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Ecological Implications of Potential Climate Change and Sea-Level Rise

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ABSTRACT

Implications of the WMO/ICSU/UNEP global climate-change scenario of a 20 cm sea-level rise and a 1.5°C temperature rise on the ecology of lands bordering the Caribbean Sea, Gulf of Mexico, and the Bahamas-area of the western tropical North Atlantic Ocean is considered. Human settlements will probably be more impacted by sea-level rise affecting potable and agricultural water supplies than by temperature change. Coral reefs on the other hand will be stressed more by temperature, not so much an average rise of 1.5°C, but the concomitant 'hot snaps' associated with natural thermal variance. Mangroves are judged to be more susceptible to precipitation changes than temperature or sea-level rise, but future regional rainfall is even more difficult to predict. Similarly, seagrass beds are probably more sensitive to change in the quality of light due to changed water turbidity than to 1.5°C/20 cm climate changes. Response strategies and management recommendations concerning these and other ecological aspects of climate change are hampered throughout the region by lack of adequate information; the most difficult task will be to separate anthropogenic effects not directly associated with climate.

1 INTRODUCTION

The region is suitably described as a community of contrasts. It is an area of wide cultural, political and ethnic diversity, rich natural endowments and scarce financial resources. It has some of the world's clearest waters and finest beaches, yet it is faced with increasing environmental stress to its marine and coastal resources. In this chapter the potential effects of climate change on human settlements, agricultural resources, and coastal systems is discussed, and recommendations are made for mitigation of future change.

1.1 Human Settlements

The region is characterized by the uneven spatial distribution of its population. Data on population density per country frequently do not show this clearly because they do not reflect the often very uneven distribution of population within a given country. This has to be taken into account when considering the apparently low density of the region as a whole.

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The islands of the Antillean arc have reached such a high population density that any significant further increase in their population would endanger their carrying capacity. (All these islands have more than 100 inhabitants/km², with the exception of Cuba and the Dominican Republic, which have less; Barbados has over 550/km².) As most of these islands (with the exception of Cuba and the Dominican Republic) have few flatlands, the high population density results in a very intensive land use of hills and mountain slopes causing serious environmental degradation of their forests and of their marine coastal systems.

In contrast to islands, the continental countries of the region have a population density of slightly more than 25 inhabitants/km². Most of these countries therefore have relatively large territorial reserves and natural resources to accommodate an expansion of their populations. El Salvador is an exception, as its limited territory, coupled with rugged topography and a markedly high population density (169.5/km²), make it very similar to the highly populated islands of the Caribbean Sea.

Historically, the populations of tropical Latin America settled in the valleys, plateau, and watersheds of the highlands, i.e., in the less humid conditions that favoured human habitation. In Central America these lands are either near the Pacific coast or are hinterlands far away from the coasts and separated by topographic barriers.

In recent times, the population of the coastal areas of the region has experienced a marked increase, showing a continuous trend towards the occupation of these areas. As the population pressure will probably increase in the future, if adequate administrative measures are not taken, it could result in unacceptable environmental and social consequences.

Venezuela and Colombia are the only countries with trends of population increase in the hinterlands. On the Caribbean Sea coasts of these two countries, population increases are limited to a few specific areas, influenced principally by the expansion of existing cities. Due to the very low population densities existing at present in the interior plains of these countries and expected growth rates of lower magnitude, the future stress probably will be different from that of the rest of the Central American subregion.

Large metropolitan areas make enormous demands on water resources, and sometimes sources in the nearby surrounding areas cannot suffice. Wastage due to bad maintenance aggravates the problem. Increased infrastructure using more distant sources not only increases costs but can also prejudice activities such as agriculture.

1.2 Agricultural Resources

The diverse soil resources of the region include 517,525,000 hectares, of which 9.7% are classified as arable and permanently cultivated, 22.7% pasture, 50.3% forest, and 17.3% miscellaneous. There are four main problems relating to utilization of these resources: erosion, salinization, waterlogging and chemical degradation.

The most serious problem affecting the soils of the region is erosion which is related to specific soil characteristics, type of vegetation cover, intensity of rainfall, winds, topography, and agricultural practices. The most vulnerable areas are the Greater Antilles and parts of Venezuela, Colombia, Guyana and Trinidad and Tobago. Also, desertification due to soil erosion is high in some parts of Mexico, including the Yucatan Peninsula. It is estimated that Panama has 1 million hectares of eroded soil, Venezuela 10 times more.

Agriculture in the region is typified by three main systems of production: large-scale estate or plantation agriculture (e.g., sugar cane); small-scale sedentary agriculture (e.g., truck products); and migratory or shifting agriculture. The first of these, large-scale plantation agriculture, is the dominant system in the region. Large private estates or plantations, generally occupying most of the best land, often have been devoted to single-crop monoculture or cattle raising, traditional sources of the region's exports. The main export crops include sugar, coffee, cocoa, cotton, bananas, rice, and to a lesser extent, citrus fruits, coconuts (copra) and tobacco. With the exception of sugar cane, which is usually exported in the form of raw sugar, most of the crops are exported as unprocessed primary products.

In general, the region's agricultural production is inadequate to feed the population, in part, because so large a portion of the arable land is permanently used to produce export crops or used for purposes other than agriculture. The region is increasingly dependent on imported edible oils, cereals and dairy products. For example, imports of cereal increased from 6% of total food imports (1955–1960) to 46% (1965–1970) and then to 60% (1971–1975).

