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Conserving Coastal Wetlands Despite Sea Level Rise

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Coastal wetlands provide valuable services such as flood protection and fisheries production to a global population that is increasingly concentrated near the coast and dependent on its resources. Many of the world's coastal wetlands suffered significant losses during this century, and the creation of new wetland areas is not keeping pace with recent losses. Some destruction of wetland areas can be expected as a consequence of the continual reworking of the coastal zone by dynamic geologic processes. Yet human activities also play a role, both directly by encroaching on coastal wetlands and indirectly by influencing the hydrologic and geologic processes in the coastal zone [*Boesch et al.*, 1994; *Day et al.*, 1995].

The United States is committed to conserving and restoring its coastal wetlands, and ambitious restoration programs are now under way in Louisiana and south Florida. The effectiveness of these and other efforts to conserve coastal wetlands depends on our ability to forecast how coastal wetlands will respond to long-term environmental trends and to the local and regional impacts of human activities.

To do this, we must understand the basic dynamics of coastal wetland ecosystems and the rules that govern their evolution in the landscape [*Dickinson*, 1995]. Ten years of research in the wetlands of the Gulf of Mexico and the Atlantic coast of North America provide insight to guide conservation efforts. The dynamics and evolution of wetlands along these coasts are strongly influenced by the gradual rise of sea level that began during the last half of the Holocene and continues to the present. Rising sea level drives wetland evolution by changing the hydrology, hydrodynamics, and sediment dynamics of the coastal zone. However, the dynamics and evolution of coastal wetlands are also influenced by discrete stresses imposed by the impacts of human activities, storms, and short-term fluctuations in sea level.

Sea Level

The long-term rise in sea level establishes a background rate of change for the entire coastal zone. The change in relative sea level (RSL) captures the net effect of global sea level rise and vertical displacements of the coastal zone; for example, due to subsidence or uplift. Long-term trends in RSL, as measured by tide gage records, generally show a rise of 2–4 mm/yr over the last 50 years or so for locations along the Atlantic coast of the United States [*Stevenson et al.*, 1986]. At the upper extreme, some areas of coastal Louisiana experienced a 10 mm/yr rise over the same time due to subsidence arising from the consolidation of deltaic sediments of the Mississippi River [*Boesch et al.*, 1994]. Global warming is expected to increase the long-term, background rates of sea level rise. The EPA estimates that by 2050, global warming will be responsible for a 100-mm rise in RSL, in addition to the increases in RSL expected by extrapolating current trends [*Titus and Narayanan*, 1995, Table 9-1].

Relatively large fluctuations in RSL occur on timescales ranging from a few months to a few years. A general feature of tide gage records of RSL is that short-term rates of change often exceed the long-term trend (Figure 1). This raises the possibility that changes in coastal wetlands also occur in response to the larger, high-frequency RSL signal. A number of processes contribute to the short-term fluctuations of RSL. Surface elevation in the wetland changes measurably in response to processes occurring within the sediment, such as accretion, changes in water balance, mechanical loading by storm tides, and the annual cycle of root growth and decay [*Cahoon et al.*, 1995]. Coastal sea level fluctuates in response to climate phenomena, like the El Niño, and short-term rates of change in tide gage records sometimes exceed 20 mm/yr for as long as 2 or 3 years at a time.

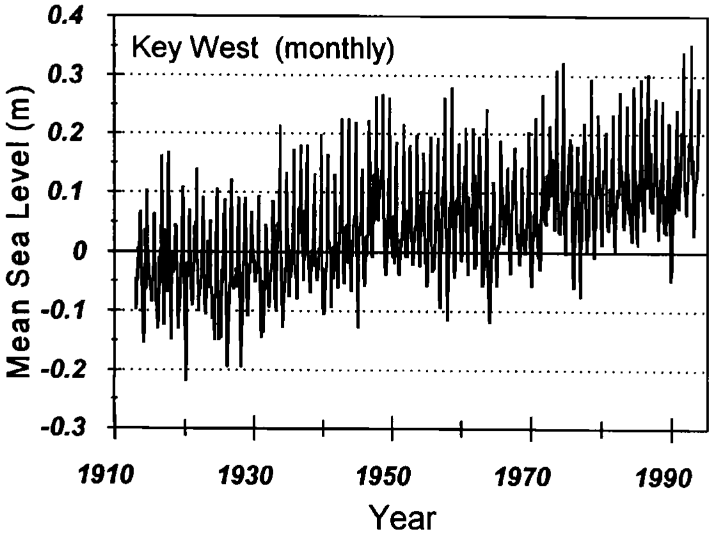

Fig. 1. Variations in RSL can be characterized as short-term fluctuations occurring on the scale of months to years, superimposed on a long-term trend. These data from Key West are typical. The long-term trend is about 2 mm/yr, but the record contains periods during which the rate of rise averaged over several years is more than 10 times the long-term rate. Data from NOAA.

