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Potential Impacts of Contemporary Changing Climate on Caribbean Coastlines

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ABSTRACT

The threat of man-induced global change on the nations of the wider Caribbean region varies from place to place because of differences in exposure to storms, differences in local tectonics and subsidence, and variations in land-use practices. Because of the large number of nations involved, many having only subsistence budgets, and the cost of deriving independently a comprehensive response to global change, the similarities and differences between national settings must be identified soon. These comparisons will form the basis for local response strategies; the common elements between nations provide a basis for responses similar to those other nations, whereas the differences mandate local adaptation. That the Caribbean will be impacted by climate change is certain: its environment, land uses, and economies are dictated in large part by this marine influence. Accompanying global change will be changes in sea level, differences in storm climate, and altered precipitation patterns; science cannot define today what form these changes will take. Because global change is inevitable—although its magnitude, timing, and geographic distribution are unknown—the wider Caribbean should begin the appropriate research and planning studies to set forth a response to global change, for implementation when scientific evidence for global change is more quantitative.

INTRODUCTION

Global change caused by increased atmospheric trace gas loading is a topic of considerable concern.[1] Included in this global change will be various secondary responses, such as rise in sea levels, changes in storm

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climates, and changes in precipitation patterns. While the exact magnitude, timing, and geographical distribution of these climate responses cannot be predicted with the level of present understanding, we can model some of the impacts of these changes. Once a region understands the consequences of global change, it can respond effectively to such changes by implementing a rational management strategy. In this article, we address some of the impacts of global change in a region highly susceptible to such impacts: the wider Caribbean. Following a discussion of sea-level rise (one consequence of climate change), we address the likely climate change impacts in the wider Caribbean area, including areas that are particularly vulnerable (distressed areas). A discussion of the Caribbean response to global change ensues, including a research agenda laid out by various concerned organizations.

The Caribbean Sea and the Gulf of Mexico, the world's largest gulf, cover an area of 3·48 million km^2 (1·35 million $miles^2$). Within this wider Caribbean region, defined here as the coastal and open waters of the Caribbean Sea proper, the Gulf of Mexico, and adjacent waters of the Atlantic Ocean, there are 33 countries.[2] Included in this figure are political entities known as 'overseas departments,' 'territories,' 'independent and associated states,' 'commonwealths' and 'colonies.' Political entities encompassing the wider Caribbean, which contains the largest concentration of small developing countries in the world, range in type and size from small islands such as Anguilla, measuring 91 km^2 (35 $miles^2$), to continental nations such as the United States, measuring 9·37 million km^2 (3·61 million $miles^2$).

The wider Caribbean (Fig. 1) may be significantly affected by global changes due to atmospheric trace gas loading, including warming and the subsequent rise in ocean levels. The wider Caribbean region includes many islands that have far more coastal zone per unit of land area than do continental areas (Table 1), and changes of relative mean sea level are beginning to concern more and more governments and government planners. Governments and international aid and relief agencies make important economic and environmental decisions about coastal projects based partly upon assumptions about climate.[3] Many of the decisions assume that past climatic data, without modification, are a reliable guide to the future. This assumption may no longer be valid,[3] since climate change may accelerate in the future due to human influence. For the wider Caribbean region, several aspects of climate change are most critical: temperature increase, sea-level rise, precipitation changes, and storm climate. These are discussed in more detail below.

Researchers believe that global warming of the atmosphere will result from build-up of atmospheric trace gases.[4] The most effective gases at heating the atmosphere include carbon dioxide, methane, nitrous oxide, tropospheric ozone, chlorofluorocarbons (freons), and water vapor, all of which absorb infrared radiation. As their concentrations increase, there will be increased global warming coupled with an intensified hydrologic cycle.[5] Projected increases of these trace gases due to past, current, and expected human activities—such as the expanded use of wood and fossil fuels for combustion—have been used as inputs to mathematical models to examine global climate changes. The mathematical models are, in general, based upon imperfectly-known geophysical and geochemical relationships and data. Yet, estimates of global climate change have been made based on these models, projecting increases in mean global temperatures in tropical regions of 0·3–5 °C during the next century.[6] In tropical low-latitude regions, including nearly all the wider Caribbean, temperature increases are expected to be smaller than the average global rise.[7] Although regional precipitation patterns are the most uncertain forecasts of the major climatic variables, studies suggest an enhancement of intense rainfall in the presently rainy low-latitudes.[7] Heavy rainfall results in a depletion of elements from surface soils by pronounced leaching, and increases erosion. Increased erosion may in turn increase water column turbidity and adversely affect coral reefs.[8]

Changes in storm climate would impact the extensive shorelines of the Caribbean. As global ocean and atmospheric temperatures increase, atmospheric stability will change in some locales. Decreased atmospheric stability, in turn, is related to storm activity. Empirical data suggest that for the tropical west Atlantic, hurricane activity depends strongly on the size of the pool of warm water exceeding 26 °C.[9] As climate changes, the size of this warm pool will change, potentially altering the intensity, range, and paths of tropical storms.

This global warming will impact sea levels as well, both through direct ocean warming causing thermal expansion,[10,11] and through a melting of continental and alpine ice sheets.[12] Both effects will lead to an increase in the volume of the oceans and, in the absence of other influences, relative sea level will rise.[13] Small, land-bound glaciers may explain as much as half of the observed relative sea-level rise during the past century.[14] Contributions from large continental glaciers are uncertain, representing a balance between increased melting versus increased precipitation.[12]

Glaciers and thermal expansion are not the sole causes of relative sea-level rise. Regional causes of relative sea-level change include

Fig. 1. The wider Caribbean region. Source: Caribbean Data Atlas/IUCN.

