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A Synoptic Examination of Causes of Land Loss in Southern Louisiana as Related to the Exploitation of Subsurface Geologic Resources

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ABSTRACT

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During the last 80 years, Louisiana has been losing wetlands at an average rate of 62 km^2/y (24 mi^2/y) for an accumulated loss of approximately 4900 km^2 (1900 mi^2). The loss seems to be the combined result of natural and anthropogenic causes that are behind primarily land subsidence averaging about 10 mm/y (0.4 in/y) coinciding with a sea level rise now at 3 mm/y (0.1 in/y), both contributing to coastal inundation. Upon completing extensive review of often controversial and conflicting views only synoptically reported here, conclusions reached by applying Monte Carlo simulation include: (1) geodetic measurements are consistent with independently postulated causes of regional subsidence; (2) ranking of subsidence factors shows that the main contributor to the regional subsidence is adjustment to sediment load in the form of lithosphere flexure followed by normal faulting dipping basinward, which combined, account on average for 70% of the subsidence, with compaction accounting for another 23%; and (3) production of oil and gas plays a tertiary role. The literature supports the historical view that before experiencing engineering modifications across the catchment area, sedimentation from the Mississippi River system was able to build a prograding coastline by overcoming subsidence rates of similar magnitude with more generous sediment loads of coarser particle size. Sea level rise will become an increasingly dominant factor in land loss only if the acceleration predicted by simulation model scenarios materializes. Wetland losses most likely will continue for as long as there is no compensation to counterbalance the negative effects of land subsidence and sea level rise, with the latter determining the pace of future losses.

ADDITIONAL INDEX WORDS: *Land subsidence, eustatic sea level, inundation, Monte Carlo simulation.*

INTRODUCTION

Historic wetland losses along the Gulf of Mexico coastline have long given support to the idea that the observed changes do not follow the conventional marine erosion of a quasi-stable continental mass. Deterioration of the Mississippi delta is no exception. In an assessment of 33 of the major deltas in the world, Syvitski *et al*. (2009) found that 85% of them face areal reduction. While some authors have concentrated their attention on isolated phenomena, others assert that different processes (discussed below) contributing to land loss are the result of multiple events taking place simultaneously at various levels of significance. While the Gulf of Mexico coastal wetlands losses extend across a large area, here we focus our attention on southern Louisiana, a region that leads the United States in terms of the magnitude of coastal land loss. Louisiana has lost a geographical area of about 4900 km^2 (1900 mi^2) (*e.g.*, Couvillion *et al*., 2011), which is roughly one-fourth of the area of the wetlands 80 years ago. The most severe loss was recorded in 1975–1977 with 404 km^2/y (158 mi^2/y; Figure 1). On average, the losses have been more moderate, with a historical average rate of about 62 km^2/y (24 mi^2/y for the period 1932–2011 (*e.g.*, Couvillion *et al*., 2011). While acceptance of the magnitude of this loss is not disputed, a wide controversy surrounds the causes and their relative importance, as well as the best steps to be taken for remedial and preventive action.

Several or all of the significant causes may be acting simultaneously in a way that isolation of individual effects is nearly impossible to discern. In this paper, for the specific case of southern Louisiana, we review all relevant underlying causes of coastal land loss, particularly those related to the exploitation of energy resources. These causes of coastal land loss include sea level rise, glacial isostatic subsidence, delta switching, sedimentary isostatic adjustment, sediment compaction, active normal faults, sediment supply reduction and river confinement, erosion, canal construction, oil and gas production, groundwater pumping, and sulfur production. We then use Monte Carlo simulation to compare causes and geodetic measurements, and determine their relative importance and effects on historic land loss. Finally, we provide a projection of coastal land loss in southern Louisiana for the rest of the 21st century.

