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Consequences of Climate Change on the Ecogeomorphology of Coastal Wetlands

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Abstract Climate impacts on coastal and estuarine systems take many forms and are dependent on the local conditions, including those set by humans. We use a biocomplexity framework to provide a perspective of the consequences of climate change for coastal wetland ecogeomorphology. We concentrate on three dimensions of climate change affects on ecogeomorphology: sea level rise, changes in storm frequency and intensity, and changes in freshwater, sediment, and nutrient inputs. While sea level rise, storms, sedimentation, and changing freshwater input can directly impact coastal and estuarine wetlands, biological processes can modify these physical impacts. Geomorphological changes to coastal and estuarine ecosystems can induce complex outcomes for the biota that are not themselves intuitively obvious because they are mediated by networks of biological interactions. Human impacts on wetlands occur at all scales. At the global scale, humans are altering climate at rapid rates compared to the historical and recent geological record. Climate change can disrupt ecological systems if it occurs at characteristic time scales shorter than ecological system response and causes alterations in ecological function that foster changes in structure or alter functional interactions. Many coastal wetlands can adjust to predicted climate change, but human impacts, in combination with climate change, will significantly affect coastal wetland ecosystems. Management for climate change must strike a balance between that which allows pulsing of materials and energy to the ecosystems and promotes ecosystem goods and services, while protecting human structures and activities. Science-based management depends on a multi-scale understanding of these biocomplex wetland systems. Causation is often associated with multiple factors, considerable variability, feedbacks, and interferences. The impacts of climate change can be detected through monitoring and assessment of historical or geological records. Attribution can be inferred through these in conjunction with experimentation and modeling. A significant challenge to allow wise management of coastal wetlands is to develop observing systems that act at appropriate scales to detect global climate change and its

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effects in the context of the various local and smaller scale effects.

Keywords Climate change · Ecogeomorphology · Coastal wetlands

Introduction

Climate affects the functioning, distribution, dimensions, and form of coastal and estuarine systems (Schubel and Hirschberg 1978; Douglas 2001; Woodroffe 1993; Scavia et al. 2002; Syvitski et al. 2005). Climate change impacts on coastal and estuarine ecosystems include accelerated sea level rise, increased temperature, changes in rainfall distribution and freshwater inputs, and in the frequency and intensity of storms, all operating over a range of temporal and spatial scales. The effects of climate change may become more severe as a result of interactions with other human activities in coastal regions (e.g., Pont et al. 2002). Phenomena that are multi-scale and inclusive of human dimensions are considered under the umbrella of biocomplexity (Michner et al. 2001). In this paper, we use a biocomplexity framework to provide a perspective of the consequences of climate change for coastal wetland ecogeomorphology—linking the physical form of fluvial sedimentary systems with ecological response of estuarine wetlands (ICCE 2003; Fagherazzi et al. 2004). Our intent is both to stimulate thought and studies on these interrelationships and to provide guidance for agencies and organizations sponsoring research, monitoring, and assessment.

We discuss the impacts of sea level rise, changes in storm frequency and intensity, and changes in freshwater, sediment, and nutrient inputs on the ecogeomorphology of coastal and estuarine wetlands, especially in the context of human activities (Kennedy et al. 2002; Poff et al. 2002; Day et al. 2007, 2008; Twilley et al. 2001; Fig. 1). Sea level rise was 1.5–2.0 mm year^{-1} during the 20th century (Miller and Douglas 2004). The rate of rise is predicted to accelerate in the 21st century, but the actual amount of increase is difficult to predict, especially because of uncertainties about ice sheet dynamics. The range of average IPCC predictions based on multiple models and scenarios is that sea level at the end of the 21st century will be 28 to 43 cm above that at the beginning of the century (IPCC 2007). Predictions based on empirical relationships between temperature and sea level suggest rates of sea level rise of 1 m or more in the 21st century (Rahmstorf 2007). Predicting changes in cyclone activity is far less certain, but recent evidence suggests that tropical storm activity has increased in frequency and intensity (e.g., Hoyos et al. 2006), but complex relationships between global warming and multiyear climatic oscillations, such as the El Nino-Southern Oscillation, or Atlantic Multidecadal Oscillation, will undoubtedly have a major effect on storms (Tarasona et al. 2001; Walsh 2004; Sutton and Hodson 2005). Changes in freshwater, sediment, and nutrient delivery are likely to be highly regional and also are difficult to predict because they will be affected by changes in regional precipitation, changes in circulation and sediment trapping processes, shoreline erosion rates, and local and regional human activities. Not all estuarine wetlands are equally vulnerable to the consequences of climate change. For example, the northern Gulf of Mexico is particularly vulnerable to sea level rise, flooding, and erosion from storms (Hammar-Klose and Thieler 2001; Fig. 2), and the southern Gulf of Mexico is much more vulnerable to sea level rise than the Caribbean portion of Mexico (Ortiz-Perez et al. 2008).

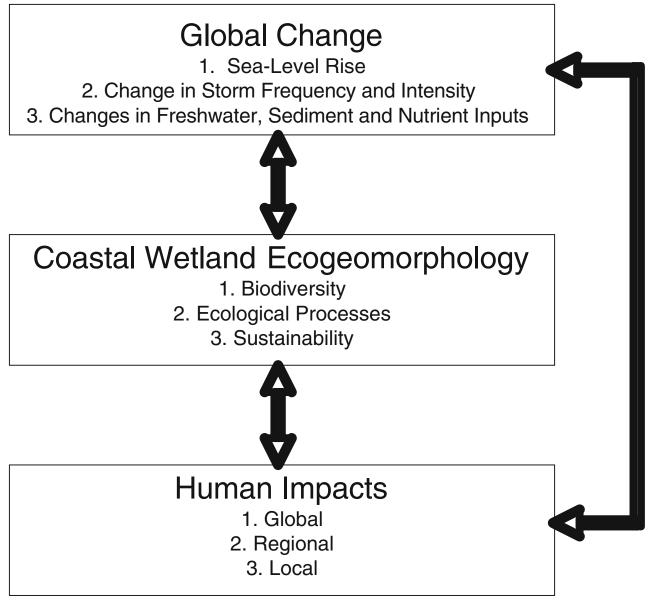

Fig. 1 Major issues of global climate change and biocomplexity of coastal wetland ecogeomorphology described here. Global climate change will have impacts on coastal wetlands, and human activities will greatly influence the nature and severity of these impacts

