Our Transition

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Coastal Wetlands

& Global climate change

Gulf Coast Wetland Sustainability in a Changing Climate

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PEW CENTER ON Global CLIMATE CHANGE

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Excerpted from the full report,
Regional Impacts of Climate Change: Four Case Studies in the United States
Prepared for the Pew Center on Global Climate Change

by

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Foreword *Eileen Claussen, President, Pew Center on Global Climate Change*

In 2007, the science of climate change achieved an unfortunate milestone: the Intergovernmental Panel on Climate Change reached a consensus position that human-induced global warming is already causing physical and biological impacts worldwide. The most recent scientific work demonstrates that changes in the climate system are occurring in the patterns that scientists had predicted, but the observed changes are happening earlier and faster than expected—again, unfortunate. Although serious reductions in manmade greenhouse gas emissions must be undertaken to reduce the extent of future impacts, climate change is already here and some impacts are clearly unavoidable. It is imperative, therefore, that we take stock of current and projected impacts so that we may begin to prepare for a future unlike the past we have known.

The Pew Center has published a dozen previous reports on the environmental effects of climate change in various sectors across the United States. However, because climate impacts occur locally and can take many different forms in different places, *Regional Impacts of Climate Change: Four Case Studies in the United States* examines impacts of particular interest to different regions of the country. This paper is an excerpt from the full report. Although sections of the full report examine different aspects of current and projected impacts, a look across the sections reveals common issues that decision makers and planners are likely to face in learning to cope with climate change.

Kristie Ebi and Gerald Meehl find that Midwestern cities are very likely to experience more frequent, longer, and hotter heatwaves. According to Dominique Bachelet and her coauthors, wildfires are likely to increase in the West, continuing a dramatic trend already in progress. Robert Twilley explains that Gulf Coast wetlands provide critical ecosystems services to humanity, but sustaining these already fragile ecosystems will be increasingly difficult in the face of climate change. Finally, Donald Boesch and his colleagues warn that the Chesapeake Bay may respond to climate change with more frequent and larger low-oxygen "dead zone" events that damage fisheries and diminish tourist appeal. These authors are leading thinkers and practitioners in their respective fields and provide authoritative views on what must be done to adapt to climate change and diminish the threats to our environmental support systems.

A key theme emerges from these four case studies: pre-existing problems caused by human activities are exacerbated by climate change, itself mostly a human-induced phenomenon. Fortunately, manmade problems are amenable to manmade solutions. Climate change cannot be stopped entirely, but it can be limited significantly through national and international action to reduce the amount of greenhouse gases emitted to the atmosphere over the next several decades and thereafter, thus limiting climate change impacts. Managing those impacts requires that we adapt other human activities so that crucial resources, such as Gulf Coast wetlands or public emergency systems, continue to function effectively. The papers in this volume offer insights into how we can adapt to a variety of major impacts that we can expect to face now and in decades to come.

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Gulf Coast Wetland Sustainability in a Changing Climate

A. Introduction

The wetlands of the U.S. Gulf Coast provide services that are significant to the quality of life in the region, help sustain the national economy, and help protect life and property from climate extremes. Fisheries, recreation, and tourism have all thrived in the Gulf Coast region alongside urban development, agriculture, shipping, and the oil and gas industries. However, some regions of the Gulf Coast, such as the Mississippi River Delta and Florida Everglades, are experiencing some of the highest wetland loss rates in the U.S., largely because of engineered modifications to regional watersheds and coastal landscapes. Such modifications increase the vulnerability of these wetlands to future climate variability and change. Sustainable restoration of Gulf Coast wetlands requires planning for a more extreme future climate by returning critical water resources in the coastal landscapes to levels that existed before humans began modifying this region three centuries ago (Day et al., 2007).

Gulf Coast wetlands support economic and ecological productivity as well as quality of life in many ways. Wetlands provide food, refuge, and nurseries for fish and shellfish, and they support the region's large commercial and recreational fishing industries. As a result, Louisiana's commercial fisheries account for about 30 percent of the nation's total fish catch. In addition, Gulf Coast wetlands provide stopover habitat for an estimated 75 percent of the waterfowl migrating along the Central Flyway (Environmental Health Center, 1998). Wetland soils and vegetation naturally store water, filter sediment and pollutants from fresh water supplies, and help stabilize shorelines by reducing erosion and storm surges associated with rising sea levels (Daily et al., 1997; Mitsch and Gosselink, 2000).

Gulf coastal systems also provide diverse natural resources that have been transformed to provide opportunities for economic development. The United States ranks second in worldwide natural gas production and third in oil production (Hetherington et al., 2007). Between 2000 and 2005, one-fifth to one-quarter of U.S. domestic natural gas and crude oil production occurred in the Gulf of

Mexico (Energy Information Administration, 2007). In 2004, shipping ports in the Gulf states (Texas, Louisiana, Mississippi, Alabama, and Florida) accounted for 49 percent (by tonnage) of all waterborne cargo entering and leaving the United States (U.S. Army Corps of Engineers, 2006). Texas and Louisiana each handled more waterborne cargo by tonnage than California, New York, and New Jersey combined. The Mississippi delta is heavily impacted by shipping—the ports of New Orleans, South Louisiana, Baton Rouge, and Lake Charles handle more than 20 percent of the nation's foreign waterborne commerce. Economic development in Florida has transformed coastal wetlands through recreational activities and residential development, along with major investments in agriculture. In 2005, Florida had almost 86 million visitors who spent more than $62 billion (Florida Tax Watch, 2006). The vast majority of tourism in Florida is to visit the state's coastal resources. Such heavy use can create pressures on natural coastal ecosystems.

