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Implications of Climate Changes in the Wider Caribbean Region

Preliminary Conclusions of the Task Team of Experts
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Implications of Climate Changes in the Wider Caribbean Region

The history of modern civilization is inexorably related to Earth's climate. Climatic changes have occurred that have influenced our literature, raised and toppled empires, altered our view of God, modified economies, forced mass migrations of both humans and animals, caused hunger and starvation; the list is nearly endless (e.g. Bryson and Murray, 1977). Yet as the quincentennial of the European discovery of the Caribbean approaches, little more is known about climate in the region than what the early explorers told their sponsors. Assessing the impact of climate change then is a particularly challenging problem.

This study emphasizes the marine and coastal environment and addresses the implications of climatic change in the Wider Caribbean Region. As was the perspective of the early explorers, it is limited to a sailor's view of the coastline, reefs, passages, harbours, deltas, estuaries, and deep waters of the Caribbean Sea, the northeast coast of South America (excluding Brazil), the Gulf of Mexico, and the Florida-Bahamas region of the western North Atlantic Ocean (Figure 1). Nevertheless, such a perspective presents a formidable challenge involving meteorology, oceanography, geology, economics, sociology, medicine, law, and ecology.

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

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

Figure 1. The Wider Caribbean Region (UNEP, 1987) is also called the Caribbean Sea and Adjacent Regions by the Intergovernmental Oceanographic Commission and its Subcommission IOCARIBE. Early European oceanographers mistakenly called it the American Mediterranean, but the author prefers the term IntraAmerican Sea to emphasize its unique geography, climate, and culture.

TERMS OF REFERENCE

Each Task Team involved in the UNEP Regional Seas Programme is using a common format in assessing the implications of climate change. The common format is called the "Terms of Reference", which was developed at the WMO/ICSU/UNEP (1985) meeting in Villach, Austria, and is given in Table 1. At Villach, an equilibrium global warming of 1.5 - 4.50C 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 Regions chose to separately question 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 1.50C and a rise in sea level of 20 cm by the year 2025 (WMO/ICSU/UNEP, 1985) is the baseline scenario. The lower values vis a vis the WMO/ICSU/UNEP scenario are chosen because by 2025 it is not expected that climatic equilibrium to CO₂ doubling will have been reached due to the thermal inertia of the oceans. Deliberations by the Task Team emphasized the point that 1.50C 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 Wider Caribbean Region. While the Task Team used these baseline values in addressing the implications, two reports asked "Does the historical record support such values for the Wider Caribbean Region?"; the answer is yes and no.

The next issue in interpreting the Terms of Reference is defining how the Task Team understands the terms "climate" and "climate change". Climate is understood to be limited to the time averaged meteorological and oceanographic conditions of the marine and coastal environment in the Wider Caribbean Region; 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 o 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.

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 what is thought to be known about temperature change, Figure 2 shows the temperature record for the last 1,000 years (upper panel), and for the last 100 years (lower panel). Although the records are from different sources, they show that Earth's temperatures have varied significantly since the European discoveries of North America, and one can see that 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 the longer records (last 1,000,000

Table 1. Terms of Reference

Under the overall guidance and supervision of UNEP's Oceans and Coastal Areas Programme Activity Centre (OCA/PAC), the Regional Coordinating Unit (RCU) of the Caribbean Environment Programme in co-operation with the Intergovernmental Oceanographic Commission (IOC) of UNESCO, will establish a Task Team on the implications of expected climatic changes in the Wider Caribbean Region:

- to examine the possible effects of the 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 the possible effects on economically important species;
 - to examine the possible effects of climatic, physiographic, and ecological changes on the socio-economic structures and activities;
 - to determine areas or systems which appear to be most vulnerable to the above changes; and
 - to prepare a comprehensive, well documented report reflecting the points above. The report should also include several detailed case studies, which would constitute the substantive annexes of the report. The region intended to be covered by the report would include the coastal and marine environment of the States and Territories participating in the Caribbean Environment Programme.
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years) show. So while an interpretation of the last 100 years shows increasing global temperatures on average (Hansen and Lebedeff, 1988; lower panel in Figure 2), the decades of 1940-1970 had declining temperatures. Translating the global records such as shown in Figure 2 to the regional level was one important challenge for the Task Team.