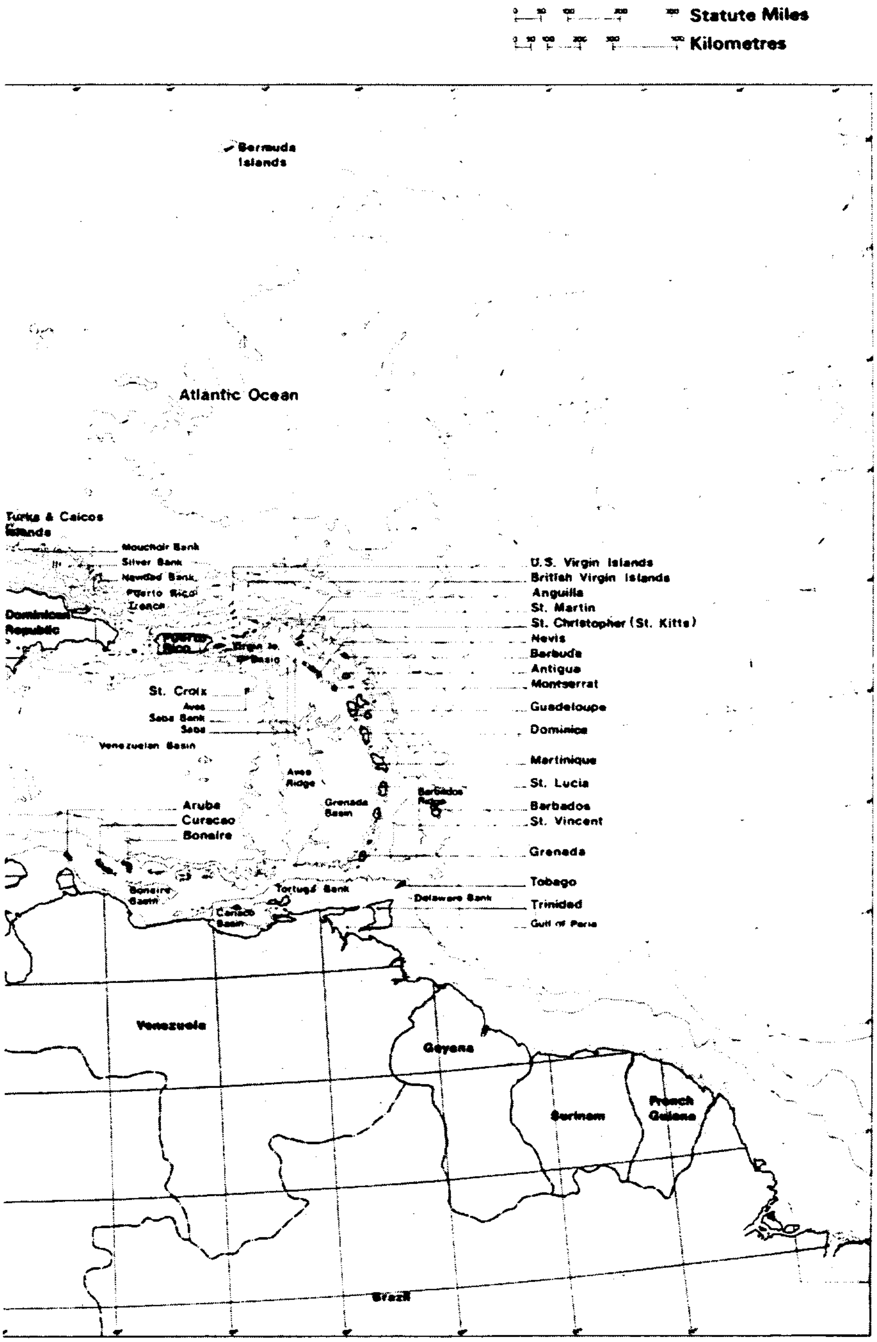

Statute Miles
Kilometres
Bermuda Islands
Atlantic Ocean
Turks & Caicos Islands
Mouchoir Bank
Silver Bank
Navidad Bank
Puerto Rico Trench
Dominican Republic
Puerto Rico
Virgin Is. Basin
St. Croix
Aves
Saba Bank
Saba
Venezuelan Basin
Aves Ridge
Grenada Basin
Barbados Ridge
Aruba
Curacao
Bonaire
Bonaire Basin
Cariaco Basin
Tortuga Bank
Delaware Bank
U.S. Virgin Islands
British Virgin Islands
Anguilla
St. Martin
St. Christopher (St. Kitts)
Nevis
Barbuda
Antigua
Montserrat
Guadeloupe
Dominica
Martinique
St. Lucia
Barbados
St. Vincent
Grenada
Tobago
Trinidad
Gulf of Paria
Venezuela
Guyana
Surinam
French Guiana
Brazil

TABLE 1
Wider Caribbean Geographical Statistics

	Area		*Length of coastline*	
	km^2	(*miles*^{2})	*km*	(*miles*^{2})
Anguilla	91	(35)	102	(63)
Antigua & Barbuda	442	(171)	153	(95)
Bahamas	11 396	(4400)	3542	(2201)
Barbados	431	(166)	97	(60)
Belize	22 973	(8870)	386	(240)
British Virgin Islands	153	(59)	304	(189)
Cayman Islands	260	(100)	214	(133)
Colombia	1 138 914	(439 735)	1600	(994)
Costa Rica[a]	50 700	(19 575)	1290	(802)
Cuba	114 524	(44 218)	3735	(2321)
Dominica	751	(290)	148	(92)
Dominican Republic	48 442	(18 699)	1288	(800)
French Guiana	90 909	(35 100)	378	(235)
Grenada	345	(133)	121	(75)
Guadeloupe	1780	(687)	306	(190)
St. Martin	—	—	—	—
St. Barthelemy	—	—	—	—
Guatemala[a]	108 880	(42 038)	400	(248)
Guyana	214 970	(83 000)	459	(285)
Haiti	27 713	(10 700)	1771	(1101)
Honduras[a]	112 088	(43 277)	820	(510)
Jamaica	11 422	(4410)	1022	(635)
Martinique	1080	(416)	290	(180)
Mexico[a]	1 978 800	(764 014)	9330	(5799)
Montserrat	102	(39)	46	(29)
Netherlands Antilles	1020	(394)	364	(226)
Aruba, Bonaire	—	—	—	—
Curacao, St. Maarten	—	—	—	—
St. Eustatius, Saba	—	—	—	—
Nicaragua[a]	147 900	(57 104)	910	(565)
Panama[a]	75 650	(29 208)	2490	(1547)
Puerto Rico	8897	(3435)	700	(435)
St. Christopher & Nevis	262	(101)	135	(84)
St. Lucia	616	(238)	158	(98)
St. Vincent & Grenadines	389	(150)	84	(52)
Surinam	142 709	(55 100)	386	(240)
Trinidad & Tobago	5128	(1980)	362	(225)
Turks & Caicos Islands	430	(166)	546	(339)
US Virgin Islands	342	(132)	175	(109)
Venezuela	912 050	(352 142)	2800	(1740)

[a] Includes Pacific Coast.

Sources: Ocean Yearbook 3, 1982; Sorensen and Brandani, 1987;[77] Mr D. Simpson, UK Hydrographic Department, 1987.

long-term changes in atmospheric pressure, temperature, currents, and wind patterns, as well as land subsidence and emergence.[15]

ESTIMATES OF SEA-LEVEL RISE

At an October 1985 scientific conference in Villach, Austria, sponsored by the United Nations Environment Programme (UNEP), the World Meteorological Organization (WMO), and the International Council of Scientific Unions (ICSU), trace gases, climatic change, and associated impacts were discussed, and estimates of sea-level rise were projected.[16] The estimates were based on observed changes during the past century, though these estimates are largely uncertain. The historical trend in global relative sea-level rise is in the order of an increase of about 12 cm[10,12,17] to 15 cm during the past century,[13,18,19] although the data can support almost any estimate in the range of 0–30 cm/century. The historical rise of sea level has accompanied an increase in the atmospheric concentration of carbon dioxide of 25–30% since the industrial revolution;[20,21] the concentration has increased by 9·5% since 1958 at the Mauna Loa Observatory in Hawaii.[22] The historical rate of sea-level rise is not a result of climatic warming linked to fossil-fuel loading, but is a result of global warming following the Little Ice Age of the mid-part of this millenium. Because of the many time scales of the climate system—biosphere, geosphere, hydrosphere, cryosphere, and atmosphere—present levels of man-induced atmospheric loading of radiative active gases would produce additional sea-level rise impacts during the next decades, even if all additional inputs were stopped immediately. For the future, imprecise projections are that global warming of 1·5–4·5 °C would lead to a sea-level rise of 20–140 cm during the next century. While model simulations suggest a gradual warming, some researchers believe that changes in the Earth's climate may be sudden rather than gradual.[23]

Other estimates of the extent of relative sea-level rise vary. The US Environmental Protection Agency (EPA) estimates an average global rise of between 72 cm and 216 cm for the next century.[24] By 2025, the EPA projects global ocean levels will be between 13 cm and 39 cm higher than today. Revised estimates for the next thirty-five years range between 11 cm and almost 21 cm rise in global sea level.[25] The most likely rise in global relative sea levels appears to range between 0·5 m to 2·0 m during the next century. These estimates all address the rise of the ocean, whereas we are concerned with relative sea-level rise.

Relative sea-level rise is the combination of rise of the sea and movement of the land. Studies of historical rates of relative sea-level rise in the Caribbean[26] show that the tectonic movement in the Caribbean is large (compared to eustatic sea-level change) and spatially complex. Eustatic change in sea level is the worldwide change of sea level as contrasted with local uplift or subsidence of the land. During the past half-century or so, relative sea levels in the Caribbean have ranged from an emergence of 5·3 mm/year to a submergence of 9·3 mm/year. Thus, one must be cautious when estimating sea-level change impacts on the wider Caribbean, as they will vary, in the short-term, from place to place.

Difficulties in estimating rise

The absence of adequate uninterrupted historical scientific data prevents our obtaining a complete picture of relative sea-level rise in the wider Caribbean region. This paucity of data from uninterrupted operational long-term tide-gauge stations makes present and future estimates of relative sea-level rise for the region difficult to ascertain.

Tide gauges are useful for measuring not only diurnal, seasonal, and episodic variations in water level, but also for long-term changes. It is the long-term and episodic changes that will show how global climatic changes affect the wider Caribbean region. Tide gauges rest on coasts and depict changes in sea level relative to the adjacent land at that location. These coasts contain topographic evidence of changes of land level, both up and down in relation to sea level. If the relation of movement of land level to sea level is known, then researchers can attempt to calculate changes in eustatic sea level. For the wider Caribbean region, which is characterized by complex geology, tectonism and other geologic processes that are associated with movements of crustal plates of the earth, are understood only schematically (Fig. 2).[26,27]

Land subsidence and uplift are associated with both natural causes due to local geologic and man-made disturbances. Common natural causes that lead to subsidence include: neo-tectonism due to relative plate movements; the consolidation of fine-grained deposits subjected to the weight of overlying sediments; glacial and hydro-isostasy; and thermal cooling.