Degradation of coastal wetlands through land development and water management reduces the capacity of wetlands to provide significant ecosystem services that reduce the risks of living and working in coastal landscapes. For example, extensive coastal wetland landscapes, especially forested ecosystems, can reduce storm surge and wind energy during tropical storms and cyclones, minimizing hurricane damage to life and property. In part because of recent hurricanes, local, state, and federal agencies have renewed their emphasis on coastal wetland restoration in the Gulf Coast region (Working Group for Post-Hurricane Planning for the Louisiana Coast, 2006; Day et al., 2007). However, such programs may fail without effective planning for future climate change, including accelerated sea-level rise and the potential intensification and increased frequency of hurricanes.

Human activities intended to reduce damage to life and property from climate extremes have unintentionally increased the vulnerability of coastal areas to climate change by altering the natural hydrologic functions of wetlands (National Research Council, 2005; CPRA, 2007). For coastal wetlands to be sustained in a changing climate, therefore, restoration planning must account for the consequences of both climate change and human engineering of the environment.

B. Gulf Coast Wetlands and Water Management

Two of the most distinctive and extensive wetland landscapes in North America and in the world are located along the Gulf Coast—the Florida Everglades and Louisiana's Mississippi River Delta. These wetland ecosystems depend heavily on water availability, as does the region's economic development. However, the natural capacity of coastal wetlands in the Gulf Coast region to store, distribute, and purify water has been greatly diminished by coastal development and the construction of water management systems.

The highly engineered landscapes of the Everglades and the Mississippi Delta were developed in response to major floods and hurricanes that occurred from 1926 to 1948 (Light and Dineen, 1994; Barry, 1997). Major federal work projects, including the Mississippi River and Tributary Project of 1930 and the Central and Southern Florida Project for Flood Control and Other Purposes of 1948, were authorized by Congress to protect life and property following these major natural disasters. Canals, floodgates, levees, and water control structures were built to reduce flood risks to agriculture, urban development, energy-related industries, and commercial transportation.

Although flood control projects provided temporary relief from flooding, they also interfered with the natural hydrological processes that are necessary to sustain the structure, function, and extent of wetland ecosystems and reduced the natural capacity of the wetlands to mitigate flooding (Boesch et al., 1994; Davis and Ogden, 1997). The loss and degradation of wetlands has resulted in increased risks from coastal storms and tidal surges, leading to unintended consequences for both human and natural systems. Today, Louisiana and Florida, along with Texas, are the top three states in the nation in terms of annual economic losses resulting from hurricanes and floods.

Net wetland elevation is determined by the balance between soil building processes (accretion) and land sinking (soil subsidence) relative to the rate of sea-level rise. Wetland soils develop from and are sustained by mineral sediments carried by rivers and deposited by floods, and from organic material produced by plants within the wetland landscape. These soil-building processes enable wetlands to gain elevation (accrete) as sea-levels rise (Mitsch and Gosselink, 2000). Human activities slow down accretion by regulating water flow and, therefore, sediment and nutrient supply. Humans also cause soil subsidence and erosion through such processes as groundwater extraction, oil and gas withdrawals, and dredging of navigation channels (Morton et al., 2003). Natural compaction processes also contribute to subsidence. In effect, sea-level rise adds to the rate of subsidence as the sea surface rises relative to the land. In order for wetland elevation to remain stable or to rise, therefore, the rate of soil accretion must equal or exceed the combined rates of natural and human-induced soil subsidence plus sea-level rise.

Prior to human modification, Gulf Coast wetlands were sustained because soil formation kept pace with natural compaction and historical sea-level rise. Today and into the future, their sustainability depends on the ability to keep pace with human-induced elevation loss and accelerating sea-level rise resulting from global warming caused by increasing concentrations of manmade greenhouse gases in the atmosphere (IPCC, 2007). If soil formation cannot keep pace with all of these competing processes, coastal wetlands will experience increased flooding from rising seas, reducing plant production and further accelerating wetland loss (DeLaune et al., 1994). Under such conditions, wetlands ultimately will “drown” and convert to open water.

The well-documented history of adaptation by ecological and social systems in both the Everglades and the Mississippi delta provides insights into the increasing challenges to sustainable development faced by coastal communities under the added stress of a changing climate.

1. Coastal Louisiana

Southern Louisiana has a working coast, with extensive human settlements across the landscape. Humans have taken a variety of actions to manage the risks of occupying the extremely dynamic river delta environment (Boesch et al., 1994; Laska et al., 2005; Day et al., 2007). Major landscape changes have occurred over the past century in the nearly 1.3 million square mile watershed of the Mississippi River, including conversion of more than 80 percent of forested wetlands to agriculture and urban areas, river channels, and dams and levees (CENR, 2000).