GEOLOGICAL BACKGROUND

The recent geology of the Louisiana Gulf Coastal Plain is dominated by the sediment distribution systems of the Mississippi River and lesser river systems, which have created a complex mosaic of river deltas to the east and chenier plains to the west of Vermilion Bay (Figure 2). The Mississippi River drains an area of 3.4 million km^2 (1.3 million mi^2; 44% of the conterminous United States land), the fourth largest drainage

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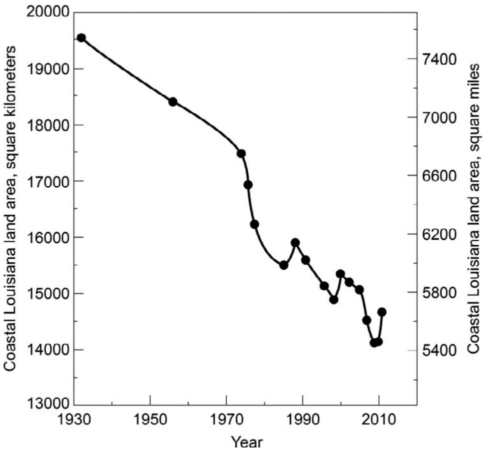

Figure 1. Time series of change in coastal Louisiana land area from 1932 to the end of 2010 (after Couvillion *et al.*, 2011).

basin in the world by area and seventh by sediment load (Blum and Roberts, 2012). Southern Louisiana is characterized by low relief topography and bathymetry associated with coastal and fluvial terraces, oxbow lakes, coastal bays, and fluvial channels. Locally, more than 200 salt domes punctuate the surface, creating local topographic highs and specialized ecosystems (Autin, 2002; Halbouty, 1979; Marsalis *et al.*, 2000; Murray, 1961). In many instances, these salt domes also bring rock salt and sulfur near the surface and provide migration pathways and structural traps for oil and gas (Halbouty, 1979; Marsalis *et al.*, 2000; Murray, 1961).

These salt domes rise out of the "mother salt," a highly deformed interval of Jurassic-age salt, which formed soon after the early Gulf of Mexico Basin opened to receive marine waters (Andrews, 1960; Galloway, 2011). Overlying the Jurassic salt are 6000 m (20,000 ft) to perhaps as much as 20,000 m (65,000 ft) of sedimentary rocks and recent sediments (Galloway, 2011). Fringing reefs and carbonate shoals persisted throughout much of the Late Jurassic and Early Cretaceous eras; however, large deltaic systems delivered siliciclastic sediments into the basin from the north during the Late Jurassic, early Early Cretaceous, early Late Cretaceous, and throughout most of the Tertiary and Quaternary (Figure 3). This thick deltaic outpouring onto the Jurassic salt and Mesozoic and Cenozoic shale intervals created volume-compensating growth faults and salt diapirs (Figure 4). Slow basinward sliding of the entire section toward the center of the Gulf of Mexico created large minibasins that captured thick accumulations of Cenozoic sand, silt, and clay. Faults that developed during this sliding, along with salt diapirism, produced conduits for oil and gas migration upward from the main source intervals in Jurassic and Cretaceous strata. Major deltaic centers formed during the early Cenozoic with the uplift of the Rocky Mountains and the rejuvenation of the Appalachian Mountains. Concurrent with the onset of glaciation in the northern and southern polar regions, major shifts in deltaic distribution centers occurred, resulting in the mosaic of deltas that characterize the modern day Louisiana Gulf Coast (Galloway, 2008, 2011).

GEODETIC DETECTION OF SUBSIDENCE AT DECADAL SCALE

Land subsidence is the result of processes whose cumulative effects reduce the distance between the land surface and the center of the Earth. These processes operate independent of potential inundation effects. There are two aspects of land subsidence: (1) the magnitude of the actual subsidence and (2) the explanations for the occurrence of that subsidence. The most extensive evidence of measured subsidence along the northern Gulf Coast is the geodetic work reported by Shinkle and Dokka (2004). Using conventional triangulation data for 2683 benchmarks located primarily along roadways, they demonstrated that most of the lower Mississippi Valley is subsiding while a smaller area along the Mississippi–Alabama border is rising (Figure 5). Benchmarks record geographic location and elevation relative to a common vertical datum. Shinkle and Dokka (2004) used the North American Vertical Datum of 1988 (NAVD 88). Resurveying of benchmarks allows detection of any changes since the previous survey. Results are based on first-order leveling data and GPS observation by the National Geodetic Survey between 1920 and 1995. Their work additionally shows that subsidence several miles inland from the coast can be equivalent in magnitude to that along the coast (Figure 5). The main difference is that coastal inundation makes subsidence more evident and dramatic.

