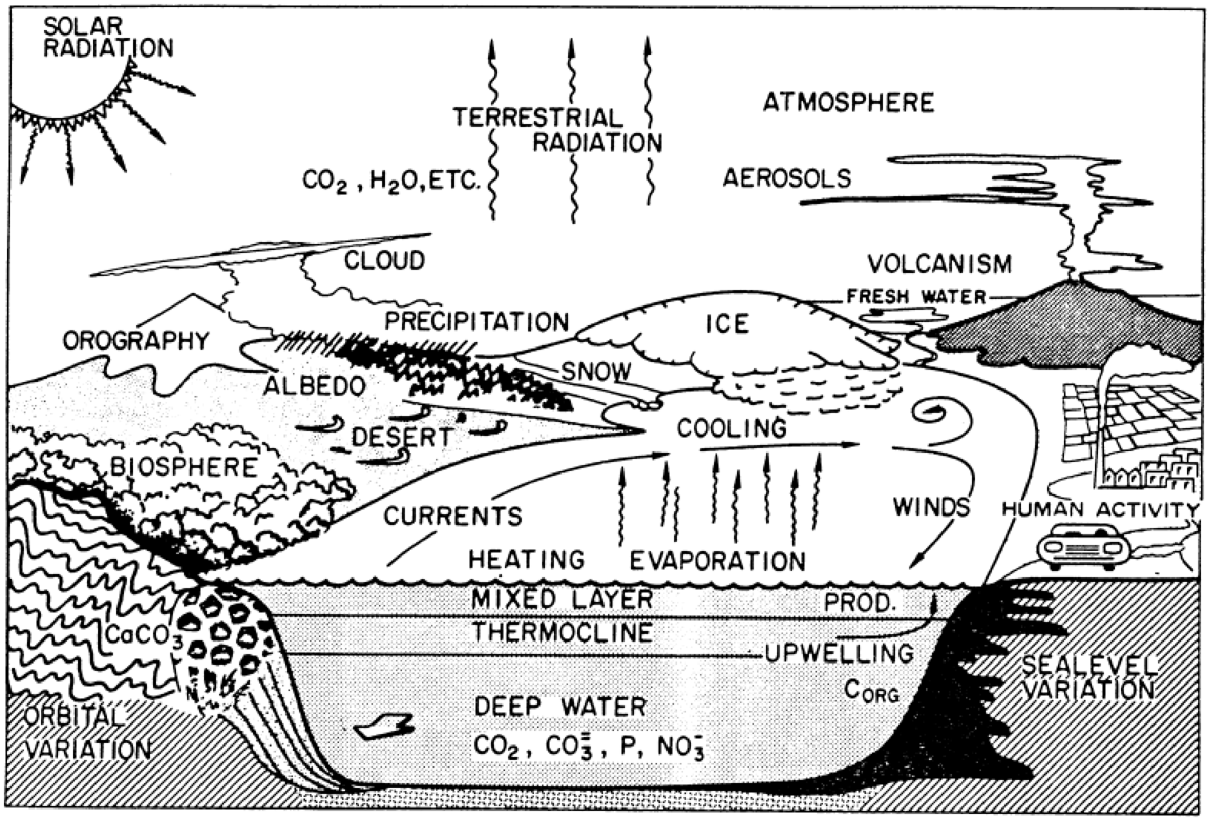

Figure 2. Schematic illustration of the components of the coupled atmosphere-ice-land-ocean climate system. See Appendix for definitions of the chemical symbols and other terms. In addition to natural variability in the components of the climate system (atmosphere, hydrosphere, cryosphere, geosphere, and biosphere), human activity is both directly and indirectly causing complex additional variability. From Berger and Labeyrie (1987).

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Although in a regional sense each of the factors illustrated in Figure 2 are operative, it is locally where the anthropogenic effects are most noticeable. For semantic reasons it might be better to think of climate change as a global phenomenon with regional implications, and to think of environmental change as a regional issue with global implications. It is at the regional and local level that human activities are most identifiable and approachable in terms of effecting meaningful immediate change. For example, the surface waters of the Intra-Americas Sea carry heat from the South Atlantic Ocean to Europe through the Caribbean Current, the Yucatan Current, the (Gulf of Mexico) Loop Current, the Florida Current, and the Gulf Stream; the same waters carry pesticides, tarballs, flotsam and jetsam that wash up on the beaches of the region that are so important to our tourism industry. So, while understanding the role of our oceanic waters is crucial to predicting Earth's climate, it is the influences of those same waters that affect our local economy and the health of many marine industries.

The Intra-Americas Sea is unique in that it is the genesis of a western boundary current, the Gulf Stream System. On the other hand it is similar to other marginal seas such as the Mediterranean Sea in that it is strongly influenced by rivers. Figure 3 (from Müller-Karger, 1993) is a composite of satellite-derived ocean surface pigment concentrations, that shows the interaction of the five largest rivers (the Amazon, the Orinoco, the Magdalena, the Rio Grande, and the Mississippi) plus the myriad of smaller rivers, and the ocean currents. Off *the Amazon,* the river waters can be seen to turn clockwise and advect towards Africa in the North Equatorial Counter Current: Orinoco River water can be traced across the eastern Caribbean Sea all the way to Puerto Rico and Hispaniola; a plume of the Mississippi River can be observed almost to the Florida Keys (it has been studied as far north as the Carolinas at other times); a large Loop Current eddy is seen south of the Rio Grande carrying its waters into the western Gulf of Mexico. The interaction of our rivers with these very strong oceanic currents is quite unique in the world ocean, and is of special interest in the context of the health of the marine environment. If there are changes in the *local* climate, the rivers will be affected.

Figure 3. October 1979 monthly mean pigment concentration field from CZCS satellite imagery.

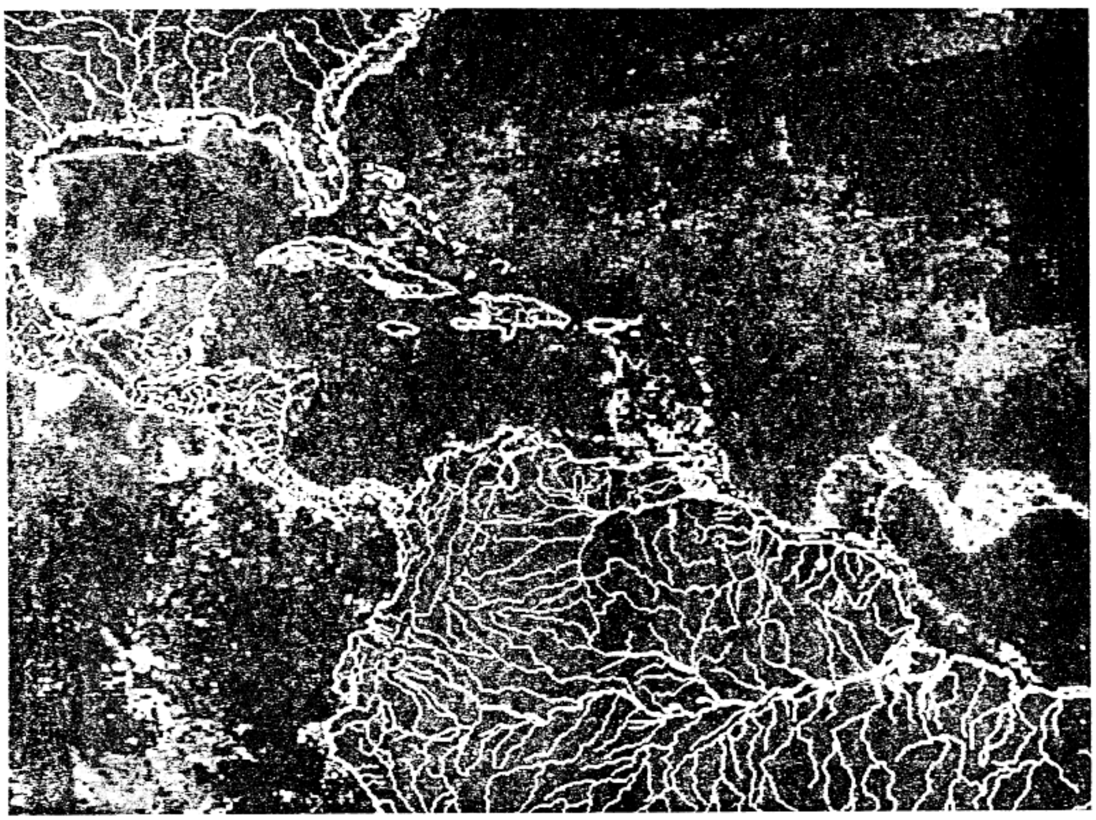

Figure 3. October 1979 monthly mean pigment concentration field from CZCS satellite imagery. Original color coded figure showed warm colors (yellow, orange, and red) representing high pigment concentration or other colored material in river plumes and shallow water, and cooler shades (purple, blue, and green) representing low concentrations; black in the original color plate represented no data, due either to cloud cover or lack of coverage; brown in the original represented land. Rivers that affect the region have been outlined using World Database II files. From Müller-Karger (1993).

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There is little doubt however that *global* 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 who made records 500 years ago, that we explore the uncharted seas of the implications of climate change.

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 1985 WMO/ICSU/UNEP meeting in Villach, Austria (see Table 1). At Villach, an equilibrium global warming of 1.5-4.5°C and a global sea level rise of 20-140 cm was forecast 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, the Task Team for the Wider Caribbean Region 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 quick 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, 1986) is the baseline scenario. The lower values are chosen because by 2025 it is not expected that climatic equilibrium to C02 doubling will have been reached due to the thermal inertia of the oceans (IPCC, 1990a). 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 (Hanson and Maul, 1993) 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 (1990) 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°C to PC 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" (*q.v.*, Appendix). Climate is understood to be limited to the time averaged meteorological and oceanographic conditions of the marine and coastal environment in the Intra-Americas Sea; 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.

Table 1. Terms of Reference

The study covers the marine environment and the adjacent coastal areas influenced by or influencing the marine environment. The terms of reference of the study are:

- to examine the possible effects of sea level changes on the coastal ecosystems (deltas, estuaries, wetlands, coastal plains, coral reefs, mangroves, *etc*.);
- to examine the possible effects of temperature elevations on the terrestrial and aquatic ecosystems, including possible effects on economically important species;
- to examine the possible effects of climatic, physiographic and ecological changes on the socioeconomic structure and activities;
- to determine areas or systems most vulnerable to the above changes; and
- to prepare a comprehensive, well-documented report reflecting the points above.