Under natural conditions, deltaic environments, such as the Mississippi River Delta in southern Louisiana, receive sediment through openings in natural levees (river crevasses) during flood pulses, adding to soil formation (Day et al., 1994; 2007; Perez et al., 2003). The construction of earthen and concrete levees and of a massive structure to regulate the flow of the Mississippi and Red Rivers has restricted the natural supply of sediment and fresh water to the delta's floodplain (Kesel, 1988). In addition, dams on the Mississippi River have decreased sediment delivery to the lower delta by more than 50 percent over the past 150 years. Together, the reduction of sediment delivery from the Mississippi watershed to the lower delta and the inability of sediment to enter wetland basins through river crevasses have caused significant losses of the region's coastal wetlands (Kesel, 1988; Day et al., 2007).

The Mississippi delta also receives sediment from hurricanes. A recent study estimates that hurricanes Rita and Katrina deposited an average of two inches of sediment over a large area of coastal wetlands in Louisiana (Turner et al., 2006). However, sediment from hurricanes alone has been insufficient to maintain the elevation of coastal wetlands in southern Louisiana over the past century relative to regional subsidence (Cahoon et al., 1995), particularly given other changes in regional hydrology caused by extensive construction of canals and other artificial water control features (Boesch et al., 1994; Stokstad, 2006).

Coastal Louisiana experiences the greatest wetland loss in the nation, and delta wetlands are now disappearing at an average rate of 17 square miles per year or about 50 acres per day (Gosselink, 1984; Conner and Day, 1988; Barras et al., 2003). Wetland loss rates over the next 20 years in coastal Louisiana, due to the combination of sea-level rise and disruption of natural coastal processes, will continue to convert land to open water, threatening the region's fisheries, aquaculture and coastal agriculture, as well as commercial shipping and other industries located near the coast (Louisiana Coastal Wetlands Conservation and Restoration Task Force, 1998; Barras et al., 2003; U.S. Army Corps of Engineers, 2004a).

2. Florida Everglades

In contrast to the heavily developed Louisiana coast, South Florida's Everglades are protected by the U.S. National Park Service, with additional international designation as a Biosphere Reserve (MAB, 2007), a World Heritage Site (World Heritage Committee, 2007), and a Wetland of International Importance (Ramsar Convention, 2007). However, the Everglades National Park is also located within a watershed of intensive human settlement, with one of the area's largest urban and agricultural regions to the north of the park boundary (Harwell, 1997).

Before European settlement, the landscape of South Florida was a mosaic of habitats connected by the flow of fresh water across a gently sloping landscape from Lake Okeechobee through the Everglades and south to Florida Bay (Light and Dineen, 1994; Harwell, 1997). The wetland landscape included sawgrass interspersed with tree islands, with mangrove forests extending over an area of three million acres in the estuarine transition zone (Gunderson, 1994). The natural evolution of the region was driven in part by the very slow relative rise in sea level over the past 3,200 years, as well as extreme episodic events—in particular, fires, freezes, hurricanes, floods, and droughts.

To protect human settlement from these natural events, the federal government developed one of the world's most extensive water management systems in South Florida. A series of canals and water control structures unnaturally reduced the flow of fresh water to Florida Bay (Light and Dineen, 1994). The subsequent alterations of wetland habitat and reduction in wading bird populations implicate these fresh water diversions in the reduced sustainability of the region's natural resources. As a result of water engineering, the Everglades is now an endangered ecosystem, the sustainability of which is vulnerable to projected climate changes (Harwell, 1997; 1998).

Mangrove forests dominate the coastal margin of the Everglades. In contrast to wetlands in the Mississippi delta, soil building and elevation in the Everglades is dominated by plant productivity, producing highly organic soils in the absence of significant river sediment deposition (Lynch et al., 1989; Parkinson et al., 1994). Although mangroves situated at the mouths of estuaries in the southwest Everglades experience pulsed inputs of sediment during storm events (Chen and Twilley, 1998; 1999), the Everglades as a whole rely on *in situ* soil production. Hence, the rate of soil building in the Everglades is primarily limited by plant productivity, regulated by water and nutrient delivery. Because subsidence in the Everglades is insignificant, plant vulnerability is related mainly to the rise in sea level relative to the rate of soil formation. As in the Mississippi delta, soil-building processes have been altered by engineered water management systems.

C. Gulf Coast Wetlands in a Changing Climate

Global climate change is expected to affect air and water temperatures, ocean and atmosphere circulation, sea-level rise, the intensity of hurricanes, and the timing, frequency, and magnitude of precipitation (IPCC, 2007). Under natural conditions, coastal wetlands adjust to rising seas and changes in local storm patterns, but climate changes and human activities that alter natural conditions disrupt wetland hydrology, biogeochemical cycling, and other processes that sustain wetlands (Morris et al., 2002). In the Gulf Coast region, the combined effects of water engineering, land development, natural subsidence, and climate change will have tremendous consequences for coastal wetlands in the coming decades (Twilley et al., 2001; Scavia et al., 2002). The Gulf Coast region is considered especially vulnerable to a changing climate because of its relatively flat topography, rapid rates of land subsidence, water engineering systems, extensive shoreline development, and exposure to major storms. In the Mississippi delta, rapid subsidence has already produced accelerated rates of relative sea-level rise (absolute sea-level rise plus land subsidence; Working Group for Post-Hurricane Planning for the Louisiana Coast, 2006; Day et al., 2007).