The observed effect of sea rise or land subsidence at a tide gauge is an increase in the numerical reading. When both phenomena are at work, as in southern Louisiana, the amount of sea level rise must be subtracted from the tide gauge observation to calculate the land subsidence component. Shinkle and Dokka (2004) used a value for sea level rise of 1.25 mm/y (0.05 in/y) in their calculations of subsidence rates, a low rate according to most values reported in the literature, thus potentially inflating land subsidence slightly by about 0.5 mm/y (0.02 in/y). Note, however, that it is the combined effect of land subsidence and sea level rise—the uncorrected value—that decides the magnitude of the inundation. Hence, the actual magnitude of the inundation does not require any correction; it is independent of any assumption about sea level rise.

As is common in legal litigations, the validity and meaning of all work on Gulf coast subsidence has been variously attacked and defended. In the case of Shinkle and Dokka (2004), for example, there have been concerns that the frequency of releveling is too short, resulting in subsidence rates that may be exaggerated (Meckel, 2008), that the data are unsatisfactory by modern standards (Berman, 2005b), and that the benchmarks are primarily along roadways, thus potentially inadequately incorporating the conditions away from roadways. By its wide geographical extension and precision, the geodetic survey by Shinkle and Dokka (2004) remain a crucial study for the understanding and validation of the multiple causes of subsidence.

EXAMINATION OF FACTORS LINKED TO LAND LOSS

Global Sea Level Change

Global sea level rise tends to inundate low-lying coastal areas. Between the start of the Holocene (11,500 BP) and 7000