Does the historical record support the WMO/ICSU/UNEP (1985) scenario of a 1.5 °C temperature rise in the Wider Caribbean Region by the year 2025? Data to assess a rise of sea surface temperature was considered scarce, so Hansen and Maul 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 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 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 1.0 °C rise by 2025 appears to be a more plausible picture of future temperature in the Wider Caribbean Region

Figure 2. Temperature change for the last 1,000 years based on records in eastern Europe (upper panel; from NAS, 1975), and a global estimate (lower panel; from Hansen and Lebedeff,

1988). Temperature scale for the last 1,000 years is only approximate and is chosen to be in agreement with the record for the last 100 years which is based on direct observations.

Sea Level Rise of 20 cm by 2025

As with questioning the validity of the global temperature change for the Wider Caribbean Region, the Task Team looked into the historical sea level record to put the WMO/ICSU/UNEP (1985) scenario into perspective. In Figure 3 (from Wanless et al., 1988) what is thought to be known about sea level for south Florida during the last 7,000 years is shown. It is felt that south Florida is tectonically stable, so the relative sea level rise shown in Figure 3 represents oceanic variability rather than a combination of both land subsidence and sea level rise, and it is thought to be representative of the Wider Caribbean Region. The remarkably slow rate of sea level rise during the last 3,200 years (only about 0.04 cm/year according to Wanless et al.) 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 3 gave the Task Team a benchmark against which to judge the WMO/ICSU/UNEP global scenario of 50 cm rise per 100 years.

Does the modern historical record of the Wider Caribbean Region support the WMO/ICSU/UNEP (1985) scenario of a 20 cm sea level rise by the year 2025? To answer this question, the highest quality (revised local reference) data on file with the Permanent Service for Mean Sea Level (PSMSL) were studied by Maul and Hanson for the wider Caribbean region, and from Venezuelan records by Aparicio for the coast of Venezuela. For the longest records, Maul and Hanson found that sea level is rising on average at about 0.36 cm/year (0.25 cm/year) over the last 30 years, but due to complicated tectonic activity and petroleum/groundwater extraction, the values ranged from +1.0 cm/year in Texas (rising sea level) to -0.3 cm/year in Mexico (falling sea level). At Key West, Florida, a site of tectonic stability, the rise is 0.22 cm/year (0.01 cm/year), based on the years 1913-1986. As with the temperature scenario, a lower value, perhaps 10 cm by 2025, is a more plausible regional value, but the high spatial variability makes a regional average value nearly meaningless; site specific values are required for adequate climate impact assessment.

Thompson and Evans cautiously advise that many more long records are required in order to sort out the decadal and longer wave motions, which are not climate signals, 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, periodic behaviour of the Sverdrup balance, interbasin modes of oscillation, and so forth. Progress in numerical modelling will give the resolution to determine submesoscale features and subdecadal oscillations, but it may be 10 years before such calculations are possible. 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.

Figure 3. Sea level change based on geological records taken in south Florida by Wanless et al, 1988, and from Jamaica by Digerfeldt and Hendry, 1987. The relative rise of 18 cm per 100 years shown in the inset is based on direct observations at all PSMSL (Pugh, et al.,

1987) RLR sea level stations in the region; dots show range of standard error of the mean. The shoreline retreat associated with sea level rise occurs in storm-driven steps and is often-times not immediately seen as beach erosion or lowland inundation.

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 the sea level changes on the coastal ecosystems. Gable gives an overview of the ecosystems in the Wider Caribbean Region, and *Oceanus* (1987/88) 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), sea level rise is less than the 0.5 cm/year implied by the assumptions at the International Conference in Villach, and in the last 3000 years RSL rise has been almost nil. All other things being equal, 0.5 cm/year is expected to place an unusual stress on coastal ecosystems.

Deltas

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

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 Wider Caribbean (Vicente, Singh, and Botello). Because of local uplifting, 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; 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 the deltas, other Caribbean 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, could all suffer from saline intrusion, but lagoons should be

able to support their usual nurseries; salinas on the other hand (Vicente, et al.), could be flooded over continuously, and lose their economic value.

Wetlands

The ability of a wetland to sustain vertical growth is a balance between sedimentation and RSL rise. In the tectonically complicated Wider Caribbean Region, no single definitive statement is possible, but in the last 5,000 years, many Caribbean wetlands have been able to keep pace with rising sea level. In areas where marked subsidence is occurring, particularly if there is canalization of organic silts and clays away from the wetland into the marine environment (Hendry), wetlands will be submerged and lose their 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 the problem may be less severe. Loss of wetland economies such as shellfish industries is expected to occur with the 20 cm RSL rise scenario.

