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Coastal Louisiana in Crisis: Subsidence or Sea Level Rise?

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The drowning of wetlands and barrier islands in coastal Louisiana has become a widely publicized environmental catastrophe in the wake of hurricanes Katrina and Rita in 2005. The devastation caused by these storms has reenergized the debate about restoring the natural coastal-defense system and building higher and sturdier levees, in anticipation of future storms. Understanding the contributions of land subsidence and eustatic (global) sea level rise to Louisiana's wetland loss is crucial to the success of any plan designed to protect coastal communities. It is argued here that accelerated sea level rise in the future may pose a larger threat than subsidence for considerable portions of coastal Louisiana.

Quantifying the relative contributions of tectonism, isostasy, and sediment compaction—the principal forces driving subsidence in coastal Louisiana—is fundamental to any plan that aims at coastal restoration and coping with future sea level change. New, high-resolution relative sea level (RSL) data from the western Mississippi delta encompassing the period from 600 to 1600 A.D. challenge the exceptionally high tectonic subsidence rates (5–10 millimeters per year) that recently have been proposed by *Shinkle and Dokka* [2004]. In addition, the 'background' rate of RSL rise can help to provide more realistic scenarios of what is in store in terms of future RSL rise for coastal Louisiana. Finally, current estimates from the Intergovernmental Panel on Climate Change (IPCC) of future eustatic sea level rise are considered, allowing for the evaluation of Louisiana's subsidence hazards in the context of global environmental changes.

The Subsidence Controversy

The problem of land subsidence in the Mississippi delta is controversial not only in terms of driving mechanisms, but also with respect to the rate at which it is occurring. In most large deltas, subsidence involves a shallow component driven by compaction of mostly Holocene strata, and a deep or 'tectonic' component caused by flexure and failure of the lithosphere due to sediment loading, growth faulting, and related processes. However, along the U.S. Gulf Coast, glacio-isostasy, expressed as the gradual collapse of the forebulge associated with the Laurentide Ice Sheet, also contributes to subsidence [e.g., *Mitrovica and Milne*, 2002]. In addition, human interventions in coastal Louisiana have intensified the subsidence problem locally: artificial drainage has increased compaction rates of Holocene sediments and subsurface fluid extraction has accelerated compaction of pre-Holocene strata.

A recent geodetic study by *Shinkle and Dokka* [2004], based on first-order leveling data of U.S. National Geodetic Survey (NGS) benchmarks, suggests that land subsidence is a widespread process that extends far beyond the Mississippi delta into the surrounding uplands, as far north as Memphis, Tenn. (Figure 1). Their study presents maximum rates of land subsidence of approximately 25 millimeters per year, with large sections of the delta subsiding at rates of 10–15 millimeters per year and much of the state of Louisiana subsiding 5–10 millimeters per year. Although not explicitly stated by those authors, only a tectonic mechanism could account for this subsidence at such a regional scale.

Penland and Ramsey [1990] showed that Louisiana is experiencing higher rates of RSL rise than any other state on the U.S. Gulf Coast. Rates as high as 10.6 milli-meters per year were recorded by tide gauges in the Mississippi delta where the Holocene deposits are the thickest. These authors attributed the subsidence problem primarily to sediment compaction, a phenomenon that has been analyzed more rigorously by *Meckel et al.* [2006]. However, tectonic subsidence due to sediment loading could, in principle, be a significant contributor to these high rates of RSL rise.

A New Relative Sea Level Record

A new RSL chronology using basal peat as a tracer of sea level has been assembled following the methodology of *Törnqvist et al.* [2004]. This chronology is based on 27 sea level index points that record approximately 55 centimeters of RSL rise over a thousand-year time frame spanning 600 to 1600 A.D. (Figure 2a). Basal peat forms on a highly consolidated, mostly Pleistocene basement. Thus, the role of compaction of Holocene strata is minimized, and the record tracks the interplay of eustasy, isostasy, and tectonism.

Samples were collected on the northern fringe of marshes about 10 kilometers from the coast (Figure 1). These wetlands overlie the Pleistocene basement, and Holocene deposits are less than a few meters thick. Herbaceous charcoal fragments extracted from the peat were carbon-14 (^{14}C) dated by accelerator mass spectrometry. Precise elevation measurements of sampling sites were achieved by a combination of differential GPS and optical surveying. To obtain the long-term rate of RSL rise for the 1000-year time window covered by the data, linear regression analysis was performed on the median of the ages and the altitudinal center of each sample dated, yielding a rate of 0.55 millimeters per year (Figure 2a). When inspected in detail, the data exhibit a more complex pattern of RSL rise that will be reported on in more detail elsewhere.