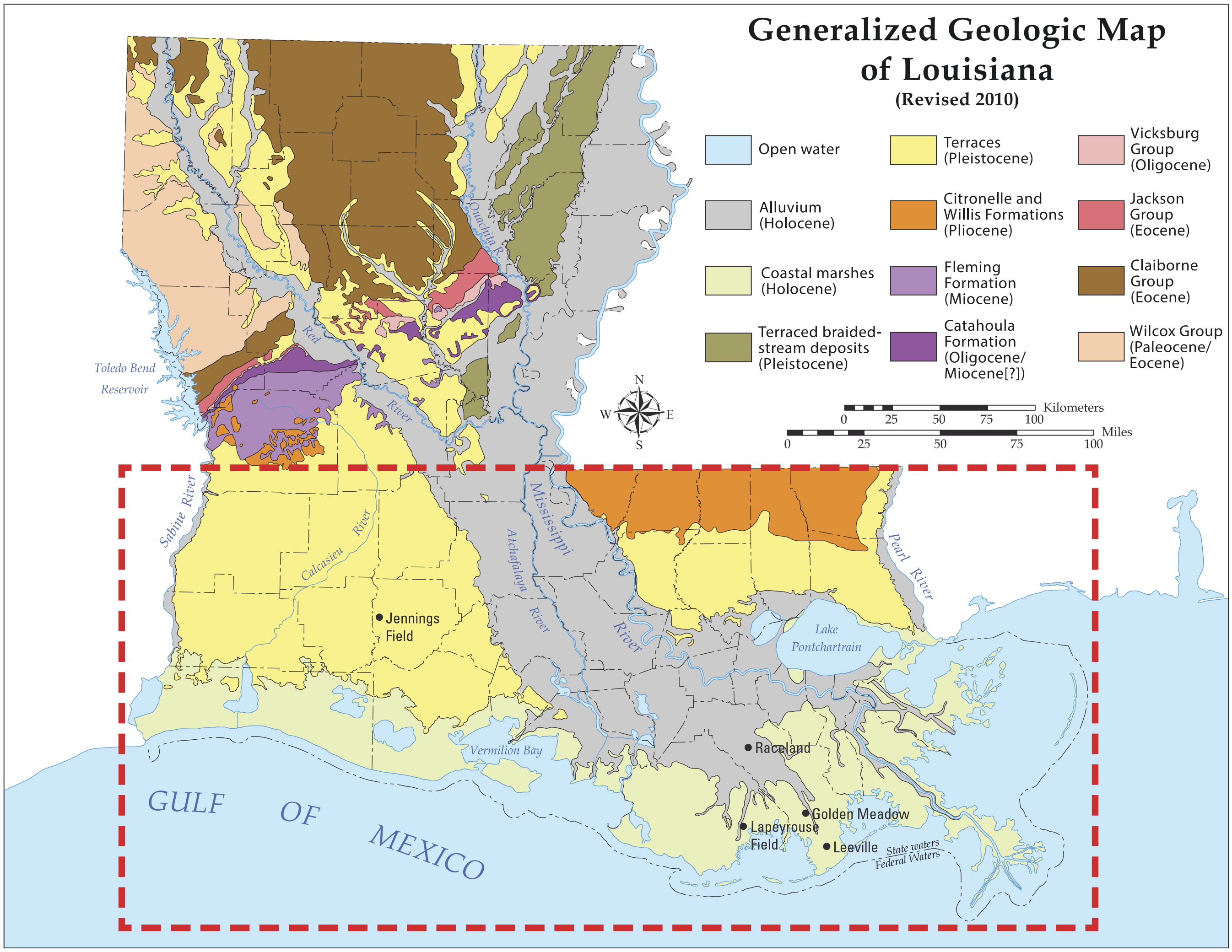

Figure 2. Generalized geologic map of Louisiana (modified from Louisiana Geological Survey, 2010). The red box denotes the study area. (Color for this figure is available in the online version of this paper.)

BP, global sea level started rising by about 12 to 13 mm/y (0.47–0.51 in/y) (Smith *et al.*, 2011), followed by a reduced rate of rise between 0.4 and 7.0 mm/y (0.02–0.28 in/y) (Fleming *et al.*, 1998; Carlson *et al.*, 2008) and then stabilizing about 2500 years before present. Subsequently, sea level remained essentially constant until the 19th century, when it started to rise again (Figure 6). We postulate that this stabilization of sea level for more than two millennia indicates that the potential influence of global plate tectonic changes is not contributing to the current sea level rise in southern Louisiana.

Up until 20 years ago, all sea level data came from tide gauges (*e.g.*, Church and White, 2011). Measurements from the second half of the 20th century detected an average rate of global sea level rise of 1.75 mm/y (0.07 in/y) (Church and White, 2006). Sea level surveillance began to use satellite technology in 1993 coinciding with the start of another accelerated rise in sea level not related to the application of the new technology. Values provided by the two technologies from 1993 to present show minor but significant discrepancies. For example, during 1993–2007, the average global tide gauge rate increased to 2.85 mm/y (0.11 in/y), while the satellite rate is 3.3 mm/y (0.13 in/y) (*e.g.*, Cazenave and Llovel, 2010). The expansion of oceans is global, but regional fluctuations in salinity and temperature seem to be responsible for a variable sea level rise (Cazenave and Llovel, 2010). One good tide gauge is no longer enough to extrapolate sea level rise across the entire world now that it is no longer accepted that, at any given time, the rate of rise is a single value for the entire planet. Fluctuation at a gauge in Pensacola, Florida (see Figure 5), regarded as responding purely to eustatic changes, follows well the global average sea level rise (Cazenave and Llovel, 2010).

Understandably, discrepancies in the extrapolation of historic sea level change into the future are much wider and uncertain that those about present rates. Most predictions agree, however, that sea level rise rate will continue with concomitant coastal inundation. Table 1 lists the predictions