Coastal Plains

The primary effect on coastal plains will be increased flooding during storms (either 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). 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 Caribbean 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 population in the poorly drained low-lying coastal plains is a source of concern in many Caribbean 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 centered area of the U.S. Texas-Louisiana coast, are coastal plains areas that are particularly 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, and all but the northern Gulf coast have extensive reef systems. Growth of individual coral organisms is estimated between 1-20 cm/year (Vicente et al.), and reef growth rates as a whole are known to be up to 1.5 cm/year (Hendry). Not all reefs accumulate at these rates, but if they did, they could keep pace with the rise in RSL of 20 cm by 2025 if other factors do not alter growth conditions. Environmental stress on the reefs from other variables (storms, sedimentation, disease, rainfall, radiation, turbidity, overfishing, mass mortality in algal grazers, etc.) is causing some to be unable to keep 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 in coastal lowlands of the tropics and subtropics; their prop roots stabilize the soil, dampen wave energy, provide habitat shelter for organisms, and form the base of the marine food web. RSL of 20 cm by 2025 will affect different mangrove species differently. The black mangrove (*A. germinans*) has a root system that is different from the other three common Caribbean species, and it should be particularly monitored. There is some evidence (S. Snedaker, U. Miami, personal communication) that red mangrove replace black mangrove when mean water elevations increase. In general however, if the mangroves are not juxtaposed to a steep coastline, they are expected to be able to tolerate the anticipated RSL change (Vicente et al.), provided other environmental stress factors do not change the natural balance.

Seagrass Beds

Seagrasses are a bottom feature throughout the Wider Caribbean Region that are of importance in stabilizing the bottom sediments, serve as nurseries for juveniles, and like mangrove roots provide surfaces upon which many organisms attach. A 20 cm RSL rise per se is not expected to seriously affect the six common species, 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. Turbidity increase could have a negative impact on fisheries particularly during the early life history stage (W. Richards, NOAA/NMFS, personal communication). Estuarine dependent species in areas such as Mississippi, the Everglades, Guyana and the Orinoco Delta, may be particularly vulnerable to sea level rise especially if salinity changes are involved.

EFFECTS OF TEMPERATURE ELEVATIONS ON ECOSYSTEMS

As discussed above, there is considerable question if trace gas induced temperature elevation can be seen in the records at Key West, Venezuela, Jamaica, or in Trinidad and Tobago. Temperature change however is only one aspect of the meteorology that will effect terrestrial and aquatic ecosystems. Hanson and Maul found no evidence for changes in precipitation at Key West during the last 101 years; similarly, Aparicio found none along the southern Caribbean. In the Wider Caribbean Region, Gray found decreased rainfall in the last 20 years, which he associates with decreased hurricane activity (a major contributor to the total). An increase of 1.5 °C in sea surface temperature could increase the number of hurricanes by as much as 40% (Shapiro), and the maximum wind speed by 8%; Shapiro is quick to point out that there is considerable uncertainty in these figures (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 change in strength or frequency.

In the sense that Lamb (1987) develops climate change scenarios as plausible future events, Gray argues for the following likely effects (cf. Aparicio): rainfall will continue to decrease, air temperatures will continue to increase, 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 lowered number 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 sees 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.

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 will probably increase, but poor management practices are probably more contributive than temperature elevation and saline intrusion. Finally, Vicente et al., argue that it is unlikely that inland and hilly forests will be affected much by increased temperature, although Gray 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.

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 Wider Caribbean 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. 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. Similarly, only seagrass beds that are 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 (1985) temperature rise.

Fisheries

The blue, clear waters of the Caribbean are relatively poor in nutrients, 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. 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) or other circulation changes (Thompson and Evans), and thus to increased productivity (cf. Gable).

Tropical fish eggs hatch very quickly (12 A-48 hours) and development is associated with temperature. Just as "cold snaps" can be devastating, so can "hot snaps", particularly during early juvenile stages. Extremes in temperature usually get 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 (W. Richards, NOAA/NMFS, personal communication). The complexities of the ecosystem could be greatly effected by slight temperature changes. It is unknown for example why fish stocks decline or increase by orders of magnitude except due to early life history events - either directly by the physical world or indirectly through complex chains in the 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 SOCIO-ECONOMIC CHANGES

This section concerns the third item in Table 1, examining the possible effects of climatic physiographic and ecological changes on socio-economic structures and activities. Climate change will have socio-economic impacts on both the micro-economic or localized level, and on the macro-economic or economy-wide level. The smaller or the more coastal-oriented an economy is, the greater will be the impact of sea level rise (Alm, Blommestein, and Broadus). The Wider Caribbean Region, with its many small island-based economies such as fishing and/or tourism, is most 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 only the true cost due to climate change that is of interest.

