PAPER

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CLIMATE CHANGE IMPACTS ON COASTAL BIODIVERSITY

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ABSTRACT: The physical configuration of coastal ecosystems is determined by a combination of marine, terrestrial, and atmospheric processes that shape the land/ocean interface. As the world's present coastlines evolved over the past 7,000 years (a period when sea level was relatively stable) assemblages of organisms that represent the current biodiversity of the coastal margins of the Americas also emerged. Located along the narrow transition zone at the ocean edge of continents and islands, coastal ecosystems and their biodiversity are affected by changes in the processes that created and sustain them. They are intrinsically dynamic due to their exposure to alternate flooding and drying, winds, waves, tides, and storms. Organisms that inhabit coastal ecosystems are uniquely adapted to environmental conditions that occur along the energy, salinity, and moisture gradients that extend from the subtidal region of the coast to the inland boundaries of its wetlands, estuaries, and floodplains.

Impacts on coastal systems are among the most costly and most certain consequences of climate change. As temperature increases and rainfall patterns change, soil moisture and runoff to the coast are likely to be altered. As sea level rises, coastal shorelines will retreat and low-lying areas will tend to be inundated more frequently, if not permanently, by the advancing sea. The salinity of estuaries, coastal wetlands, and tidal rivers will increase, thereby restructuring coastal ecosystems and displacing them further inland. If tropical cyclones increase in intensity, as projected by many studies, shoreline retreat and wetland loss along the low-lying coastal margins will accelerate further. As temperature increases along polar coastlines, a combination of permafrost thawing, sea level rise, and sea ice retreat will cause coastal erosion and land loss. This chapter examines the known effects of these and other key climate change variables on coastal ecosystems and their biodiversity.

The vulnerability of coasts to atmospheric warming and the changing climate is enhanced by environmental stresses associated with human development of the coastline and adjacent watersheds. Coastal areas comprise some of the most heavily developed landscapes in the Americas. The autonomous adaptive capacity and sustainability of coastal ecosystems in North, Central, and South America will be challenged due to a combination of stressors at the ocean/land interface. Coastal river deltas, such as the Mississippi and Paraná, are particularly vulnerable due to their high sensitivity to relatively small changes in mean sea level and riverine sediment delivery. Many coastal states, provinces, and nations are planning coastal adaptation strategies but much of the current emphasis is on protection of the built environment. Some climate change adaptation options, such as flood protection levees and sea walls, can exacerbate the effects of climate change and sea level rise on coastal flora and fauna. By incorporating biodiversity considerations into adaptation planning, native fish, wildlife, and plant populations are more likely to be preserved as climate change intensifies in the 21st century.

Keywords: coastal, biodiversity, climate change, sea level rise, the Americas, deltas, barrier islands, marshes, seagrasses, estuaries, mangroves, adaptation

1. Introduction and Definitions

The United Nations Convention on Biological Diversity (UNCBD) defines biodiversity as the variability among living organisms from all sources, including the ecological complexes of which they are a part (UNCBD, 2000). The World Meteorological Organization and the Intergovernmental Panel on Climate change (IPCC) define "climate" as the average state of the weather over time with the period generally being 30 years (although for some marine climate parameters such as storminess, longer averages are required (Zhang *et al.*, 2000). Climate change is defined by the IPCC as "any change in *climate* over time, whether due to natural variability or as a result of human activity" (IPCC, 2007a, page 871). The IPCC emphasizes three levels of biodiversity in its reports – genetic, species, and ecosystem (IPCC 2001, 2007a). Under these broad definitions, biodiversity can be influenced by any change in climate that directly or indirectly affects organisms at any level of their organization.

Climate is a primary basis for many ecosystem, biome, and habitat classification schemes. The U.S. Forest Service (2008) defines "ecoregions", which comprise their basic management units, as "large areas of similar climate where ecosystems recur in predictable patterns." The four primary domains of the U.S. Forest Service's ecoregion classification are differentiated by precipitation and temperature: the polar domain, the humid temperate domain, the dry domain, and the humid tropical domain (Bailey, 1976, 1983). The ecoregion classification used by the government of British Columbia is based on a combination of climate, vegetation, and physiography (Demarchi, 1993, 1994). The widely used Köppen (1923) and Trewartha (1943) climatic zone classifications are based on the concept that native vegetation is the best expression of regional climate. Each of these commonly used classifications reflects an understanding and acknowledgement of the strong role that climate plays in biogeography.

Relationships between climate and the distribution of plants and animals in the Americas have long been recognized, described, and classified (Herbertson, 1905; Shelford, 1926; Holdridge, 1947, 1967). The role of climate change, however, is generally absent from the scientific literature that established the present-day biome and ecosystem classification maps of North, Central, and South America. Human understanding of decadal- and century-scale trends in climate and the effects of these changes on ecosystems have advanced rapidly over the past two decades, along with an exponential increase in literature published on the topic (Stanhill, 2001). Based on an analysis of roughly 30,000 datasets, the IPCC (2007a) concluded that 85% of the physical and biological changes in natural systems observed globally since 1970 were consistent with the responses that would be expected to accompany atmospheric warming.

However, our understanding of the relationship between biodiversity and climate change has not advanced as rapidly, and conservation land acquisition, coastal resource management programs, and endangered species protection programs are still based on the assumption of a static climate, even though there is evidence indicating that many species and entire ecosystems are moving, restructuring, or disappearing on every continent as a result of climate change (Parmesan and Yohe, 2003).