This and other studies are based on: a) the best available existing knowledge about and insight into the problems relevant to the subject of the study; b) assumptions accepted at the International Conference in Villach, 9-15 October 1985 with the understanding that these estimates will be revised on the basis of regional scenarios yet to be developed); and c) several detailed case studies, which constitute in part, the material used to prepare this summary.

Temperature Rise of 1.5°C by 2025

Climatologists use a variety of means to describe Earth's past climate. In the U.S. 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 1,000 years (Figure 4), show that Earth's temperatures have varied significantly since the fifteenth 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 1,000 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 Figure 4), the decades of 1940-1970 had declining temperatures. Translating the global records such as shown in Figure 4 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 Figure 4 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 5,000 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 1985 WMO/ICSU/UNEP 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 (1993) decided to analyze 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 (1993) 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 (1993), based on records from 1951-1986, reports an air temperature trend of +0.1°C /decade in Venezuela. 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 LOT rise by 2025 appears to be a more plausible picture of our future temperature.

Figure 4. Temperature change for the last 10,000 years and 1,000 years based on records in Europe (upper two panels; redrawn from IPCC (1990a) and NAS (1975), respectively), and a global estimate (lower panel; from Hansen and Lebedeff, 1988).

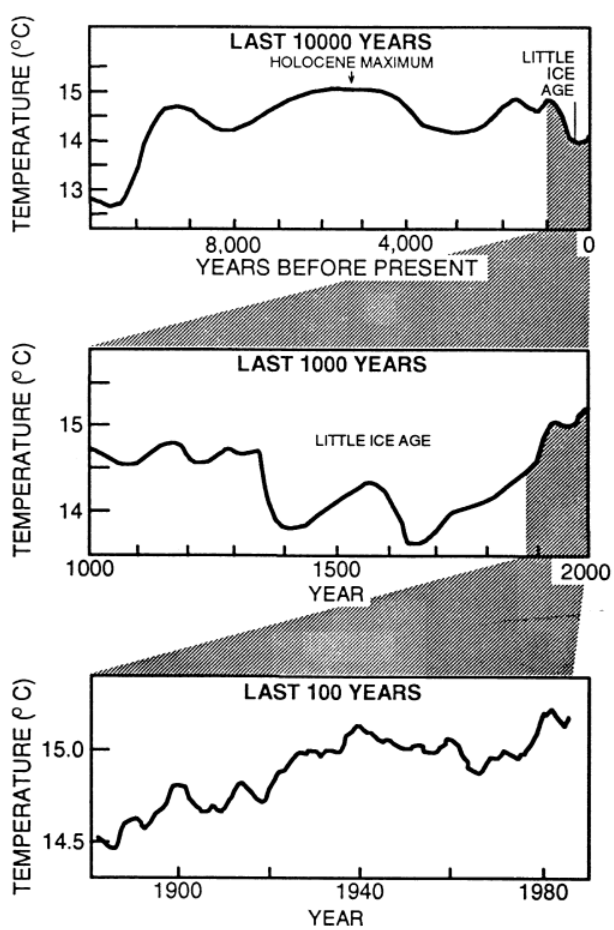
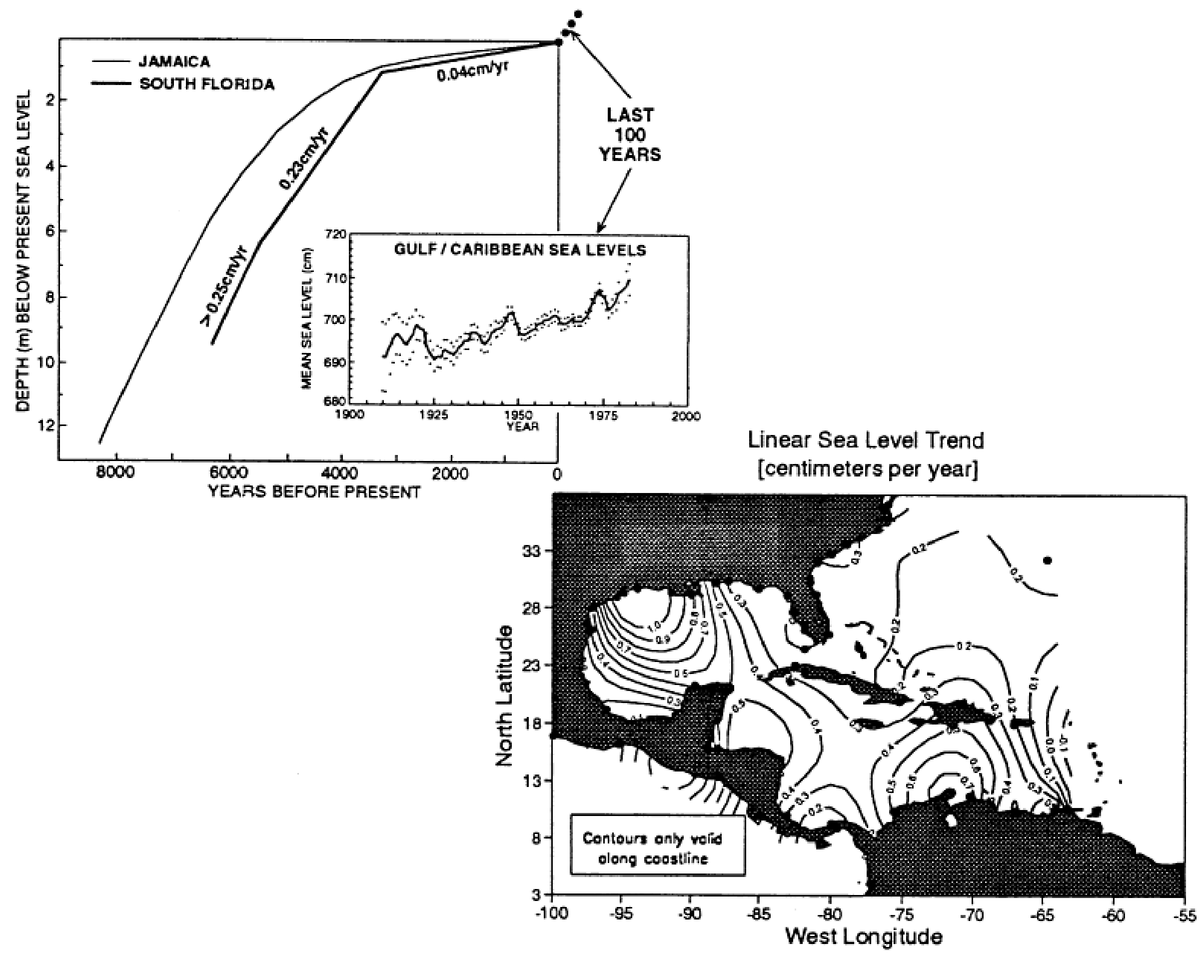


Figure 4. **Temperature change for the last 10,000 years and 1,000 years based on records in Europe (upper two panels; redrawn from IPCC (1990a) and NAS (1975), respectively), and a global estimate (lower panel; from Hansen and Lebedeff, 1988). Temperature scale for the upper two panels is only approximate 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 Hansen and Lebedeff (1988) and gives references related to the issue (*cf.* Wigley and Santer, 1993; Gallegos *et al.*, 1993).**

Temperature scale for the 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 Hansen and Lebedeff (1988) and gives references related to the issue (*cf.* Wigley and Santer, 1993; Gallegos et at., 1993).

Figure 5. 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 30 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. Panel in lower right shows range of linear trends for PSMSL RLR records ^{3} 19 years long (from Hanson and Maul, 1993).



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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 (1986) scenario into perspective. The remarkably slow rate of sea level rise in South Florida and in Jamaica during the last 3,200 years (only about 0.04 cm/yr; Figure 5; *cf.* Hendry, 1993) allowed many shorelines to stabilize or to expand, and many shallow marine environments to build. However, since the early 1930's, sea level records from many sites around Florida show much faster rates of sea level rise, very similar to the rate during the period 3,200-5,500 years ago, when there was a rapid retreat of the shoreline. The data in Figure 5 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 modem historical record of the Intra-Americas Sea support the WMO/ICSU/UNEP (1986) scenario of a 20 cm sea level rise by the year 2025? To answer this question, the highest quality (revised local reference) data on file with the Permanent Service for Mean Sea Level (PSMSL) were studied by Hanson and Maul (1993) and Hendry (1993) for the Intra-Americas Sea, and from Venezuelan records by Aparicio (1993) 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 1,000 m of the water column east of Abaco Island (Bahamas) for 1950-1987 was +0.14 cm/yr, 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.* (1993) and Mercado *et al.* (1993) 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. 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, 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, but it may be 10 years before such calculations are possible. To further complicate the issue, Chao (1991) argues that sea level should have fallen by about 7 cm in the last 100 years due to the building of reservoirs for irrigation and water control (humankind is building more than 500 15-m high dams per year). In the interim, thoughtful extrapolation of the PSMSL observations, in concert with a vigorous modelling activity, will give the most plausible estimates of future sea level.

EFFECTS OF SEA LEVEL CHANGES ON COASTAL ECOSYSTEMS

The first task in the Terms of Reference (*q.v.*, Table 1) is to examine the possible effects of sea level changes on the coastal ecosystems. Gable (1993) gives an overview of the ecosystems in the region, and *Oceanus (1987/1988)* is an issue devoted to Caribbean 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, *1993),* sea level rise is less than the 0.5 cm/yr implied by the assumptions at the 1985 International Conference in Villach, and in the last 3,000 years RSL rise has been almost nil *(q.v.,* Figure 5). All other factors being equal, 0.5 cm/yr (20 cm between 1985 and 2025) is a very rapid rise and is expected to place an unusual stress on coastal ecosystems.

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); *q.v.*, Figure 3. Deltas (Müller-Karger, 1993), 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 meters horizontally for each centimeter RSL rise; this translates into thousands of hectares of lost land. The problem is exacerbated by potential increased tropical storm activity (Gray, 1993), since most shoreline erosion occurs during storms, and by subsidence such as in the case of Louisiana. However, Mercado *et al.* (1993) argue that the 20 cm RSL rise scenario will be of no practical consequence on storm surge models (such as SLOSH; *cf.* Mercado *et al*., 1993), as far as it might introduce increased surge heights. Delta benthic systems 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.