1.2.1 Soil utilization

Significant changes have been observed in soil-resource utilization. For example, since 1969, arable and permanently cultivated land increased by 4 million hectares (8.6% increase), while land for urban and industrial development, road construction and as waste land increased by 7.5 million hectares (9.1%). Some of the agricultural problems relate to availability of arable land, which is under high pressure from urban and industrial developmental activities. The per capita arable land of the Lesser Antilles is 0.13 hectares, one-third of the average for the whole region.

The large export-oriented systems, in addition to causing environmental degradation of the soil through monocultural practices, generally lead to increasing marginalization of a large section of the farming community, thus contributing to the flow of landless population into urban areas with all the environmental consequences of rapid, unplanned growth of such new areas. Agricultural practices, especially in the continental subregions, have constantly modified the agricultural frontiers by removing the protective forest cover, possibly causing unwanted environmental changes in the microclimate, availability of water resources, soil erosion, etc. In some cases, particularly in the smaller islands, there is insufficient suitable land, even where the land tenure system is satisfactory. Also, large-scale farming often is characterized by under-utilization of the resource.

Nowadays, a number of factors have contributed to the decline of agricultural production: droughts, floods and hurricanes; crop diseases, industrial disputes; labour shortages; reduced acreage; shortages of chemicals and machinery; and political instability and poor management decisions. Development agricultural plans should follow a similar approach as the one used by Vicente-Chandler (1987) for Puerto Rico.

Drought is the major climatic constraint in soil productivity. Poor soils and/or serious erosion problems limit agriculture in some areas as in Curacao and Aruba in the Netherland Antilles; Antigua, Cariacou and Nevis in the Lesser Antilles; Haiti, Jamaica, and Puerto Rico in the Greater Antilles; Colombia, parts of Venezuela, the Guyanas and Trinidad and Tobago.

1.2.2 Forest lands

The total area under forest was estimated for 1975 as 221 million hectares. Since 1966, however, 10 million hectares have been lost and, taking into account present forest-management practices, the forest area is expected to shrink to 194 to 175 million hectares by 1980 and 2000, respectively. Many areas originally covered by forests could not be reforested, since centuries of man's activities have changed the basic characteristics of soils and the topography. Barbados, once totally forested, no longer has forests; Colombia and Mexico are losing substantial forest lands. Development of commercial forests frequently leads to serious environmental damage.

The most serious ecological consequences of deforestation are erosion and the disturbance of the hydrological equilibrium. Erosion leads to destruction of the soil characteristics and fertility and, in hilly or mountainous areas, encourages landslides. Disturbance of hydrological equilibrium affects the surface-water supply of the river basins, leading to extremely exaggerated differences in river flow between seasons, reduction of underground aquifer recharge, sedimentation of rivers, estuaries, swamps and coastal areas, as well as to increased incidence of flash flooding. Also, because of changed surface-air moisture equilibria and the reduction in evapotranspiration, changes in microclimates occur, and in severe cases of deforestation major large-scale climatic changes can occur, leading to serious drought or desertification.

Deforestation has occurred throughout the region and therefore, forests are disappearing at an alarming rate. UNEP estimates that Colombia is loosing 800,000 hectares per year (ha/yr), Mexico 400,000 ha/yr, and Venezuela 250,000 ha/yr. Every year nearly 1.8 million hectares of forests are destroyed while only 34,000 hectares are replanted. In Central America, the process has been accelerated through the conversion of forest to pasture for cattle raising, mainly for export to the United States.

Other factors that have caused large-scale deforestation in the region include bad silviculture practices, 'slash and burn' agriculture practiced by landless subsistence farmers, and the felling of trees for firewood and for timber. In the insular Caribbean Sea and in particular in the Lesser Antilles, where soils suitable for food crops are very scarce, most of the best land is permanently under export-oriented plantation crops such as sugar cane, bananas, tobacco, coffee and cocoa.

The environmental effects of deforestation in the humid tropics are quite different from those in the temperate regions of the world. The humid tropics are, in general, subject to far higher annual rainfall, and this precipitation is also much more intense for longer periods. For example, Hurricane Flora reportedly caused extensive damage in deforested areas of Cuba, yet relatively insignificant losses were reported in natural forest areas. A similar situation occurred in Honduras when Hurricane Fifi struck that country.

Another significant problem associated with deforestation relates to the fact that, in the tropics in general, and the humid tropics in particular, the nutrient cycle is very rapid. Most nutrients are found in the first few centimetres of soil and in the vegetation itself. Consequently, total elimination of the forest biomass means that the majority of the nutrients are lost from the ecosystem and a poor soil is left. This can create serious obstacles to reforestation efforts if the two activities are not undertaken at the same time.

One of the prime causes of deforestation in much of the region is the migratory agricultural practice of clearing land using the 'slash and burn' technology. Much deforestation is carried out to extract mineral resources, to shift rapidly increasing urban populations, and to increase agricultural land required to feed the growing populations.

1.3 Coastal Systems

Some of the most productive and biologically complex ecosystems in the world are found within the coastal zones of the region. These include coral reefs, seagrass beds, mangrove forests, and coastal lagoons. The economic importance of these systems stems primarily from their linkage to other resources, especially fisheries and coastal tourism.

Surface waters of the Caribbean Sea are warm throughout the year, resulting in a relatively stable horizontal layering between surface and deeper waters. This stratification is indicative of a circulation system that prevents the upwelling of nutrient-rich deep water except along the northern coast of South America. Lack of nutrients limits phytoplankton production in tropical climates; the Caribbean Sea is generally clear because biological productivity is low (Muller-Karger, Chapter 8).