Ecosystems located along continental and island margins are intrinsically dynamic due to their exposure to alternate flooding and drying, winds, waves and currents, and changes in the elevation of the land or the ocean surface. Located along the narrow transition zone at the land/ocean boundary, coastal ecosystems and their biodiversity are affected by any changes in the processes that created and sustain them. Organisms that inhabit coastal ecosystems are uniquely adapted to the often extreme environmental conditions that occur along the energy, salinity, and moisture gradients that extend from the subtidal region of the coast to the inland boundaries of its wetlands, estuaries, and floodplains. In some coastal systems, such as rocky intertidal zones, the diversity of life forms is considered very high (and very sensitive to perturbation) (Raffaelli *et al.*, 1991) while in others, such as salt marshes and mangrove forests, single plant species can dominate in what can appear to be a monotonic assemblage of halophytes (Saenger, 2002). In contrast to terrestrial and ocean systems which have physical gradients that can stretch over 10s or 1000s of km, coastal ecosystem gradients can be as small as meters, particularly along steep rocky shores.

The structure of plant and animal communities in coastal regions is governed by the tolerances of species to environmental conditions such as light availability, temperature, moisture, disturbance (for example storms, fire), tides, water depth, salinity, and nutrient availability. All of these limiting factors can be affected by climate change — even light availability, which is influenced by the abundance of algae in surface waters and the density of the canopy in a coastal forest.

2. Key Climate Change Variables in the Coastal Zone

Human-induced climate change is likely to intensify during the coming decades and beyond due to increasing greenhouse gas composition and land use change (IPCC, 2007b). In its 2007 fourth assessment report, the IPCC identified six physical factors associated with climate change that can alter the structure and function of coastal ecosystems (Nicholls *et al.*, 2007) (Figure 1). Some of these variables are primary drivers that directly affect coastal biota, while others lead to higher-order effects that can be equally significant in terms of their potential for altering plant and animal community structure. This section describes the pathways by which these major climate change factors can impact biodiversity along the coasts of the Americas with examples for each.

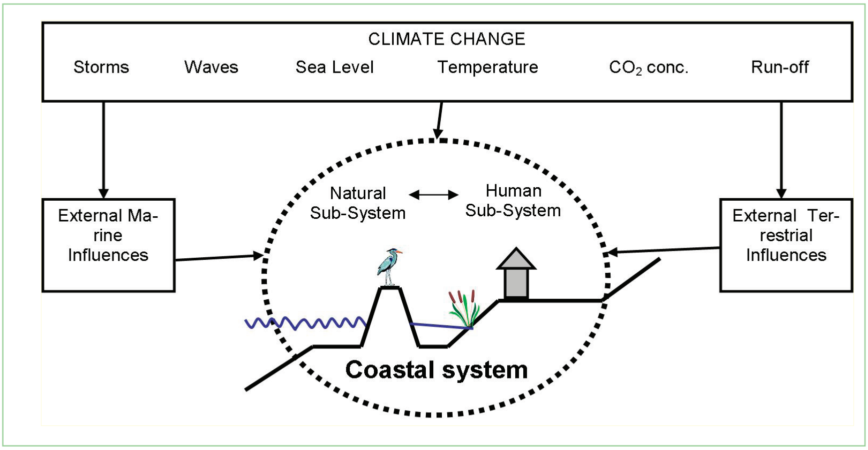

FIGURE 1
Major climate change factors in coastal regions (source: Nicholls *et al.*, 2007, reprinted with permission from IPCC).

3.1 Atmospheric and ocean water CO_2 enrichment

In addition to altering the climate, greenhouse gas emissions can independently impact coastal flora and fauna. The concentration of CO_2 in the Earth's atmosphere has increased by approximately 30% since the Industrial Era (from about 270 ppm in the mid-1800s to 379 ppm in 2005) (IPCC, 2007b). The IPCC attributes this increase to human emissions of greenhouse gases into the atmosphere and changes in land use, such as deforestation.

The increased availability of CO_2 directly affects the growth and metabolism of plants and many microorganisms. An increase in atmospheric CO_2 has a fertilizing effect on most herbaceous plants by enhancing photosynthesis and water-use efficiency (Acock *et al.*, 1985; Nijs *et al.*, 1989; Allen *et al.*, 1988, Rabbinge *et al.*, 1993; Anderson *et al.*, 2001). Growth in woody plants is also stimulated by increases in CO_2, but there is a wide range of responses among species (Eamus and Jarvis, 1989; NCASI, 1995). As CO_2 levels in the atmosphere increase, transpiration rates in plants tend to decrease because stomates are not open as long. This can have a positive effect on plant productivity and survival because it decreases plant water demand.

Differential responses among plants to the effects of rising atmospheric CO_2 can alter competition among plant species. (Bond and Midgley, 2000). Plants that use the C3 photosynthetic pathway (so called because carbon is initially fixed as a 3-carbon compound) generally respond more favorably than do C4 plants (Ainsworth and Long, 2005). Most trees and shrubs are C3 plants while most herbaceous plants use the C4 pathway. Several field and greenhouse studies confirm that growth rates of herbaceous wetland plants that use the C3 pathway are more likely to be enhanced than those with C4 systems (Drake *et al.*, 1996; Marsh, 1999). Warming, on the other hand, appears to favor C4 herbaceous types (Epstein *et al.*, 2002). Growth rates and biomass accumulation for each plant species can respond somewhat differently to the combination of CO_2 fertilization and warming (Burkett and Kusler, 2000), which could theoretically alter species interactions along coastal gradients, from seagrass beds to coastal grasslands and forests. Very few studies have been conducted that will help predict the net impacts of CO_2 enrichment on plant diversity in coastal environments. Some experiments, in short grass prairie for example, show no difference among photosynthetic responses under a combination of elevated CO_2 and warming (Morgan *et al.*, 2001).