Agriculture and Forestry

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

Fisheries and Coastal Zones

Most fishing in the coastal zone in the Wider Caribbean Region is artisanal except for a few larger industries such as the menhaden fishery in the Gulf of Mexico. The WMO/ICSU/UNEP (1985) 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). There does remain an unanswered question of the effect on fisheries of extreme temperature events. Aquaculture in the region 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.

Tourism

The single most important industry in the Wider Caribbean Region is tourism, especially in Florida, The Bahamas, Jamaica, and the Lesser Antilles. Of all the possible climate change impacts that affect tourism, none can be so clearly demonstrated as being important as is beach erosion (q.v. Hendry). 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, will be an increasing socio-economic impact. It is difficult to estimate the impact of climate induced sea level rise, in addition to the erosion associated with the relentless interaction of the sea on the coast, that is not associated with climate change; in addition, certain sand mining practices (such as in Trinidad and Tobago) already are considered important. Indirect socio-economic 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 socio-economic impact of a 20 cm sea level rise is not considered serious (Alm et al). Some nearshore roads, seawalls, and bridges will have to be increasingly repaired, and if the RSL rise is augmented by increased storm activity, the impact 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 sewerage systems, will have to be modified; areas of particular concern in this regard are coastal cities of Guyana and Belize (Vicente et al). The most damaging socio-economic aspect is climate change coupled with population growth and migration to coastal cities. Often-times 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 water levels, because water is a principal agent for many diseases and organisms that carry disease (de Sylva). If higher temperatures are coupled with higher humidity as Gray 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 micro-organisms; 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). Socio-economic effects relate not only to increased spread of tropical diseases and their associated shift in costs and benefits to the health industry, but also to potential losses in other industries due to health related absenteeism. It is anticipated that there will be a transfer of costs and benefits associated with climatic change to public health in the Wider Caribbean Region, but that the health-care delivery systems will be capable of keeping 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.

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), and their impact on ecological and socio-economic structures and activities, three broad topics are addressed: Physical Processes; Ecological Aspects; and Socio-Economic Issues.

The overwhelming consensus of the Task Team was that "case studies" were the most cost effective method of quantifying the effects of climatic change. Several sites that are deemed to be at high risk from sea level change and/or temperature rise should be selected for an extensive and intensive study. Site selection must be based on the applicability of the results to as many other similar sites as possible; it therefore must be representative of a class of problems rather than an individual problem. The following short list suggests five important case study themes: Coastal Erosion; Groundwater/Petroleum Extraction; Tropical Storm Frequency/Intensity; Wind Stress and Ocean Transport; Riverine Discharge Quantity/Quality. As discussed below, case studies must address three interrelated subjects: physical processes, ecological aspects, and socio-economic issues.

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. In order to strengthen quantitative information transfer to states, regional climate models nested in coupled ocean-atmosphere global circulation models are needed, along with a vigorous, stable, longterm *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 Wider Caribbean Region, is absolutely necessary to improve the physical basis upon which quantitative information is provided to ecologists, sociologists, economists, politicians, and managers.

Table 2. Implications of Climatic Changes in the Wider Caribbean Region^{1/}

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

Terms of Reference	(a) RSL 20 cm	(b) SST 1.5 o C
<i>Ecosystems</i>		
	<i>Level of Vulnerability</i>	
Deltas	H	L
Estuaries	M	M
Wetlands	M	M
Coastal Plains	M	L
Coral Reefs	L	M
Lagoons	M	M
Mangroves	M	L
Seagrass Beds	M	M
Fisheries	L	M
Agriculture	L	L
Forests	L	M
Rivers	L	M
Coastal Lakes	L	L
Beaches	H	L
<i>Socio-Economic</i>		
	<i>Level of Vulnerability</i>	
Coastal Zones	L	M
Tourism	M	L
Settlements & Structures	M	L
Public Health	L	M
Tropical Storms	L	H
Human Migration	L	M
Cultural Heritage	M	L

^{1/} 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.

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 sewerage

and toxic wastes of nearby human population centers and agricultural regions. Conversely, impacts of saline intrusion on local fresh water supplies and inundation particularly during storms of seaside population centers, 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, and Cartagena, are particularly vulnerable.

Socio-Economic Issues

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

MODELS OF FUTURE CLIMATE

Wigley and Santer give a very detailed discussion of the possible future climate of the Wider Caribbean Region. They compare the results of four numerical models that predict future surface air temperature change and precipitation change for each of the four seasons. Each model

calculates the effect on temperature and rainfall of doubling all the greenhouse gases, expressed as doubled CO₂. All four numerical models are global models, but Wigley and Santer only report the regional results of interest herein.