Nutrient limitations are overcome in nearshore marine habitats of the region through:

1) fixation of nitrogen by shallow-water, blue-green algae found on coral reefs, mud flats, seagrass beds and other environments;
2) for example, the remineralization of the organic material characteristic of recycling of certain nutrients within and between systems;
3) input of nutrients and organic material derived from terrestrial freshwater run-off into coastal lagoons and mud bottoms.

These mechanisms result in physical, chemical and biological linkages between coastal habitats. Changes or disruptions to pathways of interaction can have some effect upon all of these habitats (Ogden and Gladfelter, 1983). The separation of nearshore resources in the following discussion is for organizational simplicity. Development and management of these resources must be based upon a perspective of the entire coastal zone rather than on individual components.

1.3.1 Coral reefs

There are approximately 60 species of corals in the region including about six dominant species that are primary reef builders. Individual corals grow at rates ranging from 1–25 cm/yr. Coral reefs, consisting of the consolidated skeletons of corals and other $CaCO_3$-depositing organisms, accumulate rapidly in geological time. Modern coral reefs in the region represent about 10,000 years of coral growth (Goodwin *et al.*, 1986).

Coral reefs require clear, clean water and relatively high wave energy to grow and flourish. Thus, they are best developed on the windward side of coasts and are absent where sedimentation from terrestrial runoff and rivers is heavy, such as most of the northern coast of Puerto Rico (Bak, 1983).

Coral reefs are one of the most important coastal resources of the region (*cf.* Milliman, Chapter 13). They are the basis of many coastal fisheries, providing food, shelter, and nursery areas for commercially valuable fishes and crustacean species. Reefs form breakwaters which protect harbours and bays and limit coastal erosion. Coral skeletons are a major source of sand and gravel resources in some islands. The beaches and visual attractions provided by coral reefs are the focus of much of the tourism in the region (Salm and Clark, 1984).

1.3.2 Mangroves

Mangrove forests are a coastal feature unique in lowlands of tropical and subtropical regions. Prop roots of some mangrove trees provide a surface for the attachment of marine organisms, reduce tidal and wave energy, and stabilize the soil, thus promoting deposition of nutrient-rich mud and silt. Mangroves provide habitat and shelter for a variety of animals such as small fishes, crabs, and birds. By breaking stormwaves and dampening tidal currents, mangroves help to maintain the coastline against erosion, and may actually extend coastal lands by trapping and binding sediments. As a result, sediment loads into coastal waters are reduced, and normally there is little, if any, resuspension of sediment through shoreline erosion. Decomposed leaves of the mangroves form the base of a food web that extends to large fishes and birds (Cintron and Schaeffer-Novelli, 1983). See Snedaker (Chapter 12) for a detailed discussion of mangroves.

1.3.3 Coastal lagoons, salinas, deltas and estuaries

Coastal areas of the region near major watersheds often contain huge lagoons of fresh or brackish water that provide important sources of organic material and nutrients as well as feeding, nesting and nursery areas for various birds and fishes. Large coastal lagoons are most prominent along the mainland and are often the breeding grounds for nearshore shrimp fisheries. Coastal lagoons buffer controlling terrestrial runoff, providing natural settling basins for suspended sediments.

Salinas, shallow ponds and lakes with limited or only tidal contact with the sea, are characteristic of many dry islands of the Caribbean Sea. Traditionally, salinas have been used as salt evaporators and have been targeted for mariculture or marina construction in more recent development schemes. These ponds also function as sediment traps and are important to the protection of nearby coral reefs from excessive sediment loading.

Mud bottoms are extremely productive, supporting commercially important shrimp and groundfish fisheries. Wide bands of relatively flat mud bottom are associated with the coasts of North, Central and South America. Mud bottoms result from seasonal runoff of fresh water carrying terrestrial sediment and are enriched in organic material by outflow from coastal lagoons.

Deltas and estuarine areas are marginal marine coastal systems that are impinged, either permanently or temporarily, by fresh-water intrusions. These systems, although usually turbid, are colonized by seagrass vegetation (especially sciophilic species), mangroves or other critical benthic habitats. Deltas are usually subsiding zones. Photosynthetic active radiation (PAR) may become limited at very shallow depths. Nonetheless, habitats within or in the vicinity of deltas and estuaries are essential to a wide diversity of euryhaline species, many of which (e.g., the oyster *Crassostrea rhizophorae* in the southern Caribbean Sea, and *C. virginica* in the northern Caribbean Sea) are of commercial importance.

1.3.4 Seagrass beds

Large meadows of seagrasses of three major species occur in close association with coral reefs in the region. Seagrasses are true flowering plants with male and female flowers and seeds borne in fruits, yet the most common form of reproduction is asexual via a rhizome growing horizontally through the sediments penetrated by the roots.

The seagrasses covering the bottom of coastal bays trap fine sediments and stabilize the bottom with interwoven rhizomes beneath the sediment surface. Sediment retention and stabilization are important for adjacent coral reefs because they prevent abrasion or burial of these reefs during storm conditions (Zieman, 1983).

Seagrass blades provide surfaces upon which many organisms attach, including a variety of algae which may produce calcareous sediment or provide food for grazing organisms (Vicente *et al.*, 1980). Seagrasses serve as nurseries for the juveniles of commercially important species (Ross, 1982) including fishes (i.e., snappers, grunts) and invertebrates (i.e., lobsters, conchs).

1.4 Coastal

Coastal resources of the entire region are under increasing impact from human activity such as:

1) Tourism.
2) Waste disposal.
3) Marine and coastal pollution.
4) Poor land-use practices.

1.4.1 Fisheries resources

Fish protein forms a significant part of the protein intake of the people in the region, and fisheries figure prominently in the national economies. This is especially true of smaller islands, which lack facilities for livestock production. Although much of the fish requirement continues to be imported, fisheries are developing and expanding.