Human intervention can accelerate or even induce subsidence. The most common man-made subsidence occurs because of removal of fluids from the subsoil.[28,29] Examples include ground water withdrawal

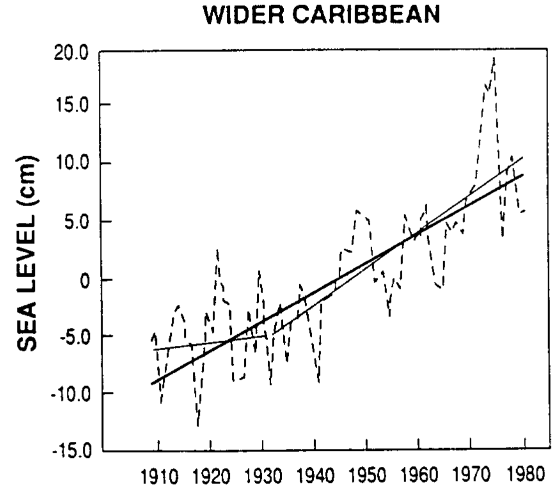


Fig. 2. Gulf of Mexico and Caribbean Sea—sea level curves, 1910–1980. Source: Gornitz & Lebedeff, 1987.[12]

for drinking and the pumping of crude oil and natural gas. Both can result in the consolidation of fine-grain sediments. Local compaction, which causes a settling of the ground, set in motion by loading of buildings or other engineering works, and vibration on sediments,[29] can cause isolated subsidence. Further, biochemical oxidation of peat and other organic soils is playing a major role in anthropogenic, i.e. man-induced, subsidence in the wider Caribbean.[30] Because of their narrow shelves and their distance from major areas of Pleistocene ice sheets, glacio- and hydro-isostasy is not a major source of relative sea-level rise in the Caribbean.[31] Other examples of man's impact on coastal Caribbean resources include reclamation, land drainage, coral mining, and mineral and other forms of mining, particularly sand and gravel mining, both on and offshore. Sand and gravel mining can be detrimental because it can aggravate shore erosion,[32] which in turn destroys features attractive to tourism, an important source of income in many Caribbean countries.[27]

IMPACTS OF GLOBAL WARMING IN THE WIDER CARIBBEAN

While lack of historical scientific data in the wider Caribbean means one must accept considerable uncertainty in determining local effects of global changes, nonetheless it is possible to anticipate significant consequences. Historical temperature change contains a large amount of spatial and temporal natural variability. In regions such as the wider Caribbean where there is incomplete tidal and weather station coverage, estimates of past and future temperature changes must rely on extrapolation from other regions. While our knowledge of global mean temperature change is still uncertain, even in the present era of instrumental meteorology, researchers calculate that global mean warming since 1880 has been about 0·5[18,33] to 0·6 °C.[34] Although the earth was about as warm in the 1930s and 1940s as it is today, the earlier warming was concentrated at high northern latitudes, while the recent warming is more global.[35] The global warming of 1987, which was approximately as warm as 1981—the warmest previous year in the history of instrumental records—is attributed to a large increase in temperature, more than 0·4 °C at low latitudes (23·6°N–23·6°S), which includes most of the wider Caribbean.[36] Model studies project that the highest increases in temperature accompanying global change will occur near the poles, with smaller temperature increases near the equator.[6,7] It is not clear how one interprets the recent historical temperature change trends in light of these model results. Accompanying these increases in temperature will be various climate change associations, including sea-level rise and storm climate change, with their associated impacts. Some of these impacts are discussed below; for instance, a one or two-meter rise in relative sea level would likely inundate wetlands, alter patterns of coastal erosion, threaten coastal structures including powerplants, and increase the penetration landward of saline waters into estuaries and aquifers.

Accelerated sea-level rise might cause consequential changes to a fragile, significant ecosystem of the Caribbean coral reef. If sea-level rise does accelerate, some Caribbean reef flats could become subtidal within the next 50 years. These changes might lead to large scale changes in the abundance and distribution of organisms inhabiting a reef flat.[37] Modern coral reef communities (Fig. 3) would be threatened if sea level rises more than about 0·3–0·5 cm year,[38] since they would be unable to produce skeletal material fast enough to keep up with such a rapid rise. For instance, the coral *Acropora palmata,* found throughout the wider Caribbean, generally does not form an interlocking framework in depths greater than 5 m.[39] Considering projections of sea-level rise over the next century and observations regarding past and present rates of coral reef growth, reef growth may not keep pace with sea-level rise.[40]

Wetlands along undeveloped coastlines lacking protective engineering structures are expected to migrate onto adjacent lowlands if sediment supply is sufficient and erosion does not increase. Yet, because many coastal lowlands have steeper slopes than present-day wetlands, the areas of wetlands lost to flooding may exceed areas gained, causing a net reduction in wetlands. Changes in sedimentation rates may offset or exacerbate this wetland balance.

Wetlands that are mostly mangrove swamps in subtropical and tropical regions typically occupy low wave energy, protected coastlines in bays, estuaries, and lagoons (Fig. 4). Mangrove ecosystems are important to the ecology and economy of coastal areas for several reasons.[41] They constitute a feeding ground and nursery, exporting decomposable organic matter into adjacent coastal waters. This organic matter provides an important nutrient input and primary energy source for vertebrates, crustaceans and other organisms. Equally important, mangroves act as shoreline and coastal erosion inhibitors, provide support for commercial and artisanal fisheries, aquaculture, breeding places for many water fowl, and as refuges for a variety of mammals, many important as human food sources. In the Caroni Swamp in Trinidad, for example, tourists and local citizens also utilize mangroves and their secluded waterways for recreational boating, fishing, and nature study.[29]

In the wider Caribbean, as elsewhere, the mangrove forests act as a buffer against destructive hurricanes and lesser tropical storms. During the period for which written records are available, more than 20 hurricanes have claimed about 30 000 lives in the Caribbean islands alone.[42] Illustrated in numerous eastern Caribbean cities by waterfront development, much of which is on reclaimed land, is the movement of the region's population and infrastructure to vulnerable areas, with consequent increase in storm damage potential. This seaward encroachment has led to an increased risk for the inhabitants because the low elevation and proximity to the sea mean increased exposure to large waves and storm surges associated with hurricanes, and because protective mangrove screens have been removed for shorefront development.

In the wider Caribbean area record hurricane storm surges of greater than 7 m, and associated 200 km/h winds, have been recorded within the past twenty years.[17,43] Changing climate could alter the range, intensity, and paths of these storms. Generally, hurricane formation requires sea surface water temperatures in excess of 26 °C.[9] Since the Caribbean Sea is on average 27 °C,[44] higher water temperatures accompanying global warming might extend and intensify the tropical storm hurricane season. One of the most powerful storms on record, Hurricane Gilbert, one of only three Category 5 storms affecting the northern wider Caribbean this century (a catastrophic storm with

