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Recent Reduction of Subsidence Rates in the Mississippi River Delta Plain

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Abstract

The Mississippi River delta plain has long been characterized as an area with high rates of relative sea-level rise. This concept was tested by integrating National Ocean Service tide-gauge records with National Geodetic Survey benchmark releveling data and GPS elevations at Continuously Operating Reference Stations, providing a basis for understanding historical subsidence trends and most recent rates for southeastern coastal Louisiana. Tide-gauge records indicate that rates of relative sea-level rise at Grand Isle accelerated from about -2.2 mm/yr between 1947 and 1964 to about -11.5 mm/yr between 1964 and 1991 and then decelerated to about -3.4 mm/yr between 1991 and 2006. These trends and rates are independently verified by repeat leveling surveys that yielded average subsidence rates of -9.6 and -11 mm/yr from 1965/66 to 1993 at benchmarks between Raceland and Grand Isle and between Houma and Cocodrie, respectively, and GPS-derived elevation changes at Boothville, Houma, and Cocodrie that yielded average subsidence rates of -3.5 to -6.3 mm/yr from 2002/03 to 2007. The most recent slow rates of subsidence are similar to those averaged over geological time scales (e.g., radiocarbon-dated peats) that are attributed to natural sediment compaction and crustal loading.

The historical pattern of slow, then rapid, then slow subsidence may be caused by natural deep-basin processes (e.g., faulting, salt migration) but is more likely related to regional hydrocarbon production that followed the same general temporal trends. If accelerated subsidence was induced by reservoir compaction and fault reactivation associated with fluid withdrawal that also accelerated in the 1960s and 1970s, then the most recent reductions in subsidence rates likely reflect a balancing of subsurface stresses and a return to near-equilibrium conditions. Understanding historical and current trends in subsidence rates and their causes is critical for designing and successfully implementing coastal-restoration activities and for modeling and predicting expected impacts of relative sea-level rise on the delta plain.

Introduction

High historic land-loss rates in Louisiana's Mississippi River delta plain have resulted in the submergence of approximately 4000 km² of formerly emergent wetlands since the 1930s. Recent U.S. Geological Survey (USGS) studies in the south-central delta plain identified rapid subsidence leading to marsh-surface submergence as a primary cause of historic delta-plain wetland loss, especially at interior hotspots that opened up in the late 1960s and 1970s. However, although it is generally agreed that the delta plain has historically been an area of high subsidence rates, there is a poorer understanding of the magnitude of the most recent subsidence rates. The objective of this study was to evaluate historic subsidence trends and processes in the central and eastern delta plain by integrating National Ocean Service (NOS) tide-gauge records with National Geodetic Survey (NGS) repeat leveling surveys and continuous GPS measurements at Continuously Operating Reference Stations (CORS).