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.,* 1993). 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. 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 Florida; the estuary of Port au Prince; and the western Gulf of Honduras. Coastal lagoons, salinas and estuaries, depending on their location, all could suffer from saline intrusion, but lagoons should be able to support their usual nurseries; salinas on the other hand (Vicente *et al.*, 1993), could be flooded over continuously and lose their economic value.

Wetlands

The ability of wetlands 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 5,000 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 wetlands into the marine environment (Hendry, 1993), wetlands will be submerged and lost to productivity. Where wetlands are bounded by steep-sided basins, as is the case in many of the Caribbean 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 wetlands economies such as shellfish industries is expected to occur with the 20 cm RSL rise scenario (Snedaker, 1993).

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.*, 1993). 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 U.S. Texas-Louisiana coast, are coastal plains areas most vulnerable to flooding from sea level rise and storms.

Coral Reefs

The second largest coral reef system in the world dominates the offshore area of the western Caribbean Sea (Milliman, 1993), and all but the northern Gulf coast have extensive reef systems. Growth of individual coral organisms is estimated between 1-20 cm/yr (Vicente *et al*., 1993), and reef growth rates as a whole are known to be up to 1.5 cm/yr (Hendry, 1993). 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, souvenir-hunting, rainfall, radiation, turbidity**,** overfishing, mass mortality in algal grazers, *etc*.) may prevent some 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.

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*., 1993). The five species comprising the mangrove flora of the region 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 sulfate reducing microorganisms, it is postulated that mangroves can keep pace with RSL in rainfed 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, 1993). Notwithstanding the current high rate of regional mangrove loss by overcutting, land clearing and habitat conversion suggests that global climate change is a minor factor in considerations of the fate of this regionally important coastal habitat.

Seagrass Beds

Seagrasses are a benthic environment throughout the region that are important in stabilizing bottom sediments, serve as nurseries for juveniles, and 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*., 1993), 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.

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 (Müller-Karger, 1993). 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 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.

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, Florida (U.S.A.), 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 (1993) find no evidence for changes in precipitation at Key West during the last 101 years; similarly, Aparicio (1993) finds none along the southern Caribbean. In the Intra-Americas Sea, Gray (1993) finds decreased rainfall in the last 20 years, which he associates with decreased hurricane activity. An increase of 1.5°C in sea surface temperature could increase the number of hurricanes by as much as 4.0% (Gray, 1993), and the maximum wind speed by 8%; Shapiro (1982) is quick to point out a considerable uncertainty in these numbers (40% increase means on average +1.6 ± 1.2 hurricanes/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.

Many people argue that recent major hurricanes such as Gilbert (Figure 6) in 1988, or Andrew in 1992, are examples of global warming causing more powerful storms. However, there is no scientific evidence that increased sea surface temperatures (SST) are causing such storms, in fact the average SST of the Caribbean Sea is steady (or perhaps slightly decreasing) over the last 40 years or so. Gray (1993) shows that the number of tropical storms originating in the Caribbean Sea are fewer in number during the last three decades than during the 1935-1955 period, and leaves open the question of whether or not we are seeing natural cyclical changes in the storm patterns and strengths.

In the sense that Lamb (1987) develops climate change scenarios as plausible future events, Gray argues for the following likely effects (*cf.* Gallegos *et al.*, 1993; Aparicio, 1993):

- rainfall will continue to decrease;
- air temperatures will continue to rise;
- surface wind speed will continue to increase; and
- evaporation will 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 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.* (1993) and Hendry (1993) see no clear indication of a significant change in storm surges or waves associated with elevated temperature. With these thoughts in mind, the second item in the Terms of Reference *(q.v.,* Table 1), "effects of temperature elevation on the ecosystem, including on economically important species" is considered *(cf.* IPCC, 1990b).

Figure 6. Satellite infrared image of Hurricane Gilbert observed at 13 September 1988 by the Geostationary Operational Environmental Satellite (GOES-7).

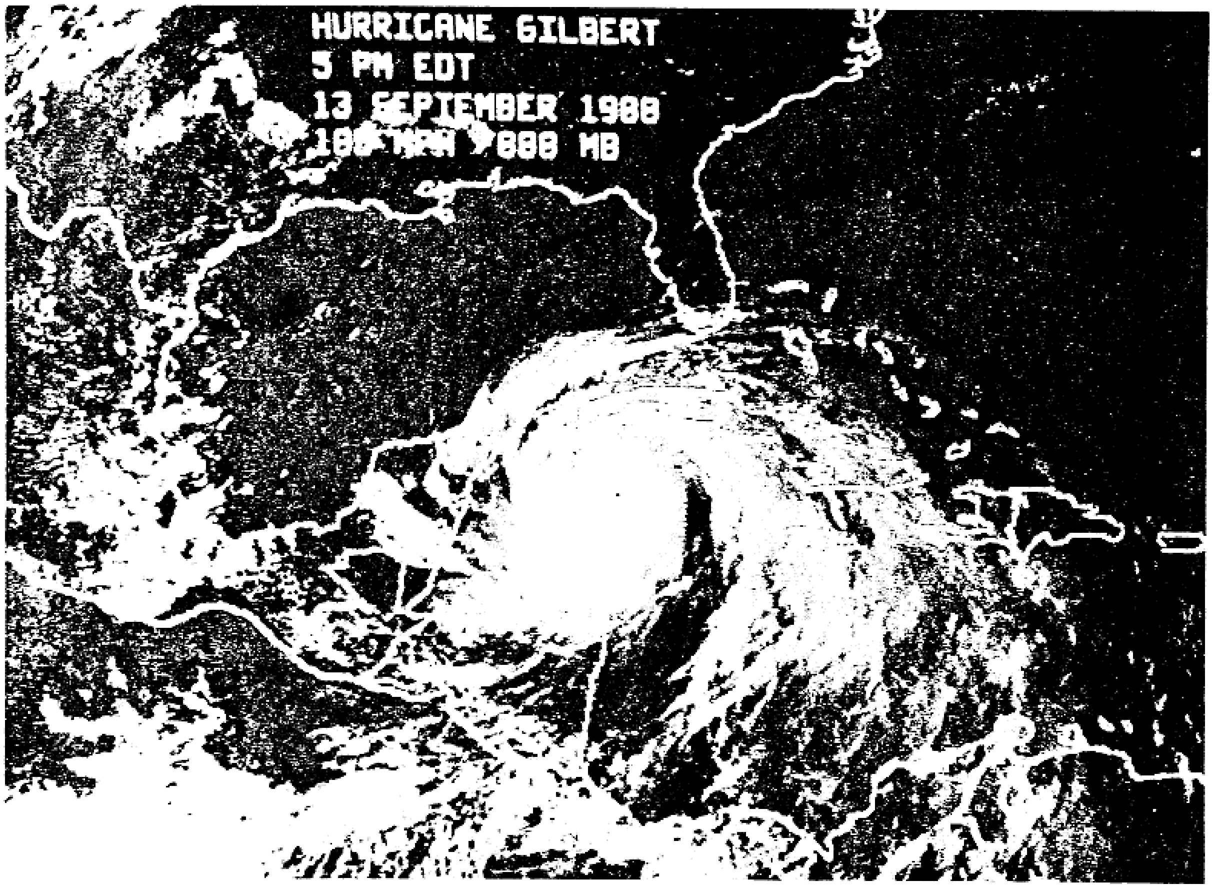

Figure 6. Satellite infrared image of Hurricane Gilbert observed at 13 September 1988 by the Geostationary Operational Environmental Satellite (GOES-7). Hurricane Gilbert was the most intense Atlantic tropical storm on record, causing 318 deaths (202 in Mexico alone) and US$ 5,000,000,000 in estimated damages. At NOAA aircraft flight altitude (10,000 feet or 3,000 m) the maximum wind gusts were 173 knots (89 m/s) and the central pressure was 888 mb. Hurricane Andrew in 1992 caused US $20,000,000,000 in damage, far exceeding Gilbert because it struck the heavily populated Miami, Florida area and then the southwestern Louisiana region.

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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.* (1993) argue that it is unlikely that inland and hilly forests will be affected much by increased temperature, although Gray (1993) 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.*, 1993).

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 (viz. the 1983 and 1987 bleaching events), but it is expected that other environmental stresses will be more important (D'Elia *et al.*, 1991; Milliman, 1993). 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 likely cause unmeasurable results (Snedaker, 1993). Similarly, only seagrass beds located in thermal stress situations already (*i.e.*, in shallow lagoons or near power plant effluents) are expected to become negatively affected by the projected WMO/ICSU/UNEP (1986) temperature rise.

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 Suriname, Guyana and French Guiana (Gable, 1993). 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, 1993) or other oceanic circulation changes, (Gallegos *et al.*, 1993) and thus to increased productivity (*cf.* Vicente *et al.*, 1993).

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 (W. Richards, NOAA/NMFS, pers. comm.). Extremes in temperature usually are averaged out in climate analysis, but with increased temperature, the likelihood of "hot snaps" increases; the 1987 Caribbean coral bleaching event was attributed to "hot snaps" by some researchers (Milliman, 1993). 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.

POSSIBLE SOCIOECONOMIC CHANGES

Climate change will have socioeconomic 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 summarized in Figure 7, showing the numerous pathways possible in complex social systems (*cf.* Alm *et al.*, 1993; Engelen *et al.*, 1993) and showing that the generic effect of human activity is the strongly linear relation between human population and atmospheric C02 concentration (Idso, 1989). The smaller or the more coastal- oriented an economy is, the greater will be the impact of sea level rise (Alm *et al.*, 1993). 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 (raising 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.*, 1993).

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 socioeconomic 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.

Fisheries and Coastal Zones

Most fishing in the coastal zone in the region is artisanal except for a few larger industries such as the menhaden fishery in the Gulf of Mexico. The WMO/ICSU/UNEP (1986) scenario of 1.5°C and 20 cm increases by 2025 AD 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.*, 1993). 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.