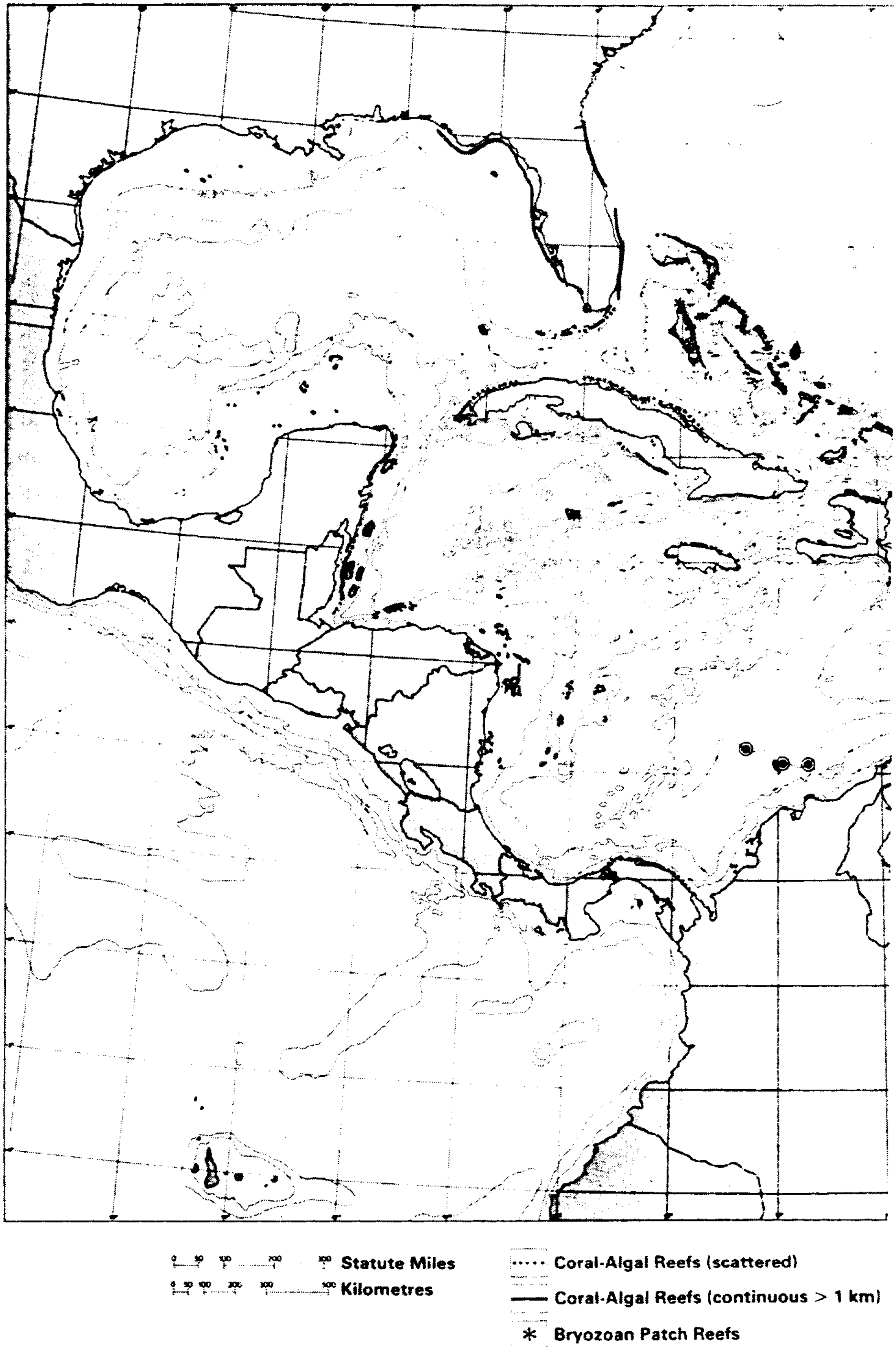
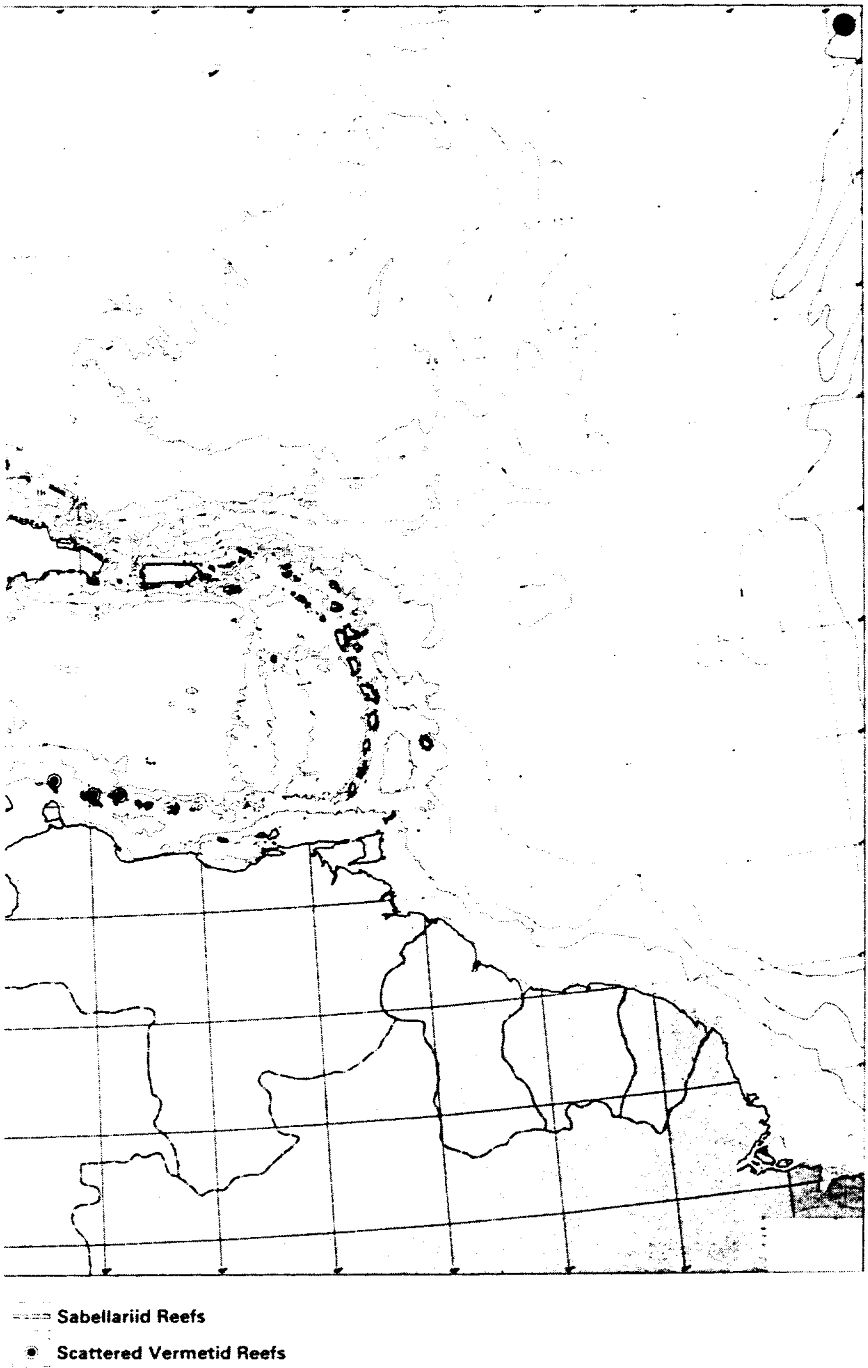


Fig. 3. Wider Caribbean living reefs Source: Caribbean Data Atlas/IUCN.