Four ecogeomorphical responses of coastal and estuarine wetlands to climate-related factors are changes in elevation, boundary or edge distribution, areal extent (wetland:water area), and composition of soil or sediment. Sea level rise, storms, sedimentation, and changing freshwater input can directly influence coastal and estuarine wetlands. Some physical outcomes will depend heavily on biological processes such as aboveground baffling of currents by plant communities and subsequent sedimentation, below-ground plant productivity, organic soil formation by wetland plants, and activities of resident communities (e.g., Day et al. 1999; Christensen et al. 2000; Morris et al. 2002; Blum and Christian 2004; Silliman et al. 2005). Feedbacks between the biotic and abiotic components of ecosystems will affect the response of coastal wetland

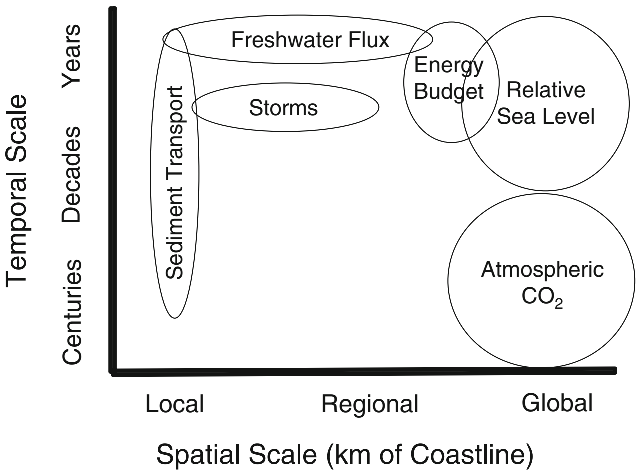

Fig. 2 Temporal and spatial scales of the impacts on estuarine geomorphology of processes that are directly or indirectly controlled by global climate

systems to climate change (e.g., Stevenson et al. 1985; Wooddruffe 1990, 1995, Morris et al. 2002; Day et al. 1997; Mendelssohn and Morris 2000). Geomorphological changes to coastal and estuarine wetlands can induce complex outcomes for the biota that are not intuitive due to biological interactions.

Biocomplexity, Biodiversity, and Ecogeomorphology

Biocomplexity refers to the complex interactions of organisms with their environments and its expression on biodiversity. Biodiversity is usually defined at different levels, i.e., species, populations, and ecosystems (Ray and McCormick 1992). "Biodiversity components" refers as an ecological reference to these hierarchical levels, and the idea is particularly appropriate to describe biocomplexity of estuarine ecosystems (Yáñez-Arancibia et al. 1999). Biodiversity of estuaries can refer to the diversity of species, life histories, habitats, links in food webs, or the diverse pathways of energy flow and nutrient cycles that couple terrestrial, freshwater, estuarine, and marine ecosystems at the land–ocean interface. The biodiversity and biocomplexity of coastal wetland systems can be better understood within the context of the ecogeomorphology of those systems and the larger coastal landscapes of which they are a part (Twilley et al. 1996; Yáñez-Arancibia 2005). The diverse landforms of coastal regions can be considered as a biodiversity component of coastal wetland ecosystems, and they are susceptible to a changing climate.

At a landscape scale, the ecogeomorphology of wetland systems results from the interactions of geophysical processes with feedback from ecological processes within a local habitat, and controls plant zonation and growth (Twilley et al. 1996; Christian et al. 2000; Hedgpeth 1957; Thom 1984; Woodroffe 2002, Fig. 2). Gradients in geophysical processes of a coastal region result in variation in energy flow and material cycling of estuarine wetlands (Thom 1984; Woodroffe 1992; Twilley 1995; Ewel et al. 1998), which are reflected in different ecosystem states and their patterns of plant zonation, biomass, productivity, biogeochemistry, and exchange of nutrients and organic matter with coastal waters (Brinson et al. 1995).

At a local scale, the formation and physiognomy of estuarine wetlands is controlled strongly by local tides, freshwater discharge, precipitation, terrestrial surface drainage, soil characteristics, and biological interactions. Tidal frequency decreases with distance from shore often causing changes in salinity and other edaphic factors resulting in mechanisms controlling plant zonation (Christian et al. 2000; Mendelssohn and Morris 2000). Edaphic and other ecological factors are associated with the biology of these systems along this transect, including modified plant growth (Bertness and Pennings 2000, Blum and Christian 2004), gradients in processes such as burrowing activity of crabs (Smith 1987, 1992), and herbivory (Silliman and Bertness 2002). The structure and function of wetland systems are based not only on external drivers but also the interrelationships between microtopographic and biological factors.

This combination of different ecogeomorphological settings at different scales results in a diversity of coastal and estuarine wetland ecosystems at different scales (*sensu* Allen and Hoekstra 1992), each with specific characteristics of community structure and ecosystem function (Twilley 1988, 1995; Twilley et al. 1999; Ewel et al. 1998). Although vascular plant diversity in coastal wetlands is low (e.g., 54 true species of mangroves, Tomlinson 1986), the biodiversity components of these ecosystems are unique because they include structural niches and refugia for numerous faunal and microbial species and a high diversity of biogeochemical processes. Coastal wetlands at the land–sea interface link the nearshore marine environment with coastal ocean and upland landscapes (Macnae 1968; Chapman 1976; Odum et al. 1982; Tomlinson 1986; Twilley et al. 1996; Deegan et al. 2000; Kneib 2000). The interactions among water levels, vascular plants, sediments, microbes, and soil chemistry determine the production, health, and survival of a particular wetland. The relative importance and intensity of these environmental factors vary in space and time.