Recent evidence suggests that human-induced global warming has already increased both the intensity and frequency of hurricanes in the North Atlantic, including the Gulf of Mexico (Emanuel, 2005; Webster et al., 2005; Mann and Emanuel, 2006; Santer et al., 2006; Trenberth, 2006; Trenberth and Shea, 2006). A recent analysis of Atlantic basin hurricane activity by Goldenberg and others (2001) indicated a five-fold increase in hurricanes affecting the Caribbean when comparing 1995–2000 to the previous 24 years (1971–1994). Hurricanes exhibit multi-decadal patterns that appear to be associated with variations in tropical sea-surface temperature patterns and vertical wind shear, and the Atlantic basin is in a period of high-level hurricane activity that could persist for 10–40 years, irrespective of global warming (Goldenberg et al., 2001). Moreover, several ocean-coupled global circulation models project that the intensity of hurricanes will increase as the climate warms during the next 100 years (Knutson and Tuleya, 2004; IPCC, 2007).

Recent Gulf Coast hurricanes demonstrate the damaging effects that intense hurricanes can have on life, property, and natural resources in coastal areas. However, hurricanes can also increase the rate of soil accretion in coastal wetlands, helping to maintain wetland elevation relative to sea-level rise

(Poff et al., 2002; Turner et al., 2006). In addition, the increased runoff resulting from hurricanes transports more water and nutrients to coastal habitats (Poff et al., 2002). These positive effects, however, will depend on local wetland conditions, and in highly altered systems, hurricane-related changes in accretion and runoff patterns may be more damaging than beneficial, especially considering that these processes were insufficient to maintain coastal wetlands during the 20th century.

The frequency and magnitude of the El Niño/Southern Oscillation (ENSO) also has a strong effect on ecological conditions in coastal areas. During ENSO events, large-scale disruptions to global weather patterns occur in the atmosphere and in the tropical Pacific Ocean. In general, El Niño events (the warm ENSO phase associated with unusually warm waters in the tropical Pacific) are correlated with greatly increased winter precipitation in the Gulf Coast region. During La Niña (the cool ENSO phase), fall and winter along the Gulf Coast are warmer and drier than usual. Hurricanes increase during La Niña events, but are less frequent during El Niño events (Bove et al., 1998). El Niño events have occurred more frequently and have persisted longer since the 1970s, a trend that has been linked statistically to global warming (Trenberth and Hoar, 1997), although this linkage remains to be confirmed (McPhadden et al., 2006). Future intensification of El Niño events could alter marine and terrestrial ecosystems in unpredictable ways (McPhadden et al., 2006).

The future hydrology of Gulf Coast watersheds, including peak flows, will depend on the balance of rainfall and evaporation in a warming climate, as modified by human consumption and management of water resources. In major rivers such as the Mississippi, water flows will be determined by rainfall trends in watersheds hundreds of miles upstream from the coast, as well as by the region's massive flood control projects. However, regional predictions of runoff are uncertain because runoff is sensitive to interactions among precipitation, temperature, and evaporation (Poff et al., 2002). The future of local precipitation remains uncertain, but the intensity of rainfall events can increase even if average precipitation decreases (Knutson et al., 1998). Intense rainfall can contribute to marsh flooding. On the other hand, extended periods of drought during La Niña events can lead to marsh dieback. A 25-month drought, interacting with other environmental stresses, is considered the main cause of a severe dieback of 100,000 acres of salt marsh in coastal Louisiana in 2000 (Kennedy et al., 2002; McKee et al., 2004).

Even if storm intensities remain constant, sea-level rise may contribute to increased shoreline erosion, wetland flooding, and higher storm surges. Rising sea levels will generate higher storm surges even from minor storms (Reed, 2002). Flood damage in Gulf Coast states will increase as a result of the combined effect of increased storm surges and the decreased storm surge-reduction capacity of altered wetlands (Working Group for Post-Hurricane Planning for the Louisiana Coast, 2006).

Climate models project sea-level rise along the Gulf Coast to range from one to three feet in the next century (Twilley et al., 2001; Kennedy et al., 2002). The position of wetlands relative to the sea surface will remain constant over time only if the combined effects of land subsidence and rising seas can be balanced by elevation gain from wetland soil formation (Morris et al., 2002; Reed, 2002). With regional subsidence projected to range from 8 to 40 inches in the next century, relative sea-level rise—the combination of absolute sea-level rise and land subsidence—over the next 100 years could range from two feet along most of the Gulf Coast to more than six feet along the Mississippi delta and coastal Louisiana (Penland and Ramsey, 1990; Church, 2001; IPCC, 2007).