Figures 4 and 5, from Wigley and Santer (personal communication) show the model results for temperature and 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 modeled temperature change (Figure 4) and annual average modeled precipitation change (Figure 5), are discussed below

The annual average temperature change caused by effective CO₂ doubling shows a fairly consistent result in each GCM: an increase of 2 °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 Wider Caribbean Region are modeled to have higher annual average temperatures than the islands. Annual average precipitation changes due to effective CO₂ doubling also shows significant variability between GCMs, but each model shows that the zero contour (in millimeters per day), which runs through the center of the Caribbean Sea, is the dominate feature of the calculation. Precipitation in the Wider Caribbean Region is strongly influenced by tropical storms however, which are not in these GCMs.

Although the results shown in Figures 4 and 5 vary considerably between GCMs, the general conclusion is in agreement with the WMO/ICSO/UNEP (ec1985) scenario of rising temperature. Climate however is the sum of many geophysical factors, the greenhouse gases only being one of them, and there may be competing factors (particularly on a regional scale) that can modify these modeled 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 cautiously, but thoughtfully, have to interpret the results shown in Figures 4 and 5

Figure 4. Annual average temperature change due to effective CO₂ doubling from GCMs of the Geophysical Fluid Dynamics Laboratory (GFDL), Goddard Institute for Space Studies (GISS), Oregon State University (OSU), and the National Center for Atmospheric Research (NCAR). Maps courtesy of Wigley and Santer.

Figure 5. f Annual average precipitation change due to effective CO₂ doubling from GCMs of the Geophysical Fluid Dynamics Laboratory (GFDL), Goddard Institute for Space Studies (GISS), Oregon State University (OSU), and the National Center for Atmospheric Research (NCAR). Maps courtesy of Wigley and Santer

CONCLUSION

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 Wider Caribbean Region than rising temperature, but it is too early to be definitive. This is the dilemma that any forecaster must confront.

Of primary concern to forecasting is the availability of adequate data. The Caribbean sea level network, which was in such good repair for earlier regional programmes such as BOMEX in 1969, is now in substantial disarray. From a climate perspective, a sea level observing network must be re-established 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, archaeological, and historical data analysis is considered a cost-effective means of strengthening those conclusions. There must also be rapid and free exchange of the observations, a basin-wide commitment to common problems, a responsibility to calibrate and intercompare measurements, and adequate sustained funding. Establishing and maintaining a modern sea-level/weather observing network is absolutely necessary to document and ultimately forecast climate change impacts. Of particular importance in such an observing system is the ability to record extremes in sea level and temperature of both the water and air. It is in these extreme events that climate change impacts may be most noticeable.

Finally, we choose not to argue for wholly negative impacts. There is a realistic expectation that certain positive benefits may accrue; the local response to global change is simply not predictable at this time. What may be perceived as negative to one sector of society in the Wider Caribbean Region may be beneficial to another. Two examples: a change in precipitation associated with a temperature rise 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 European and native cultures.

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Additional references can be found in the Chapters of the Task Team Report to be published on Pergamon Press and edited by John Milliman of the Woods Hole Oceanographic Institution and which contains the following Chapters:

Global Climatic Changes and Regional Needs by G. S. Giese.

Future Climate of the Caribbean Basin by T.M.L. Wigley and B.D. Santer.

Analysis of the Historical Meteorological Record at Key West, Florida (1851-1986) for evidence of Trace-Gas Induced Climate Change by K. Hanson and G.A. Maul.

Meteorology by C. R. Gray.

Impact of Climate Change on Hurricanes by L. J. Shapiro.

Geology: Physical Processes, Coastal Impacts by M. Hendry.

Some Meteorological and Oceanographic Conditions along the Southern Coastal Boundary of the Caribbean Sea (1951-1986) by R. Apacicio.

On the Impact of Changed Water Depth (Sea Level Rise) on Storm Surge and Storm Wavesq Modelling for Island and Continental Shelf Locations by A.íMercado.

Sea Level Variability in the IntraAmerican Sea with concentration on Key West as a Regional Example by G.A. Maul and K. Hanson.

The Rise of Sea Level in the Wider Caribbean Region: The Role of Dynamical Oceanography and Ocean Modeling by J.D. Thompson and J.C. Evans.

Climate Changes and Socio-Economic Impacts in the Caribbean by A. Alm, E. Blommestein, and J. Broadus.

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Marine Habitats of the Wider Caribbean Region: Selected Environmental and Ecological Charts by F. Gable.

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