Figure 7. Pathways in socioeconomic aspects of the climate change problem

(from Alm *et al.*, 1988; populations vs. CO, (1650-1990 AD) redrawn from Idso, 1989). The full complexities are further discussed in Alm *et al.*, 1993 and Engelen *et al.*, **1993, but the interested reader is also referred to IPCC (1990b) for impact assessments and IPCC (1990c) for response strategies.**

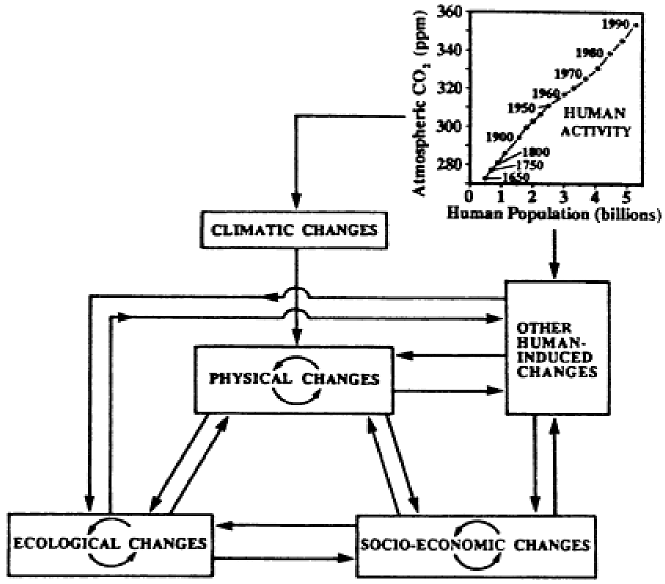


Figure 7. Pathways in socioeconomic aspects of the climate change problem (from Alm *et al.*, 1988; populations *vs.* CO_2 (1650-1990 AD) redrawn from Idso, 1989). The full complexities are further discussed in Alm *et al.*, 1993 and Engelen *et al.*, 1993, but the interested reader is also referred to IPCC (1990b) for impact assessments and IPCC (1990c) for response strategies.

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, 1993). 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, represents a principal socioeconomic 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) already are considered important. Indirect socioeconomic effects on tourism due to increasing pollution, coral reef mortality and storm damage are also involved.

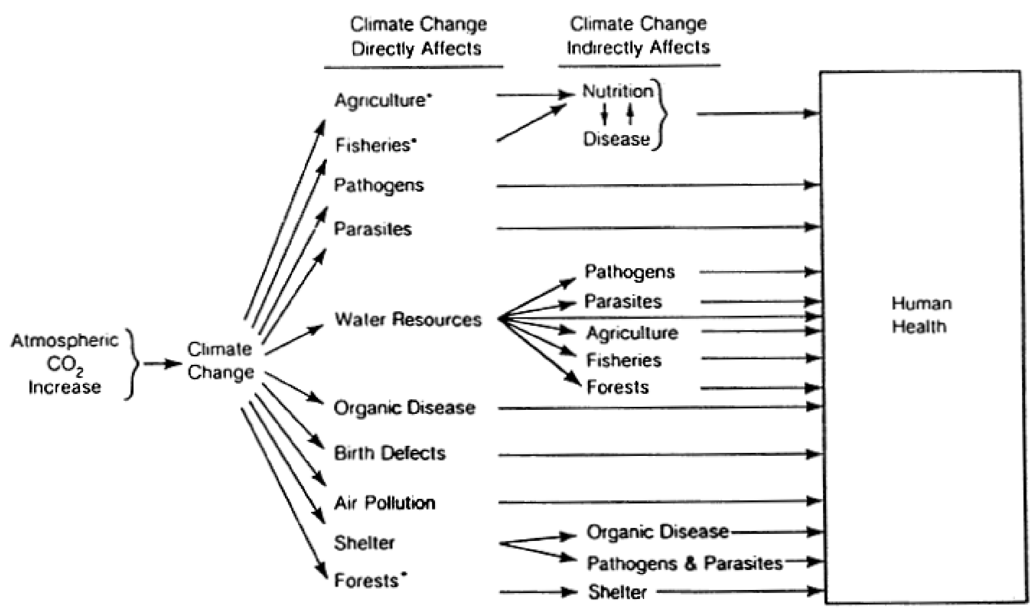
Settlements and Structures

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 socioeconomic impact of a 20 cm sea level rise is not considered serious (Alm *et al.*, 1993). 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 coastal cities of Guyana and Belize (Vicente *et al.*, 1993). The most damaging socioeconomic aspect is climate change coupled with population growth and migration to coastal cities. Oftentimes 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).

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 (Figure 8; de Sylva, 1993). If higher temperatures are coupled with higher humidity as Gray (1993) expects, 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, 1993). Socioeconomic 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.

Figure 8. Pathways by which C02-induced climate change may affect human health (from de Sylva, 1993).



*Agriculture and forests may also be directly affected by an increase in the concentration of atmospheric CO_2. Fisheries may be affected by CO_2-induced changes in ocean chemistry.

Figure 8. Pathways by which CO_2-induced climate change may affect human health (from de Sylva, 1993).

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, Table 1; *cf.* IPCC, 1990b), and their impact on ecological and socioeconomic structures and activities, three broad topics are addressed: Physical Processes; Ecological Aspects; and Socioeconomic 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 to the Task Team 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" (PC) technology.

- Reduce uncertainties in the regional impact of the global 1.5ºC/20 cm scenario by data generation, case studies, and modelling, obtaining improved 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.

Physical Processes

Climate change involves much more than RSL rise and temperature increase; precipitation, evaporation, humidity, wind velocity, hurricanes, cloudiness, insolation, ocean currents, waves, mixing, riverine input, etc., are all important variables *(q.v.,* Figure 2). In order to strengthen quantitative information transfer to governments, regional climate models nested in coupled ocean-atmosphere global circulation models are needed, along with a vigorous, stable, long-term in situ verification programme, coupled 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 in the region 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.

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 particularly during storms of seaside population centres, 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.

Socioeconomic Issues

Before effective socioeconomic 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 socioeconomic 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 countries such as 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 socioeconomic responses to climate change. Probably the greatest single socioeconomic 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.

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 2. Three subjective levels of vulnerability to rises in sea level and temperature are chosen and assigned to the ecosystems and socioeconomic topics outlined in the Terms of Reference *(q.v.,* Table 1). 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.

From the entries in Table 2, it is clear that the Task Team was most concerned with tourism, both because of its economic importance and because it is crucial to the social fabric in most of the island states. Appended to the concern over the impacts on tourism, is that of tropical storms and beaches since they both are associated with that industry. Only the impact on deltas was considered high for purely ecological reasons. Several entries were considered to have moderate risk due to both temperature and sea level rise (estuaries, wetlands, salinas, and lagoons), and hence are more vulnerable because either effect could cause stress. Table 2 does not reflect our overriding concern for mangroves and coral reefs, which are not excessively vulnerable to the 1.5°C/20 cm scenario, but being of such importance to the ecological health of the Intra-Americas Sea (and indeed to subtropical/tropical regions globally), are worthy of special mention outside the confines of this study (D'Elia *et al*., 1991).

MODELLING

Numerical and Scenario Models of Climate Change

Wigley and Santer (1993) 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 C02 (2XC02). All four numerical models are global models, but Wigley and Santer only report the regional results of interest herein. Figure 9, from Wigley and Santer (pers. comm.) show the model results for annual mean temperature and annual mean precipitation respectively. 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 (Figure 9a) and annual average *modelled* precipitation change (Figure 9b), are discussed below.

Table 2. Implications of Climatic Changes in the Intra-Americas Sea

(L) Low Impact; (M) Moderate Impact; (H) High Impact

Terms of Reference	(a) RSL 20 cm	(b) SST 1.5°C
Ecosystems: Level of Vulnerability*		
Agriculture	L	L
Beaches	H	L
Coastal Lakes	L	L
Coastal Plains	M	L
Coral Reefs	L	M
Deltas	H	L
Estuaries	M	M
Fisheries	L	M
Forests	L	M
Lagoons	M	M
Mangroves	M	L
Rivers	L	M
Seagrass Beds	M	M
Wetlands	M	M
Socioeconomic: Level of Vulnerability*		
Coastal Zones	L	M
Cultural Heritage	M	L
Human Migration	L	M
Public Health	L	M
Settlements and Structures	M	L
Tourism	H	M
Tropical Storms	L	H

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

The annual average temperature change caused by effective $C0_2$ doubling shows a fairly consistent result in each GCM: an increase of 2°C to 4°C is calculated. Details of increased annual averaged 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 $C0_2$ doubling also shows significant variability between GCMs, but each model shows that the zero contour (in millimeters 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 Figure 9 vary considerably between GCMs, the general conclusion is in agreement with the WMO/ICSU/UNEP (1986) scenario of rising temperature. Climate however is the sum of many geophysical factors *(q.v.,* Figure 2), 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 Figure 9 cautiously.

An alternative method of considering future climate is the scenario modelling (Lamb, 1987) discussed earlier. Gallegos and his colleagues have applied the scenario model to the Intra-Americas Sea. As with Wigley and Santer (1993), Gallegos *et al.* (1993) have focused 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 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, 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 $2xC0_2$-$1xC0_2$ forecasts. Of particular importance is "How is the global surface temperature change distributed?"

Figure 9a. Annual average temperature change due to effective CO_2 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 (1993).

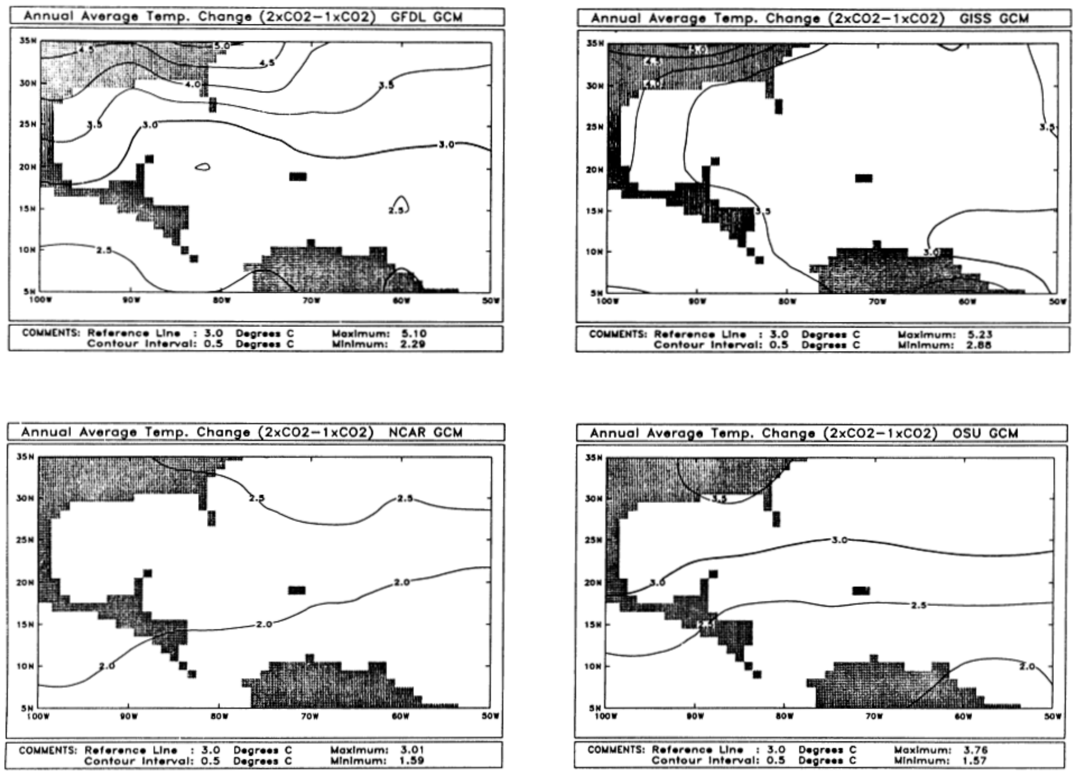


Figure 9a. Annual average temperature change due to effective CO_2 doubling from GCMs of the Geophysical Fluid Dynamics Laboratory (GFDL), Goddard Institute for Space Studies (GISS), Oregon State University (OSU), and the National Center for Atmospheric Research (NCAR). Maps courtesy of Wigley and Santer (1993).