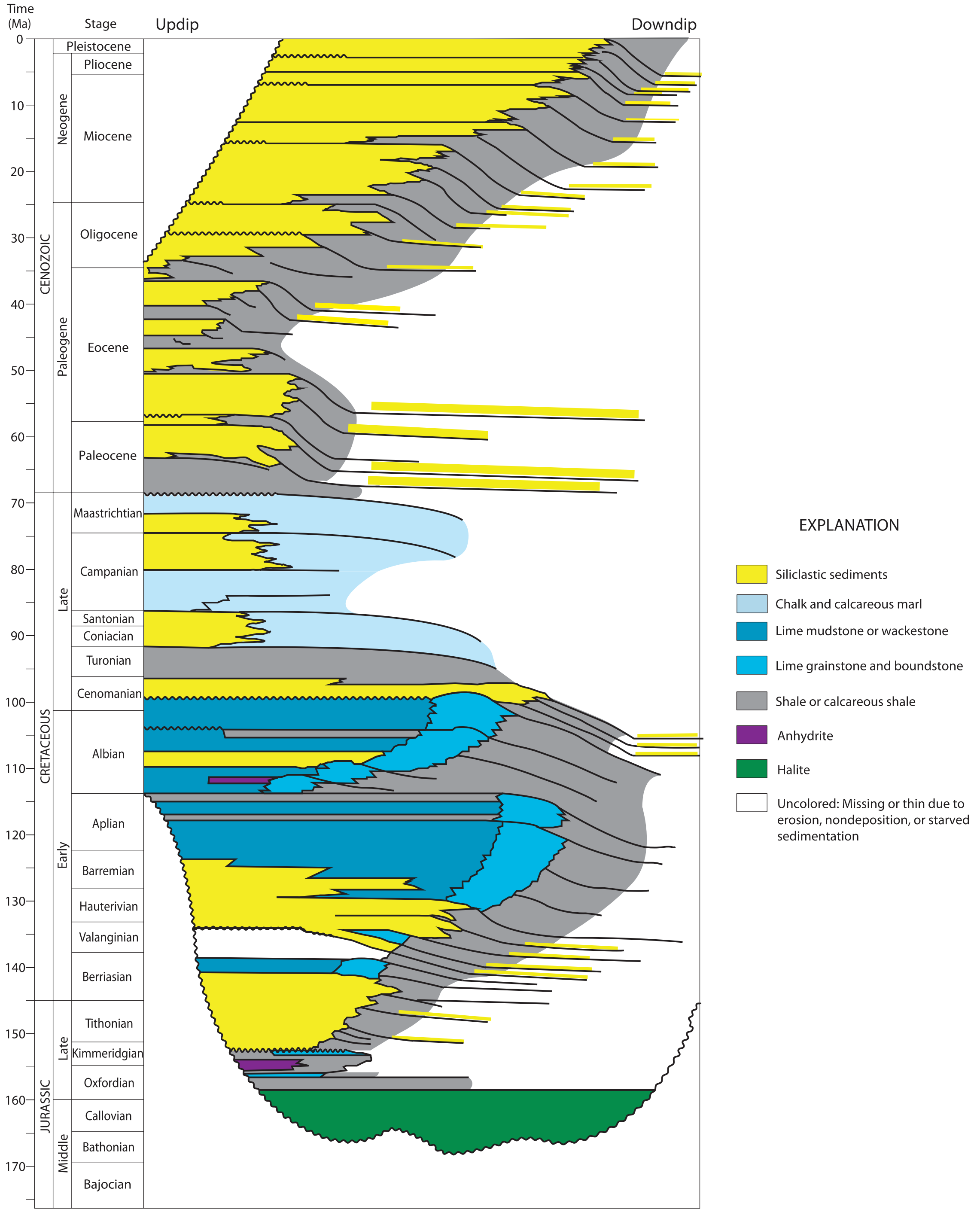

Figure 3. Generalized Cenozoic and Mesozoic stratigraphic succession and architecture of the north-central Gulf of Mexico. Lithology color codes are for the dominant lithology in each interval (adapted from Galloway, 2011). (Color for this figure is available in the online version of this paper.)

for sea level rise during the 21st century most often cited in the recent scientific literature.