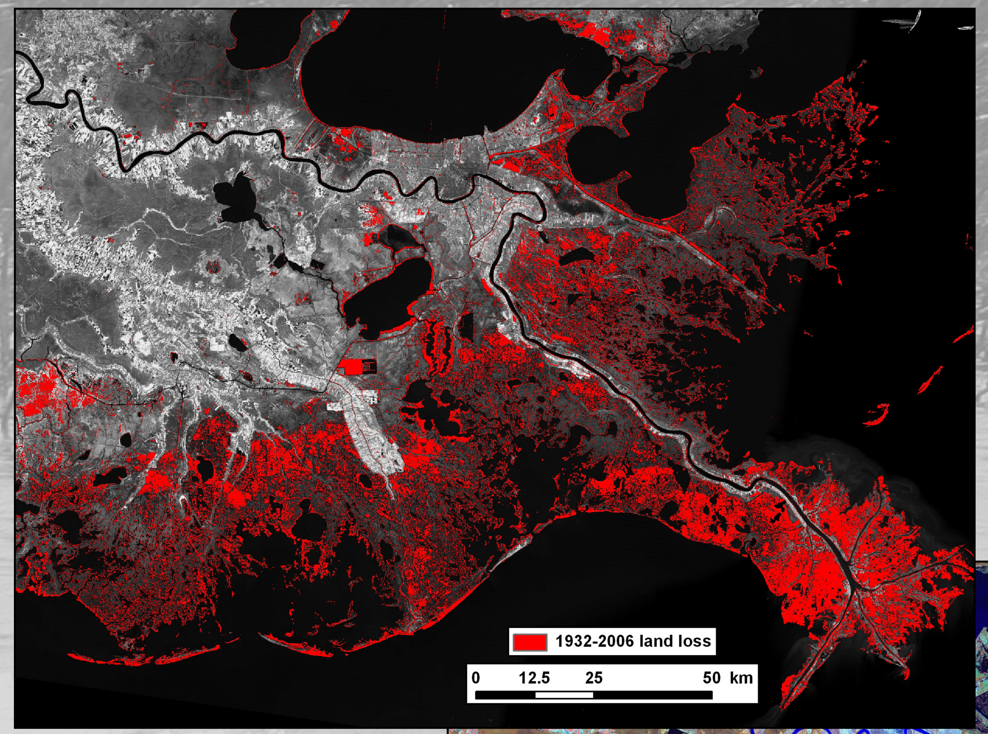

Figure 1. Regional map of the Mississippi River delta plain showing extent of historic wetland losses from 1932 to 2006.

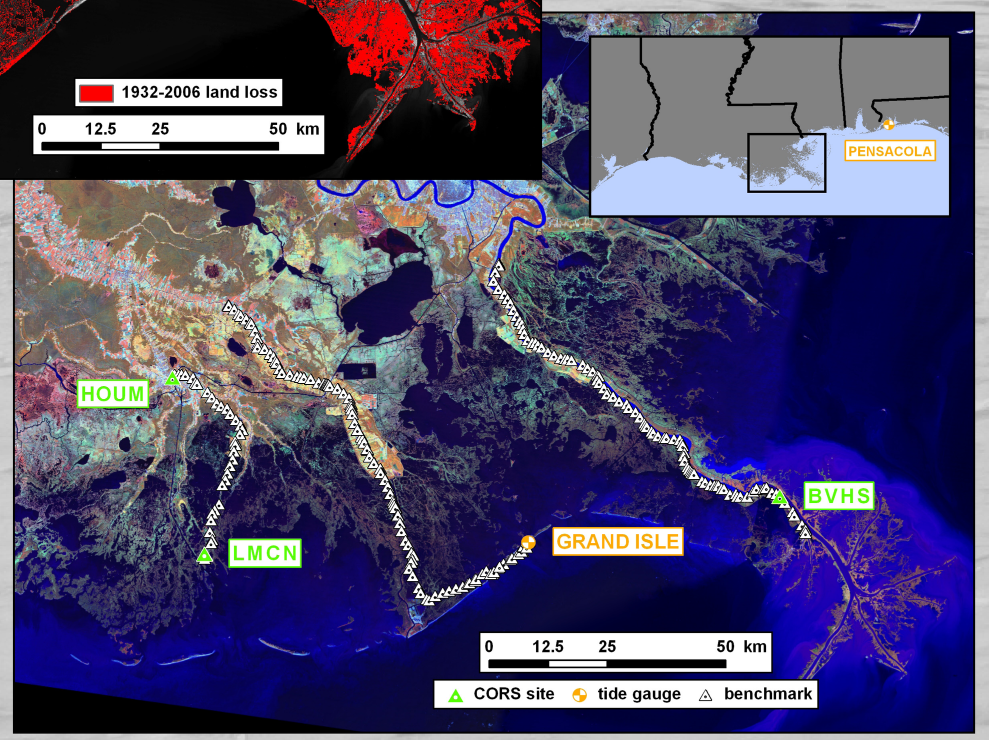

Figure 2. Regional map of the Mississippi River delta plain showing locations of the Grand Isle tide gauge, benchmark surveys, and CORS stations at Houma (HOUM), Cocodrie (LMCN), and Boothville (BVHS).

Subsidence Measurements

Tide-Gauge Records

Rates of RSLR can be used as a proxy for vertical land motion if the records are long enough that trends can be established. The NOS tide gauge at Grand Isle, Louisiana has a nearly-continuous record since 1947 – the longest such record in Louisiana and one of the longest in the northern Gulf of Mexico. The average rate of RSLR at Grand Isle is about 9.3 mm/yr; however, this rate has not been constant through time. Rates of RSLR accelerated from about 2.2 mm/yr between 1947 and 1964 to about 11.5 mm/yr between 1964 and 1991 and then declined to about 3.4 mm/yr since 1991. The potential effects of interannual and decadal variations in regional water levels on the Grand Isle RSLR trends can be evaluated by comparison with the record at Pensacola, Florida, which is the nearest tide gauge that is located in a relatively stable geologic setting. Here, the overall trend is a relatively uniform rate of RSLR of about 2.1 mm/yr since 1924. There are no pronounced periods of RSLR acceleration and deceleration at Pensacola, indicating that the Grand Isle RSLR temporal variability is specific to the southern Mississippi River delta plain.