As shallow coastal waters absorb more CO_2 from the atmosphere, an increase can be expected in dissolved CO_2 and dissolved inorganic carbon (DIC), both of which can affect estuarine biota. Shirayama and Thorton (2005) demonstrated that a 200 ppm increase in carbon dioxide adversely affects the growth of gastropods and sea urchins. Photosynthesis rates of submerged aquatic vegetation tend to increase when exposed to elevated CO_2 and DIC, but responses can diminish rapidly if temperature (or other thresholds) are reached (Short and Neckles, 1999; Harley *et al.*, 2006). Algal growth in estuaries may also respond positively to elevated DIC and CO_2 (Beer and Koch, 1996). An increase in epiphytic or suspended algae can decrease light available to submerged aquatic vegetation in coastal waters and large-scale algal blooms reduce oxygen available to fish and shellfish (Nicholls *et al.*, 2007). Hypoxia is often cited as the cause of declining fisheries productivity in mid-latitude and subtropical coastal waters and toxic algal blooms (red tides) can result in direct mortality to fish and benthos (Boesch *et al.*, 2001; Day *et al.*, 2003; Niemi *et al.*, 2004).

Another important consequence of increasing the uptake of CO_2 by estuaries is the lowering of the pH of the water because of the well documented reaction:

$CO_2 + H_20 + CO_3^{2-} = 2HCO_{3-}$ (Andersson *et al.,* 2003). This reaction leads to a lowering of the carbonate saturation state of the water because of the titration of the carbonate ion (CO_3^{2-}) by the invading CO_2. Coupled atmospheric-ocean models that simulate the effects of atmospheric CO_2 level on ocean pH suggest that the carbonate saturation state of both the global ocean and nearshore coastal waters will decrease significantly through this century (Mackenzie *et al.,* 2001; Caldiera and Wickett, 2005). Reductions in pH and carbonate saturation state have at least three implications for estuarine biota: a reduction in the ability of carbonate flora and fauna (such as shellfish, hard corals and diatoms) to calcify, changes in the dissolution of nutrients and carbonate minerals in sediments, and a reduction in the capacity of the ocean to function as a "biological pump" that removes CO_2 from the atmosphere (McLean *et al.,* 2001; Andersson *et al.,* 2003; The Royal Society, 2005; Turley *et al.,* 2006). Some studies suggest that there might be a 10-30% reduction in the skeletal growth of corals in response to a doubling of CO_2 (Kleypas *et al.,* 2001; Guinotte *et al.,* 2003) as well as a weakening and dissolution of coral skeletons (Marubini *et al.,* 2002; Hallock, 2005). Changes in pH need to be considered in relation to increases in sea surface temperature (SST), which result in increased calcification rate in massive *Porites* (Lough and Barnes, 2000; McNeil *et al.,* 2004). However, it is clear that coral response to SST is nonlinear, and SST increase beyond a key threshold is incontrovertibly linked to mass bleaching, and in many cases mortality (Kleypas *et al.,* 2005).

Several experiments involving exposure of plankton to elevated CO_2 concentrations have shown small effects (10% or less) on photosynthesis rates (Beardall and Raven, 2004; Schippers *et al.,* 2004; Giordano *et al.,* 2005). These small increases in productivity, however may cumulatively affect estuarine and ocean productivity. In its assessment of the effects of increased CO_2 and its effects on ocean pH, the Royal Society (2005) concludes that it is impossible to differentiate unequivocally between the effects of increased CO_2 and those of decreased pH in experiments on marine organisms, since there is significant co-variance of these environmental factors.

Even if they respond favorably to elevated CO_2 levels, organisms have a threshold at which further CO_2 enrichment will not continue to increase photosynthesis levels or decrease water use because of other limiting factors. The availability of soil nutrients, for example, in emergent coastal marshes and forests can limit the potential improvement in water-use efficiency due to suppressed transpiration. Temperature, disease, pests, pollutants, and light availability can also constrain the potential enhancement of plant growth by elevated CO_2. These limiting factors and their interactions with other natural and human-induced environmental change have not typically been accounted for in models that predict the impacts of climate change on coastal biomes. There remains considerable uncertainty about how mangroves will respond to elevated atmospheric CO_2. Mangroves may respond to increased levels of atmospheric CO_2 by reduction in stomatal conductance to minimize water loss without a concomitant increase in photosynthetic rates, but this may also lead to an increase in growth rate through improved plant water balance (Saenger, 2002). If stomatal conductance remains unchanged at higher CO_2 levels then mangrove photosynthesis rates and productivity are likely to increase (Cambers *et al.,* 2007).

Hence, a better understanding of the effects of rising CO_2 concentrations on coastal ecosystems is essential in order to predict future changes in mangroves and other coastal vegetation types.

3.2 Increased Air and Water Temperature

Temperature affects the growth, survival, reproduction, and distribution of plants and animals. Through its effects on basic metabolic processes such as respiration, photosynthesis, budburst, egg laying, and food availability, an increase in temperature could, in theory, alter biological diversity at every level in the food web.

As air and water temperature increase, species ranges will likely expand toward environments that are presently cooler (IPCC, 2007a; Parmesan and Yohe, 2003). If dispersal capabilities are limited or suitable habitat is not available, local extirpations and extinctions are likely to occur (Thomas *et al.,* 2004). For fishes, climate change may strongly influence distribution and abundance through changes in growth, survival, reproduction, or responses to changes at other trophic levels (Brander *et al.,* 2003; Reid, 2003). Further temperature rises are likely to have profound impacts on commercial fisheries through continued shifts in distribution and alteration in community interactions (Perry *et al.,* 2005). There is a lack of information on how tropical fish will respond to temperature increases (Cambers *et al.,* 2007).

Seasonally elevated water temperatures along the Caribbean, Gulf of Mexico, and Mid- and South Atlantic shorelines are often associated with extensive algal blooms that impact living resources, local economies, and public health (Day *et al.,* In Press; Cambers *et al.,* 2007). Impacts of harmful algal blooms include human illness and death from ingesting contaminated shellfishes or fish, mass mortalities of wild and farmed fish, loss of seagrasses by reduced light availability, and alterations of marine food chains through adverse effects on eggs, young, and adult marine invertebrates (for example corals, sponges), sea turtles, seabirds, and mammals. Recently, algal blooms have occurred in areas where they had not occurred in recent decades and new species have appeared (GEOHAB, 2001, 2005).