Discrepancies in estimates of rates of future sea level rise among experts extend over all fundamental aspects behind the modeling of predictions: analytical methods, historical interval to analyze, gauges to consider, and influence of global warming. Results are extraordinarily sensitive to each of these considerations, thus the discrepancies that exist between them (*e.g.*, Baart, van Koningsveld, and Stive, 2012; Christiansen, Schmith, and Theill, 2010). The highest rates of average sea

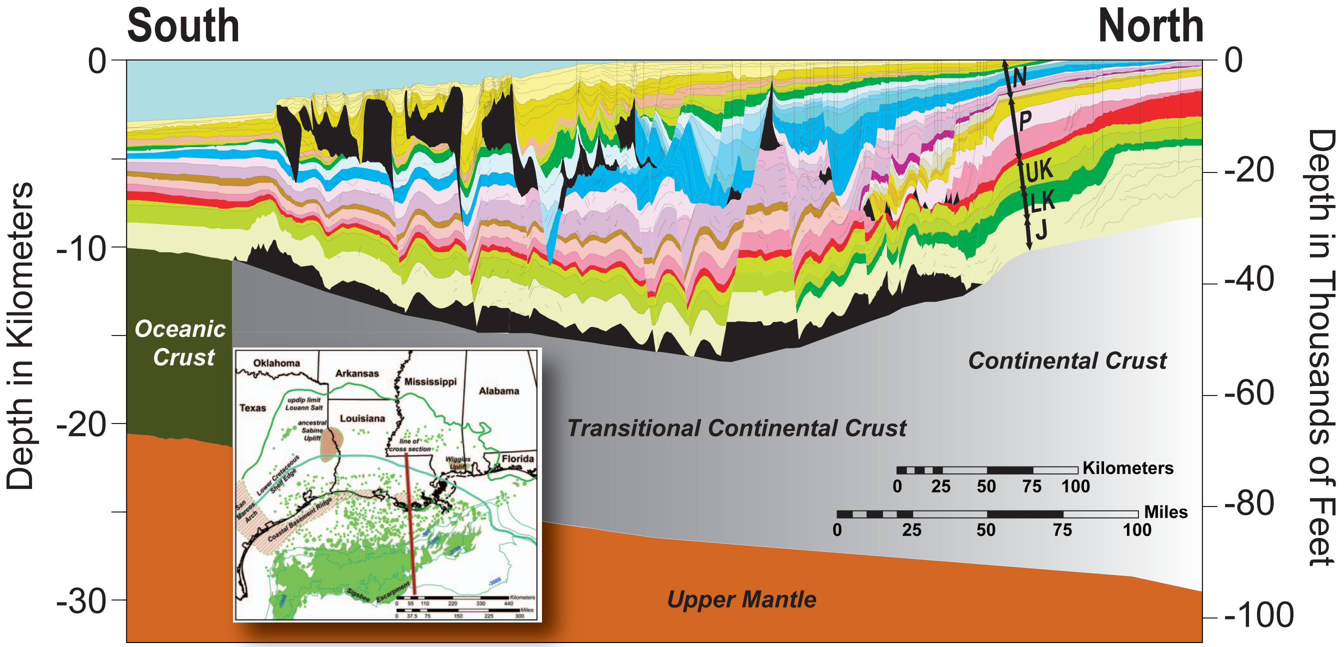

Figure 4. Generalized structural cross section of north-central Gulf of Mexico Basin, central Mississippi to offshore Louisiana (modified from Nelson *et al.*, 2000). Color codes are: N = Neogene, P = Paleogene, UK = Upper Cretaceous; LK = Lower Cretaceous; J = Jurassic. Black areas = Jurassic Louann Salt (base map modified from Garrity and Soller [2009], Lopez [1995], Stover *et al.* [2001]; green areas = Jurassic Louann Salt domes and massifs; light brown = basement high areas with thin or no salt; light brown striped = inferred basement high areas with thin or no salt; red line = line of cross section). (Color for this figure is available in the online version of this paper.)

level rise are based on close dependency between sea level and accelerated temperature rise (*e.g.*, Rahmdorf and Vermeer, 2011). Researchers who have reported decelerating rates in sea level rise have restricted their analyses to data from tidal gauge time series and disregarded climatic considerations (*e.g.*, Boretti, 2012; Houston and Dean, 2011b,c; Watson, 2011). Donoghue and Parkinson (2011) argue that the past centuries have been so different from the present one that it is invalid to extrapolate future sea level rise based solely on historic data without making adjustments to accommodate the effects of global warming in those predictions. Note that a slightly decelerating rate does not mean that the sea level will start going down. Instead, it will still continue to rise, but at a decreasing pace. For example, if the rate is 2.80 mm/y (0.110 in/y) during a certain year, the following year may be 2.77 mm/y (0.109 in/y), for a cumulative rise of 5.57 mm (0.219 in) in these two years. A zero acceleration or deceleration implies a constant rate of change, thus a sea level rise following a linear increase.