The total estimated potential of fisheries resources for the region's continental platform ranges between 3 and 4.5 million tons per year. The theoretically sustainable exploitable potential is between 1.3 and 2.6 million tons per year. Data on the amount of these resources actually extracted are incomplete. Data on fishing by countries from outside the region are missing altogether. Incomplete data from countries of the region indicate that their present fishing practices are unlikely to result in overexploitation of their resources over the continental platform, except possibly in localized areas.

The most significant fishery activities of the region are found at Campeche Bank in the Gulf of Mexico, at Mosquito Bank in the Caribbean Sea off the coasts of Honduras and Nicaragua, in the Gulf of Paria between Venezuela and Trinidad and Tobago, and the coastal waters in the Guyana–Surinam area. Coastal and inland fishing in the region is mainly artisanal in nature.

Because of a pronounced lack of upwelling and the existence of a stable thermocline, nutrient-rich waters do not rise to the surface except along the Caribbean Sea coast of Venezuela (Aparicio, Chapter 6). This results in a generally low-level of zooplankton in the food-chain and in significantly smaller populations of exploitable fish. As a consequence, coastal mangroves, estuaries and coral-reef communities play a proportionately large role in providing nutrients and breeding grounds for many species.

Few or no statistics relating to inland fisheries or aquaculture in the region are available. Inland fishing is generally carried out in a small, unorganized, private capacity. Aquaculture is underdeveloped in the region. However, in the last few years substantial interest on mariculture has been generated in some countries. Limitations of capture fisheries, efforts to reduce imports, and the need for economic diversification have contributed to public- and private-sector interest in the culture of high-valued marine species for export and less expensive species for local consumption. The physical characteristics and resources of the region indicate considerable potential for coastal mariculture. Many countries are endowed with long coastlines dotted with protected bays, coves, harbours and lagoons; relatively fertile brackish water, estuaries, mangrove swamps and other wetlands; large areas of coastal land with marginal agricultural potential; and a tropical climate favouring year-round growth.

The presence of edible or commercially valuable species of crustaceans, molluscs, fishes, seaweeds, etc. also favours the development of coastal mariculture systems. Of special concern are marine shrimp species (*Panaeus schmitti* and *P. duorarum*), spiny lobster (*Panulirus argus*), Caribbean king crab (*Mithrax spinosissimus*), the queen conch (*Strombus gigas*), mangrove oyster (*Crassostrea rhizophorae*) and the American oyster (*C. virginica*). See Gable (Chapter 10) for the distribution of the most important species.

1.4.2 Sandy beaches

Sandy beaches are shoreline areas exposed to some degree of wave action. In contrast to rocky shorelines, the dominant substrate type is sand which may be autogenic or allochthonous in character. Sandy beaches are not biotically barren grounds. On the other hand several infaunal and epifaunal organisms inhabit the unstable bottom. They are capable of movement, both vertical (e.g., *Donax denticulatus* and *Emerica* spp) as well as horizontal movement (*Luidia* spp, *Astropecten* spp and *Mellita* spp). Their mobile character makes these species capable of adjusting to the continuously shifting substrates.

Not only do sand beaches harbour some peculiar endemic components, but also, are a major attraction of the touristic resources of the region in general (Hendry, Chapter 7).

1.5 Climate

Although the entire region lies within the tropics (2 to 30° north of the equator) there are substantial macro- and microclimatic variations due to topography and orientation with respect to the prevailing northeasterly winds. Even comparatively small islands such as Jamaica show marked differences from one area to another; thus, on the northeast coast and over the Blue Mountain range, annual precipitation averages 7600 mm, whereas it is only 760 mm on the southwest coasts, giving an island-wide reported annual average of 2000 mm. Such large variations for even a small island illustrate the lack of meaning attributable to national average rainfall figures (UNEP/CEPAL, 1980). Nevertheless, the following broad climatic zones, with reference to rainfall and temperature, can be identified within the region (*cf*. Gray, Chapter 5):

1) Humid tropics are found along most of the coastlines of Central America, eastern Venezuela, the Guyanas and the majority of the islands, as well as in the tropical rain forests below an altitude of 100 m. Here average annual rainfall is heavy (in excess of 2000 mm), although there are distinct wet and dry seasons, with the majority of precipitation occurring during a six- to seven-month period.
2) Sub-humid tropics with much lower rainfall are found in several inland areas of Central America, along the northern coast of Colombia and Venezuela and in some of the natural savannah areas of those two countries, as well as Barbados, the Netherlands Antilles, Antigua, southern Haiti and southern Jamaica. In these areas rainfall averages between 100 and 1500 mm annually.
3) Semi-arid and arid areas occur in a few locations in the region, such as northern Venezuela and northeastern Colombia. However, by far the largest area occurs in Mexico. In these regions annual rainfall averages less than 700 mm, but precipitation is highly unpredictable and can vary by as much as 40% from one year to the next.

In general, it can be said the the region does not suffer from serious water deficiency, as measured by annual rainfall minus evapotranspiration.

2 Climate-Change Impacts

Impacts on the resources and ecosystems described above would result in mainly from the rate of change of:

1) CO_2 and other greenhouse gases.
2) Climatic elements such as temperature; net precipitation; storm frequency, origin, and intensity.
3) Sea level change.

The assumed scenarios for the period leading up to the year 2025 are given in Table 11.1.