Figure 9b. Annual average precipitation change due to effective C02 doubling from GCMs

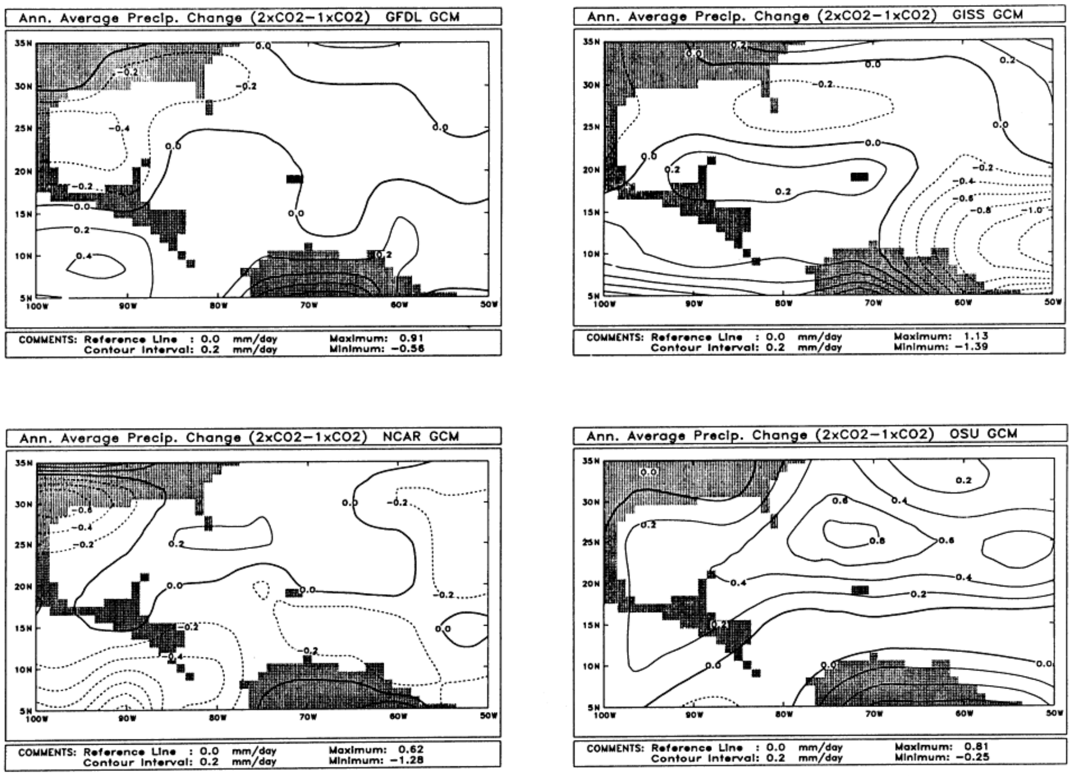


Figure 9b. Annual average precipitation change due to effective CO_2 doubling from GCMs of the Geophysical Fluid Dynamics Laboratory (GFDL), Goddard Institute for Space Studies (GISS), Oregon State University (OSU), and the National Center for Atmospheric Research (NCAR). Maps courtesy of Wigley and Santer (1993).

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.,* Figure 4) and the Eemian interglacial optimum (125,000 ybp) minus the latter half of the 19th century; these are shown in Figure 10 for winter (lower panel) and summer (upper panel) along with a similar meridional profile of predicted temperature change from the four GCMs *(q.v.,* Figure 10). For the tropical/subtropical region with which this report is concerned, there are some remarkable differences.

All three profiles in Figure 10 show that the surface temperature 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 $2xCO_2$-$1xCO_2$ predictions. Readers are reminded that the WMO/ICSU/UNEP (1986) 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. Figure 10 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 2 100 is given in Figure 11. 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 (ΔT_{2x}=2.5°C due to the equivalent $C0_2$ 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 (1986) scenario dealt with herein (1.5°C and 20 cm by 2025 respectively), Figure 11 suggests that the 1.5°C temperature rise is most likely to occur *ca.* 2060 and the 20 cm sea level rise *ca.* 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.

Numerical Models of Climatic Change Socioeconomic Impact

A class of PC-based models to assist decision makers has been developed by Engelen *et al.* (1993). The authors write that socioeconomic systems may be influenced by climatic change in ways ranging from minor or very local to drastic and nationwide. Any such changes will be superimposed on trends already present in these evolving systems. Therefore, it is vital to anticipate dangers, as well as new opportunities, as soon as possible. To allow governments and policy-makers to play an active role in managing these socioeconomic systems effectively, they should be provided with tools that will permit them to explore impacts in their full holistic, spatial, and temporal contexts. Decision support systems are designed to assist in such tasks. The most essential part of such systems is a set of tools, mostly quantitative models and methods, which at relatively low cost, allow the user to analyze and evaluate a range of possible futures resulting from different scenarios and hypotheses.

Figure 10. Paleoclimate and greenhouse model comparisons of the meridional profile of seasonal average surface temperature in the Northern Hemisphere

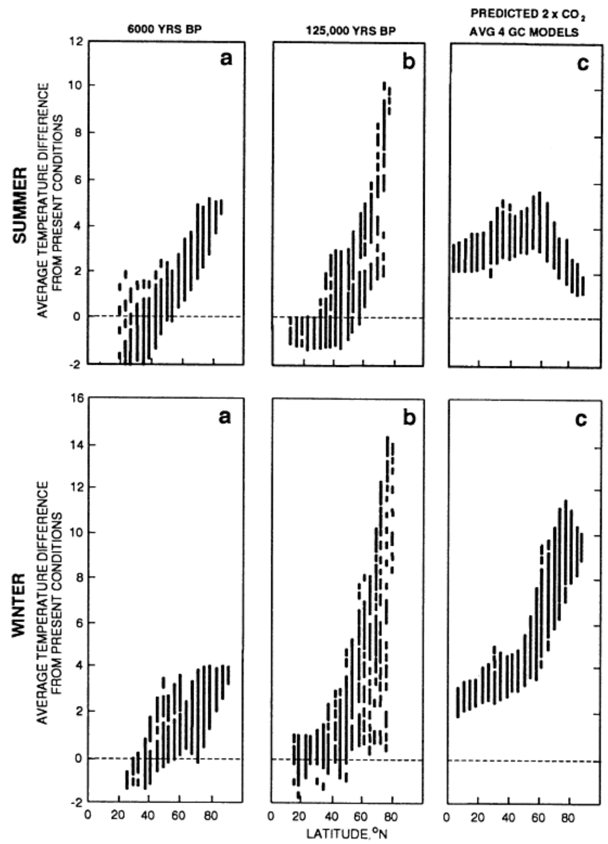


Figure 10: Paleoclimate and greenhouse model comparisons of the meridional profile of seasonal average surface temperature in the Northern Hemisphere. (a) Holocene minus latter half of the 19th century; (b) Eemian minus latter half or the 19th century; (c) average predicted from four GCMs of $2xCO_2$-$1xCO_2$. From MacCracken (pers. comm.) following an analysis in MacCracken *et al.* (1990).

As part of a larger decision environment, a two-level mathematical modelling framework, geared to study the effects of climatic change on the level of the individual island or mainland state, is being developed (Engelen *et al.*, 1993). The long-range mechanisms of change are modelled in a classic, non-equilibrium spatial interaction model. This model then feeds regional growth coefficients into a low-level cellular model that deals with the short-range location and interaction mechanisms. This technique of linked models is necessary in order to capture successfully the effects resulting from climatic change on the appropriate scales. The prototype is a first, mostly conceptual step towards a system for use in real world applications.

The Engelen *et al.* model can best be operated using a 386 personal computer with a mathematics co-processor or a 486DX, a Super-VGA monitor, and a "windows" operating system. The model components are illustrated in Figure 12. On the high level, long range interactions are modelled by means of a dynamic spatial interaction sub-model. The regional growth coefficients are fed into a low-level cellular sub-model to preform the allocation on a detailed scale based on short range interaction mechanisms. Both sub-models will store and retrieve information from the same geographical database. In use, decision-makers are able to view the effects of three sea level rise scenarios on a hypothetical "Caribbean" island. In the no-sea- level- rise scenario, population growth and external demand for goods and services are the cause of most land use changes, but in the 20-cm- sea- level- rise in 40 years scenario (0.5 cm/yr), much of the change was due to loss of mangroves and beaches. The case of sea level fall, a real possibility for some islands in the Intra-Americas Sea, was ecologically dominated by coral reef stress and mangrove forest advance, and economically by population growth. Other aspects of socioeconomic effects can be simulated in such models, and they are easily learned. Plans are being formulated to apply the model to a real "Caribbean" island, and to make the technology available to interested policy-makers and planners throughout the region.