Increased temperatures in terrestrial habitats will reduce streamflow and alter water quality into deltas, estuaries and in coastal regions, causing addition change and/or degradation of coastal ecosystems.

A particularly insidious result of the increase in sea surface temperatures (SST) is the impact of coral bleaching on coral reefs. Bleaching occurs when SST rises to ~1° C above the monthly maximum, leading to expulsion of the symbiotic algae (zooxanthellae) and paling of the coral surface (Hoegh-Guldberg, 1999; Douglas, 2003). Corals may recover, but if SST remains at these high levels for prolonged periods combined with high solar radiation, or exceeds 2 °C above the threshold, coral mortality is likely (Lesser, 2004). In the Caribbean, there has been a widespread decline in coral cover as a result of the synergistic effects of multiple stresses such as disease, hurricane impact and dust input. The extent to which the thermal threshold at which corals bleach could increase through adaptation or acclimatision with ongoing global warming remains uncertain. According to one recent study (De'ath *et al.,* 2009) calcification of long-lived massive corals on the Great Barrier Reef has declined by 14.2% since 1990, largely through a decrease in extension rate. SST warming threatens repeated bleaching events and further reduction in both coral cover and diversity on reefs over the next few decades, and there is an urgent need for focused management to improve the ecological resilience of coral reefs (Hoegh-Guldberg, 2004).

While increasing SST is clearly affecting coral reef systems in the Caribbean region (Nicholls *et al.,* 2007), there is evidence that some coral species off of the coasts of the Americas are responding to increased SST by expanding their latitudinal ranges. Examples include the recent establishment of staghorn coral (*Acropora cervicornis*) off Fort Lauderdale in Broward County, Florida (Vargas-Angel *et al.,* 2003) and the expansion of range of staghorn and elkhorn coral (*Acropora palmata*) into the northern Gulf of Mexico, coincident with increasing sea temperatures (Precht and Aronson, 2004). In the face of continued global warming, the northernmost limit of this range expansion will ultimately be determined by a combination of temperature and other physical constraints, as well as interactions among species (Precht and Aronson, 2004).

3.3 Sea Level Rise

The IPCC global-mean sea-level rise scenarios are based on thermal expansion and ice melt: the best estimate shows an acceleration of up to 2.4 times compared to 20th Century values and a rise in the range 18 to 59 cm by the end of the 21st century (Meehl *et al.,* 2007). Superficially, these projections are smaller than Church *et al.* (2001), but this largely reflects differences in methodology and the IPCC (2007b) synthesis report emphasizes that the upper 95% range of the model predictions is not an absolute upper bound on global-mean sea-level rise during the 21st Century, with the contributions from the major ice sheets (Antarctica and Greenland) being a major uncertainty. Several recent papers support the view that a 1+ meter rise in sea level over the next century cannot be entirely discounted at present (Rahmstorf, 2007; Rahmstorf *et al.,* 2007; Rohling *et al.,* 2007). Further even with stringent climate mitigation (reduced greenhouse gas emissions) sea levels will continue to rise for centuries due to the thermal inertia of the oceans among other factors.

Importantly, local (or relative) changes in sea level depart from the global-mean trend due to regional variations in oceanic level change and geological uplift/subsidence: it is relative sea-level change that drives impacts and are of concern to coastal managers (Bird, 1993; Harvey, 2006). Regional sea-level change will depart significantly from global-mean trends: for the A1B scenario the spatial standard deviation by the 2080s is 0.08 m, with a larger rise than average in the Arctic (Meehl *et al.,* 2007). Hulme *et al.* (2002) suggested that impact analysis explore additional sea-level rise scenarios of +50% the amount of global-mean rise, plus uplift/subsidence, to assess the full range of possible change. Furthermore, coasts subsiding due to natural or human-induced causes will experience larger relative rises in sea level which must also be considered (Bird, 1993; Nicholls *et al.,* 2007; Syvitski, 2008). Increases of extreme sea levels due to the combination of rising sea levels and changes in storm characteristics are also of significant concern (Zhang *et al.,* 2000; Nicholls *et al.,* 2007; von Storch and Woth, 2008).

A report that summarizes the opinion of a group of 23 experts concerning the implications of climate change in the Intra-Americas Sea (Gulf of Mexico - Caribbean Sea - Bahamas - Bermuda - Guianas) indicates a wide range in response in coastal systems to a scenario of a 20 cm rise in mean sea level and 1.5 °C increase in mean temperature. For some ecosystems in the region, the effect of the increase in temperature will be much more important than an increase in mean sea level rise, and vice versa for others; for some neither is important; for others both are important. Of the 14 Central American ecosystems considered, the most heavily impacted are expected to be deltas and beaches, both because of sea level rise; neither is particularly vulnerable to a modest temperature rise (Maul, 1993).

Several studies have focused on the impacts of sea level rise on tropical mangrove forests (Field, 1994; Bacon, 1994; Lugo, 2002; Diop, 2003). Negative effects produced by the permanent or prolonged inundation on reproduction and viability of individual mangroves trees have been described (Yáñez-Arancibia, 1998). An assessment of the impacts of a 0.3 and 1 meter of sea level rise on Guacalillo mangroves in Costa Rica indicated that 65% of these mangroves would be lost due to flooding and erosion processes with a 1 meter increase in mean sea level (Piedra and Piedra, 2007). In South America, other ecosystems at risk due sea level rise are the wetlands in the San Borombom Bahia, which is a Ramsar site. This area also has the protected area "Campus del Tuyu", which is almost the last relict of Pampa ecoregions ecosystems. This area will be threatened trough sea level rise and associated changes in salinity and flooding patterns (Fundación Torcuato Di Tella, 2005).