Accretion

Any attempt to forecast the evolution of coastal wetlands must take into account their basic nature as self-regulating, ecological

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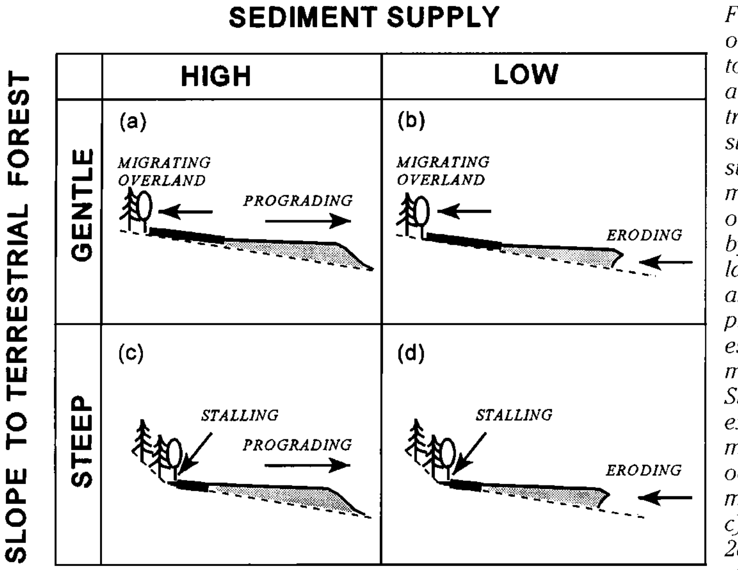

Fig. 2. Four modes of wetland response to rising sea level are defined by extremes in landscape slope and sediment supply: a) High marsh encroaches on terrestrial forest by migrating overland; tidal creeks and lagoon margins prograde toward the estuary because sediment is abundant. b) Similar to Figure 2a, except that marshward erosion occurs because sediment supply is low. c) Similar to Figure 2a, but steep slope stalls overland migration. d) Similar to Figure 2c, but erosion occurs [from Brinson et al., *1995]. [Reprinted by permission of the Estuarine Research Federation. © Estuarine Research Federation.]*

systems. Self-regulation arises from an ecosystem's ability to respond to outside forcing through changes in the ecosystem itself and in its interactions with its environment. Coastal wetlands accumulate sediment by accretion–which is why they increase in elevation over time, relative to stable features of the coast. Negative feedback between the process of accretion and the wetland's elevation, measured relative to local sea level, regulates wetland elevation so that it tracks long-term changes in sea level [*Nyman et al.*, 1993]. When wetland elevation is low relative to sea level, frequent inundation by tides enhances the supply of suspended sediment and nutrients to the wetland. This stimulates accretion by sedimentation. The enhanced nutrient supply also supports abundant growth of vegetation, and this also contributes to accretion through the production of roots and rhizomes and by trapping suspended sediment to incorporate into new wetland sediment. If the elevation of the wetland increases relative to sea level, tidal inundation becomes less frequent, accretion slows, and the rate at which wetland elevation increases is reduced.

A key to understanding the basic dynamics of coastal wetlands is knowing under what conditions this feedback mechanism fails to operate. As long as negative feedback occurs, the wetland will tend to maintain its elevation relative to sea level and avoid either submergence or invasion by upland species. If accretion is not regulated, rapid deterioration and loss of the wetland are possible. This process is occurring at some locations in coastal Louisiana, where events conspire to induce persistent flooding of the sediment surface [*Nyman et al.*, 1993].