Wetland response to sea-level rise depends on local interactions between sediment and organic matter accumulation, hydrology, subsurface processes, and storm events (Reed, 1995; Cahoon et al., 1995). Over the past several decades, the engineering of water management systems and the increased frequency and intensity of storms have altered the timing and amount of sediment delivered to the wetlands of the Mississippi River deltaic plain. Under natural conditions, deltaic environments receive river sediment during pulsed flood events (Day et al., 1994; Perez et al., 2003). However, river management systems, such as levees and flow diversions, have reduced river-pulsed floods and the delivery of sediment to delta wetlands, decreasing their ability to form soil and raise elevation (Baumann et al., 1984; Day et al., 2007).

Some Louisiana marshes have adjusted to this change in the magnitude and source of sediment delivery, and still survive in hydrologic basins where relative rates of sea-level rise measured at tide gauges reach 0.4 inches per year (three feet per century; Penland and Ramsey, 1990). But other wetland areas within these same basins are showing reduced soil build up and a decreased ability to keep pace with the net changes in water levels. Salt marshes with high sediment loading (such as those in Louisiana) are likely to keep pace with a relative sea-level rise of less than four feet per century, based on models for similar marshes along the U.S. Atlantic Coast (Morris et al., 2002). However, in some parts of the central Gulf region, relative sea-level rise is projected to reach six feet by the end of the century, exceeding the ability of many Louisiana marshes to cope under the present conditions of reduced sediment delivery. If inundation exceeds accretion, and if inland migration is blocked by shoreline development (see below), sea-level rise will flood wetlands and lead to plant death.

Accelerated sea-level rise is also likely to be one of the most critical environmental challenges to the sustainability of mangrove ecosystems along the Florida coast, in spite of the lack of subsidence in these systems (Davis et al., 2005). In regions with little sediment input, the maximum rate of relative sea-level rise that mangroves can sustain is estimated to be 0.75 feet or less over the next century, much lower than estimates for sediment-rich deltaic regions and projected sea-level rise for the Gulf region (reviewed in Twilley, 1997). This estimate assumes stable geologic formations and minimum rates of subsidence, which generally apply for Florida wetlands underlain with limestone (Wanless et al., 1994).

The ability of wetlands to migrate inland to areas of decreasing tidal inundation along undeveloped shores is another way coastal wetlands in south Florida and coastal Louisiana can persist in spite of rising seas (Ross et al., 2000). However, in many areas coastal development just above the extreme high tide line has limited or eliminated opportunities for wetland migration, a phenomenon that has been labeled "coastal squeeze" (Twilley, 1997). The maximum rate that Gulf Coast wetlands can migrate into available inland areas is unknown relative to projected changes in sea level over the next century. Nonetheless, the vulnerability of coastal resources and infrastructure to sea-level rise can be expected to increase as both human development and climate change progress (Twilley et al., 2001).

D. Water Management, Climate Change, and Wetland Restoration

In some areas, Gulf Coast wetlands have adapted thus far to major changes in hydrology and sediment transport resulting from human engineering of river basins. In other areas, wetlands are being lost because they no longer have the natural capacity to adapt to these changes. These observations demonstrate that wetland vulnerability is based on the ability of wetland systems to cope with varying rates of environmental change. With capacity for adaptation already reduced by human activities, additional climatic changes have important implications for wetland sustainability.

Many coastal restoration projects proposed for the Mississippi River Delta and the Everglades are predicated on returning many ecosystem functions to natural wetlands (CERP, 2004; U.S. Army Corps of Engineers, 2004b; Day et al., 2007). One of the hurricane protection opportunities being considered is related to the natural hydrologic functions of coastal wetlands (Working Group for Post-Hurricane Planning for the Louisiana Coast, 2006). Modification of water management systems in both the Everglades and the Mississippi River basin is being considered as a way to increase freshwater and sediment supply, respectively, to promote wetland development (Harwell, 1997; Day et al., 2007). However, wetland vulnerability to present conditions has provided the traditional context for restoration planning; this context is insufficient to assure wetland sustainability over the century-long lifetime of major restoration efforts in the face of projected sea-level rise and hurricane intensification. Forward-looking measures are required to ensure that the necessary water resources will be restored to allow wetlands to build soil sufficient to survive a changing climate.

There is still time to plan and execute large-scale coastal restoration projects for the Everglades and Mississippi delta that would be sustainable against projected climate change through the 21st century (CPRA, 2007). The long-term sustainability of coastal wetlands will have to be re-evaluated over time as coastal systems respond to restoration measures. Ultimately, sea-level rise will continue for centuries after human-induced greenhouse gases are stabilized in the atmosphere (IPCC, 2007). The benefits of coastal wetlands to society can only be secured by accounting for the long-term effects of climate change in the design of near-term restoration projects.

References

Barras, J., S. Beville, D. Britsch, S. Hartley, S. Hawes, J. Johnston, P. Kemp, Q. Kinler, A. Martucci, J. Porthouse, D. Reed, K. Roy, S. Sapkota, and J. Suhayda. 2003. *Historical and Projected Coastal Louisiana Land Changes: 1978–2050.* Open File Report 03-334. U.S. Geological Survey, Reston, VA.