Sabellariid Reefs
Scattered Vermetid Reefs

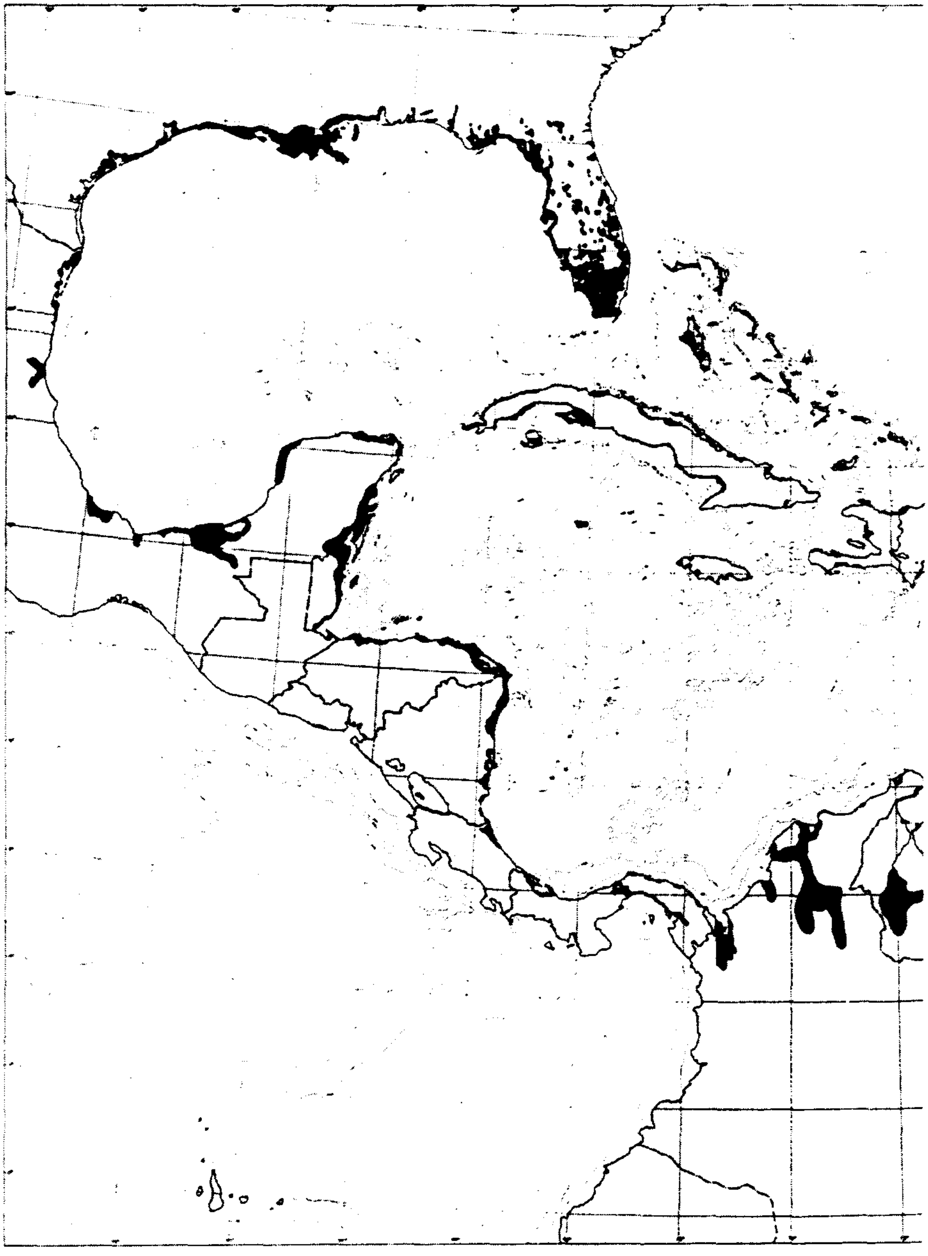
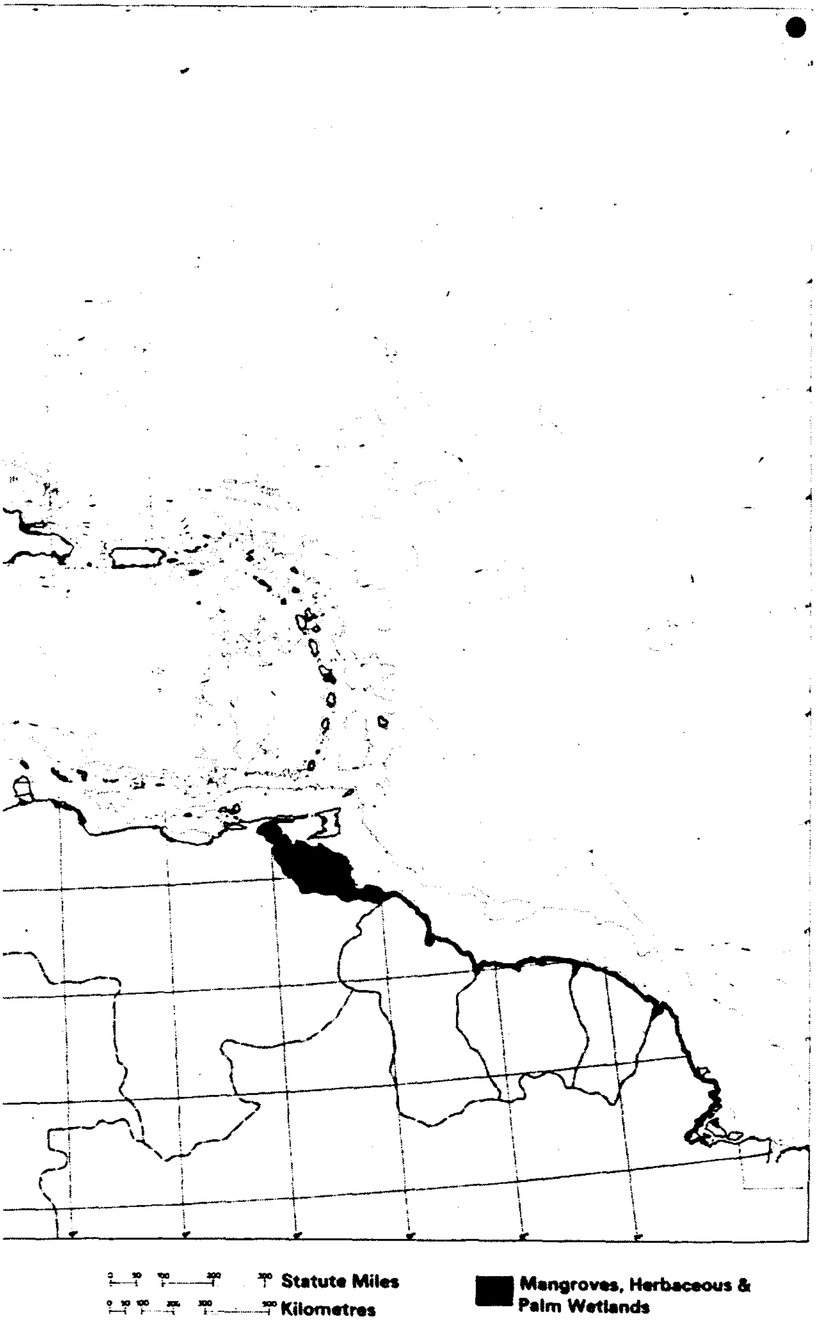


Fig. 4. Wider Caribbean mangroves and palm wetlands distribution. Source: Caribbean Data Atlas/IUCN.


Statute Miles
Kilometres
Mangroves, Herbaceous & Palm Wetlands

central pressure lower than 920 mbars), caused considerable damage and loss of life in Jamaica and the Yucatan peninsula, Mexico.[45] Hurricane Joan, reaching landfall on 22 October 1988 in Nicaragua, caused much damage and loss of life and can be considered a late season storm.[45] General circulation model estimates of increased storm activity based on mean conditions for August over the tropical oceans, with a twofold increase in present CO_2 content—resulting in a surface water temperature increase of between 2·3 and 4·8 °C—could yield as much as a 50% expansion in the damage potential of hurricanes.[46] In partially enclosed basins such as the Gulf of Mexico, where minimum sustainable pressures are below 800 mbars (with a twofold increase in present CO_2 content), the maximum damage potential of tropical hurricanes could be substantially increased, perhaps by as much as 60%.[46] This global warming may cause hurricanes to form at higher latitudes within the wider Caribbean region itself. In general, an increased frequency of severe storms would tend to increase erosion and shoreline recession.

The economic impacts of relative sea-level rise are widely considered to be all effects that the physical causes of rising sea-level will have on the production and consumption of goods, services, and amenities.[47] One of the most important economic effects for the Caribbean region is shoreline movement, resulting in a decrease in the availability of land for recreational, residential, or commercial purposes. To simplify the conversion of physical and/or ecological changes to socio-economic terms, a systematic matrix method has been employed. Alm *et al.*[48] have provided a preliminary checklist of relevant physical and/or ecological variables cross-referenced to socio-economic variables under analysis, for example, the impact of an increased frequency of tropical storms on the construction (resort) sector.

Tourism in many parts of the wider Caribbean is an important source of revenue (Table 2). In the Caribbean as a whole, tourism is the leading economic sector.[2] On the Caribbean islands, effectively all tourism development has occurred in the coastal areas, where the beaches are the principal attraction.[49] Tourist development in most of the wider Caribbean has been and will continue to be oriented towards the coast,[50] concentrated along narrow strips, particularly in semi-enclosed bays.[51] For example, Jamaica depends heavily on tourism which is centered on the beaches and inshore waters, and that is supported by broad real-estate development close to the sea.[52] In the Grenadines, the primary attraction for tourism development is centered along the coastlines and nearshore waters.[53] In the Bahamas, the

TABLE 2
Selected Caribbean Countries: Tourism Activity and Expenditure

	Visitor arrivals (thousands)		Increase	*Estimated expenditure (US $ millions)*		Increase
	1982	1984	(%)	1982	1984	(%)
Antigua & Barbuda	164	195	19	44	65	48
Bahamas	1948	2325	19	654	810	24
Barbados	415	467	12·5	251	284	13
Belize	67	88	31	8	10	25
British Virgin Islands	156	162	4	66	86	30
Dominica	23	29	26	4	5	25
Jamaica	670	844	26	338	407	20
St. Christopher & Nevis	46	64	39	9	11	22
St. Lucia	106	128	21	32	42	31
St. Vincent & Grenadines	79	115	45·5	26	29	11·5
Trinidad & Tobago	NA	NA	NA	138	198	43·5

Source: Survey of Latin America and the Caribbean, United Nations Economic Commission for Latin America and the Caribbean (ECLAC), Santiago, Chile, 1986.
NA, not available.