Eugene Odum (1980) recognized the importance of physical variations early on when he described estuaries as tidally subsidized, fluctuating water level ecosystems. He called this concept *pulse-stability*. We now recognize that the tide is only one of the energy subsidies to coastal systems. Energetic forcings occur over a broad hierarchy of different spatial and temporal scales (*Estuaries*, volume 18, Blum 1995; Day et al. 1995, 1997, 2000b). These energetic events range from waves and daily tides to switching of river channels in deltas that occur on the order of every 500–1,000 years, and include frontal passages and other frequent storms, normal river floods, strong but infrequent storms such as hurricanes, and great river floods (Table 1). A primary importance of the infrequent events such as channel switching, great river floods, and very strong storms (e.g., hurricanes) is in sediment delivery to coastal systems and in major spatial changes in geomorphology. The more frequent events such as annual river floods, seasonal storms such as frontal passages and tidal exchange are important in maintaining salinity gradients, delivering nutrients, and regulating biological processes. The analog of pulsing in coastal systems in lower rivers is the flood pulse concept (Junk et al. 1989; Junk 1999; Tockner et al. 2000) where exchange between a river and its floodplain is emphasized as the main factor determining the function of both the river and its adjacent riparian floodplains. To understand the impacts of climate change on coastal wetland systems and to effectively manage these systems with climate change, it is necessary to understand how climate change impacts coastal wetlands on all these spatial and temporal scales.

Sea Level Rise (Eustatic and Relative)

Potential Impacts Eustatic sea level (ESLR) rise over the 20th century is estimated to have been 15 to 20 cm (Miller and Douglas 2004). Most climate models predict that eustatic sea level rise (ESLR) during the 21st century will be somewhere between 20 and 60 cm (IPCC 2007), but recent evidence suggests that ESLR may be greater than 1 m (Rhamstorf 2007). Relative sea level rise (RSLR) will be much greater for specific areas and is of greater concern for coastal and estuarine areas. This sea level rise has led to significant geomorphological changes of coastal systems, salinity intrusion in estuaries, and loss of associated wetlands around the world, including Chesapeake Bay (Stevenson et al. 1985) and other mid-Atlantic estuaries (Kana et al. 1986; Hackney and Cleary 1987), Long Island Sound (Clark 1986), the Mississippi (Salinas et al. 1986; Conner and Day 1988; Day et al. 2000a, 2003, 2007), Grijalva/Usumacinta (Ortiz-Perez et al. 2008), Rhone (Pont et al. 2002), Nile and Ganges (Stanley 1988; Milliman et al. 1989), Indus (Snedaker 1984) and Ebro (Ibañez et al. 1997; Day et al. 2006) deltas, and Venice Lagoon (Pirazzoli 1987; Sestini 1992; 1996, Bondesan et al. 1995; Day et al. 1999).

Table 1 A hierarchy of forcings or pulsing events affecting the formation and sustainability of coastal wetland ecosystems (modified from Day et al. 1997)

Event	Time scale	Impact
Major changes in river channels	500–1,000 year	New delta lobe formation Major sediment deposition
Major river floods	50–100 year	Avulsion enhancement Major sediment deposition Enhancement of crevasse formation and growth
Major storms	20–25 year	Major sediment deposition Enhanced production
Average river floods	Annual	Enhanced sediment deposition Freshening (lower salinity) Nutrient input Enhanced 1° and 2° production
Normal storm events (frontal passage)	Weekly	Enhanced sediment deposition Enhanced organism transport Higher net materials transport
Tides	Daily	Marsh drainage Stimulated marsh production Low net transport of water and materials

High rates of geological subsidence, which contribute to high rates of relative sea level rise (RSLR), commonly occur in deltas due to compaction, consolidation, and dewatering of sediments. Compared to ESLR of 1–2 mm $year^{-1}$ for the 20th century, RSLR for the Mississippi delta was in excess of 10 mm $year^{-1}$ (Conner and Day 1991; Baumann et al. 1984; Boesch et al. 1994). RSLR in the Nile delta region is as high as 5 mm $year^{-1}$ (Stanley 1988; Milliman et al. 1989) and is between 2 and 6 mm $year^{-1}$ for the Rhone and Ebro deltas (Sestini 1992; Ibañez et al. 1996; Pont et al. 2002). Humans have accelerated RSLR by drainage and withdrawal of water, oil, and gas (Sestini 1992; Morton et al. 2002; Ko and Day 2004). An understanding of vegetation response in areas with high RSLR can provide insights into the effects of accelerated ESLR in the future (Stanley 1988; Day and Templet 1989; Stevenson et al. 1985; Day et al. 1997, 2005, 2000b, 2007; Pont et al. 2002). What are the limits to accretion of coastal wetlands, and how may human activities affect this accretion?

Biocomplex Response

Coastal wetlands can survive sea level rise only if they accrete vertically at a rate at least equal to water level rise (Cahoon et al.; 1995a, Day et al. 1997; Pont et al. 2002). The rate of accretion is a function of the combination of the inputs of both inorganic and organic material to the soil (Cahoon et al. 1995a; Day et al. 2000b; 2003). Inorganic sediments can come from either the sea or from terrestrial (often riverine) sources, whereas organic inputs tend to be *in situ*. River water brings in sediments and nutrients that tend to enhance organic soil formation (Delaune et al. 2003; Delaune and Pezeshki 2003; Ibañez et al. 1999). Organic material is generally from *in situ* belowground plant production that leads to organic soil formation. The higher the inputs of both organic and inorganic material to the soil, the higher is the rate of RSLR that can be tolerated without loss of wetland surface elevation.