Barry, J. 1997. *Rising Tide: The Great Mississippi Flood of 1927 and How It Changed America.* Simon and Schuster, New York, NY.

Baumann, R.H., J.W. Day, and C.A. Miller. 1984. Mississippi deltaic plain wetland survival: sedimentation versus coastal submergence. *Science* 224:1093-1095.

Boesch, D.F., M.N. Josselyn, A.J. Mehta, J.T. Morris, W.K. Nuttle, C.A. Simenstad, and D.J.P. Swift. 1994. Scientific assessment of coastal wetland loss, restoration and management in Louisiana. *Journal of Coastal Research* 20:1-103.

Bove, M.C., J.J. O'Brien, J.B. Elsner, C.W. Landsea, and X. Niu. 1998. Effect of El Niño on U.S. landfalling hurricanes, revisited. *Bulletin of the American Meteorological Society* 79:2477-2482.

Cahoon, D.R., D.J. Reed, J.W. Day, R.M. Boumans, J.C. Lynch, D. McNally, and N. Latif. 1995. The influence of Hurricane Andrew on sediment distribution in Louisiana coastal marshes. *Journal of Coastal Research* 18:280-294.

CENR (Committee on Environment and Natural Resources). 2000. *Integrated Assessment of Hypoxia in the Northern Gulf of Mexico.* National Science and Technology Council, Washington, DC.

CERP (Comprehensive Everglades Restoration Plan). 2004. *Comprehensive Everglades Restoration Plan Annual Report.* South Florida Water Management District, West Palm Beach, FL and Florida Department of Environmental Protection, Tallahassee, FL.

Chen, R. and R.R. Twilley. 1998. A simulation model of organic matter and nutrient accumulation in mangrove wetland soils. *Biogeochemistry* 92:1-12.

Chen, R. and R.R. Twilley. 1999. Patterns of mangrove forest structure associated with soil nutrient dynamics along the Shark River estuary. *Estuaries* 22:1027-1042.

Church, J.A. 2001. Climate change—how fast are sea levels rising? *Science* 294:802-803.

Conner, W.H. and J.W. Day, Jr. 1988. Rising water levels in coastal Louisiana: implications for two coastal forested wetland areas in Louisiana. *Journal of Coastal Research* 4:589-596.

CPRA (Coastal Protection and Restoration Authority). 2007. *Integrated Ecosystem Restoration and Hurricane Protection: Louisiana's Comprehensive Master Plan for a Sustainable Coast.* Coastal Protection and Restoration Authority of Louisiana, Baton Rouge, LA.

Daily, G.C., P.A. Matson, and P.M. Vitousek. 1997. *Ecosystem services supplied by soil. In Nature's Services: Societal Dependence on Natural Ecosystems.* G.C. Daily (ed.). Island Press, Washington, DC.

Davis, S.E. and J. Ogden. 1997. *Everglades: The Ecosystem and Its Restoration.* St. Lucie Press, Boca Raton, FL.

Davis, S.M., D.L. Childers, J.J. Lorenz, H.R. Wanless, and T.E. Hopkins. 2005. A conceptual model of ecological interactions in the mangrove estuaries of the Florida Everglades. *Wetlands* 25:832-842.

Day, J.W., Jr., C.J. Madden, R.R.Twilley, R.F. Shaw, B.A. McKee, M.J. Dagg, D.L. Childers, R.C. Raynie, and L.J. Rouse. 1994. The influence of Atchafalaya River discharge on Fourleague Bay, Louisiana (USA). In *Changes in Fluxes in Estuaries.* K.R. Dyer and R.J. Orth (eds.). Olsen and Olsen, Fredensborg, Denmark.

Day, J.W., Jr., D.F. Boesch, E.J. Clairain, G.P. Kemp, S.B. Laska, W.J. Mitsch, K. Orth, H. Mashriqui, D.R. Reed, L. Shabman, C.A. Simenstad, B.J. Streever, R.R. Twilley, C.C. Watson, J.T. Wells, and D.F. Whigham. 2007. Restoration of the Mississippi Delta: lessons from hurricanes Katrina and Rita. *Science* 315:1679-1684.

DeLaune, R.D., J.A. Nyman, and W.H. Patrick, Jr. 1994. Peat collapse, ponding, and wetland loss in a rapidly submerging coastal marsh. *Journal of Coastal Research* 10:1021-1030.

Emanuel, K. 2005. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* 436:686-688.

Energy Information Administration. 2007. Official Energy Statistics from the U.S. Government. Available online at http://www.eia.doe.gov/ (accessed August 23, 2007).

Environmental Health Center. 1998. *Coastal Challenges: A Guide to Coastal and Marine Issues.* National Safety Council, Washington, DC.

Florida Tax Watch. 2006. *The Impact of Tourism on Florida's Economy: Telling a More Complete Story.* Research Report No. 6. Florida Tax Watch, Tallahassee, FL.

Goldenberg, S., C. Landsea, A. Mestas-Nunez, and W. Gray. 2001. The recent increase in Atlantic hurricane activity: causes and implications. *Science* 293:474-479.