CONCLUSION

The atmospheric concentration of CO_2, the primary anthropogenic greenhouse gas, is undoubtedly increasing, and as the upper right hand panel of Figure 7 shows, the increase is clearly associated with human population growth (Idso, 1989). Atiyah and Press (1992) write "If current predications of population growth prove accurate and patterns of human activity on the planet remain unchanged, science and technology may not be able to prevent either irreversible degradation of the environment or continued poverty for much of the world." Lending institutions, such as the World Bank (1992) recognize the crucial role of population growth, and not only echo sentiment with Atiyah and Press, but have created programmes to link population and sustained development. Thus, the box in Figure 7 marked "human activity" not only shows a linkage to global "climatic changes", it also shows a relationship to "other human-induced changes" particularly on the local or regional level. In the near-term, it is the local anthropogenic effect of human activity that dominates "physical", "ecological", and "socioeconomic" change in the Intra-Americas Sea.

Figure 11. Global temperature (upper curves) and sea level (lower curves) projections for the various IPCC 1992 scenarios.

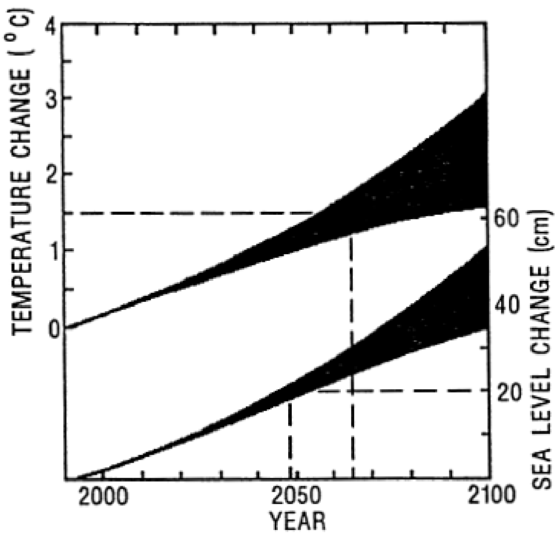
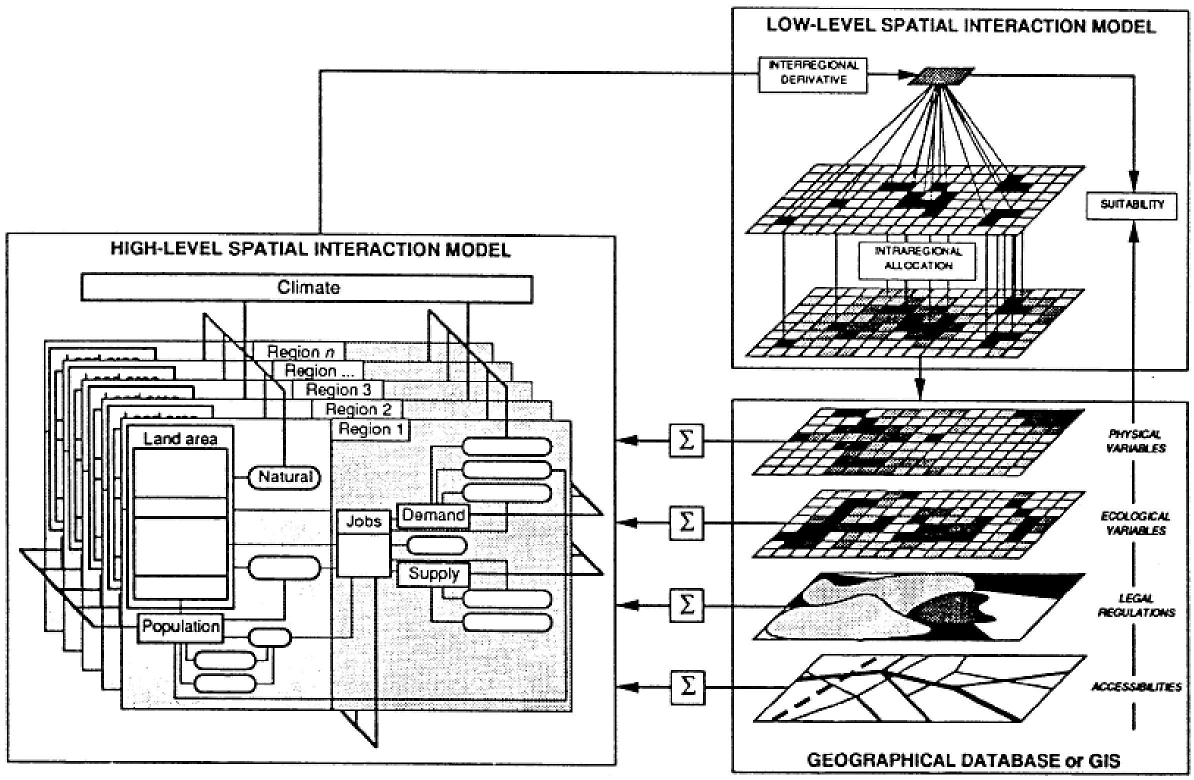


Figure 11. Global temperature (upper curves) and sea level (lower curves) projections for the various IPCC 1992 scenarios. A range of projections within each stippled area are calculated for the "best-guess" set of ice-melt and climate modes. Redrawn from Wigley and Raper (1992), the projections only show the anthropogenic component of a future climate, with natural variability superimposed on them.

A range of projections within each stippled area are calculated for the "best-guess" set of ice-melt and climate modes. Redrawn from Wigley and Raper (1992), the projections only show the anthropogenic component of a future climate, with natural variability superimposed on them.

Figure 12. Schematic of the two-level PC-based socioeconomic numerical model.
On the high-level, long range interactions are modelled by means of a dynamical spatial interaction model. The regional growth coefficients are fed into a low level cellular model to perform the allocation on a detailed scale based on short range interaction mechanisms. Both models will store and retrieve information from the same geographical data base. From Engelen *et al.* (1993).



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In order to understand these physical, ecological, and socioeconomic interactions on the marine and coastal environment, six 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, freshwater resources, precipitation patterns, terrestrial ecosystems, coastal industries and settlements, and littoral zone population dynamics. The underlying thread oftentimes 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.

There is a realistic expectation that certain positive benefits may accrue from climate change; 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:

- a change in precipitation associated with a temperature fluctuation may allow the introduction of different crops but perhaps at the sacrifice of others;
- 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.

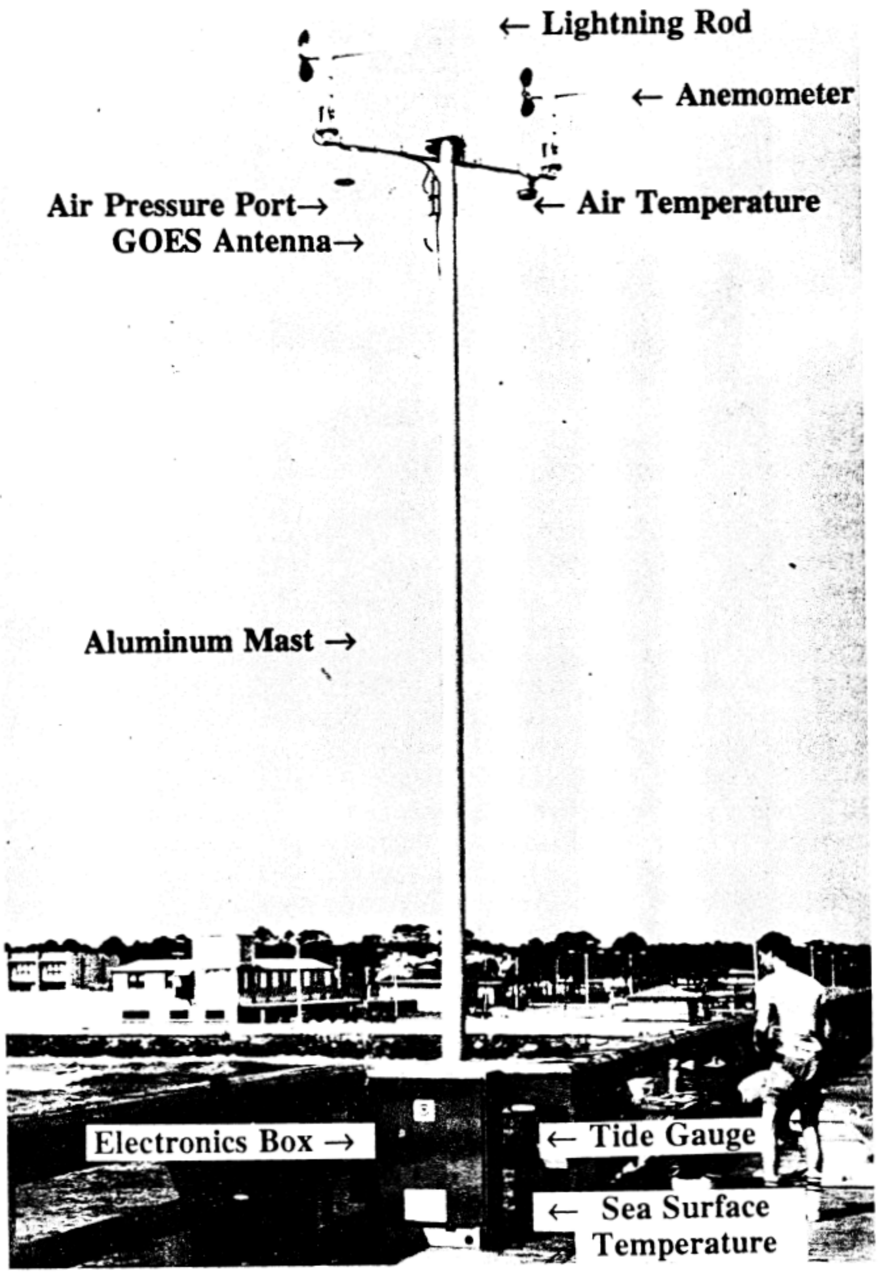
A truly challenging and interesting problem will be to identify and explore the legal and institutional implications under the diverse systems and governments which characterize a region that has been influenced by so many native, European, and African cultures.

Of primary concern is the availability of adequate data. The Caribbean Sea sea-level network, which was in such 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 reestablished and include marine meteorological data, geodetic leveling data, sea water 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, archeological, 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 modem sea-level/weather observing network is absolutely necessary to document and ultimately forecast climate change impacts. It is particular important in such an observing system to have the ability to record extremes in 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. Figure 13 is an example of such a observing station that has both meteorological and oceanographic instruments, part of what is known as the C-MAN network. C-MAN stations are typically configured to record and report via GOES variables such as air and sea temperature, wind velocity, sea level, precipitation, insolation, cloud cover, etc. The system is completely digital, and data can be acquired either directly via a PC and modem or from the Global Telecommunications System (the WMO real-time data exchange network). Careful placement, maintenance, and calibration of sensor packages such as illustrated in Figure 13 not only will provide information to unequivocally detect climate change, but form the database for sustained economic development.