Under such so-called "waterlogged" conditions, the productivity of the vegetation is suppressed and accretion is reduced rather than enhanced, which exacerbates the waterlogged conditions. Maintenance and recovery of the wetland are possible only if there is an adequate supply of mineral sediment to maintain accretion rates by sedimentation. Prolonged inundation and reduced sedimentation are unintended consequences of the construction of canals and spoil banks during oil and gas exploration in the Mississippi Delta [*Boesch et al.*, 1994].

Another issue is whether there is a maximum rate of accretion that can be sustained in a given wetland, and if so, what factors determine that rate. There is empirical evidence for the existence of an upper limit on the accretion rate. Measured accretion rates for wetlands along the U.S. Gulf of Mexico and Atlantic coasts generally equal or exceed the local long-term rise in RSL. However, accretion lags behind RSL at a few locations in the southeastern United States and in coastal Louisiana. *Stevenson et al.* [1986] relate the failure of accretion to keep pace with sea level to the small tide range in these wetlands and changes in the sediment budget of the coastal zone that have occurred since the wetlands were first formed. For example, the flux of sediment supplied to the coastal zone by the Mississippi River was reduced by about 50% between 1963 and 1982 following the construction of several large reservoirs in its basin [*Boesch et al.*, 1994; *Day et al.*, 1995].

Recent research on the structure of coastal wetland sediment suggests that accretion may be more directly affected by the rate at which organic matter is produced by the wetland. Organic matter forms the major structural component of coastal wetland sediments, accounting for over 90% of the sediment volume, even in the relatively high mineral content sediments of a northeastern U.S. salt marsh [*Bricker-Urso et al.*, 1989; *Nyman et al.*, 1993]. Based on the assumption that accretion is controlled by the in situ production of organic matter, *Bricker-Urso et al.* [1989] estimate the maximum sustainable rate of accretion to be about 16 mm/yr, a figure that is comparable to the 20 mm/yr upper range of short-term rates of rise in RSL mentioned above. Tide range and available sediment supply may affect accretion indirectly by influencing the supply of nutrients needed to maintain the growth of the vegetation.

Landscape Dynamics

The structure of a coastal wetland reflects the hydrology, geomorphology and hydrodynamics of its setting and the characteristics of the tides and sediment transport that derive from these factors. Coastal wetlands occur in the transitional region between terrestrial upland on one side and estuarine or shallow marine waters on the other. These endpoints bound the wetland ecosystem both geomorphically and hydrologically. The terrestrial boundary is characterized by mineral soils, infrequent flooding, and low-energy fluxes of fresh water. The estuarine boundary is characterized by sediment type, frequent inundation, salinity, and high-energy flows driven by storm events and lunar tides. This gradient in environmental conditions strongly influences the structure of the wetland ecosystem. The different species of vegetation arrange themselves into spatially distinct associations—for example, freshwater swamp, high salt marsh, and low salt marsh—according to each species' tolerance for flooding frequency and salinity [*Brinson et al.*, 1995]. Changes in the internal structure of the wetland over time are influenced by the strong association between the vegetation and these environmental conditions.

Conditions at the boundaries constrain the evolution of a coastal wetland within the coastal landscape. For example, an increase in RSL has foreseeable consequences for the positions of the terrestrial and estuarine boundaries. *Brinson et al.* [1995] describe four modes of coastal wetland evolution in response to rising RSL. These are based on all possible combinations of either progradation or erosion at the estuarine boundary and migration or stalling at the terrestrial boundary (Figure 2). In the first mode (Figure 2a), a supply of suspended sediment is available that enables the wetland to expand laterally into open water areas even as wetland accretion, in response to rising sea level, drives the migration of the wetland inland over a shallowly sloping, upland topography. The second mode (Figure 2b) corresponds to the response at a sediment-poor coastal setting, where the estuarine boundary retreats due to erosion, and the wetland shifts landward over time. The two remaining modes (Figures 2c and 2d) are characterized by "stalling" in the migration of the wetland's terrestrial boundary due to a steeply sloping upland topography or a man-made structure such as a revetment or a dike.