tourism sector accounts for about 33% of gross domestic product (GDP), and directly or indirectly for 50% of employment.[2] For the Netherlands Antilles, tourism is the second largest sector for employment and earner of foreign exchange.[54] Tourism revenue represents a particularly high proportion, nearly 50%, of revenue as a percentage of exports in Mexico and Panama.[49] In Grenada, revenue from tourism accounts for over 35% of exports of goods and services.[54] For St. Lucia, tourism earnings in 1983 accounted for around 45% of the exports of goods and services. These tourists in St. Lucia spent US $39·7million in 1983, and tourism provided direct employment for about 3000 persons, and perhaps a larger number indirectly.[55] While in 1964 there were only two hotels in St. Lucia, with a total of only 20 rooms, by 1984 there were 1705 rooms. In the latter part of 1984, periods of 100% room occupancy rates were attained.[54]

Relatively few of the most intensively developed resorts have beaches broader than about 30 m at high tide.[34] Hotels and related facilities are commonly less than 20 m from the shore at high tide. The set-back requirement for St. Croix, for example, is 15 m (50 ft) from the low tide level as set by the enabling legislation for coastal zone management. The projected rise in relative sea level of 30 cm over the next 35 years or so could erode many recreational beaches in developed areas.[34] Qualitative assessments indicate that most of the world's sandy shorelines are already in retreat.[56] Some of this erosion may be mitigated by beach nourishment; however, beach nourishment becomes more and more expensive as the ocean level rises.[57] Moreover, sand resources for beach replenishment are often lacking for island countries, because of the limited sediment supply and narrow shelves. Beach nourishment therefore is an expensive, temporary solution that must be balanced against other alternatives.[58] Shoreline structures (sea walls, embankments, groins, and revetments), represent one alternative; however, such structures often exacerbate beach loss while protecting the upland, destroying the very resource that attracts tourists. Proper set-backs are the alternative that must be considered more ambitiously, particularly in this time of rapid development of the many Caribbean coastlines. Adequate land-use planning controls at both national and local levels, and a population sensitive to the problems and willing to adhere to central planning controls, are also needed.[59]

Wider Caribbean distressed areas

The rapidly expanding population of the wider Caribbean is making increasing demands for the limited coastal resources and the space the natural resources occupy. These demands are both direct and indirect. Direct demands include, among others, encroachment of development on the coast, mining of sediment for aggregate, and construction of shore protection devices. Indirect demands include those imposed as a secondary result of human activity, examples of which are global warming and sea-level rise, partly resulting from local land-use practices. These human activities have combined with natural environmental variability to form some distressed areas within the wider Caribbean. Examples of these distressed areas, resulting from a varying mix of causes, are presented below.

In the northern Gulf of Mexico, geodetic leveling data and more than 75 local tide-gauge stations were used to document relative sea-level rise and land subsidence for a 40-year period ending in 1982. The mean rate of Gulf of Mexico sea-level rise is 0·23 cm/year.[60] For Louisiana, the relative sea-level rise rates over the study period were 0·85 cm/year. During the last half of the study period the rate was 1·12 cm/year, an increase over the first half of the record. Because of the richness in the spectrum associated with varying causes for relative sea-level rise, this calculated acceleration cannot necessarily be ascribed to global change processes.

The results of the study[60] revealed that sediment consolidation and perhaps tectonic subsidence account for 80% of the observed relative sea-level rise in Louisiana. Other factors, such as decreased sediment supply and the diversion and channelization of rivers and streams, may contribute to the rate increases observed during the past quarter century. The greatest rate of subsidence, 0·39 cm/year, occurs west of New Orleans at the Paridis oil field, presumably due to withdrawal of fluids from the subsurface.[60]

The Gulf coast states have the most rapid average erosion rates in the US, partly due to the high rate of relative sea-level rise. The US national average shoreline erosion rate is 0·40 m/year, while the northern Gulf of Mexico's rate is 1·8 m annually.[61] For Louisiana, which has the most fluctuating coast within the Gulf region, the yearly rate of erosion is 4·2 m. During the past century, parts of the Louisiana coastline have disappeared at rates as high as 130 km^2/year.[62] One of the primary factors contributing to this land loss is the low level of sedimentation from the Mississippi River, depriving wetlands of sediment needed to maintain their elevation relative to sea level.[62,63]

The largest rate of erosion recorded along the Gulf coast occurred at Gulf Shores, Alabama. In 1979, Hurricane Frederick, with its associated 3·66 m storm tide, contributed to an estimated US $16.2 million of damage[64] in addition to either breaching, overwashing or flooding the coastal dunes.[65] Since more than 50% of Alabama's ocean front coast is developed, flood insurance payments to Gulf Shores was 25% of all US flood insurance payments during the six-year period ending in 1984. Another 25% during the same period was allocated to storm-struck Galveston, Texas. Mobile, Alabama, a non-barrier island community, received more than US $26 million in reimbursement during the same time period.[64] Further, despite a recent history of progradation (shoreline advance), the Mobile Bay delta has been receding since at least the early 1970s, perhaps in response to sediment impoundment by upstream dams in the drainage basin.[66]

North American sandy beaches and barrier islands erode at average annual rates of 0·8 m,[61] although the Gulf coast barrier islands are receding at a mean rate of 1·6 m annually.[61] However, coasts with fine-grained sediments, mud flats, and deltas have the highest mean rates of recession due to erosion: 2·0 m annually. Erosion rates on islands vary considerably, depending on their age, composition, geological history, exposure to the erosive forces, and human impact. On the tourist-oriented south and west coasts of Barbados, erosion has caused a loss of 6 m over the past 30 years, equivalent to 0·2 m/year.[67] Grand Anse is the major tourist center on Grenada; consequently, most of the hotels are situated on and behind this 2 km-long beach. This beach eroded at a rate of 0·7 m/year between 1970 and 1982. The primary causes of the erosion included sand mining and perhaps relative sea-level rise.[67] Concurrent climate change impacts will likely alter the erosion history in the wider Caribbean.

Other wider Caribbean distressed areas are due to other causes. Depletion of reef-dependent fishery resources in Jamaica, for example, may be exacerbated by relative sea-level rise. Coastal wetland reclamation in many countries of the region could lead to some areas being severely altered. In Jamaica and elsewhere, the key role played by peatlands is threatened. Since peat is a 'sink' for plant remains, nutrients and carbon, the conversion of peatlands to other uses may change them from carbon 'sinks' to carbon sources.[30] Since the early 1980s the Jamaican government has explored the idea of peat extraction for electricity generation from the Negril and Black River Lower Morasses of the southwest and western coastal areas.[30] These areas represent 75% of Jamaica's wetlands. The economic livelihood of approximately 1000 Jamaicans depends upon the catch of freshwater shrimp from the Black River Lower Morass. The average annual *per capita* income derived from shrimp alone is US \$1750.[30] Elimination or large reduction in size of these valuable wetlands is certain to have dramatic environmental, social, and economic consequences.

Other areas in the wider Caribbean are experiencing accelerated land loss due to natural and anthropogenic influences. In Venezuela, the coast is unstable due to tectonic uplift of about 0·5 mm/year in the Cordillera de la Costa region and subsidence of unknown proportions in the east.[66] Although less than 2% of Venezuela's shore has been altered as a result of man's direct influence on the coast,[66] oil-extraction related subsidence of 3·4 m has been measured in the period 1926–1954 near the Lagumillas oil field.[29] In extreme eastern Falcon State bordering Triste Gulf, a sector of low-lying sandy shoreline has eroded severely in recent times.[66] In Sucre State partially bordering the Gulf of Paria, a subsiding fine-grained sandy coast is slowly eroding behind a narrow shelf.[66] On the opposite side of the Gulf of Paria, the southwestern coastline of Trinidad is experiencing an annual rate of erosion of unconsolidated Miocene sand and clay deposits, in the order of 0·5–2·0 m in recent decades.[66] On Colombia's Caribbean coast, cliffs are receding near Palamino, and beach erosion is widespread around Barranquilla in the State of Atlantico, despite the presence of one of the world's major river deltas, the Magdalena.[68,69] In coastal Bolivar State around Cartagena, annual subsidence is at a rate of 0·36 cm.[26] Other wider Caribbean coasts are also eroding, such as Cuban, Mexican (along the Bay of Campeche), Panamanian, and other Antillean coasts.[69] In some cases this erosion is accelerated by relative sea-level rise.