Some writers urge "the time for action to prevent global warming is now; we should not spend more money on studies". Such well-meaning persons quite misunderstand the level of uncertainty in the climate record and in models. For example, Hanson and Maul (1993) report that the thermometer at Key West was moved 17 times during the 136 years of record that they studied. Oftentimes the location of the Key West instrument, its condition, and its calibration, etc., or even how daily means were calculated, were unknown. Yet it is from the patching together of such records (and Key West is one of the *best!)* that scientists attempt to determine climate change. Whatever time for "action" it is, that action must first be to obtain records that are accurate, reliable, and not biased by urbanization or other locale-specific influences, if only to give the next generation of scientists proper data for model verification. Today's "politically correct" frenzy for action must include a *sustained* commitment to improved forecasts and improved observations.

Figure 13. Photograph of a typical C-MAN station
showing the meteorological and oceanographic instrumentation needed for detecting local climate change and for socioeconomic modelling of climate change impacts. The instruments are typically located in an exposed site in order to avoid anthropogenic influences such as the microenvironment change associated with infrastructure development at airports or seaports. The mast is typically 5 m (15 feet) tall and the ground space required is typically 1 m^2 (10 feet^2).



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APPENDIX: GLOSSARY AND ABBREVIATIONS

Aerosol: Atmospheric particles with radii ranging from 10-3 to 10 μm (micrometers), which are important in scattering of radiation.

Air-Sea Interaction: The scientific study of the rates of energy transfer from the atmosphere to the ocean, and from the sea to the air; considerable feedback exists between the two fluids.

Albedo: The ratio of total radiant energy reflected from a body to the total radiant energy incident upon it; Earth's albedo, is typically 0.4, the ocean's albedo is less than 0. 1, but cloud albedos can be 0.9 or greater.

Altithermal Period: A dry, warm postglacial period 7500-4000 ybp (*cf.* Little Climatic Optimum).

Anthropogenic: Involving the impact of humankind on nature; induced or altered by the presence and activities of humans.

Anticyclonic: Fluid flow having a sense of rotation (clockwise in the northern hemisphere) opposite to Earth's, rotation, and associated with an oceanic or atmospheric high pressure cell.

Aquifer: A subterranean layer of unconsolidated material containing water, which may be connected to the sea.

Atoll: A torus-shaped organic reef enclosing a lagoon in which there is no pre-existing land, and being surrounded by open sea.

Bathymetry: The science of measuring ocean depths to determine sea floor topography.

Beach: A zone of unconsolidated material that is in alongshore or onshore- offshore active transport.

Benthic: A zone of ocean bottom always under water; pertaining to organisms that live there.

Bruun Rule: An empirical rule of beach erosion for a closed system in which there is no external source or sink of sand, given by $W \cdot \Delta Z/D$ where W is the active beach width, ΔZ is sea level rise, and D is tide range; W/D is often found to be ~100.

Canalization: The restricting of river flows into channels or canals; oftentimes this prevents flooding, in deltas but leads to a loss of the very sediment that builds deltas.

Carbon Dioxide ($C0_2$): The primary radiatively active atmospheric gas responsible for the greenhouse effect; its concentration is approximately 350 parts per million (ppm).

Carbonate ($CO_3^=$): A salt or ester of carbonic acid; the most common form in the Intra-Americas Sea is calcium carbonate ($CaC0_3$), *i.e.*, limestone.

Caribbean Current: A branch of the North Equatorial Current (NEC) passing through the Lesser Antilles and flowing into the Gulf of Mexico through the Yucatan Channel.

Catchment Area: Geographical region from which rainfall drains into a common river system; also called drainage area.

Cellular Automata: A numerical modelling approach where a large number of small areas (cells) are used to represent details in a physical or socioeconomic process, and where the cells are mathematically connected in a computer algorithm.

CFC (chlorofluorcarbon): A non-radiatively active anthropogenic compound made of one or two carbon atoms, chlorine, and fluorine; CFC's interact with UV radiation to chemically destroy ozone in the stratosphere.

Chlorophyll: A green organic molecule active in photosynthesis; it can be detected in ocean waters by satellite sensors such as the CZCS and (if successful) SeaWIFS.

Circulation: The three-dimensional change associated with the motion of the ocean or the atmosphere, and giving rise e.g., to surface currents and winds respectively.

Climate: The statistical collective of weather for a given region over a specified length of time, typically 30 years.

Climatology: The scientific study of climate.

Cloud Feedback: Radiation from Earth at visible and infrared wavelengths is absorbed and reemitted by clouds and can interact again with Earth's surface; this interaction is termed feedback.

C-MAN: Coastal-Marine Automated Network.

Coastal Zone: The area of Earth's surface from near the coast to the continental shelf break (~200 m isobath) where marine species (saltwater) dominate the ecology.

Compaction: The geological process whereby a soil mass loses pore space, becomes more dense, and thus increases its bearing capacity.

Coral Bleaching: A condition of corals when photosymbiotic organisms, e.g., dinoflagellates such as zooxanthellae, are forced to leave the host coral animals.

C_{ORG}: Organic Carbon; a generic term for marine organic matter.

Coriolis Force: An apparent force on moving particles when measured relative to a rotating coordinate system; the force is to the right in the Northern Hemisphere and is proportional to $2\Omega \sin(y)$ where Ω is Earth's angular velocity and y is latitude.

Cryosphere: The region of Earth dominated by ice.

CZCS (Coastal **Z**one **C**olor **S**canner**):** An experimental global ocean color sensing (visible wavelength) multispectral scanning radiometer launched in 1978 on the NASA NIMBUS-7 satellite (no longer operating).

Delta: An alluvial deposit formed at the mouth of a river or a tidal inlet.

Downwarping: Subsidence of a broad region of Earth's crust.

Ecosystem: A community of animals, bacteria, and plants, and their inter-relation with their immediate chemical and physical environment.

Eemian Period: North European climatostratographic and floral stage equivalent in time to the Riss/Würm interglacial about 125,000 ybp.

Ekman Transport: The volume flow that occurs at right angles to the wind in the Northern Hemisphere; it arises from the balance of the Coriolis force and wind stress. Alongshore coastal winds lead to upwelling or downwelling.

El Niño: A condition, originally applied to the surface waters of the eastern equatorial Pacific Ocean, wherein the usual cold, marine-life-supporting surficial. waters are replaced by unusual warm waters; it was thought to occur around Christmas, hence the Spanish name for "The Child."

Energy: The capacity for doing work, expressed as a result of motion (kinetic), of availability to cause motion (potential), of being associated with light (radiant), of the exchange of heat and cold (thermal), etc.

ENSO: (**E**l **N**iño-**S**outhern **O**scillation) A term that connects the oceanic phenomenon (El Niño) with the atmospheric phenomenon (Southern Oscillation) leading to the realization of the global consequences of air-sea interaction (see TOGA).

Equilibrium Temperature: The temperature Earth would achieve in due time after an increase in greenhouse gases.

Estuary: A tidal bay formed from the drowning of a non-glaciated river valley juxtaposed to the ocean.

Eustatic: Simultaneous world-wide change in sea level associated with growth or melting of continental and/or mountain glaciers (*cf.* Glacial).

Fishery: The business of catching and selling fish (e.g., being associated with single boats: artisanal), or type of fish *(e.g.,* bottom feeders: demersal); also the study of fishing in a particular environment (*e.g.,* estuarine) or with an age class *(e.g.,* juvenile).

Florida Current: That branch of the Gulf Stream System flowing through the Straits of Florida from Dry Tortugas to Cape Canaveral.

Forecasting: In ceophysical fluid dynamics, the art of predicting future states of the atmosphere or ocean through computer models (numerical forecasting), through projection of observed trends (persistence forecasting), or through comparisons with prior epochs (scenario forecasting).

GCM: General **C**irculation **M**odel.

Geoid: An equipotential (level) surface (*i.e.*, one to which, at every point, the plumb line is perpendicular). Specifically, the figure of the earth considered as the level surface of a motionless $\alpha_{35,0,p}$ ocean, where $\alpha_{35,0,p}$ is the specific volume of a 35 psu, O°C , ocean, at a particular time.

Geomorphology: The study of the form of the earth and the general configuration of its surface.

Geosphere: The solid earth or land as compared to the atmosphere or hydrosphere.

GFDL: NOAA **G**eophysical **F**luid **D**ynamics **L**aboratory, located in Princeton, New Jersey U.S.A.

GISS: NASA Goddard **I**nstitute for Space Studies located in New York, New York U.S.A.

Glacial: Pertaining to ice that is on land, thus affecting eustatic sea level; sea ice does not contribute to changes in sea level.

Greenhouse Effect: The analogy to the atmosphere of how a greenhouse works, *i.e.*, that the Earth is some 30°C warmer because certain gases (notably water vapor and $C0_2$) allow shortwave radiation (sunlight) to pass through to the surface, but absorb some of the longwave (infrared) radiation emitted by the ground and sea.

Groundwater: Water below the water table (minimum water-well depth) as distinguished from interflow and soil moisture.

Gulf Stream System: The primary oceanic current system of the western North Atlantic Ocean including the Caribbean Current, the Yucatan Current, the Loop Current, the Florida Current, and the "Gulf Stream" proper.

Halocarbon: A molecule of carbon and any of the five chemical elements fluorine, chlorine, bromine, iodine, and astatine.

Holocene: The most recent geological epoch, usually taken as the last 10,000 years or so.

Hot Snap: A short (several day or week-long) period of elevated temperature; the opposite of a cold snap.

Hydrology: The science of Earth's waters, especially concerning evaporation, precipitation, and the character of water in streams, lakes, and under ground.

Hypersalinity: Extremely high salinity condition, often leading to detrimental conditions for marine organisms.

ICSU: International **C**ouncil of **S**cientific **U**nions.

Infrastructure: The basic facilities upon which a modem human community is dependent such as roads, schools, ports, dams, etc.

Interglacial: The periods in Earth's history when glaciers are a minimum in size and extent, and the temperatures are warm, such as at present.

Intra-Americas Sea: The region of the tropical and subtropical western North Atlantic Ocean that includes the Guianas coast of South America, the Caribbean Sea, the Gulf of Mexico, the Bahamas, and Bermuda; *approximately* bounded by 0°-30°N latitude and 50°W-100°W longitude.