2.1 Human Settlements

These are unlikely to suffer from changes in the climatic elements except increased length of hurricane season, which can be partially planned for. Sea-level rise however, coupled with land subsistence (both natural and anthropogenic) could lead to flooding of nearshore property in island and low-lying coastal states. Damage or overwhelming of sea-defense works and saline intrusion into drinking and irrigation water could become a serious problem for low-lying coastal states such as Belize and the Guyanas.

2.2 Agricultural Resources

Saline intrusion could have severe deleterious effects on large-scale coastal agricultural operations such as rice production on the Guyana coast. An ongoing programme of varietal testing might be necessary.

2.2.1 Soils

Soil-erosion problems could increase but these should be manageable by improved conservation practices. Saline intrusion might render low-lying coastal areas (in Belize, Guyana, etc.) unfit for traditional crops or varieties.

2.2.1 Forests

Forest adaptation is slow compared to other agricultural operations and hence may suffer or benefit more from rapid climatic changes over historical norms. It is unlikely that such changes would be significant for inland and hilly forests. In any case active programmes of reforestation can only help towards a sustainable solution of the overall problem.

2.3 Coastal Systems

2.3.1 Introduction

The classical case of the *Lithophaga*-bored columns in the Temple of Jupiter Serapis near Naples (Allison and Palmer, 1980a and b) and the more recent

Table 11.1 Assumed scenarios for estimating climate-change impact by the year 2025.

Parameter	*Predicted rate of change*	*Historical average*
1. CO_2 build-up in atmosphere	50% over next 30 years (global)	8% over last 25 years (global)
2. Temperature	1.5°C over next 100 years	1.5 ± 0.5°C over last 10,000 years
3. Net precipitation	Uncertain, but likely increase in humidity	
4. Storms	Uncertain, except that hurricane season could be lengthened due to increased SST	
5. Sea-level rise	20 cm by 2025 (i.e., approx. 0.5 cm/yr)	20 to 100 cm per 100 years (0.2 to 1 cm/yr)

example of littoral faunal uplift of the fouling populations growing on a concrete bridge piling at LeJeune Road in Miami (Wanless, 1982), are two popular examples of sea-level changes (although by different causal agents) during Holocene times. The numerous coral fossils and terraces now sitting on land 400 m or more above present sea level (Horsfield, 1975), further reflect that sea-level changes have occurred on a much larger scale in the past, with significant (and perhaps at times catastrophic) consequences to the shallow benthic systems associated with these ancient shorelines. We have evidence that changes may be occurring at present (Hanson and Maul, Chapter 9), but the specific sea-level trend is still not clear because of the endemic geomorphological complexity of the region. Some of the most important factors that influence sea level are discussed below. Geoid changes are discussed in detail by Morner (1976) and will not be included in this discussion.

Predictable periodic factors that have measurable effects upon mean sea level are the tides, the 14-month cycle of the Chandler motion and the 18.6-year nodal cycle of the moon (Lisitzin, 1983). Furthermore, the complex hydrographical and meteorological character of the region can cause significant measurable effects on mean sea level. However, most of these factors have been studied to some extent and are usually considered or corrected for when determining present eustatic sea-level trends. Diastrophic movements also can cause changes in the relationship between a specific land mass and the sea. These movements, whether epeirogenic or orogenic in character influence sea level, particularly in geologically active areas like most of the boundaries of the Caribbean Plate.

An ecological evaluation of the impact of a sea-level rise on shallow benthic marine systems (e.g., coral reefs, seagrass beds, mud flats, deltas) cannot be accurate unless one considers the geological scenario of each locality. For example, if all other sea-level-influencing factors remain constant and the general environment is unchanged, a particular area that is presently becoming uplifted may partially (e.g., Barbados) or totally (e.g., the Huon Peninsula, New Guinea, is rising at a rate of 3 mm/yr) balance the sea-level rise effect on the benthic assemblages. On the other hand, the effect of the expected rise may be accentuated on benthic systems lying on top of subsiding zones (e.g., river deltas in general).

Horsfield (1975) gives a general overview of Quarternary vertical movements in the Greater Antilles by interpreting the variable elevation of raised Quarternary marine terraces. Quarternary tilting was also inferred from depth variations over shallow submarine banks. Using his estimates of tilt direction and assuming that this trend will continue unchanged for the next century, and assuming that all other physical factors remain the same, then the following localities in the Antilles will become uplifted to some extent (actual rates are not given) and therefore could at least in part locally reduce the increase in depth expected by the predicted sea-level rise: east coasts of Cayman Islands, north coast of Jamaica, southeast coast of Cuba, north coast of Bahia, and the southwest coast of Haiti. By the same token, the coasts on the opposite end of the tilt axis are more likely to become deeper or drowned.

Unfortunately, information on the diastrophic trends of islands is controversial, and qualitative. One exception may be made for the extensive geological studies done on the island of Barbados, perhaps, because of its unique composition. Unlike all of the other Lesser Antilles which are volcanic, Barbados is formed of folded sediments with a cap of reef limestone. The island is being uplifted at a rate of 0.3 mm/yr (Stoddart, 1976). Geological complexity of the region results from the entrapped position of the Caribbean Plate. Stresses along the northern plate boundary have caused uplift in many of the islands and subsidence in many others. For example, upraised limestone strata on a fault block create the spectacular cliffs of Mona Island on the west coast of Puerto Rico. Along its western boundary, the Cocos Plate is being thrust beneath the Caribbean Plate. The eastern boundary of the Caribbean Plate is a subduction zone in which the north and south American Plates are being driven under (see Fig. 7.4). Although there are some general agreements among geologists concerning the position and general eastward drift of the Caribbean Plate, there is major disagreement when it comes to modelling it in any detail. This was a major point discussed during the 7th Annual Symposium on Caribbean Geology held in Puerto Rico during 24–28 February 1988.