Numerous studies document the vertical accretion rates of salt marshes and, in particular, the feedback between accretion rates and sea level rise (i.e., for recent British studies, see French and Stoddart 1992; French and Spencer 1993; French 1993; Allen and Duffy 1998; for the Mediterranean, see Sestini 1992; Bondesan et al. 1995; Ibañez et al. 1997; Pont et al. 2002; Day et al. 1999; Stanley 1988; for the Mississippi delta, see DeLaune et al. 1983; Hatton et al. 1983; Conner and Day 1991; Cahoon et al. 1995a, b). Coastal marshes have accreted at a rate equal to the historical rate of sea level rise (1–2 mm year^{-1}) that persisted for thousands of years (Redfield 1972; McCaffey and Thompson 1980; Orson et al. 1987). Given that the rate of ESLR is projected to increase up to 2 to 7 mm year^{-1} over the next 100 years, accretion will have to occur at a rate two to seven times that observed over the last century just to keep pace. Coastal and estuarine wetlands in areas with high rates of subsidence (i.e., large river deltas) will have to accrete at even higher rates.

Recent studies also document climate change impacts on mangrove ecosystems (UNEP 1994, Lynch et al. 1989; Woodroffe 2002; Cahoon and Lynch 1997; Parkinson et al. 1994). The diversity of mangrove wetlands and ecosystem processes can be viewed in an ecogeomorphical classification linked to the geophysical and geomorphological processes (Twilley et al. 1996, Fig. 3), which is a conceptual bridge for understanding positive vs. negative effects of RSLR in mangroves (Yáñez-Arancibia et al. 1998).

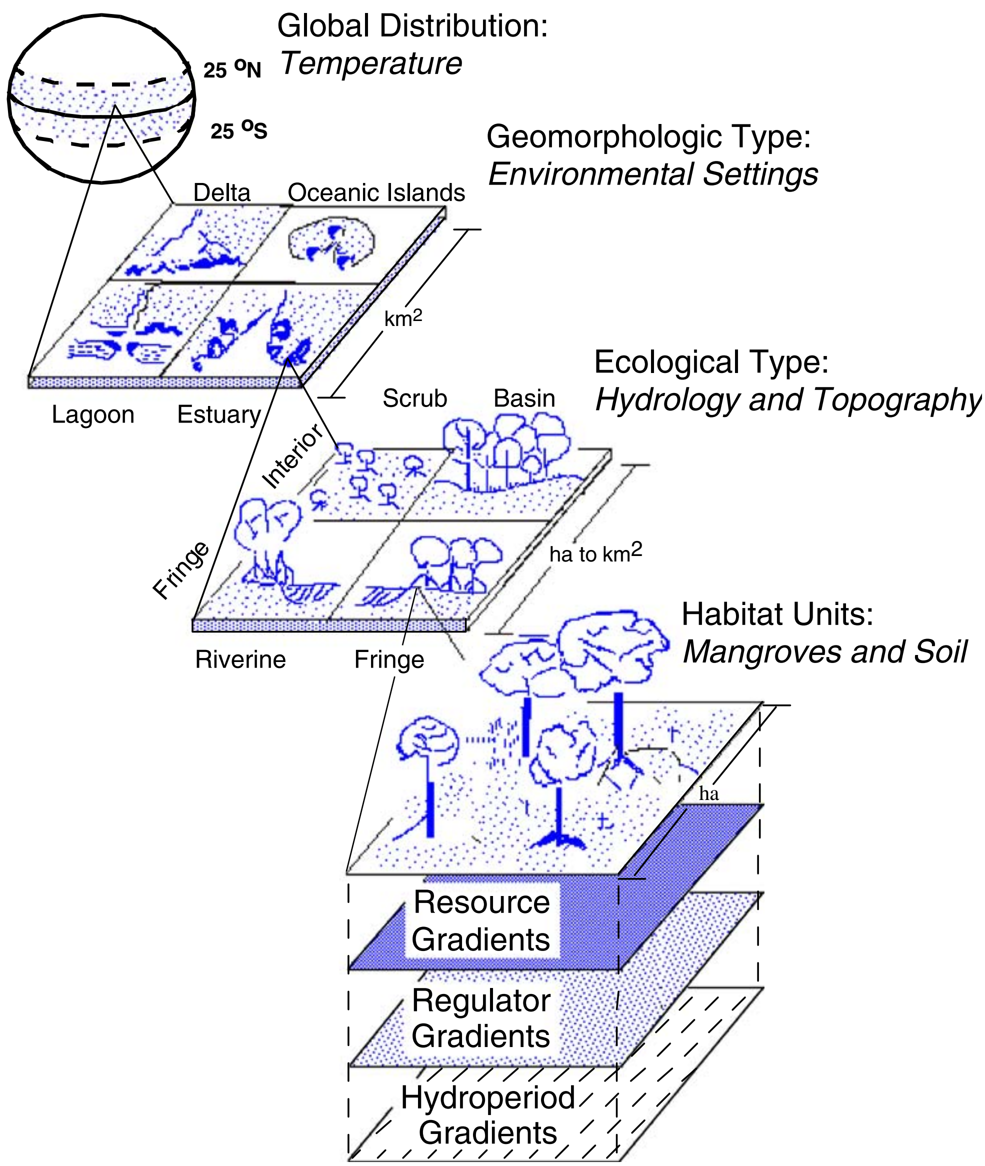

Fig. 3 The impacts of global climate change on the biodiversity and biocomplexity of coastal wetland systems will take place at several different landscape spatial scales as illustrated here for mangrove ecosystems (from Twilley et al. 1996)

High accretion rates are possible. In the Mississippi delta, accretion rates greater than 10 mm year^{-1} have been measured where there is sufficient sediment input from the river and resuspension to deliver sediments and nutrients to wetlands which leads to accretion due to mineral inputs and organic soil formation (DeLauane et al. 1983; Hatton et al. 1983; Conner and Day 1991; Day et al. 2000a; Cahoon et al. 1995a). While critical rates in sea level rise, >1.2–2.3 mm year^{-1}, have been estimated above which there is a projected collapse of mangrove ecosystems (UNEP 1994; Woodroffe 1990), there is also evidence that mangroves have existed through periods of accelerated rates of sea level rise above these critical rates in particular environmental settings. Mangroves in the South Alligator tidal river in Australia keep pace with changes in sea level rise with rates ranging from 0.2 to 6 mm year^{-1} (Woodroffe 1990). Mangrove forests in many estuaries in northern Australia tolerated sea level rise of 8–10 mm year^{-1} in the early Holocene (Woodroffe 1995). These rates are higher than most projections of accelerated rates of sea level rise. Mangrove systems that receive terrigenous sediments and exist in macrotidal environments may better keep pace with high rates of RSLR relative to mangroves ecosystems in microtidal and oligotrophic (carbonate) environments. Coastal wetlands can survive high rates of sea level rise if there is sufficient mineral and organic soil formation.