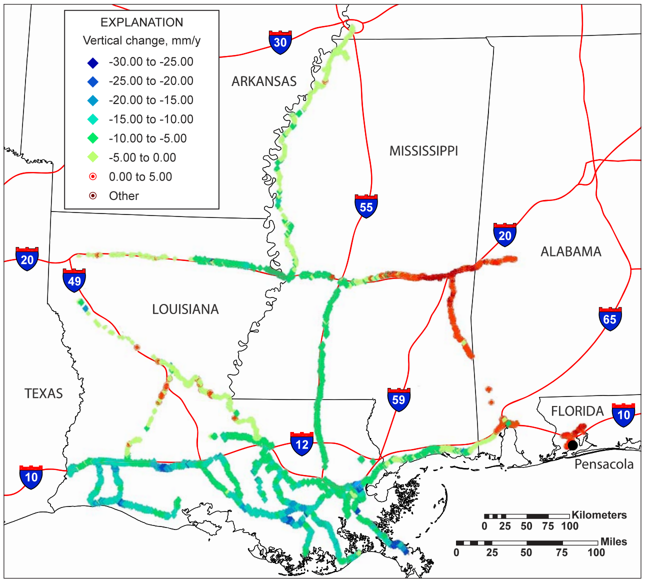

Figure 5. Rates of surface elevation change (modified from Shinkle and Dokka, 2004). (Color for this figure is available in the online version of this paper.)

Glacial Rebound

Glacial isostatic rebound is part of the response by the earth's crust to the subsidence produced by the weight of glacier ice and the compensational uplift peripheral to the glaciated area. In central North America, this uplifted area extended possibly as far south to an east-west line slightly south of the current Mississippi delta. North America was covered with ice as far south as St. Louis, Missouri, during the last glaciation that concluded approximately 11,500 years ago (Figure 7). After ice melting, the isostatic process reversed. Thus, under this

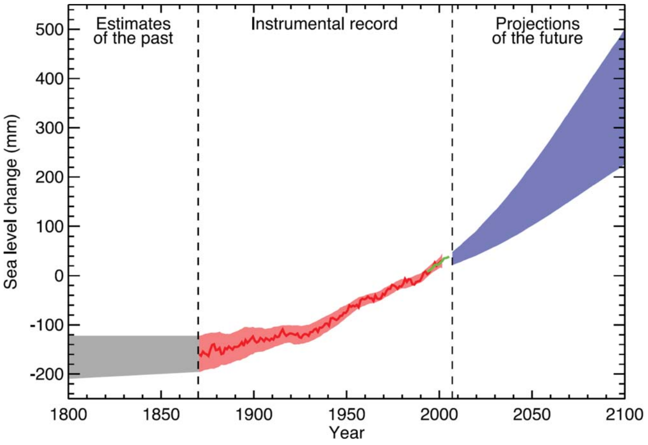

Figure 6. Global sea level rise over three centuries relative to 2007 (Bindoff *et al*., 2007, p. 409). Their projection of future sea level change represents a middle-of-the-road prediction on the conservative side relative to rates listed in Table 1. (Color for this figure is available in the online version of this paper.)