Relative sea-level rise impacts other island regions, including the Lesser Antilles, such as Burnaby Spit on Nevis. During a 14-year time period roughly 50 m of land has been submerged.[70] Other sites on Nevis, around the northern end of Pinney's beach on the leeward coast, exhibited erosion rates in excess of 1 m/year.[70] Cambers states that the erosion may be due to increased wave energy and winter swells, as well as a rising sea level. Erosion is also threatening beachfront homes in the Loiza Aldea community of Puerto Rico. Over the past 30 years the beach has receded about 91 m.[71] There, a gradual immersion of most of the north coast of the island from Arecibo to Fajardo results from tectonics.[71] Although more than 150 beaches occupy 28% or 208 km of Puerto Rico's coast, the beaches generally are narrow. They are also divided into distinct systems with little interaction.[66] East of Ponce on the south coast, more than 50% of this almost continuous beach plain coast is suffering severe erosion, despite the presence of rip-rap installed to slow it down.[66]

In the face of a rising sea-level and changes in storm climate, a dune/beach system can migrate landward if sediment replenishment is available. Sand, gravel and shell mining in offshore shoals in waters that are shallower than 15 m reduce sediment availability in the wider Caribbean region. Dredging these shoals has eliminated natural breakwaters that reduce wave energy impinging on the shoreline. Further, the artisanal mining of calcium carbonate from nearshore reefs has contributed to coastal erosion problems in several developing countries in the region.[72] The island of St. Lucia is one such location, where mining sand and aggregate from beaches and nearshore zones has led to localized beach recession on the average of 0·6 m/year.[43] Before offshore sand extraction is undertaken, prospective alterations of the offshore bed should be examined in light of possible damage to the beach, as offshore sand deposits play a role in beach stability and sediment supply.[73] With projected relative sea-level rise and increase in tropical swells from storms, beach stability and sand supply should be of great concern. The islands of Dominica, Grenada, Guadeloupe, Jamaica, Martinique, St. Christopher and Nevis, St. Lucia, and St. Vincent appear to be most in jeopardy to these projected natural hazards, because of the level of sand mining activities on these islands.[74] On the windward coast of St. Vincent, beach erosion has increased following the extraction of sand and gravel from the foreshore for industrial usage.[68] Modification of tidal inlets can also exert significant influence on the erosional and depositional patterns of abutting beaches.[75,76]

There are other potential problem spots in the Caribbean region besides the mangroves and beach zones. These problem areas include municipal infrastructure built along the coasts, for example, Belize City, Belize, where about 28% of the country's population of 160 000 reside. Today, Belize City is only 15 cm above sea level with potential for great damage during directly impacting hurricanes that hit every 30 years or so. Belize has lost several cays along its nearshore reef, presumably due in part to hurricane erosion.[68] Several Caribbean island capitals are positioned near sea level, for example, St. Johns, Antigua and Basse-Terre, Guadeloupe.

Caribbean responses to the existing and potential climate change issues

There are several institutional frameworks in the Caribbean region that governments can look to for examples of coastline management schemes. One example is the US Virgin Islands Coastal Zone Management Plan (VICZMP), which was approved by the US government in June 1979. Since 1 July 1979, federal (US) funding under Section 306 of the 1972 Coastal Zone Management Act (CZMA) in the US Virgin Islands has amounted to US $4 039 000.

The VICZMP was designed to manage all development activities in the Virgin Islands coastal zone, which includes St. Thomas, St. John, and St. Croix islands, all offshore islands and cays, and the territorial sea. The program centers intensive management attention on development activities occurring in the 'first tier,' a relatively narrow coastal strip, along with all the offshore islands and cays, through the use of a general system of major and minor Coastal Zone Management (CZM) permits. A number of laws and related permits and programs administered by the Department of Public Works (DPW) controls activities within the 'second tier,' which includes the interiors of the three major islands.

The Virgin Islands Coastal Zone Management Act of 1978 (VICZMA) established the coastal zone permit system and the organizational structure for the VICZMP by designating the Department of Conservation and Cultural Affairs (DCCA) as the lead administrative agency, and creating the Coastal Zone Management Commission (CZMC) as having the primary responsibility for implementing the VICZMP. The VICZMA created the Bureau of Environmental Enforcement (BEE) within the Department.

The Commissioner of the DCCA is responsible for directing the activities of the DCZM (Department of Coastal Zone Management), for issuing, denying, or modifying all minor coastal permits, and for taking all enforcement actions arising from the implementation of the major and minor permit system. The DCCA also issues earth change permits for public entities in the second tier. The DPW retains the authority for all other earth change permits in the second tier. The CZMC (comprised of 15 citizen members, five from each major island, who serve also on one of three separate island committees), along with the Commissioner and the Director of the Virgin Islands Planning Office (VIPO) (both ex-officio, non-voting members), are empowered to promulgate rules and regulations and to issue major coastal permits.

The VIPO is responsible for reviewing and developing any changes to the VICZMP, reviewing and granting subdivision permits and historic district approvals, and ensuring that they are consistent with the goals of the VICZMA. The DPW has the statutory authority to grant building permits in both tiers, and zoning permits in the second tier, and must ensure that they are consistent with the goals of the VICZMA. The DPW also is responsible for monitoring activities permitted in the second tier by the Soil Conservation Districts and under the Virgin Islands Earth Change Program.

The DCCA has identified 18 Areas of Particular Concern (APCs). Eight are special management areas and 10 are areas for preservation or restoration. The DCCA developed detailed site-specific plans for most of these areas. The VICZMP is currently updating these for presentation to the CZMC. The plans give priority planning, monitoring, and enforcement status to each of these areas. The Virgin Islands Legislature may designate new APCs upon recommendation by the CZMC.

The VICZMA also provides for appeals to CZM Committee decisions on major permits through the Board of Land Use Appeals. The Act gives aggrieved parties 45 days from the committee's decision to appeal. The VICZMA (Section 907) authorizes the preparation of a Coastal Land and Water Use Plan to provide long-range guidance on coastal decision-making to the CZMC, the DCCA Commissioner, the VIPO, and other territorial agencies. Though there is no section of the CZMA that specifically deals with sea-level rise, the Act provides the mechanism or framework for addressing impacts of sea-level changes, leading to implementation of planning or policy actions for areas that are vulnerable to shore loss.

Besides the Virgin Islands plan, other institutional examples are available. Costa Rica's Coastal Area Management Program (CAMP), is, for the most part, a shoreline restriction strategy on a country-wide scale. Legislation was enacted in 1977, asserting that the first 200 m inland from mean sea level are part of the national heritage. Permits from the Costa Rica Tourism Institute and the Ministry of Public

Works and Housing must be secured in order to develop within 200 m from mean sea level along 75% of Costa Rica's shoreline.[77] The remaining, excluded 25% is comprised of municipally administered lands, deeded privately-owned lands prior to 1977, and national parks. In any event, the first 50 m of the 200 m national heritage zone is known as the 'public zone,' which cannot be owned or controlled by any private group. No type of construction or development is allowed in the public zone except infrastructure work deemed essential. This infrastructure work must be approved by the Costa Rica Tourism Institute, the National Institute of Housing and Urban Affairs, and the Ministry of Public Works and Transportation. The remaining 150 m of the zone is known as the restricted zone. In this area concessions can be granted but only by municipalities, the Tourism Institute, or the National Institute of Housing and Urban Affairs.[77]

Barbados has maintained a Coastal Conservation Project Unit (CCPU) since April 1984, which is totally funded by the government.[67] Among the tasks of the CCPU is the monitoring of natural phenomena such as hurricanes, storm swells and sea-level rise. There is now, through this program, an implementation of a 30 m—from the high tidemark—development set-back requirement.

Grenada, in 1983, performed a Physical Tourism Development Plan funded by the Organization of American States. From this study a coastal monitoring program was begun in August 1985. One of the four major tasks of the program is to set up one or more tide-gauges and initiate long-term sea-level measurements. It is further anticipated that a recommended 50 m development set-back policy will be legislated and implemented by the Grenada government in the near future. The examples cited above illustrate the concern of many wider Caribbean nations for their fragile environments. However, many wider Caribbean nations have no equivalent governmental organizations in place to address environmental concerns. In addition, no nations, to our knowledge, have major policy or management foci on global change issues.

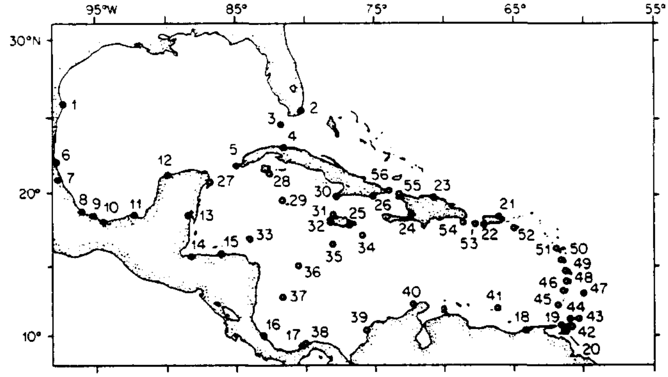
Caribbean research agenda

As a response to the concern expressed in the wider Caribbean region about the implications of expected natural and man-induced climatic changes for the marine and coastal environment, the United Nations Environment Programme (UNEP) has prepared a study of the wider Caribbean through the UNEP Regional Seas Programme. Some of the objectives of the study comprise an examination of the possible effects of sea-level changes on the coastal ecosystems, including but not limited to, deltas, estuaries, coral reefs, beaches, and wetlands. Another objective has been to determine areas or systems that appear to be most vulnerable to the projected climate changes and related effects. In this regard, beach systems were determined to be among the most vulnerable areas potentially affected.