Human activities alter the ability of wetlands to accrete both at local and regional scales. While upstream modifications of river discharge and sediment load often reduce input of materials to wetlands (Snedaker 1984; Syvitski et al. 2005), other activities enhance erosion and nutrient availability that support the maintenance of wetlands (Ellis et al. 2004). In some cases, management may increase the ability of coastal wetlands to survive rising sea level by creating conditions that lead to higher inorganic sedimentation and higher plant productivity. Management should attempt to increase both organic soil formation and the input of inorganic sediments if wetlands are to survive increasing sea level rise.

Changes in Storm Frequency and Intensity

Potential Impacts

Until recently, there was only empirical evidence that the frequency of tropical cyclones and hurricanes would increase with increasing sea surface temperatures (Raper 1993; Walsh 2004), although the uncertainty in such predictions was high (Wigley 1999; Walsh 2004). Storm surges will impact farther inland and at higher elevations as relative sea level rises, independent of increases in storm intensity (Najjar et al. 2000). Increases in hurricane and cyclone intensity predicted by the models, however, fell within the range of natural interannual variability (Henderson-Sellers et al. 1998; Wigley 1999).

Recent reports have drawn stronger conclusions concerning storms and climate change. Emanuel (2005) reported that sea surface temperatures in the tropics increased by about 1 C over the past half century, and during this same period, total hurricane intensity or power increased by about 80%. This increase in intensity was due both to more powerful storms and to an increased duration of these storms. Webster et al. (2005) reported an increase in the number of category 4 and 4 storms over the past several decades. It has been argued that these increases in storm intensity, strength, and duration are not linked to climate change but are due to decadal cycles in tropical storm activity. Hoyos et al. (2006), however, analyzed factors contributing to hurricane intensity and concluded that the increasing numbers of category 4 and 5 for the period 1970–2004 was directly linked to the increase in sea surface temperatures. Regardless of whether the recent intensification of hurricanes is due to climate change or is part of a decade-long cycle, it is likely that there will be more and stronger hurricanes in the coming decades. Changes in the intensity and frequency of storms can have a variety of impacts on coastal wetlands, as outlined below.

Biocomplex Response

Storms affect coastal wetland ecogeomorphology in a variety of ways and at different scales. From a physical and geomorphical point of view, winds and waves lead to movement of barrier islands, erosion of upland and wetland edges, and to blow down of wetland trees (Stone and Finkl 1995; Riggs and Ames 2003). Subtidal and intertidal sediments can be scoured, locally increasing depth. The resuspended materials may then be deposited elsewhere, increasing elevation, causing progradation or transgression, and reducing depth (Stone and Finkl 1995; Baumann et al. 1984). All of these factors affect coastal wetlands.

Most coastal wetland ecosystems and their components are substantially structured by storms. Storms provide a pulsing that leads to indirect and biocomplex effects in both beneficial and detrimental ways. Storms may reduce wetlands locally through mortality, cause diversion of introduced pollutants into a locale or flush them from it, alter productivity for periods beyond the extent of an event, and cause ecosystem state changes with a significant change in trajectory of succession (Conner et al. 1989; Day et al. 1995, 1997, 2000b, Hayden et al. 1995; Odum et al. 1995; Christian et al. 2000; Davis et al. 2004).

Some of the ecosystem state changes can be relatively subtle and incorporated into the general response of ecosystems to sea level rise, such as changing position of salt marsh zonation (Brinson et al. 1995). Other changes can be dramatic, such as altering the ecogeomorphology of the broader coastal landscape (Hayden et al. 1995) and reducing the structural complexity of coastal habitats, such as tidal freshwater forested wetlands and mangroves (Chen and Twilley 1998; Baldwin et al. 2001; Sherman et al. 2000; Smith et al. 1994; Rybczyk et al. 1995).

Long-term changes in the frequency, intensity, timing, and distribution of strong storms will likely alter the species composition and biodiversity of coastal wetlands, and important ecosystem rates such as nutrient transformation processes, primary and secondary productivity, and material export (Conner et al. 1989; Twilley and Day 1999; Baldwin et al. 2001; Sherman et al. 2000; Twilley et al. 1999). There can be both beneficial and detrimental effects. It has been shown that hurricanes greatly increase the rate of soil accretion in marshes, thereby helping to offset accelerated sea level rise (Baumann et al. 1984; Cahoon et al. 1995b). Runoff generated by hurricanes introduces freshwater and nutrients which can enhance coastal wetland productivity (Conner et al. 1989). In the arid areas of south Texas, freshwater input can also have a stimulatory impact by reducing salinity stress (Conner et al. 1989). How wetland plants compete in the context of these factors will determine the nature of the communities that will develop in the context of the long-term changes (Brinson et al. 1995; Bertness and Pennings 2000). Hurricanes can reduce the structural complexity of coastal forested wetlands (Flores et al. 1987; Rybczyk et al. 1995; Stone and Finkl 1995; Smith et al. 1994).

Storms cause substantial losses to human society. Humans and their structures have become dominant features of the coast, affecting the impact of storms on coastal ecosystems. Effects of humans occur in two ways: humans modify the coast in ways that may either promote or prevent storm damage, and storms can cause losses to life and property that are important to human society. For example, loss of wetlands can lead to more hurricane damage due to the loss of storm buffer (Day et al. 2007). The full range of interactions between immediate effects of storms on both wetland and human systems, and longer term, subsequent responses make this a biocomplex issue.