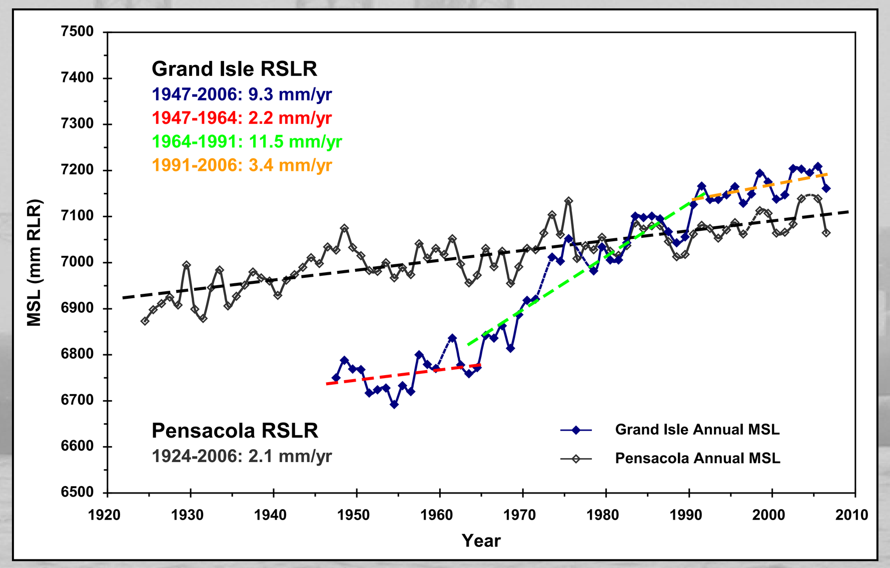

Figure 3. Annual mean sea level for NOS tide gauges at Grand Isle and Pensacola. For Grand Isle, variability in the rate of RSLR is largely determined by land subsidence.

Benchmark Surveys

Data from repeat leveling surveys conducted by NGS at benchmarks along state highways that follow the natural levees of (from west to east) Bayou Petit Caillou between Houma and Cocodrie, Bayou Lafourche between Raceland and Grand Isle, and the Mississippi River between Chalmette and Venice can be used to derive decadal-scale elevation changes between leveling epochs. Although only a few benchmarks were included in all surveys, general temporal and spatial trends can be identified by comparing magnitudes and average rates of subsidence for the same area and for consecutive periods. Average subsidence rates along Bayou Lafourche accelerated from about -8 mm/yr prior to 1982 to about -11.1 mm/yr from 1982 to 1993. Average subsidence rates along the Mississippi River north of the Lake Washington – Empire Fault area first increased from about -17 mm/yr between 1938 and 1951 to about -20.1 mm/yr between 1951 and 1964 and then systematically decreased to about -10 mm/yr by 1971 to 1984. Average historic subsidence rates at benchmarks south of Lake Washington were substantially higher than to the north but also decreased from greater than -25 mm/yr between 1964 and 1971 to about -18 mm/yr between 1971 and 1984. Along all three survey lines, the highest historic subsidence rates generally occur over nearby oil-and-gas fields and inferred faults. A lack of reported data since 1993 prevents using this method to determine more recent trends.

Continuously Operating Reference Stations (CORS)

Vertical velocities determined from the GPS records provide the most recent, highly accurate, measurements of vertical land motion in the southern Mississippi River delta plain since the CORS stations were established in 2002 (BVHS) and 2003 (HOUM and LMCN). Through 2007, the GPS-derived subsidence rates at BVHS, HOUM, and LMCN are -3.5, -4.4, and -6.3 mm/yr, respectively.