Other studies are being conducted in the Caribbean Sea and adjacent areas. At its annual general meeting held in Tortola in September 1987, the Caribbean Conservation Association sponsored a number of topical technical sessions. The implications of sea-level rise on long-term tourism development planning was included as a major research topic.[78] About 90 regional and international environmentalists and non-governmental organizations will formulate policy options on this and similar issues. The United Nations Educational, Scientific, and Cultural Organization (UNESCO) Pilot Project on Coastal and Beach Stability, which commenced in early 1985, covers several islands of the Eastern Caribbean: Antigua, Dominica, Grenada, St. Lucia, St. Vincent, and St. Christopher and Nevis. This pilot project entails three phases: an overview survey of coastal management policies and problems, a series of awareness seminars held in the six island countries, and the training of domestic specialists. The major focus of this project is in developing internal capabilities to manage and conserve, for socioeconomic benefits, the beach and nearshore resources. One of the recommendations put forth during discussions held on each island was the need to implement a system of tide-gauges at each island in the Caribbean. One recommendation was that at least two tide-gauges per island be installed to determine local land-sea level changes.[79] Another recommendation was the establishment of a set-back policy of 100 m on lowland coasts.

In May 1987, a 20-month cooperative project to produce 'country environmental profiles' for four Eastern Caribbean countries was announced by the Virgin Islands-based Island Resources Foundation and the Barbados-based Caribbean Conservation Association. Priority environmental issues will be identified and analyzed, with follow-up policy and program recommendations provided. A broad spectrum of 'topics,' including marine systems, is being examined.

Another project, under the auspices of the Intergovernmental Oceanographic Commissions (IOC), United Nations, was a workshop on Physical Oceanography and the Climate of the Caribbean Sea and Adjacent Regions held in Cartagena, Colombia, in August 1986. The goal of the workshop was to convene a small working group of physical oceanographers from the wider Caribbean region to design a research agenda. One of the two projects proposed was the creation of a network of open sea and coastal sea level/weather stations which contribute to both island-scale and basin-scale measurement needs (Fig. 5). It was recognized that the interest of many area states was primarily in the economic and applied aspects of shelf and coastal processes, and that a sea-level project was essential to achievement of that goal.



• - Existing

1 Port Isabel, Texas
2 Miami Beach, Fla.
3 Key West, Fla.
4 Havana, Cuba
5 Cape San Antonio, Cuba
6 Tampico, Mexico
7 Tuxpan, Mexico
8 Veracruz, Mexico
9 Alvarado, Mexico
10 Coatzacoalcos, Mexico
11 Carmen, Mexico
12 Progreso, Mexico
13 Chetumal, Mexico
14 Port Cortes, Honduras
15 Port Castilla, Honduras
16 Limon, Costa Rica
17 Cristobal, Panama
18 Cumana, Venezuela
19 Chaguaramas, Trinidad
20 Port of Spain, Trinidad
21 San Juan, Puerto Rico
22 Magueyes, Puerto Rico
23 Port Plata, Dominican Republic
24 Port au Prince,Haiti
25 Port Royal/Kingston, Jamaica
26 Guantanamo Bay, Cuba

∘ - Proposed

27 Port Morelos, Mexico
28 Carapachibe, Cuba
29 Grand Cayman
30 Cape Cruz, Cuba
31 Montego Bay, Jamaica
32 Savanna-La Mar, Jamaica
33 Swan Isle, Honduras
34 Morant Cay, Jamaica
35 Pedro Cay, Jamaica
36 Serranilla, Colombia
37 San Andres Isle, Colombia
38 Colon, Panama
39 Cartegena, Colombia
40 Riohacha, Colombia
41 La Orchila, Venezuela
42 Toco, Trinidad
43 Crown Point, Tobago
44 Charlotteville, Tobago
45 Kingston, St. Vincent
46 Georgetown, Grenada
47 Bridgetown, Barbados
48 Castries, St. Lucia
49 Fort de France, Martinique
50 Roseau, Dominica
51 Basse Terre, Guadaloupe
52 St. Croix, U.S.V.I.
53 Mona Is., Puerto Rico
54 Isla Saona, Dominican Republic
55 Cape Du Mole, Haiti
56 Cape Maisi, Cuba

Fig. 5. Existing and proposed Caribbean Sea Level Stations. Source: Adapted and modified from the Intergovernmental Oceanographic Commission for the Caribbean and Adjacent Regions Workshop on Physical Oceanography and Climate, Report No. 45, August 1986, and the Permanent Service for Mean Sea Level. Birkenhead, Merseyside, UK.

A clear, pervasive thread in the research agenda is the need to document past climate change and related issues within the wider Caribbean, and the response of the region to such past climate change. Then, as scientific certainty of the mode, magnitude, timing, and distribution of global climate change grows, future climate change impacts can be better estimated based on past responses. This challenge requires improved understanding of local sea-level rise, tectonics, ecosystem response and causes, and climate variability. In most instances, new research facilities must be planned, funded, constructed, and manned by trained local personnel.

CONCLUDING REMARKS

Management of wider Caribbean coastal areas has been hindered by the general lack of understanding of complex coastal ecosystems and by the shortage of trained expertise in the integration of coastal management policy and science issues.[80] For this region, tourism planning should be a major component of comprehensive land use planning and development. The primary needs in terms of climate change research are both global monitoring observation devices and regional and local measurements of physical processes.[81] Fortunately, the existence of generalized environmental and ecological charts on a regional scale for the wider Caribbean may provide insight into the spatial relationships between, and among, natural systems located there.[82] In addition, satellite and airborne sensors have the potential of being valuable in the definition of coastline and beach width studies.[83] For example, Clark *et al.* have analyzed a part of the shoreline of Vieques Island in the Caribbean with remarkable success.

The continued industrialization of the wider Caribbean region may lead to increasing demands on domestic sand and aggregate supplies for construction. For instance, the industrialization of Puerto Rico led to the sand resources being exploited with little or no concern for the coastal areas where it was mined.[73] This exploitation led to the establishment of Federal and Commonwealth legislation either prohibiting outright or strictly regulating onshore sand extraction from most beaches and dunes.[73] Legislation should also be enacted for alternative offshore sites in and around the region. Both actions could help dampen the anticipated coastal effects of rising sea level.

To address the scientific and human aspects of global environmental change, policy decisions must include an understanding and concern for climate change. These decisions, preferably not *ad hoc* responses, may best be made through a combination of international treaties, much like the Montreal Protocol, which limits the use of chlorofluorocarbons. The Montreal Protocol mandates to its signatories a 50% reduction in emissions by the year 2000 of specific trace gases, notably several chlorofluorocarbons and industrial halocarbons.[1,84,85] Regional action plans, based on knowledge of local response to climate change with guidance from the latest scientific findings on timing and magnitude of human-induced climate change, are also required, so appropriate decisions concerning global environmental change can be made. At the least, continued attention should be focused on global climate change by the international community through interdisciplinary conferences and workshops, as well as basic research.

Education and awareness of possible global change and its impact on the wider Caribbean must be stressed at all levels: regional, national, local, and individual. While the scientific uncertainties associated with human-induced global change preclude the promulgation of sweeping environmental and developmental regulations, long-term infrastructural considerations must address global change impacts as part of the matrix of issues. Projects or activities having time scales of many decades may require closer examination and harsher performance standards than shorter-term projects. Set-backs and construction standards may have to be re-evaluated based on the expected duration of the project. The academic and applied challenge centers on how one derives equitable performance standards for projects impacted by climate change when the scientific uncertainties are so great.

The wide diversity in storm exposure, local tectonics, and land use practices suggests that nations in the wider Caribbean cannot rely solely on a generic response to climate change. Although some common elements exist, each nation will need to design its own set of policy responses, on the basis of the particular mix of factors present in each location. The similarities between these physical and environmental systems, as well as their differences, must be identified soon, at which point each nation can focus resources on the local issues of greatest potential impact.

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