Fresh Water Input, Sediment Transport, and Nutrient Delivery

Potential Impacts

For much of the U.S. coast, with the exception of the Gulf coast, most GCMs agree that winter and spring rainfall will increase, although there is disagreement among models as to whether precipitation will increase or decrease in summer and fall (Wigley 1999). The latest IPCC report (2007) suggests that there will be increased water availability in the moist tropics and at high latitudes. Changes in freshwater inflow are likely to be a function of latitude. These changes will bring about respective decreases and increases in sediment and nutrient input to estuaries. The degree to which these alterations in supply are affected depends on both the degree to which humans control the flow of water to the coast and our management of land and wastes.

Biocomplex Response

Changes in fresh water and sediment input to coastal ecosystems leads to biocomplex interactions that can increase or decrease the susceptibility of coastal wetlands to sea level rise. As previously stated, the rate at which accretion occurs, and thus the response to sea level rise, is a function of the combination of the inputs of both inorganic and organic material. Organic material is mostly derived from the growth of plant roots (i.e., organic soil formation), whereas particulate inorganic material is mostly supplied in the form of sediments that come from either the sea or freshwater sources.

There is a considerable literature showing that multiple stresses on coastal wetlands are much more detrimental than individual stressors acting alone (i.e., Mendelssohn and Morris 2000). Coastal plants have evolved physiological, morphological, and reproductive strategies to deal with the impacts of increased and fluctuating water level. Plants are often able to deal with moderate increases in single stressors such as increased salinity, water logging, anoxia, and toxins. But when plants are subjected to multiple stressors, their ability to adapt is greatly reduced (Mendelssohn and Morris 2000). Freshwater input into coastal systems reduces the level of a number of stressors (e.g., freshwater reduces salinity, mineral sediments directly stimulate accretion, iron precipitates sulfides, and nutrients stimulate belowground productivity and thus organic soil formation, Delaune and Pezeshki 2003; DeLaune et al. 2003; Delaune et al. 2005). Thus, freshwater input is a way to deal with sea level rise which causes both excessive flooding and salinity stress.

Apparently, because of an increase in intensity and frequency of tropical depressions and hurricanes in the Caribbean, there has been a recent increase in the discharge of major rivers in Middle America (Yáñez-Arancibia 2005) compared to several decades earlier (Longhurst and Pauly 1987). Major rivers can modify coastal morphology and enhance the ability of coastal wetlands to survive sea level rise. Major rivers, such as the Usumacinta/Grijalva (Mexico), Rio Dulce (Guatemala), Magdalena (Colombia), and Orinoco (Venezuela) have not only impacted inshore areas and coastal wetlands but have also affected sediment conditions on adjacent continental shelves, and have built sediment fans on the continental slope on the Atlantic coast of Mesoamerica. On both the Atlantic and Pacific coasts of Central America, a few tropical rivers dominate sediment transport to the coastal ocean in Middle America. These include the Usumacinta/Grijalva (Mexico), Rio Dulce Guatemala, Gulf of Honduras/El Salvador/Nicaragua, Tempisque River (Costa Rica), Terraba Sierpes (Costa Rica), and the Magdalena (Colombia). The effects this high discharge can be seen in wetlands and patterns of coastal fish community structure, food availability, and coastal productivity (Yáñez-Arancibia 2005). For Middle America, the total combined freshwater discharge is 21,951 m^{-3} s, and the total sediment discharge is 288 million tons $year^{-1}$ (Yáñez-Arancibia 2005). This high sediment discharge can enhance mangrove survival with respect to sea level rise but is a potential stress for coral reefs in Mesoamerica (Wilkinson and Buddemeier 1994).

Enhanced aboveground production of plants from nutrient enrichment and fresh water also acts to promote trapping of sediments (Morris et al. 2002). Thus, a reduction of freshwater input due to climate change reduces, in a variety of ways, the ability of coastal plants to cope with sea level rise. To complicate such a trend, humans have reduced freshwater flows and sediment loads to the coast worldwide (Syvitski et al. 2005). This interaction of sea level rise and changes in fresh water input is an example of the biocomplex responses to both climate change and human interventions. Reduced fresh water input leads to a reduced ability of coastal wetlands to survive accelerated sea level rise, while increased fresh water input (as a result of increased river flow or because of river reintroduction) enhances survivability (Delaune et al. 2003).

Regional Examples of Ecogeomorphology, Climate Change, and the Impacts of Human Activities

We have assembled examples of coastal and estuarine systems that represent a range of responses to environmental factors related to climate change. The examples represent different ecogeomorphical types and are subject to different influences from human activities. Each system has been studied extensively. We describe the biocomplex responses in the context of the issues of scale, pulsing, and human activity including major river deltas, temperate salt marshes and coastal waters, and environmental settings of the Caribbean basin. Details of each sites are provided in the following website at the University of Maryland: www.umces.edu/archives/. The findings are summarized in Table 2.

The seven regional systems shown in Table 2 can be considered as a representative of a broad range of coastal systems, as they span a range of environmental conditions and coastal settings, from the tropics to higher temperate, with varying degrees of freshwater input, and with varying degrees of human impact. Several conclusions can be drawn from this analysis. Of the three aspects of climate change considered in this paper, sea level rise is of least concern in the short term for coastal wetlands in most regions. Coastal wetlands with high relative sea level rise and human impact are more susceptible to sea level rise. This may change as SLR accelerates, and other factors interplay with it. The importance of the other two aspects (e.g., storms and freshwater inputs) are greater largely because of human activities within, around, and upstream of the systems. It is also clear that these three aspects of climate change interact in biocomplex ways that lead to greater stresses on coastal wetlands. Thus, the human dimension is a dominant factor in how climate change will impact these and similar coastal wetland systems.