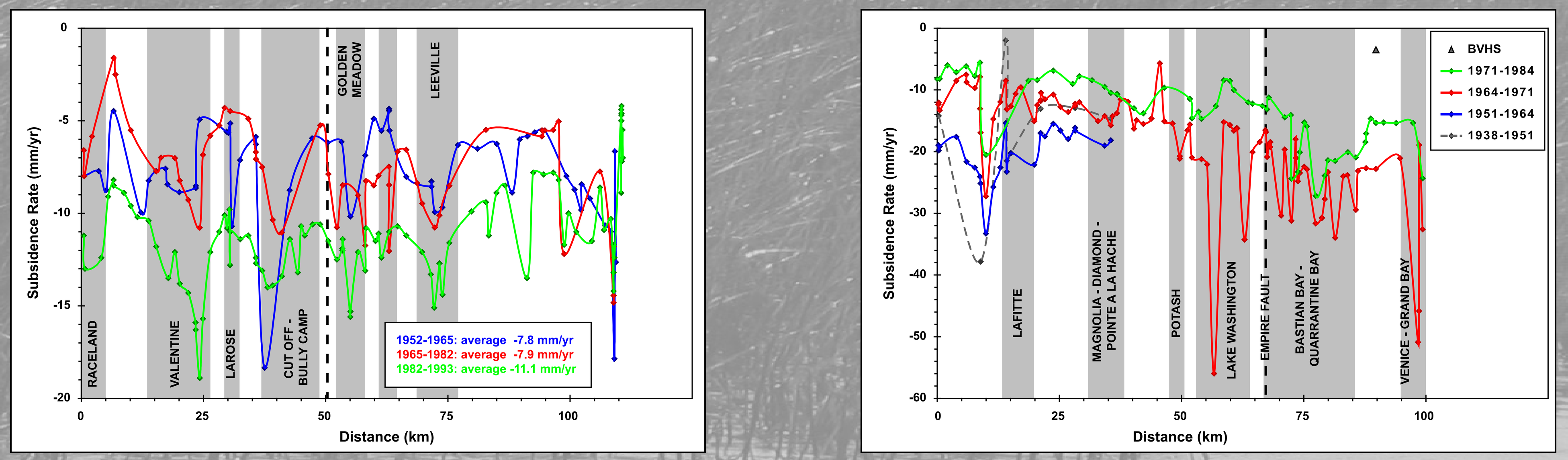

Figure 4. Historical subsidence rates calculated by the National Geodetic Survey from repeat leveling surveys at benchmarks along (A) Bayou Lafourche between Raceland and Grand Isle and (B) the Mississippi River between Chalmette and Venice. The most recent subsidence rate derived from GPS measurements at BVHS is plotted as a filled triangle is (B). Shaded areas delineate approximate productive boundaries of nearby oil-and-gas fields; dashed vertical lines show projected intersection with subsurface faults. Survey-line locations are shown on Fig. 2; plot distances increase from north to south.

Temporal Trends

Integration of rates of RSLR from tide-gauge records, elevation changes from repeat leveling surveys, and vertical velocities from continuous GPS measurements reveals a decadal pattern of slow, then rapid, then slow subsidence on the Mississippi River delta plain. Subsidence rates accelerated from about -3 mm/yr prior to the mid-1960s to greater than about -10 mm/yr from the mid-1960s to the early 1990s. Stratigraphic analysis of shallow cores from interior delta-plain wetland-loss hotspots indicates that subsidence rates were likely substantially higher away from the natural levees: an estimated 50 to more than 100 cm of subsidence occurred at some study sites in less than 50 years (Morton et al., 2005). The most recent subsidence rates, generally less than about -5 mm/yr, are comparable to the earliest historic subsidence rates and are similar in magnitude to geologic subsidence rates estimated from radiocarbon dating of delta-plain peats and numerical modeling.