IOC: Intergovemmental Oceanographic Commission of UNESCO.

IOCARIIBE: IOC Subcommission for the Caribbean and Adjacent Regions (*cf.* Intra-Americas Sea; Wider Caribbean Region).

IPCC: Intergovernmental Panel on Climate Change of the WMO, ICSU and UNEP.

Lagoon: A shallow pond generally separated from the open sea (*cf.* atoll, coral reef).

Leveling: The art of determining the vertical height difference between two points on Earth. Geodetic leveling is extremely precise and is always referenced to the vertical control datum.

Little Climatic Optimum: The period in Earth's history, approximately 8,000 to 5,000 ybp, when mean air temperatures were 1-2°C warmer than today (*cf.* Altithermal Period).

Little Ice Age: The period in Earth's history, approximately the years 1300 to 1800 AD, when mean surface air temperatures were 1-2°C colder than today.

Littoral: The newshore zone, typically encompassing the high tide line to below the low tide line (in some usage, out to the continental shelf break, *i.e.*, -200 m).

Loop Current: That portion of the Gulf Stream System flowing into the Gulf of Mexico beyond the Yucatan Channel, turning (or looping) an ticyclonic ally within the Gulf, and exiting through the Straits of Florida.

Mangrove: One of several genera of tropical and subtropical trees and shrubs that have prop roots and that grow in the shallow waters of the coastal zone.

Mean Sea Level: The mean surface water level determined by averaging heights at all stages of the tide over (traditionally) a 19-year period. Mean sea level is not an equipotential surface (*i.e.*, not the geoid).

Medieval Warn Epoch: That period in Earth's history, approximately the years 800-1200 AD, when air temperatures were 1-2°C warmer than the Little Ice Age, and similar to today's.

Mesoscale: A length dimension associated with a circulation feature, typically of the order of 100-1,000 km; the scale upon which ocean eddies and hurricanes occur.

Methane (CH_4): A colorless naturally occurring and anthropogenically generated atmospheric greenhouse gas that contributes to the radiative warming of Earth (*cf.* carbon dioxide).

Milankovitch Cycle: Regularly changing insolation due to variations in Earth's orbit around the sun, theorized to cause ice ages; for the next 5,000 years Earth will undergo decreasing insolation due to orbital parameters.

Mixed Layer: Vertical zone in the ocean between the surface and the thermocline where wave action mix%-.-s the water to a uniform temperature and salinity (typically 25-100 m thick).

Model: A mathematical or heuristic description of a physical, chemical, biological, geological or socioeconomic process, which can be prognostic (forecasting) or diagnostic (analytical).

Morphology: The scientific study of form and structure, especially in biology and geology.

Nitrous Oxide (N_20): A colorless naturally occurring and anthropogenically generated atmospheric greenhouse gas that contributes to the radiative warming of Earth (*cf.* carbon dioxide).

NASA: U.S. National Aeronautics and Space Administration.

NCAR: National Center for Atmospheric Research located in Boulder, Colorado U.S.A.

NEC (North Equatorial Current): A westward flowing ocean current driven by the northeast

Trade Winds; in the Atlantic Ocean it enters the Caribbean Sea primarily through the Windward, Mona, and Anegada Passages.

NECC (North Equatorial Counter Current): An ocean current flowing eastward near the equator; in the Atlantic Ocean it seems to be related to the retroflection zone off the Guianas.

Nitrate ($N0_3^-$): A salt or esther of nitric acid; the most abundant and readily assimilable form of nitrogen for marine organisms; like phosphate, it is an essential nutrient.

NOAA: U.S. National Oceanic and Atmospheric Administration.

OSU: Oregon State University located in Corvallis, Oregon U.S.A.

Ozone (0_3) Layer: The stratum of the atmosphere between 10 and 50 km above the surface where 0_3 is highly concentrated; also called the ozonosphere. 0_3 is a faintly blue gaseous form of oxygen formed photochemically when ultraviolet light interacts with oxygen. Ozone reacts with CFC's which reduces the ozonosphere's UV absorbing properties.

Paleoclimate: The climate of a time in the geological past.

PC: Personal Computer (usually refers to IBM design systems using Intel microprocessors).

Phaeopigment: Chlorophyll-like plant molecules that can contribute to water discoloration. They can be sensed by satellite systems such as the CZCS.

Phosphate (P): An ionic form of phosphorous occurring in nature; an essential marine nutrient.

Population Density: The number of humans per unit area.

Productivity: In oceanography, it is the amount of carbon fixed by living organisms per unit area per unit time.

PSMSL: IOS Permanent Service for Mean Sea Level located in Bidston, Merseyside, U.K.

PSU (Practical Salinity Units): The modem units of salinity; very approximately the same as per mille (0/00) *or parts per thousand* or grams of salt per kilogram of seawater.

Radiation: The energy output of an object, usually expressed with the wavelength band such as infrared (3-20 µm), microwave (1-50 cm), net (all wavelengths), ultraviolet (2000-4000 Å), visible (400-700 nm), *etc*.

Retroflection: An ocean current *zone* off the Guianas where the northwestward moving crossequatorial flow turns anticyclonically and continues out into the open Atlantic Ocean (see the book cover for a CZCS image of the retroflecting flow).

Rossby Wave (or β-wave): Horizontal wave motion in a rotating fluid, such as the ocean or atmosphere, when the change in Coriolis parameter (f) with latitude (y) is considered a constant ($\beta = \delta f / \delta y$).

RSL (Relative Sea Level): The long-term change in ocean water level measured by a tide gauge, including the (usually unknown) vertical motion of the gauge plus the change in the water due to eustatic, steric, and/or wind-driven effects.

Salina: A shallow salt marsh or pond separated from the ocean but flooded by high tide.

Salinity: The grams of salt in a kilogram of seawater (*cf.* psu); specifically, the total amount of dissolved solids by weight when all the carbonate has been converted to oxide, the bromide and iodide to chloride and all organic matter is completely oxidized.

Saltwater Intrusion: The inflow of saltwater into a normally freshwater aquifer; associated with sea level rise and/or groundwater extraction.

Seagrass: Members of either the Hydrocharitaceae or Zosteraceae families - of bottom growing grass-like spermatophytes, usually found in waters less than 10 m deep, and important in stabilizing unconsolidated bottoms.

Sea Level (or water level): The height of the surface of the sea at any time. In surveying and mapping the term "sea level" should be avoided, but if used it should be with the meaning of mean sea level. Sea level is *not* an equipotential (level) surface (*cf.* Geoid).

SeaWIFS, (Sea Wide-Field Sensor): Follow-on ocean color multispectral scanner planned to be orbited by NASA in 1993.

SLOSH (Sea Lake Overland Surges from Hurricanes): Storm-surge model for predicting the height of water levels associated with a tropical storm or hurricane.

Specific Volume Anomaly (δ): The excess of the actual specific volume (reciprocal of density, $\rho_{s,t,p}$) of seawater at any point in the ocean ($\alpha_{s,t,p}$) over the specific volume of seawater of salinity s=35 psu and *in situ* temperature t=0°C at the same pressure **(** $\alpha_{35,0,p}$ **);** $\delta = \alpha_{s,t,p} - \alpha_{35,0,p}$.

Spheroid: A mathematical figure closely approaching the geoid in form and size, and used as a reference for geodetic surveys.

SST (Sea Surface Temperature): The temperature of the upper meter of the water column, usually measured with a thermometer from a bucket sample.

Steric: In oceanocraphy, steric refers to the expansion or contraction of the water column due to the distribution of temperature and salinity.

Stratosphere: The region of the atmosphere above the troposphere or from about 10 to 25 km, characterized by ozone in addition to the normal gases.

Sulfate: A salt or ester of sulfuric acid (H_2SO_4), that occurs naturally and anthropogenically in the ocean and the atmosphere (where it is associated with acid rain).

Sverdrups (**Sv**): A commonly used measure of oceanic volume transport equal to $10^6 m^3 s^{-1}$ or 1 gigaliter/second; Florida Current volume transport is 30 Sv, but the Amazon River is only 0.2 Sv.

Tectonic: The investigation of the origin and evolution of the broad structural features of Earth, particularly associated with the motion of crustal plates (plate tectonics).

Thermocline: Vertical zone in the ocean below the mixed layer where the temperature decreases rapidly with increasing depth (typically 500- 1,000 m thick).

Tidal Benchmark: A bronze disk firmly cemented into a solid foundation that serves, as the vertical (leveling) reference for a tide gauge or tide staff.

Tide Gauge: A device for measuring water level as a function of time, and which is referenced to tidal benchmarks through periodic leveling surveys.

TOGA (Tropical Ocean - Global Atmosphere): A term describing the relationship between the Pacific Ocean's interaction with (and forcing of) the whole atmosphere; also the name of a scientific research programme.

Topography: The configuration of a surface including its relief. In oceanography the term is applied to a surface such as the sea bottom (*cf.* Bathymetry) or a surface of given characteristics within the water mass.

Transport: In fluid flows, it is a measure of amount per unit time; used to define volume transport (liters per second), heat transport (watts), mass transport (grams per second), etc.

Troposphere: The atmospheric shell closest to Earth's surface, extending approximately 10 km upwards; the zone where weather occurs.

Turbidity: A measure of the amount of suspended matter in water or aerosols in air; a-more precise term is attenuation which is the sum of scattering and absorption.

UNEP: United Nations Environment Programme.

UNESCO: United Nations Educational, Scientific, and Cultural Organization.

Upwelling: The vertical motion of seawater (as distinct from rising air) often associated with Ekman Transport in the ocean.

UV: (ultraviolet): Radiation invisible to the naked eye, with wavelength shorter than violet (*i.e.*, less than 400 nm).

Wetlands: Areas that are covered with fresh surface water for some period of each year on a recurring seasonal basis.

Wider Caribbean Region: UNEP term for the Gulf of Mexico/Caribbean Sea/Bahamas/Guianas region; *cf.* IOCARIBE.

Wind Stress: The force per unit mass per unit area exerted by atmospheric flow on the ocean's surface; units are dynes per square centimeter.

WMO: World Meteorological Organization of the United Nations.

ybp: Years Before the Present.

Yucatan Current: That portion of the Gulf Stream System that flows northward along the Belize-Mexico coast through the Yucatan Channel into the Gulf of Mexico where it becomes known as the Loop Current.

Zooxanthellae: An algal cell living symbiotically in the cells of certain invertebrate animals such as corals.