Unraveling Gulf Coast Relative Sea Level Rise

The close proximity (5–15 kilometers) of the study area to some of the NGS benchmarks used by *Shinkle and Dokka* [2004], plus the fact that most of those benchmarks rest immediately on the Pleistocene basement (Figure 1), provides an excellent opportunity for a direct comparison of these distinctly different data sets.

The long-term rate of RSL rise reported here is an order of magnitude lower than the lowest subsidence rate reported by the nearby leveling data. According to *Shinkle and Dokka* [2004], subsidence rates at these benchmarks vary between 5.2 and 8.1 millimeters per year, values that are low when compared with rates reported by the same authors elsewhere in the region. It should be noted that *Shinkle and Dokka* [2004] caution against extrapolating their evidence beyond the short (5–6 year) time interval covered by the leveling surveys. Nevertheless, the two data sets are hard to reconcile unless one assumes long-term tectonic qui-

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escence punctuated by a recent episode of rapid tectonic-induced subsidence near the study area (e.g., due to growth faulting).

The trend of RSL rise as reported here is compatible with longer RSL records that cover much of the Holocene at various localities across the Mississippi delta [*Törnqvist et al.*, 2006]. That recent study inferred negligible tectonic subsidence rates in large sections of the Mississippi delta during the past 8000 years. Collectively, the findings by *Törnqvist et al.* [2006] and the rates reported here show that the conflict between the long-term RSL records and the near-modern high subsidence rates advocated by *Shinkle and Dokka* [2004] is a widespread, regional phenomenon. An abrupt and recent acceleration of tectonic subsidence rates across such a vast area must be considered an extremely improbable scenario. The absence of major seismic activity in large portions of the southern United States during the past century raises serious concerns about the subsidence rates derived from the leveling data.

Having ruled out tectonic subsidence as a significant long-term process in the study area, the next variable to be examined is glacio-isostasy. Geophysical models [e.g., *Mitrovica and Milne*, 2002] suggest that the north central Gulf Coast still is responding isostatically to the melting of the Laurentide Ice Sheet. The viscoelastic response of the lithosphere by means of forebulge collapse could be a significant contributor to the 0.55 millimeters per year rate of RSL rise.

This argument is supported by an analysis that involves the RSL trend for the north central Gulf Coast as recorded by the Pensacola, Florida, tide gauge (~2.1 milli-meters per year; Figure 2b), and the most recent estimate of eustatic sea level rise for the twentieth century, 1.7 ± 0.3 millimeters per year [*Church and White*, 2006]. The Pensacola tide gauge was chosen for two reasons. First, it is tectonically relatively stable given its location on Upper Pliocene sediments. Second, this record is long (1923 to the present) and continuous. Thus, the Pensacola tide gauge primarily records a combination of the eustatic and isostatic signals. The tide gauge record at Grand Isle, Louisiana (Figure 2b), located in the central Mississippi delta that undergoes rapid, compaction-driven subsidence, is shown for comparison.

The difference between the Pensacola record and the rate of global sea level rise for the twentieth century is approximately 0.4 millimeters per year, a number that compares favorably with that derived from the basal peat record. This suggests that the basal peat record primarily tracks the glacio-isostatic contribution to subsidence in coastal Louisiana. It should be noted that this analysis assumes a negligible eustatic sea level contribution during the 1000-year period covered by the RSL data reported here.