Florida, the Bahamas, the Bermudas, Cuba (except the southeastern tip), and the Yucatan Peninsula are not part of the Caribbean (Tectonic) Plate, and probably will remain more stable geologically in the next century than Hispaniola, Puerto Rico, the Lesser Antilles and the Caribbean Sea coast of Central and South America where strike-slip faults or subduction zones are found. Contrary to the block faulting of late Quarternary movements in the island, western Jamaica has had a history of relative tectonic stability since the Holocene (Digerfelt and Hendry, 1987). Shlemon and Capacete (1976) show that no major epeirogenic uplift has occurred along the north-central coast of Puerto Rico over the last 10,000 years. Other authors, however, suggest that up to 4 m of epeirogenic uplift over the last 4000 years has indeed occurred (= 1 mm/yr) in this region. The north coast of the Dominican Republic is being uplifted (A. Foster, pers. comm.).

Before discussing the detailed ecological implications of a real rise in sea level on shallow tropical benthic communities, areas where subsidence is occurring at significant rates should receive particular attention since they could be affected the most. Natural subsidence by tectonic tilting or just plain sinking of the coast by deposition and compaction of sediment occur in various places (e.g., Gulf of Mexico). Regional geosynclinal downwarping has been widely recognized as a subsidence process affecting deltaic regions as well as subsidence through compaction (Morgan, 1967). For example, the birdfoot delta of the Mississippi has been operative for some 500 to 600 years. The subsidence rates there are as much as 5.3 cm/yr. Furthermore following the abandonment of a deltaic distributary system, sedimentation ceases but subsidence continues. There are anthropogenic sources of subsidence which perhaps should be considered in particular areas. Some of these sources are pumping of groundwater for agriculture or industry and extraction of crude oil and natural gas. For example, a subsidence of 3.4 m in an oil field in Venezuela occurred between 1926–1954; this represents a subsidence rate of 12 cm/yr.

2.3.2 *Coral reefs*

The evaluation of one factor on coral-reef assemblages must be done within the context of additional variable disturbances that at present are structuring (if an ecological deterministic approach is taken) or have structured (the historical approach) the community. For example, we have evidence that both physical and biological disturbances in various scales of time and intensity have measurable effects on coral-reef populations and therefore on community structure. Some of the biological factors are: bioerosion, overgrazing, overgrowth, territorial behaviour, massive mortalities, predation and disease. Some physical factors important in determining community structure are: hurricanes, rainfall, tides, UV radiation, sediments, turbidity, erosion, sun hours, temperature, upwelling, hydrographic conditions and others. Reefs at present may be considered to be more prone to disruption in view of the recent mass bleaching event (Williams *et al.*, 1987; *cf.* Atwood *et al.*, 1992).

When evaluating what might be the result of a sea-level rise of 20 cm by the year 2025 on a reef, several factors must be taken into consideration simultaneously: the type of reef (e.g., fringing, patch, atoll barrier); the geomorphology of the coast; the ecological state of the reef and the zones and depth of the reef in question. At first one might think that the reef flat zone, if not able to grow in pace with sea-level rise, will be drowned and therefore this zone should be of primary concern. In fact, Cubit (1985) showed landward extensions and retreats of a zone of the red alga *Laurencia papillosa* that corresponded to rises and falls of yearly mean sea levels. The local temporary extinctions appeared to be the result of herbivores which expanded their grazing range when sea level was high. Also, the role of predation in limiting the distribution of intertidal invertebrates is well established in the ecological literature. On the other hand, if water level increases over the reef flat, perhaps seagrasses and algae better adapted to permanent submerged conditions, and sublittoral invertebrates will increase in abundance as a temporary result of the reduction of mortality caused by subaerial exposure (Cubit, 1985). However, due to the existing general turbid conditions generated in many reefs as the inevitable consequence of upland deforestation and poor coastal management decisions and/or as a consequence of discharges of organic pollutants and elimination of seagrass beds by thermoelectrical power plants, one should be particularly concerned with deeper zones that might be deprived of the proper photic conditions necessary to maintain the light-dependent coral and sponge populations. The potential reduction of PAR to sub-minimal levels that may significantly alter photosynthetic populations (e.g., sponges, corals and algae) could result in part, by the increase in height of the water column standing over the reef zone in question which will increase scattering and absorption of incident light. Furthermore, incursion into nearby mud flats during high tides may resuspend unstabilized fine sediments into the water column which may favour sciophilic or maybe even cryptic or fouling species considered of less ecological value than corals. Corals, both live and dead, are being bioeroded at a faster rate than Indo-Pacific scleractinians. Therefore, any change in conditions (e.g., increase in organic particle suspension) that would enhance bioeroding populations (e.g., *Lithophaga*, clionids, sprastrellids, sipunculids) or fouling populations that can transform nutrients into biomass at a fast rate, could competitively displace many corals and possibly cause more local coral-population extinctions that in turn could decrease or cease coral-reef accretion.

Accurate predictions on the effect of a sea-level rise can perhaps be made in reefs that have been physically and biologically monitored for many years. Such reefs do exist in Panama and Puerto Rico (see Vicente, 1987).

Although an increase of 1.5°C in surface-water temperature would change the normal winter temperature maxima to 27.5°C and the summer average maxima to 30.5°C, these increased temperatures in general are not high enough to impair physiological processes in marine organisms. However, potential physiological kinks could occur in photosynthetic organisms, especially at temperatures around 30°C. Furthermore, although the highest temperature endurable by West Indian and Hawaiian corals is 36°C, it is generally accepted that corals grow best between 25-29°C. Indirect long-term effects of an increase of 1.5°C are at present difficult to evaluate.