Gosselink, J.G. 1984. *The Ecology of Delta Marshes of Coastal Louisiana: A Community Profile.* Biological Services Program Report No. FWS/OBS-84/09. U.S. Fish and Wildlife Service, Washington, DC.

Gunderson, L.H. 1994. Vegetation of the Everglades: determinants of community composition. In *Everglades: The Ecosystem and Its Restoration*. S.M. Davis and J.C. Ogden (eds.). St. Lucie Press, Delray Beach, FL.

Harwell, M.A. 1997. Ecosystem management of South Florida. *BioScience* 47:499-512.

Harwell, M.A. 1998. Science and environmental decision-making in South Florida. *Ecological Applications* 8:580-590.

Hetherington, L.E., T.J. Brown, A.J. Benham, P.A.J. Lusty, and N.E. Idoine. 2007. *World Mineral Production, 2001–05*. British Geological Survey, Keyworth, Nottingham, United Kingdom.

IPCC (Intergovernmental Panel on Climate Change). 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Kennedy, V.S., R.R. Twilley, J.A. Kleypas, J.H. Cowan, Jr., and S.R. Hare. 2002. *Coastal and Marine Ecosystems and Global Climate Change: Potential Effects on U.S. Resources*. Pew Center on Global Climate Change, Arlington, VA.

Kesel, R.H. 1988. The decline in the suspended sediment load of the Lower Mississippi River and its influence on adjacent wetlands. *Environmental Geology and Water Science* 12:271-281.

Knutson, T.R and R.E. Tuleya. 2004. Impact of CO_2-induced warming on simulated hurricane intensity and precipitation: sensitivity to the choice of climate model and convective parameterization. *Journal of Climate* 17:3477-3495.

Knutson, T.R., R.E. Tuleya, and Y. Kurihara. 1998. Simulated increase of hurricane intensities in a CO_2-warmed climate. *Science* 279:1018-1020.

Laska, S., G. Woodell, R. Hagelman, R. Gramling, and M. Teets Farris. 2005. At risk: the human community and infrastructure resources of coastal Louisiana. *Journal of Coastal Research* 44:90-111.

Light, S.S. and J.W. Dineen. 1994. Water control in the Everglades: a historical perspective. In *Everglades: The Ecosystem and Its Restoration*. S.M. Davis and J.C. Ogden (eds.). St. Lucie Press, Delray Beach, FL.

Louisiana Coastal Wetlands Conservation and Restoration Task Force. 1998. *Coast 2050: Toward a Sustainable Coastal Louisiana.* Louisiana Department of Natural Resources, Baton Rouge, LA.

Lynch, J.C., J.H. Merriwether, B.A. McKee, F. Vera-Herrera, and R.R. Twilley. 1989. Recent accretion in mangrove ecosystems based on ^{137}Cs and ^{210}Pb methods. *Estuaries* 12:284-299.

MAB (Man and the Biosphere). 2007. Biosphere Reserves' Directory Interactive Map. UNESCO Man and the Biosphere Programme. Available online at http://www.unesco.org/mab/BRs/map.shtml.

Mann, M.E. and K. Emanuel. 2006. Atlantic Hurricane Trends Linked to Climate Change. *Eos, Transactions, American Geophysical Union* 87:233, 238, 241.

Mckee, K.L., I.A. Mendelssohn, and M.D. Materne. 2004. Acute salt marsh dieback in the Mississippi River deltaic plain: a drought-induced phenomenon? *Global Ecology and Biogeography* 13:65-73.

McPhadden, M.J., S.E. Zibiak, and M.H. Glantz. 2006. ENSO as an integrating concept in earth science. *Science* 314:1740-1745.

Mitsch W.J. and J.G. Gosselink. 2000. *Wetlands*. John Wiley & Sons, New York, NY.

Morris, J.T., P.V. Sundareshwar, C.T. Nietch, B. Kjerfve, and D.R. Cahoon. 2002. Response of coastal wetlands to rising sea level. *Ecology* 83:2869-2877.

Morton, R.A., G. Tiling, and N.F. Ferina. 2003. Causes of hot-spot wetland loss in the Mississippi delta plain. *Environmental Geosciences* 10:71-80.

National Research Council. 2005. *Drawing Louisiana's New Map: Addressing Land Loss in Coastal Louisiana.* National Academies Press, Washington, DC.

Parkinson, R.W., R.D. DeLaune, and J.R. White. 1994. Holocene sea-level rise and the fate of mangrove forests within the wider Caribbean region. *Journal of Coastal Research* 10:1077-1086.

Penland, S. and K.E. Ramsey. 1990. Relative sea-level rise in Louisiana and the Gulf of Mexico: 1908–1988. *Journal of Coastal Research* 6:323-342.

Perez, B.C., J.W. Day Jr., D. Justiç, and R.R. Twilley. 2003. Nitrogen and phosphorus transport between Fourleague Bay, Louisiana, and the Gulf of Mexico: the role of winter cold fronts and Atchafalaya River discharge. *Estuarine, Coastal and Shelf Science* 57:1065-1078.