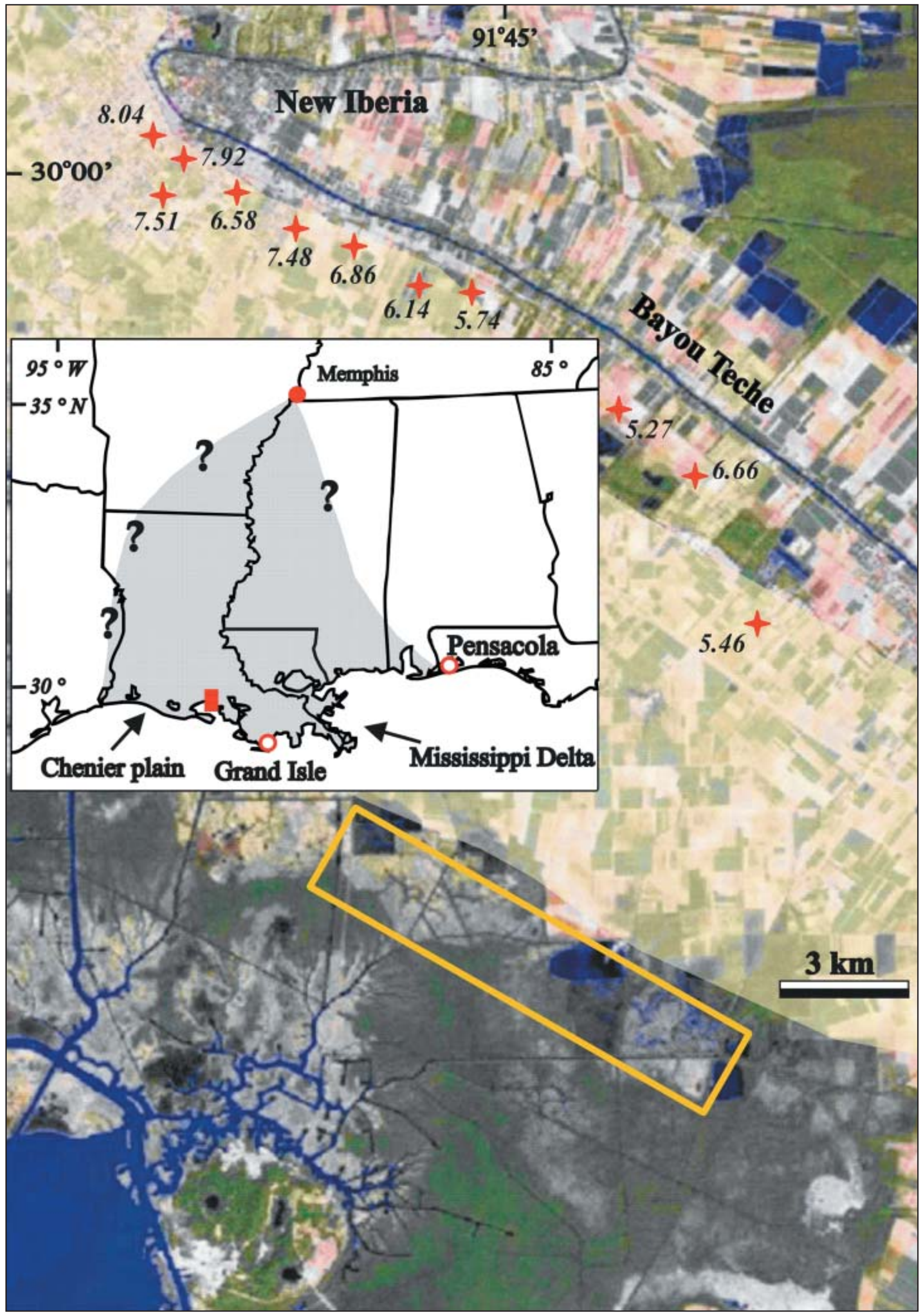

Fig. 1. Landsat Thematic Mapper image of a portion of the western Mississippi delta. The location is shown by the red rectangle on inset map. The yellow box defines the boundaries of the study area; red crosses indicate locations of benchmarks with subsidence rates (in millimeters per year) according to Shinkle and Dokka *[2004]. Most of the benchmarks are anchored on the Pleistocene basement, shown in light shading. Gray shading on the inset map shows the areal extent of subsidence according to* Shinkle and Dokka *[2004]. The locations of the tide gauges are shown by red open circles in the inset. Image obtained from the LOSCO Environmental Baseline Dataset Thematic Mapper Image of Louisiana (1999).*

Predictions for the Next Century

The 2001 report of the IPCC provides a midrange scenario of averaged global sea level rise of approximately 4.4 millimeters per year from 1990 to 2100 [*Church et al.*, 2001]. However, that may prove to be an underestimation. Recent calculations with a coupled atmosphere-ocean climate model [*Overpeck et al.*, 2006] suggest atmospheric temperatures around the Greenland Ice Sheet that could be much higher by 2130 than they were during the last interglacial, when global sea level stood four to more than six meters higher than today. These findings reinforce concerns about a considerably more dramatic eustatic sea level rise for the next century.

These concerns are echoed by reports of recent rapid mass loss of the Greenland Ice Sheet [*Dowdeswell*, 2006]. Thus, a best-case scenario of RSL rise for the next 100 years in areas with a comparatively thin Holocene cover where the role of compaction is limited, such as the chenier (beach ridge) plain of southwestern Louisiana, can be obtained by adding the background rate of RSL rise as derived by this study to the IPCC central value, yielding approximately 4.9 millimeters per year. Clearly, a much higher rate is to be expected in areas where the Holocene deposits are thick and rapidly compacting, such as is the case at Grand Isle.