Along the Patagonian coast in Argentina there are important sites for biodiversity that have large intertidal habitats and tidal sea level variations that reach 12 meters, particularly the Peninsula de Valdez wetlands y the Atlantic coast of Tierra del Fuego (Boltovskoy *et al.,* 2008). Sea turtles are among the vulnerable species along this coastal region. All seven species of marine turtle are listed as "threatened" or "endangered" under the U.S. Endangered Species Act. Accelerated sea level rise will decrease sea turtle nesting beaches and the availability of some of their food sources (Fish *et al.,* 2005).

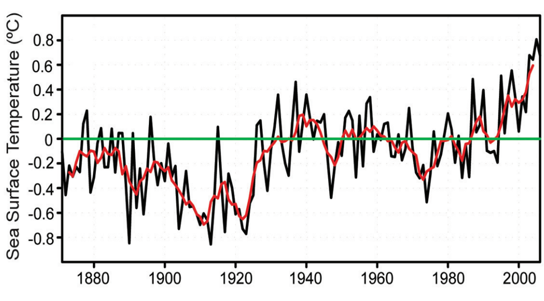

FIGURE 2
Sea surface temperature trend in the main hurricane development region of the North Atlantic during the past century. Red line shows the corresponding 5-yr running mean. Anomalies are departures from the 1971-2000 period monthly means. (Source: Bell *et al.*, 2007).

3.4 Changes in Storm intensity

The kinetic energy of tropical storms and hurricanes is fueled from heat exchange over warm tropical waters. Increased tropical storm activity is likely to accompany global warming as a function of higher SSTs, which have been observed globally (Webster *et al.,* 2005; IPCC 2007b). Sea surface temperature has increased significantly in the main hurricane development region of the North Atlantic during the past century (Bell *et al.,* 2007) (Figure 2) as well as in the Gulf of Mexico (Smith and Reynolds, 2004). Recent empirical evidence suggests a trend towards more intense hurricanes formed in the North Atlantic Basin, and this trend is likely to intensify during the next century (IPCC, 2007b).

In the Gulf of Mexico region, there is presently no compelling evidence to suggest that the number or paths of tropical storms have changed or are likely to change in the future (CCSP, 2008). Changes in other storm characteristics are less certain and the number of tropical and extra-tropical storms might even reduce (Meehl *et al.,* 2007). One recent analysis of hurricanes in the North Atlantic region suggests that an increase in intensity associated with global warming will be expressed in terms of increased windspeed and rainfall (Knutson *et al.,* 2008).

If tropical cyclones increase in intensity, coastal erosion and land loss are likely to increase along low-lying, sedimentary shorelines of the east coasts of Central and North America, with the exception of Panama. When hurricanes enter the Gulf of Mexico they veer northward away from the equator and Panama coast. Tropical cyclones in the southern hemisphere are also uncommon. Tropical cyclone Catarina in 2004 was the first recorded and subsequently struck southern with winds equivalent to Category 2 on the The coast of Argentina is vulnerable to high winds and coastal flooding during winter "sudestada", which are weather phenomena that appear to be associated with cyclogenesis (Escobar *et al.,* 2004), but the effects of climate change on these events, if any, have not been documented.

The greatest damages to coastal systems during hurricanes and other tropical storms are due mainly to storm surge, waves, and wind. If a strong hurricane makes landfall along the shallow Gulf of Mexico coastal margin when the tide is high and barometric pressure is low, the effects can be particularly severe. An increase in storm surge associated with hurricanes that make landfall in the Gulf coast region could affect the sustainability of some natural coastal systems and the species that depend upon them. Loss of beaches would affect bird rookeries and sea turtles nesting sites. Aquatic and terrestrial species limited to coastal areas (Alabama Beach Mouse, Okaloosa Darter) may be threatened throughout their range. Many small islands along the northern Gulf of Mexico coastline were lost to open water during the 2005 hurricane season. During Hurricane Katrina in 2005, approximately 388 km^2 of coastal marshes and barrier islands in coastal Louisiana were converted to open water (Barras, 2006).

3.5 Changes in Wave regime

Few studies have examined potential changes in prevailing wave heights in coastal regions as a consequence of climate change. In the Northern hemisphere, a multidecadal trend of increased wave height has been observed (Figure 3), but the cause is poorly understood (Guley and Hasse, 1999; McLean *et al.*, 2001; IPCC, 2007b), and if the time period is extended there is no evidence of any trends in the drivers of waves (winds and storminess) (WASA Group, 1998). The increasing North Atlantic wave height in recent decades has been attributed to the positive phase of the North Atlantic Oscillation, which appears to have intensified commensurate with the slow warming of the tropical ocean (Wolf, 2003). Increasing average summer wave heights along the Mid-Atlantic coastline of North America appear to be associated with a progressive increase in hurricane activity between 1975 and 2005 (Komar and Allan, 2007)

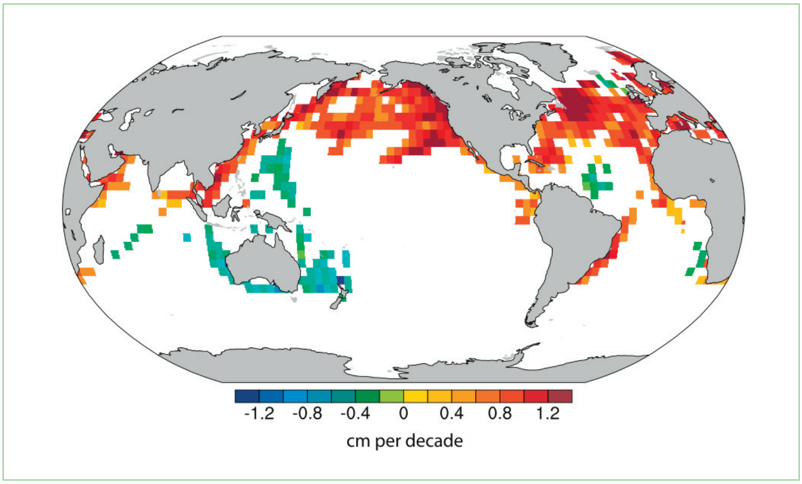

FIGURE 3
Linear trends in significant wave height (cm per decade) for regions along the major ship routes of the global ocean for 1950 to 2002. Adapted by IPCC (2007) from Gulev and Grigorieva (2004).