The coral reefs that would be more susceptible to becoming thermally stressed would be those occurring in the vicinity of thermal effluents from power plants and those growing in protected shallow lagoons (e.g., some patch reefs). In these particular situations temperatures of 40°C might be reached and would cause a mass mortality event, particularly in calm cloudless summer days during low tide. In the tropics, marine organisms are living closer to their maximum thermal tolerance than are temperate organisms. This is particularly true of southern Caribbean-reef biotic components which are exposed to a higher water temperature regime during the year than reef organisms in marginal tropical grounds (e.g., Florida) where even freeze-kills or cold-water stunting of marine faunal and floral elements have been documented.

It is also important to note that coral reefs, during the process of the biological calcification, removes carbon dioxide, the principal greenhouse gas, from the air–ocean system contributing to a more permanent solution.

2.3.3 *Mangroves*

Of the four common species of mangroves found in the region (*Rhizophora mangle*, *Avicenia germinans* (= *A. nitida*), *Laguncularia racemosa* and *Conocarpus erectus*), perhaps *A. germinans* should receive particular attention. For example, while the red mangrove (*R. mangle*) can send off prop roots of various dimensions in response to local hydrographic conditions, the black mangrove (*A. germinans*) has aerial roots which project only vertically for short distances above tidal muds. If the roots become permanently submerged by a relatively sudden rise in sea level, then, massive local extinctions of black mangrove with their associated floral (cyanophytes) and faunal (e.g., fiddler crabs) assemblages may occur throughout the region. The geographical extension and ecological implications of this potential demise of black mangrove forests, therefore, should receive particular attention. Furthermore, seedlings and seeds of *A. germinans* can literally drown, and will not develop or germinate under prolonged flooding conditions.

Contrary to the more (yet changing) stable coral-reef and seagrass-bed communities, the faunal and floral biocoenocis living on mangrove roots are quite ephemeral. The temporary existence of this type of community is due to periodic sloughing-off of the root itself, carrying down with it all the epibenthic biota into an anoxic-reduced mud environment. Organisms that have an early age of reproduction which helps produce high, instantaneous populations (e.g., selected species such as barnacles, oysters, some sponges and many ascidians) are usually found in this type of system. The effect of a sea-level rise on red mangrove-root community structure would probably be insignificant (everything else being held constant) because the prop roots of *R. mangle* usually stand much higher than mean sea level (sometimes more than 6 m) so that the diapores (which are adapted to colonize quickly) are not limited by lack of spatial resources. The overall effect would be a faunal-floral uplift which in a considerably short time will return to pre-existing conditions.

The littoral-supralittoral elements, furthermore, are adapted to tolerate high temperature and temporary subaerial exposure so that an increase of 1.5°C would probably cause unmeasurable changes in the population of these taxa. However, the sexual reproductive cycle of many mangrove-root organisms may undergo significant changes when the cycle is dictated primarily by temperature changes. This may cause uncoupling of sexual reproductive strategies with some other important requisite, and may become important to the biota whether of commercial importance (e.g., mangrove oysters) or not.

Although a landward extension of mangrove forests is likely to occur at first sight, this could only occur if the proper edaphic conditions exist in the new shoreline.

2.3.4 Coastal lagoons, salinas and estuaries

Marine benthic communities lying on or close to estuarine or deltaic grounds, whether these are seagrass beds, mangroves, or infaunal benthic assemblages, are, by definition, on marine marginal conditions which are hampered by periodic freshwater and terrestrial intrusive elements. These areas are generally turbid with measurable changes in salinity, and therefore are subjected to photic and osmotic stresses. Furthermore, these systems, particularly deltas, are usually sinking at measurable rates as mentioned before. As the delta fronts continue to be built forward, foreset beds are deposited over existing bottomsets, and in time, topset beds of the floodplain are extended over the foreset beds, causing subsidence. Deposition, however, has generally kept pace with subsidence but in some ancient delta deposits, marine limestone and shales are found interbedded with fresh-water sediments and soils. Therefore, benthic systems associated to deltas, particularly seagrass beds, which are already sinking under light-limited conditions as the result of the inherent nature of deltas and some estuaries, would be particularly affected or destroyed by the expected sea-level rise.

The lagoons could suffer from increased saline intrusion but depending on the rate should be able to support its usual nurseries. Salinas on the other hand could be flooded-over continuously and loose their economic value.

2.3.5 Seagrass beds

Seagrass beds are of unquestionable value not only to tropical, but also to temperate coastal systems. In order to be able to predict what will be the impact of the predicted sea-level rise on seagrass beds, baseline information about the particular seagrass bed in question is necessary. Furthermore, we need first to know the type of seagrass species in the meadow, since different species have different tolerances to physical factors such as depth and light. For example, shoal grass (*Halodule wrightii*) is a colonizing species which tolerates extreme physical stress, but sea vines (e.g., *Halophila decipiens*) is a stenotopic species if compared to *Halodule*. If the landward extension of the shore resulting from the increase in sea level includes unconsolidated aerobic substrates, then, one would expect an extension of *Halodule* beds into the new available spatial resource, assuming that enough propagules (seeds or turions) are present in the area. However, other factors, such as the wave energy of the locality, the light regime, the herbivore populations, the slope of the shoreline and in general, the history of the site, may make possible the establishment of a different seagrass species or may prevent the establishment of any seagrass species.