Human Interference with Biocomplex Responses

Humans are altering the global climate at rates that are rapid compared to the historical and recent geological record. Thus, all of the aforementioned examples are subject to the global impacts of humans. These changes may disrupt wetland ecological systems if these changes occur at characteristic time scales shorter than ecological system response and cause changes in ecological function that foster changes in structure or alter the interactions of functions. If sea level rises at a greater rate than accretion, coastal wetlands will be submerged. If the return time of major storms exceeds the rate of reestablishment of mangroves, these systems may be in jeopardy. What complicates prediction is that climate and associated changes also may alter ecological processes. Alterations in climate, CO_2, and nutrient concentrations can alter production, respiration, and community structure and manifest in tissue concentrations of elements and compounds, causing changes in susceptibility to either decomposition or herbivory (Arp et al. 1993; Pennings and Silliman 2005). Global change sets the context for myriad ecological functions at all scales.

Human and wetland ecosystem interactions provide feedbacks at regional and local scales. Humans have become a major restrictor of wetland accretion and horizontal migration, as for example, in deltas and English marshes (on line regional examples). Land use for cities, industry, agriculture, roads, bulkheads, and levees all prevent wetlands from moving inland and being sustainable in the face of rising sea level. Accelerated sea level rise is projected to increase coastal erosion and destabilize shorelines presently colonized by estuarine wetlands. Restricted access of this vegetation to migrate to inshore areas will limit the stability of shorelines under scenarios of accelerated sea level rise and increase the likelihood of coastal

Table 2 Biocomplex interactions within coastal ecosystems associated with three aspects of global climate change (relative sea level rise=RSLR)

System	Sea level rise	Changes in storm frequency and intensity	Changes in freshwater, sediment, and nutrient inputs
Major river deltas			
Mississippi River Deltaic Plain, USA	Loses of wetlands are ongoing linked to human impacts (levees and altered hydrology) and high RSLR due to subsidence	Evidence from previous storms of major impacts to human dominated and natural ecosystems. Hurricanes result in major sediment input and saltwater intrusion..	Human modifications to land use & river flow have led to both increased and decreased freshwater input. Areas with high freshwater input are more stable. Lack of river input a major factor in wetland loss.
Usumacinta-Grijalva River Deltaic Plain, Mexico	High RSLR due to subsidence and coastal erosion but much of delta is sustainable because of high connectivity between river and delta.	Since Hurricane Gilbert 1988, there has been an increase in the frequency and intensity of major storms, representing an important sediment supply.	Evidence of altered hydrology from petroleum exploration. In these areas, there is wetland loss because of petroleum activity and land use change due to agriculture. Evidence of increase freshwater input
Sundarbans, Indian Ocean	Even though there is high RSLR due to subsidence, ESLR is not immediate threat because of high river inputs.	Cyclone patterns represent important sediment supply but also threaten mangroves	Shift in river flow has altered distribution pattern of sediments and increased salinity stress in interior mangrove. Damming and irrigation in Ganges basin will further reduce river input.
Mediterranean deltas	RSLR is very site specific, but it can be high. Human impacts combined with RSLR leading to high wetland loss.	Absence of strong tropical storms, but strong storms can lead to sediment input in marine parts of delta.	Upstream water use and levees have greatly reduced river input to most deltas, causing vegetation shifts and loss of wetlands.
Temperate salt marshes and coastal waters			
Estuaries of UK	Currently most marshes can keep up with ESLR, but higher rates will affect some areas.	Long history of human responses to storm surge and management for flooding.	Long history of river modifications and embankment of wetlands. Managed retreat is important management option.
Lower Delmarva Peninsula, USA	Regionally high but not affected yet, but higher rates pose a problem.	Storms historically have made major changes to landscape.	Small watersheds and relatively rural setting defers problems.
Mangroves			
Caribbean Basin	Most mangroves are currently keeping up with ESLR, but higher rates pose a threat.	Long history of impacts of tropical storms, which provide a sediment source but also lead to decrease in forest structure	Major problems linked to human impacts with reduction in freshwater input leading to salinity stress and reduction in sediment input.

erosion. River dikes prevent changes in the course of the lower river, restricting the development of crevasse splays, and input of riverine freshwater, sediments, and nutrients during river floods. Sea dikes and canals, with their associated spoil banks, inhibit water movement into coastal wetlands, and the deposition of sediments during pulsing events such as coastal storms and frontal passages (Swenson and Turner 1987; Reed 1992; Boumans and Day 1994; Pont et al. 2002). Impoundments consisting of a system of dikes and water control structures have been shown to reduce tidal exchange and the influx of suspended sediments, lower accretion rates, lower productivity, and reduce the movement of migratory fishes (Reed 1992; Rogers et al. 1992; Cahoon 1994; Hensel et al. 1998; Pont et al. 2002).

Many rivers now carry only a fraction of the mineral sediments that they did historically, particularly in arid and semiarid areas (e.g., Yáñez-Arancibia and Day 2004; Pont et al. 2002; Stanley and Warne 1993). This is seen for the deltaic examples (on line material). Sediment discharge to the Mississippi delta has decreased by 70% since 1860, largely due to the building of Missouri River dams, contributing to the significant loss of coastal wetlands (Kesel 1989). The amount of sediment carried in Nile, Indus, and Ebro rivers has been reduced by over 95%; for the Po, the reduction is about 75%, and for the Rhone, the reduction is greater than 50% (Stanley and Warne 1993; Milliman et al. 1984; Varela et al.1986; Ibañez et al. 1997; Sestini 1992; Pont et al. 2002). Reduction of freshwater inflow can lead to salinity intrusion and, in arid and semiarid areas, to hypersalinity that, in turn, can lead to wetland vegetation death. Hypersalinity and increased waterlogging due to lack of sedimentation is leading to wetland deterioration in the Rhone delta (Ibañez et al. 1999;

Hensel et al. 1999; Pont et al. 2002). A climate-induced reduction in sediment input combined with an acceleration of sea level rise can reduce the ability of coastal wetlands to survive rising water levels (Poff et al. 2002; Twilley et al. 2001; Day et al. 1997, 2005). In the Mississippi, Rhone, Po, and Ebro deltas and Venice Lagoon, RSLR and reduced sediment input is leading to wetland loss (Boesch et al. 1994; Pont et al. 2002; Day et al. 2007; Sestini 1992; Ibañez et al. 1997).