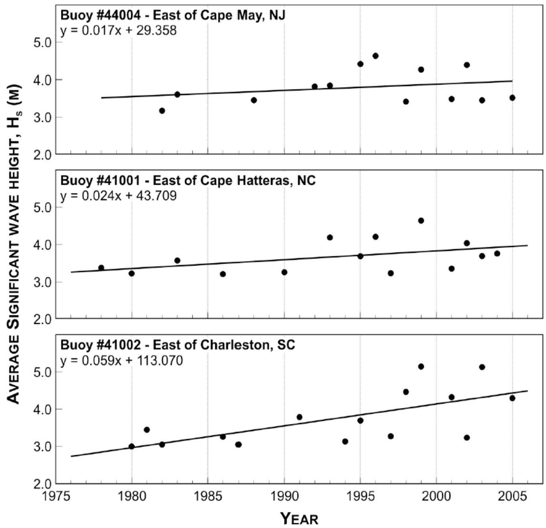

FIGURE 4

Trends in wave height at three locations along the Mid-Atlantic coast of North America (Komar and Allen, J. Coast. Res. 2008).

(Figure 4). Wave heights greater than 3 m increased by 0.7 m to 1.8 m during the three decades of study, with hourly averaged wave heights during major hurricanes increasing significantly from about 7 m to more than 10 m since 1995 (Komar and Allan, 2008). Peak and average wave heights have increased significantly during the winter months along the Pacific coast in the vicinity of Washington (Allan and Komar, 2006; CCSP, 2008).

Scenarios of future changes in seasonal wave heights constructed by using climate model projections for the northeastern Atlantic predicted increases in both winter and fall seasonal means in the 21st century under three forcing scenarios (Wang *et al.*, 2004). The IPCC (2007b) concludes that an increase in peak winds associated with hurricanes will accompany an increase in tropical storm intensity. If tropical storm windspeed increases as anticipated by the IPCC this will tend to have a positive effect on mean wave height during the coming decades. Wave heights in coastal bays and lagoons may also tend to the secondary effect of shoreline retreat and submergence increasing fetch – as already evidenced in subsiding coastal Louisiana (Stone *et al.*, 2003).

TABLE 1

Examples of adaptation options in coastal zones and potential impacts on biodiversity (modified from CBD 2005). [P] Protection, [A] Accommodation and [R] Retreat

Adaptation activity	Potential risk to biodiversity		Possible action for adaptive management
Sea walls, dikes and tidal barriers [P]	Adverse	High-Very High if concrete/ rock structures Low-medium if using mud walls and vegetation	Include biodiversity considerations in Environmental Impact Assessment (EIA)
Bridges to cross potentially inundated areas due to climate change [A]	Adverse	Medium-High depending on the location	Include terrestrial and aquatic biodiversity considerations in EIA
Elevate Buildings [A]	Adverse to neutral	Low if already in urban areas	Monitor for likely effects on biodiversity and include adaptive management
Regulating development in coastal areas	Adverse or positive	High-Very High if urbanization of high biodiversity areas; Low otherwise	Strategic environmental assessment should consider the impact on biodiversity and zone accordingly; allow for appropriate conservation areas for biodiversity
Migration of people from coastal areas and/or marginal lands (for example in semi-arid areas) [R]	Adverse or positive	Low if moving to urban areas although could place additional pressure on water and energy resources; High if moving to slightly less marginal areas	Educate the urban planners to minimise the exploitation of natural resources; effect of other migration may be hard to manage
Introduction of salt tolerant varieties of native plants and animals [A]	Positive to Neutral	Low	Monitor for likely effects on biodiversity and include adaptive management
Establishment of aquaculture or mariculture to compensate for climate-induced losses in food production [A]	Neutral to adverse	High if alien or GMOs fish or other aquatic including marine organisms escape eutrophication or harmful chemicals are released	Monitor for likely effects on biodiversity and include adaptive management
Beach nourishment and beneficial use of dredged material [P or A]	Positive or Adverse	Low if restoring natural sedimentation patterns; High if sediments are added in a manner that alters geomorphology to the point that native species are eliminated	Assess natural processes that maintain coastline; monitor coastal system and species response
Rehabilitation of ecosystems [A]	Positive	Generally Low unless invasive exotic species are used or damage to neighbouring areas	Monitor for likely effects on biodiversity and include adaptive management
Establishment of protected areas [P]	Positive or neutral	Medium-High	Monitor for likely effects on biodiversity and include adaptive management
Relocate highways and other infrastructure further inland [R]	Neutral or Negative	Potentially very high if natural coastal migration is impeded or runoff to the coast is obstructed	Elevate roads or design so that natural coastal processes can be maintained

3.6 Changes in Runoff to the Coast

Changes in precipitation and run-off patterns appear likely as climate change intensifies, but the uncertainties are large. Milly *et al.* (2005) showed increased discharges to coastal waters in the Arctic, in northern Argentina and southern Brazil, while reduced discharges to coastal waters are suggested in the western Gulf of Mexico, Venezuela and Guyana coastal zones. The additional effects of catchment management and water use also need to be considered as this may be a larger effect than climate change (Table 1).