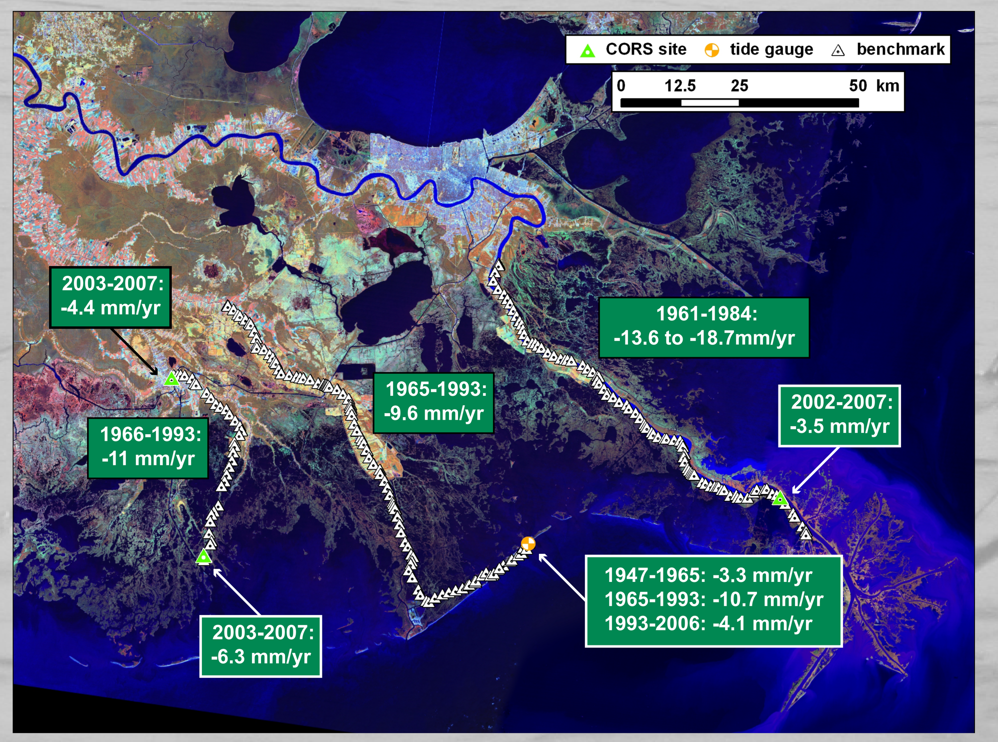

Figure 5. Regional map of the Mississippi delta plain with average historic subsidence rates from integrated datasets.

Subsidence Mechanisms

Compaction of Holocene Sediments

(Penland et al., 1988, Penland and Ramsey, 1990; Roberts et al., 1994; Tornqvist et al., 2008)

Time-averaged subsidence rates derived from radiocarbon dating of delta-plain peats and numerical models of sediment compaction are generally less than about -5 mm/yr, indicating that although compaction of unconsolidated Holocene sediments within the incised Mississippi River valley is a component of total subsidence, it cannot explain the high historic subsidence rates.

Neotectonics

(Gagliano et al., 2003; Dokka et al., 2006)

Tectonic processes such as salt evacuation, sediment loading, and growth faulting were key drivers of sediment accumulation and continental shelf-margin development beneath what is now the southern Louisiana coastal plain; however, these processes operate on geologic time scales, making it difficult to explain the observed decadal-scale acceleration and deceleration of historic subsidence rates. In addition, some subsidence trends are opposite what would be expected; for example, historic subsidence rather than uplift has occurred over the Leeville and Valentine subsurface salt domes.

Fluid Withdrawal

(Morton et al., 2006; this study)

There is close temporal and spatial correlation between rates of historic wetland loss, subsidence, and hydrocarbon production on the Mississippi River delta plain. Numerical modeling (Chan and Zoback, 2007) confirmed that rapid subsurface fluid withdrawal in the 1960s and 1970s and associated large reductions in reservoir pore pressures could induce the observed land subsidence and cause slip of growth faults after threshold stresses were exceeded. This hypothesis also predicts that subsidence rates should decrease after the overburden load and subsurface pressures re-equilibrate following a decline in production volumes.

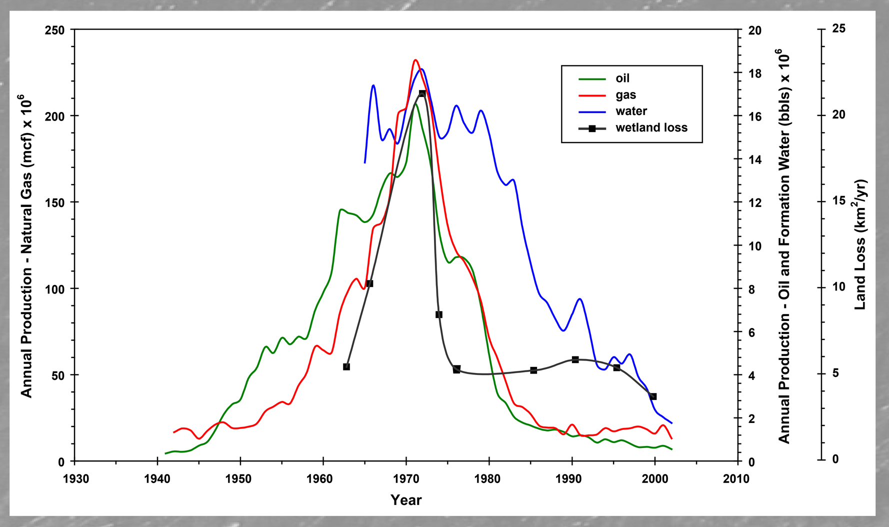

Figure 6. Composite histories delta of fluid production from delta-plain oil-and-gas fields with wetland-loss rates across five representative delta-plain wetland-loss hotspots.

Conclusions and Implications

- **Integration of datasets reveals a decadal-scale acceleration and subsequent deceleration of historic subsidence rates that was likely induced by deep subsurface hydrocarbon production.**
- **The most recent subsidence rates are comparable to rates averaged over geological time scales and the recent reductions in subsidence rates likely reflect balancing of subsurface stresses and a return to near-equilibrium condition.**
- **A better understanding of the most recent trends and process causing subsidence needs to be incorporated into coastal restoration efforts and efforts to model expected impacts of increased RSLR in a time of global climate change.**

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