Poff, N.L., M.M. Brinson, and J.W. Day, Jr. 2002. *Aquatic ecosystems and global climate change: potential impacts on inland freshwater and coastal wetland ecosystems in the United States.* Pew Center on Global Climate Change, Arlington, VA.

Ramsar Convention. 2007. The Ramsar List of Wetlands of International Importance. Available online at http://www.ramsar.org/key_sitelist.htm.

Reed, D.J. 1995. The response of coastal marshes to sea-level rise: survival or submergence? *Earth Surface Processes and Landforms* 20:39-48.

Reed, D.J. 2002. Sea level rise and coastal marsh sustainability: geological and ecological factors in the Mississippi Delta plain. *Geomorphology* 48:233-243.

Ross, M.S., J.F. Meeder, J.P. Sah, L.P. Ruiz, and G.J. Telesnicki. 2000. The southeast saline Everglades revisited: 50 years of coastal vegetation change. *Journal of Vegetation Science* 11:101-112.

Santer, B.D., T.M.L. Wigley, P.J. Gleckler, C. Bonfils, M.F. Wehner, K. AchutaRao, T.P. Barnett, J.S. Boyle, W. Bruggemann, M. Fiorino, N. Gillett, J.E. Hansen, P.D. Jones, S.A. Klein, G.A. Meehl, S.C.B. Raper, R.W. Reynolds, K.E. Taylor, and W.M. Washington. 2006. Forced and unforced ocean temperature changes in Atlantic and Pacific tropical cyclogenesis regions. *Proceedings of the National Academy of Sciences USA* 103:13905-13910.

Scavia, D., J.C. Field, D.F. Boesch, R.W. Buddemeier, V. Burkett, D.R. Cayan, M. Fogarty, M.A. Harwell, R.W. Howarth, C. Mason, D.J. Reed, T.C. Royer, A.H. Sallenger, and J.G. Titus. 2002. Climate change impacts on U.S. coastal and marine ecosystems. *Estuaries* 25:149-164.

Stokstad, E. 2006. Katrina study stirs debate on coastal restoration. *Science* 313:1713.

Trenberth, K. 2006. Uncertainty in hurricanes and global warming. *Science* 308:1753-1754.

Trenberth, K.E. and T.J. Hoar. 1997. El Niño and climate change. *Geophysical Research Letters* 24:3057-3060.

Trenberth, K.E. and D.J. Shea. 2006. Atlantic hurricanes and natural variability in 2005. *Geophysical Research Letters* 33:L12704

Turner, R.E., J.J. Baustian, E.M. Swenson, and J.S. Spicer. 2006. Wetland sedimentation from hurricanes Katrina and Rita. *Science* 314:449-452.

Twilley, R.R. 1997. *Mangrove wetlands.* In *Southern Forested Wetlands: Ecology and Management.* M. Messina and W. Connor (eds.). CRC Press, Boca Raton, FL, pp. 445-473.

Twilley, R.R., E. Barron, H.L. Gholz, M.A. Harwell, R.L. Miller, D.J. Reed, J.B. Rose, E. Siemann, R.G. Wetzel, and R.J. Zimmerman. 2001. *Confronting Climate Change in the Gulf Coast Region: Prospects for Sustaining Our Ecological Heritage.* Union of Concerned Scientists, Cambridge, MA and Ecological Society of America, Washington, DC.

U.S. Army Corps of Engineers. 2004a. *Louisiana Coastal Area (LCA), Louisiana Ecosystem Restoration Study.* U.S. Army Corps of Engineers, New Orleans, LA. Available online at http://data.lca.gov/Ivan6/main/main_report_all.pdf.

U.S. Army Corps of Engineers. 2004b. *Louisiana Coastal Area (LCA), Louisiana Ecosystem Restoration Study. Appendix A. Science and Technology Program.* U.S. Army Corps of Engineers, New Orleans, LA. Available online: http://data.lca.gov/Ivan6/app/app_a.pdf.

U.S. Army Corps of Engineers. 2006. CY 2004 Waterborne Tonnage by State (In Units of 1000 Tons). U.S. Army Corps of Engineers, Institute for Water Resources, Navigation Data Center, Waterborne Commerce Statistics Center, New Orleans, LA. Available online at http://www.iwr.usace.army.mil/ndc/wcsc/stateton04.htm.

Wanless, H.R., R.W. Parkinson, and L.P. Tedesco. 1994. Sea level control on stability of Everglades wetlands. In *Everglades: The Ecosystem and Its Restoration*. S.M. Davis and J.C. Ogden (eds.). St. Lucie Press, Delray Beach, FL, pp. 199-223.

Webster, P., G.J. Holland, J.A. Curry, and H.R. Chang. 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* 309:1844-1846.

Working Group for Post-Hurricane Planning for the Louisiana Coast. 2006. *A New Framework for Planning the Future of Coastal Louisiana after the Hurricanes of 2005.* University of Maryland Center for Environmental Science, Cambridge, MD. Available online at http://www.clear.lsu.edu/clear/web-content/Web_items/NewFramework_Boesch.pdf.

World Heritage Committee. 2007. UNESCO World Heritage Site List. Available online at http://whc.unesco.org/.

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