Changes in freshwater runoff patterns can affect coastal and estuarine biota through several pathways. If freshwater flows to the coast decrease, the salinity of coastal wetlands and estuaries is likely to increase. The distribution of coastal biota is closely linked with salinity of water and soils. Few studies have documented the interactions between runoff, salinity, and species distribution.

Earlier and faster snowmelt due to increasing temperatures portend changes in freshwater and nutrient delivery to the coast from meltwater-dominated watersheds. Changes in the timing of freshwater runoff to estuaries could affect the productivity of many estuarine and marine fishery species (Nicholls *et al.*, 2007). Changes in runoff can also affect sediment delivery, which has important implications for the sustainability of deltas and other sedimentary landforms.

Freshwater inflows into estuaries influence water residence time, vertical stratification, salinity, control of phytoplankton growth rates, and the flushing of contaminants in estuaries. In estuaries with very short water residence times, phytoplankton are generally flushed from the system as fast as they can grow, reducing the estuary's susceptibility to eutrophication and harmful algal blooms.

4. Human Development Impacts on the Resilience of Coastal Systems

Coastal areas comprise some of the most heavily developed landscapes in the Americas. The autonomous adaptive capacity and sustainability of coastal ecosystems in North, Central, and South America could be challenged due to a combination of stressors at the ocean/land interface. Coastal river deltas, such as the Mississippi and Paraná, are particularly vulnerable due to their high sensitivity to relatively small changes in mean sea level and riverine sediment delivery. Coastal habitat losses portend lower resilience of wetland dependent fish and wildlife to the effects of climate change. In North America, approximately half of the coastal wetlands in the United States have been converted to other uses. In some coastal regions of North America, such as Louisiana, Florida and Alaska, the effects of climate change have already been linked with habitat loss and changes in plant and animal community distribution (IPCC, 2007b).

A study carried out by The Nature Conservancy, in collaboration with the governments and non-governmental institutions in Brazil, Chile, Colombia, Ecuador, Peru and Venezuela, identifies the top ten threats to coastal and marine environments in South America. Almost invariably, the top three threats to coastal and marine biodiversity are fishing, urban development and pollution (Chatwin, 2007). In some coastal areas, the expansion of the agricultural frontier is a growing threat, as for example the Paraná river delta wetlands, in Argentina, where the slashing and burning is increasing for cattle ranching (Donadille *et al.,* 2006) and the Atlantic Forest in Brazil when the coastal areas are used for sugar cane plantations that increase erosion of the coastal lands which results in an unnaturally high amount sediments being carried off to sea. The mangrove areas along the South American coast are highly prone to suffer impacts from shrimp farm development, such as deforestation and changes in water quality (MMA, 2002).

Coastal zones are becoming more populated and urbanized, but basic infrastructure is not keeping up. Considering the sources of pollution, the most common form of sewage management, when it exists, in South America is to pipe it directly into the marine environment (Chatwin, 2007). In Brazil, 80% percent of the urban population is not serviced by public sewage systems and 43% of urban homes do not even have septic tanks (MMA, 2002).

Because of the dependence on maritime transportation, some productive sectors of chemical, petrochemical and petroleum industries are located near or even directly on the shore. The environmental risks posed by these sectors, added to the risks already posed by port activities, shipbuilders, and processing plants for cellulose and a number of minerals for the export market, support the conclusion that there is a high potential of environmental risk and impact in Brazil's coastal zone (MMA, 2002).

A cartographic atlas of Environmentally Sensitive Areas of Argentine coast and sea (Boltovskoy *et al.,* 2008) identifies the coastal zones that are specially vulnerable and important for conservation. The fishing industry has been identified as a particularly important threat to biodiversity along Patagonian coast. Seabirds globally at risk are threatened as by-catch by long line fishing vessels (Favero *et al.,* 2003).

The expansion of the tourist industry is the main cause of the transformations in many coastal natural areas (Magrin *et al.,* 2007). Even the areas of low population density in the coastal zone -historically, the homes of traditional communities- are experiencing growing threats from unfettered development driven by tourism. Resort development and a growing demand for second homes are further threatening coastal habitat integrity. Along with this development, the lack of adequate licensing and enforcement results in inadequate land use, changes to the landscape, and harmful impacts to fragile ecosystems (MMA, 2002). The coastal habitat loss has been remarkable in several places in Central America, for example Cocos in Costa Rica, Tortuguero-Miskitos islands in Nicaragua and Gulf of Mexico (Magrin *et al.*, 2007).

While the Atlantic Ocean and Caribbean Sea are South America's most threatened, the Pacific Ocean clearly houses the least protected coastal and marine environment in South America. All of the ecoregions have less than 0.5% of their area within existing protected areas. Currently, only 3.4% of these coasts are represented within some type of protected area (Chatwin, 2007).

5. Interactive Effects Among Climate Drivers and Human Development Activities

Environmental conditions in coastal ecosystems are unique in that they are a derivative of the combined marine and terrestrial conditions prevalent at any one site. Often dynamic coastal systems do not respond in a deterministic way to forcing factors, but show complex non-linear or chaotic behavior partly dependent on antecedent conditions (Lee *et al.,* 2001). Plants and animals in coastal regions also respond to second- and higher-order effects of increasing global temperature and changes in precipitation patterns. In the coastal zone, for example, increased salinity will lead to a shift in species that are more salt tolerant. The increased salinity is a third-order effect of atmospheric warming that causes eustacy, which causes increased tidal exchange, increased intensity and frequency of storm surge, and increased mean water levels in coastal systems. Species that have greater tolerance of increased salinity will outcompete those with lower tolerance, leading to changes in the structure and functions of the coastal ecosystem. Changes in community structure can be episodic, and in some cases, ecosystems may be eliminated if thresholds are exceeded (Burkett *et al.,* 2005).