The relationships among climate change, intertidal vegetation, and fisheries provide an illustrative example of biocomplex relationships. There is a considerable literature on the importance of intertidal vegetation to many estuarine-dependent fishery species, and vegetation area has been related to estuarine fishery production (Pearcy and Myers 1974; Turner 1977; Pauly and Ingles 1986; Chesney et al. 2000). One would expect that loss of intertidal wetland area would lead to a loss of estuarine-dependent fisheries. Despite a massive wetland loss in the north central Gulf of Mexico, landings have increased for many species (Zimmerman et al. 1991). It has been hypothesized that it is the marsh edge that is the essential habitat for many species, and as marsh fragments, marsh edge initially increases and then decreases as marsh deterioration continues (Browder et al. 1985, 1989; Chesney et al. 2000). Thus, wetland deterioration because of sea level rise may result in an increase in fishery landings until wetland loss becomes severe. An additional biocomplex result is that submerged aquatic vegetation may increase in the shallow areas that form as wetland disappears providing a different habitat for fishery species (Chesney et al. 2000).

Management and Observations at Multiple Scales

Management of human activities is necessary to minimize the impacts of climate change on coastal wetlands. Management policy must recognize the multiple scales of impacting agents and responses. It must recognize that pulses of materials, such as freshwater and sediments, and pulses of energy, such as strong storms, are natural and are necessary to sustain coastal ecosystems. It is also obvious that such pulses can negatively impact humans. A conundrum is that the coastal ecosystems provide goods and services that are prized by the public but are sustained by processes and pulses, such as river floods, which impinge negatively on human activities and structures. A balance must be struck that allows pulsing that promotes these ecosystem goods and services, while protecting humans, their structures, and their activities.

The multiple scales of human impact require multiple management strategies. At the global level, action is needed to control greenhouse emissions. This involves both national and multinational efforts with consequences far beyond the coast. At the regional level sediment, freshwater and nutrient supplies can be managed. Given reduced sediment loads and fresh water input and disruptions in coastal wetland hydrology, one management strategy to offset sea level rise and promote continued coastal wetland productivity is to actively utilize riverine freshwater and sediments that exist rather than letting most of them flow out to sea. The reintroduction of river water into coastal ecosystems is being carried out or being considered in a number of coastal ecosystems (Boesch et al. 1994, 2006; Ibañez et al. 1997; Pont et al. 2002; Day et al. 2007). At the local level, direct impacts on coastal habitats, their resident species, and surroundings can be minimized. Wetlands can migrate inland as sea level rises. But in many cases, there are development barriers that prevent this. There is often a rapid increase in elevation in the uplands bordering coastal wetlands, so that upland migration can support only a small fraction of the wetlands that are lost.

Sound, science-based management depends on multi-scale understanding of these biocomplex systems. Two aspects of the understanding of the effects of global change are detection and attribution (Santer et al. 1996). As described, pulsing of physical drivers is strong in coastal systems with potentially dramatic, local, and regional human impacts. In contrast, global climate change involves, at least in the short-term, a relatively weak signal within considerable short-term noise. The signal may be in the form of changes in some quantity (e.g., mean or maximum daily temperature, atmospheric CO_2 concentration, primary production of wetlands) or some frequency (e.g., rate of sea level change, occurrence of extratropical storms, calving of icebergs). First, such change must be detectable with some confidence, and second, the sources of causation of the change must be determined. Causation is often not simple and determinant, but rather may be associated with multiple factors, considerable variability, feedbacks, and interferences. Detection is achieved through monitoring and assessment of historical or geological records. Attribution can be inferred through these in conjunction with experimentation and modeling. All have their challenges but, for coastal wetland systems, one of the largest is to develop monitoring programs that act at appropriate scales to detect global climate change and its effects in the context of the various local and smaller scale effects.

A mechanism to provide such monitoring is the observing system structure. Observing systems include monitoring efforts that may be at local to global scales and links them to data management, modeling, and communication systems (Christian et al. 2006). The Global Earth Observation System of Systems (GEOSS) is developing an implementation plan to link various programs at the national and international levels to provide such capabilities. The United Nations, with programs by member nations, has three observing systems (the Global Climate Observing System GCOS; the Global Oceanographic Observing System, GOOS; and the Global Terrestrial Observing System, GTOS) to detect large-scale change and provide predictions of effects. Coastal ecosystems provide complications and opportunities for assessing global change (Christian 2003). Currently, two coastal observing systems are at the international level, one from GOOS (IOC 2003) and one from GTOS (FAO 2005). The GOOS will provide infrastructure for assessing physical, chemical, and biological variables across coastal marine and nearshore ecosystems. The U.S. Integrated Ocean Observing System (IOOS) is the contribution from the United States to GOOS (Ocean.US 2003). Core variables will be collected from ships, buoys, platforms, aircraft, and satellites. Terrestrial, wetland, and coastal freshwater systems will be assessed through the coastal GTOS initiative. Although both international programs will include variables of human activities, these will be more prominent within the GTOS initiative. No U.S. observing system currently exists to address specifically coastal, wetland, and freshwater ecosystems. The coastal programs of GOOS and GTOS have been designed in cooperation and with a view toward integration. This integration is through the Coastal Theme of the Integrated Global Observing Strategy and the GEOSS Coastal Zone Community of Practice, partnerships of national and international agencies, and programs to aid the observing system process. Given Hurricanes Katrina and Rita and the events of 2005, there is a clear need to extend the efforts of IOOS or some other observing system toward the land. An integrated set of observing systems will aid in the detection of climate change on coastal wetland systems.

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