Although there are only six common species of seagrasses in the region (*Thalassia testudinum, Syringodium filiforme, Halophila decipiens, H. engelmani, H. baillonis, Halodule wrightii*) the seagrass species within a bed and the relative proportion of seagrass species in a given locality may be highly variable. For example, within Jobos Bay, on the southeast coast of Puerto Rico, seagrass beds within just 100 m from each other have different species and different proportions of macrofloral species. The same was found to be true of the epifaunal and infaunal invertebrates and fish associated with these seagrass beds as demonstrated by similarity indexes and polar ordination techniques. Therefore, to make predictions on what would be the impact of a sea-level rise from a seagrass-bed community structure point of view, is at present difficult. Defining a list of the specific parameters that are to be evaluated may be fruitful.

The effect of a sea-level rise on the physiology (growth rates, primary productivity, photosynthesis and respiration) of the marine phanerogams will also be complex unless we know the annual fluctuations of these parameters and how the light conditions of a particular bed, in association with other parameters, might be affected. If the sea-level rise causes a decrease in light penetration, the maximum depth of turtle grass beds could be decreased. However, this may be compensated for by an expansion of the seagrass bed into the new shore, assuming that there are adequate conditions on the new shore. Predictions related to the vertical extension of seagrass beds as a consequence of sea-level rise, however, may be complicated by the influence of certain herbivores (e.g., *Diadema antillarum*) which can also, like light, limit the distribution of turtle grass beds (Vicente and Rivera, 1982). Better predictions of the effect of a sea-level rise on a seagrass bed can be made using seagrass beds that have been monitored for a considerable length of time.

There have been interesting cases in which apparently, mangroves have not been able to keep pace with mean sea-level rise during Holocene times, and seagrass beds have established over drowned mangroves in Florida. Preliminary observations in Guayanilla Bay (south coast of Puerto Rico) may suggest a similar situation.

Only seagrass beds that occur in natural thermal-stress conditions (e.g., a shallow lagoon in the summer) or in localities receiving thermal effluents from power plants (e.g., *Thalassia* beds in Puerto Rico and Florida), could become negatively affected by a rise of 1.5°C. As discussed before, a temperature rise of this magnitude would not impair physiological processes in marine monocotyledons. Changes in biomass and productivity might be expected to change, however, since these processes are, to some degree, temperature dependent. Temperatures of 35°C or more can, for example, prevent root development in *Thalassia testudinum*.

2.4 Fisheries

In view of the widespread use of coastal tropical systems (e.g., seagrass beds, mangrove-root environments, estuaries) as breeding, mating, feeding and habitat grounds by: (1) commercially exploited species (e.g., decapod crustaceans, molluscs, shrimps); (2) species of ecological importance; and (3) endangered species (West Indian manatee, green turtle) makes these highly productive systems one of the most important resources in the region's waters. Furthermore, shallow coastal estuaries, lagoons, and embayments are utilized even by deep-sea fishes (e.g., Trichiuridae) to complete their biological cycle. The impact of a sea-level rise, and an increment in temperature on these systems will be reflected on both the artisanal and industrial fisheries of the region.

2.5 Sandy Beach Communities:

Sandy beach communities are adapted to withstand adverse environmental conditions. They can probably adapt to an increase in sea level (assuming that the integrity of the system is not lost) better than other benthic systems. Contrary to seagrasses, corals or sponges which are clonal organisms, the dominant structural components of sandy beach communities are aclonal, and furthermore are capable of limited but efficient vertical and horizontal migration to adjust to changes in depth resulting from changes in the beach profile. Now, whether the *Ocypode, Cirolana, Donax-Emerita* and *Mellita* zones (Gonzalez-Liboy, 1971) would persist after a sea-level rise will largely depend on the thickness of the sand layer, since a sandy beach can easily and quickly become transformed to a rocky coast by coastal-erosive processes. For example, Bruun's Rule states that a 1 cm rise in sea level will generally result in a 1 m shoreline retreat. Most developed beaches are narrow and therefore, with a rise of sea level of 20 cm most beaches will be inundated (i.e., no beach). Sea level together with sand extraction (e.g., Isabela, north coast of Puerto Rico), will pose a serious hazard to beaches.

3 RECOMMENDATIONS

1) Prepare a regional map with a classification scheme that shows regions that are more prone to become affected by the climatic changes expected as well as those less likely to become affected.

2) Prepare maps showing:
    a) those ecologically critical habitats (e.g., seagrass beds, coral reefs, mangroves, lagoons) within the region that are most likely to become affected with the sea level and temperature rise expected;
    b) supralittoral zones within each locality that will contain the following information: i) edaphic factors; ii) slope; iii) wave energy; iv) shoreline extension.
3) Analyse historical photographic records, or other historical information that may provide a clue to understanding the effect of recent sea-level rises at specific sites.
4) Prepare a detailed report on how species that are endangered and/or protected internationally, which are associated to the systems mentioned above, may become affected in any way by the proposed climatic change, particularly those that utilize the seagrass beds and/or coral reefs as feeding grounds.
5) Establish the potential impacts on environmental health including vector proliferation, waste disposal, water-quality management and toxic chemicals (including natural toxins) and their human health effects.
6) Establish the indirect impacts that the expected climatic changes will have on shallow coastal marine systems by their effect on: sewage and toxic-waste disposal and on other similar activities.
7) Establish a monitoring programme for determining saline intrusion rates into agricultural resources and drinking-water resources.
8) Prepare a report that specifically deals with the potential effect of the expected climatic changes on invertebrate populations (oysters, conchs, shrimps, crabs, lobsters) and fish populations of commercial value within the region.
9) Implement a plan of action to reforest unconsolidated shores that have a high risk to the expected climatic changes. This action should resist the erosional impact of sea-level rise.

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