There is no single driver of coastal biodiversity impacts, rather a combination of stressors, including human development activities and their effects on coastal systems. A conceptual model of the physical drivers affecting the biodiversity in

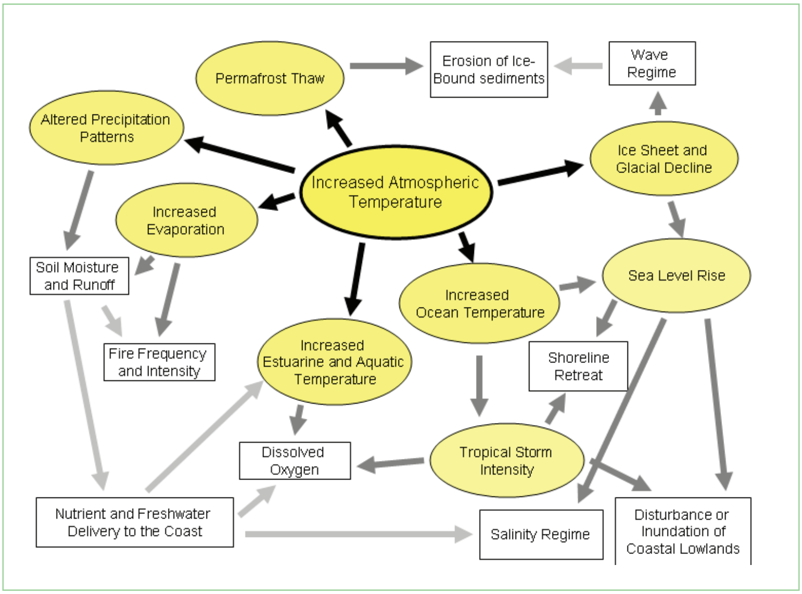

FIGURE 5
Interactions among the key physical factors associated with climate change and its impacts on coastal systems (Modified from SEI, 2007).

the coastal zones of the Americas is presented in Figure 5. Many of these feedbacks and interactions have been described but most are not quantified at scales that permit predictive modeling.

6. Incorporating Biodiversity Considerations in Coastal Adaptation Planning

Coastal adaptation approaches can be classified into three generic groups: 1) Protection, 2) Accommodation and 3) Retreat (Klein *et al.*, 2001; Nicholls *et al.*, 2007). The approaches include structural and non-structural measures. Structural measures refer to any physical (natural or artificial) construction to reduce or avoid possible impacts of hazards, which include engineering measures and construction of hazard-resistant and protective structures and infrastructures. Non-structural measures refer to policies, awareness, knowledge development, public commitment, and methods and operating practices, including participatory mechanisms and the provision of information, which can reduce risk and related impacts.

Protection involves the use of natural or artificial measures to protect landward development, attempt to hold the shoreline in its existing position and reduce hazard impacts. Traditionally, protection against coastal erosion, flooding, storm surge and tsunami inundation has been approached through mitigation or hard structural response. This has involved measures such as the construction of groins, seawalls, offshore breakwaters, and bulkheads. More recently, there has been a move to soft defences and the restoration of natural coastal storm buffers, such as barrier islands and mangrove forsest. Protection and especially, hard structural responses, may lead to significant adverse ecological impacts if migration is deliberately excluded.

Accommodation involves adjusting how people live and the way they develop land in response to coastal hazards. It includes the continued, but altered, use of land, market mechanisms and building and/or site design to reduce vulnerability to coastal hazards. Examples include elevating structures out of floodplains, on pilings or fill, elevated flood and cyclone shelters, changing crops to more flood/salt tolerant varieties, etc. Ecosystem migration is much less restricted than under protection.

Retreat, which in this context would mainly be managed or planned, means preventing future development in coastal hazard zones and progressively giving up threatened or vulnerable land by moving development away from coastal hazard areas as the opportunity arises or as individual assets come under imminent threat. This usually requires a number of measures to limit new or redevelopment and existing buildings and infrastructure may be relocated or abandoned. Ecosystem migration can occur to the maximum extent possible.

These policies have all been used in the Americas. Around major cities such as New York, hard defences have been extensively constructed and this approach has been termed the 'New Jerseyisation' of the coast (Nordstrom, 2000). Hardening of shorelines around estuaries such as the Chesapeake Bay is especially harmful to coastal ecosystems and their potential to migrate. Over the last 3 decades, soft protection beach nourishment has been extensive around the US coast (for example, Miami, FL and Ocean City, MD) and elsewhere in the Americas. Homes are also raised above the 100 year flood elevation using pilings in coastal areas subject to high velocities (breaking waves). Retreat and abandonment of coastal areas is also apparent and has been especially prevalent on islands on the U.S. East Coast, including both barrier islands and islands within the Chesapeake Bay (for example, Gibbons and Nicholls, 2006). These have allowed natural processes to run their course, and in one case (Poplar Island, MD) one of these bay islands has been recreated using beneficial use of dredge spoil.

Impacts on coastal systems are among the most costly and most certain consequences of climate change. For this reason, many coastal and island nations in the Americas are evaluating adaptation options and implementing strategies for reducing undesirable impacts. Many coastal communities are planning adaptation strategies but much of the current emphasis is on protection of the built environment.

Some adaptation options, such as restoring natural coastal hydrology, will tend to positively impact biodiversity. Other adaptation options, such as flood protection levees and sea walls, can exacerbate the effects of climate change and sea level rise on coastal flora and fauna. Retreat from coastal areas, such as the on-going relocation of native communities along the Beaufort and Chuckchi seacoasts of North America, may or may not adversely affect coastal biodiversity depending upon where these communities are relocated. By incorporating biodiversity considerations into adaptation planning, native fish, wildlife, and plant populations are more likely to be preserved as climate change intensifies in the 21st century.

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