Coastal wetlands change through a stochastic process that permits an infinite number of possible evolutionary pathways within each of the four modes outlined above. Coastal wetlands are subjected to a number of stressors—herbivory, wrack deposition, ice and freezing temperatures, and storm events. A change occurs when the impact of one or more stressors exceeds the innate capacity of the wetland to maintain itself. Conditions at the boundaries control the overall direction of change. For example, cypress and tupelo are characteristic vegetation of freshwater swamps. Mature trees tolerate extended flooding, but seedlings require dry periods to become established [*Conner*, 1994]. An aging stand of mature trees can survive long after changes in the hydrology of the site make it impossible for seedlings to become established and, thus, regenerate the stand. In this state, a storm that kills the trees precipitates a change from freshwater swamp to either high or low marsh, or it can lead to a catastrophic loss in wetland area by rapidly converting the site to open water.

In this example, changes in the site's hydrology prior to the storm determine the direction of ecosystem change. These changes may arise from the cumulative effects of rising RSL, but human activities such as diking for agriculture, mosquito control, and waterfowl management frequently cause such changes as well. Whether the ecosystem changes to marsh or open water depends on the timing of the stress imposed by the storm and interactions among the components of the ecosystem, that is, the species of vegetation. In general, forecasting the fate of coastal wetlands requires knowledge of the boundary conditions that control conditions such as flooding and salinity within the wetland as well as knowledge of the history and internal dynamics of the ecosystem.

Conserving and Restoring Coastal Wetlands

Opportunities to reverse the trend of coastal wetland loss lie with the human activities that now exert a pervasive influence on the hydrology, hydrodynamics, and sediment balance of the coastal zone. There is growing appreciation of the largely indirect impacts that activities such as flood control and dredging have on coastal wetlands, particularly on those in major river deltas [*Boesch et al.*, 1994; *Day et al.*, 1995]. Regulating activities that have an obvious, direct impact on coastal wetlands, such as filling and draining, is a significant first step toward preventing further losses. However, the benefits of these efforts will be short-lived unless we also address the impacts of human activities on conditions at the terrestrial and estuarine boundaries of coastal wetlands. This will require measures such as modifying control structures on rivers and managing dredging practices to restore sediment supplies, managing the discharges of fresh water to regulate salinity, and modifying channels to regulate the influence of tides on water levels and currents [*Day et al.*, 1995]. To effectively plan and execute these measures, we must understand the dynamics and evolution of coastal wetland ecosystems well enough to be able to forecast their response to our actions.

The Working Group on Sea Level Rise and Wetland Systems

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New "Small Comet" Images Challenge Researchers

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A decade ago, he was bombarded by criticisms and objections in the court of scientific opinion. Now Lou Frank thinks that he has enough evidence to warrant a new hearing. The challenge is for other scientists, using other instruments, to verify the observations.

Eleven years after he wrote in *Geophysical Research Letters* (*GRL*) that he had detected holes in ultraviolet images of Earth's upper atmosphere and that they were caused by previously unknown cometlike objects, space physicist Louis Frank of the University of Iowa now asserts that he has found new evidence for his once-discredited theory. Using the Visible Imaging System (VIS) on NASA's Polar spacecraft, Frank and University of Iowa researcher John Sigwarth have gathered new images of what appear to be cometlike objects streaking toward Earth, breaking up at high altitudes, and depositing clouds of water vapor that make short-lived "holes" in the upper atmosphere.

Frank announced his latest findings in a press conference and an oral presentation at the AGU Spring Meeting in Baltimore. He also sent four new scientific papers to *GRL*, where they are currently under review.

"The Polar results definitively demonstrate that there are objects entering the Earth's upper atmosphere," said atmospheric physicist Thomas Donahue of the University of Michigan, once a strong critic of Frank's proposition who finds the new images and data compelling. "These results certainly vindicate Lou Frank's earlier observations," Donahue noted.

The new observations from VIS are consistent with the controversial theory Frank advanced a decade ago when he first detected "atmospheric holes" in images from NASA's Dynamics Explorer (DE) spacecraft.

Frank's initial research was published on April Fool's Day, 1986, and more than a few people thought he was joking. But after scientists figured out that Frank was not kidding, they dismissed the idea as preposterous, penning at least a dozen rebuttals and comments in *GRL* over the course of a year. "The controversy was severe because if this is true, then we have a lot of things to reconsider," said Frank, designer and principal investigator for the VIS instrument.

Most researchers argued that "atmospheric holes" were not holes at all but the result of an instrumentation or resolution problem with the cameras on DE, particularly since the holes appeared as single pixels (picture elements) in the images sent