Land subsidence as well as eustatic sea level rise are expected to negatively affect coastal Louisiana in the near future. Which process will have the upper hand depends strongly on location. Sea level rise of the magnitude predicted by IPCC midrange scenarios plus long-term background rates as presented here will have a relatively larger impact on areas with thin Holocene sediment covers, like the study area discussed in this paper and the chenier plain. In contrast, compaction-driven subsidence will be a comparatively greater player in those sections of the Mississippi delta with a thick Holocene succession. However, this may be subject to change if *Overpeck et al.*'s [2006] worst-case scenario regarding disintegration of the Greenland and Antarctic ice sheets would become reality.

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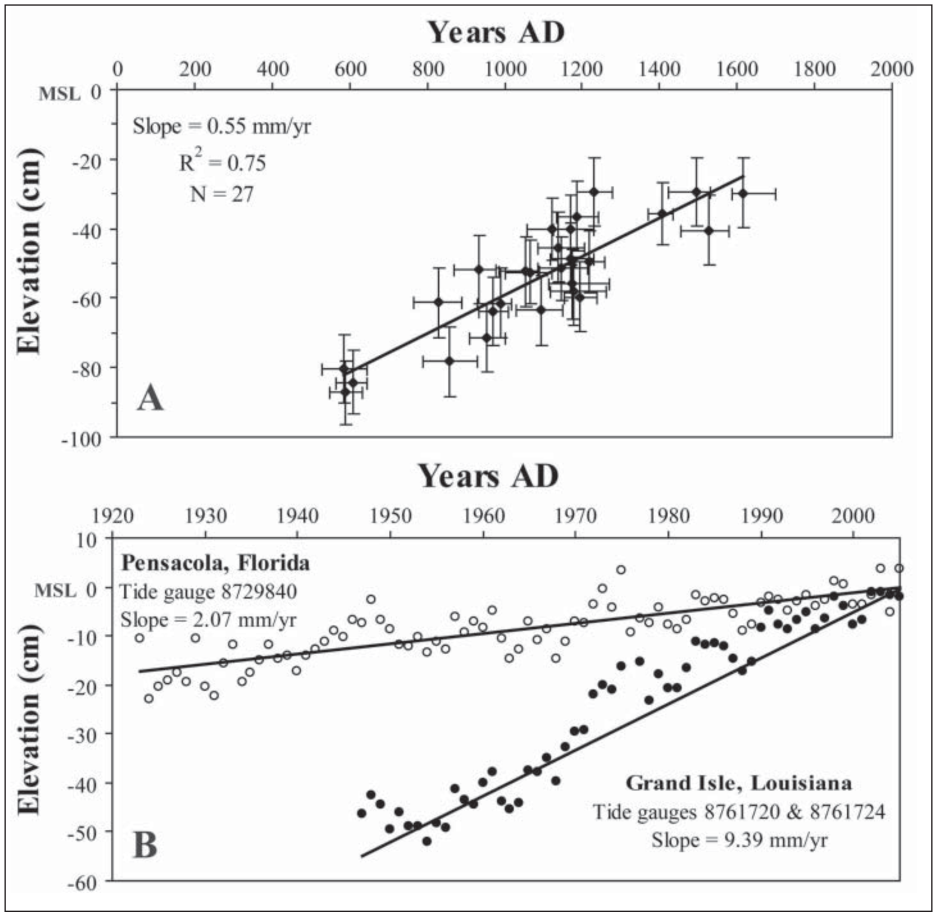

Fig. 2. (a) Long-term trend of relative sea level rise for the period 600 to 1600 A.D. The data set contains 27 sea level index points and records approximately 55 centimeters of relative sea level rise. Data points (with age and elevation errors) are defined by the median of calibrated ^{14}C ages plus elevation of the center of basal peat samples dated. Two subsamples were dated for each sample, and all but four index points were obtained by calculating a weighted mean of two ^{14}C ages. Only one sample provided a stratigraphically reversed age and was rejected. MSL is present mean sea level. (b) Trend of relative sea level rise for two selected tide gauges normalized to present mean sea level. Data were obtained from the U.S. National Oceanic and Atmospheric Administration's National Oceanic Service Center for Operational Oceanographic Products and Services. The locations of the tide gauges are shown in Figure 1.

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