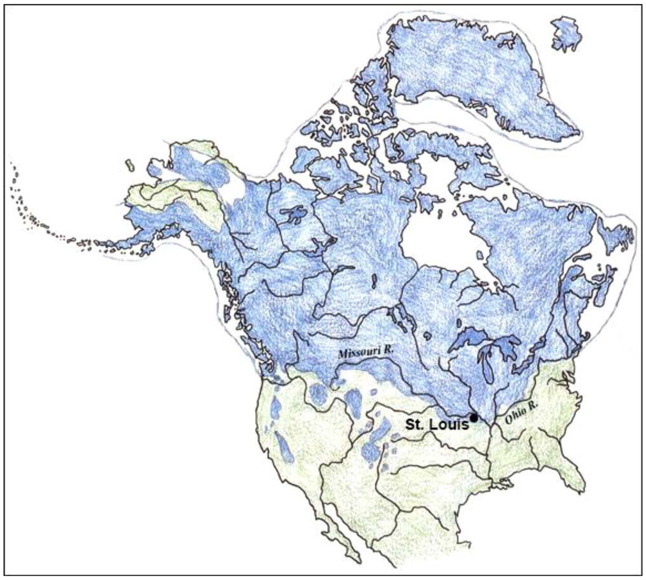

Figure 7. Extent of the last glaciation in North America denoted in blue (after Menzies, 2002). (Color for this figure is available in the online version of this paper.)

scenario, the southern coast of Louisiana may still be suffering a marginal compensational subsidence for being within the forebulge fringes during the last glaciation (Peltier and Jiang, 1997).

Even if the lower Mississippi valley was within the forebulge, and rebounding is still active, glacial subsidence should be minor to negligible because of its peripheral location, yet worth mentioning as one of the potential causes of subsidence throughout the state. Impossible to observe in isolation, mathematical modeling is the only option to assess the current glacial isostatic adjustment, which, like any modeling, is subject to approximations in the mathematical representation of the processes, selection of parameters going into the calculations, and assumptions about the timing and magnitude of crucial events. González and Törnqvist (2006) state that “the viscoelastic response of the lithosphere by means of forebulge collapse could be a significant contributor” to the widely accepted rate of 0.55 mm/y (0.02 in/y) in southern Louisiana. Sella *et al*. (2007), in a study of the entire North American continent, specifically discarded the Gulf Coast from the analysis because of complex interference of other phenomena likely to contribute to changes in land elevation. These authors observed, however, that subsidence was no larger than 2 mm/y (0.08 in/y) as far north as the Ohio River.

Table 1. *Results of modeling global average sea level rise until 2100. 1 m = 3.28 ft.*

	Rise during 21st Century (m)		Average Rate (mm/y)	
Reference	Minimum	Maximum	Minimum	Maximum
Church and White, 2006	0.25	0.31	2.5	3.1
Bindoff *et al*., 2007	0.2	0.5	2.0	5.0
Rahmstorf, 2007	0.5	1.4	5.0	14.0
Horton *et al*., 2008	0.47	1.0	4.7	10.0
Grinsted, Moore, and Jevrejeva, 2009	0.9	1.3	9.0	13.0
Vermeer and Rahmdorf, 2009	0.7	1.85	7.0	19.0
Jevrejeva, Moore, and Grinsted, 2010	0.6	1.8	6.0	18.0
Houston and Dean, 2011a	0.12	0.15	1.3	1.7

Delta Switching

Coastal accretion during the Holocene (Figure 2) has been dominated by the Mississippi River delta sedimentation. An understanding of the evolution of this delta is needed to comprehend the complex causes of subsidence discussed in this and the following subsections.

River deltas commonly change their loci of deposition by the process of avulsion, the rapid abandonment of an existing river channel and the formation of a new one as the river seeks the shortest distance to base level. Deltas of the Mississippi type develop discharge zones that evolve according to a characteristic cycle leading to abandoning basins approximately every 1000–2000 years after depositing sediments that, on average are, up to 100 m (330 ft) thick (Coleman, Roberts, and Stone, 1998; Roberts, 1997), a periodicity that has been linked to Milankovitch cycles (Lowrie and Hamiter, 1995). While experts disagree on the details and timing of these cycles, there is a fair amount of overlap in their views. Figure 8 depicts one of the most widely accepted possibilities for the evolution of the Mississippi River delta system. Worldwide, by their own nature, deltas are unstable and display both high vertical and lateral variability.

In the particular case of the Mississippi River, the river incised a valley about 130 m (400 ft) deep during the transition period between the beginning of accelerated ice melting at the end of the last glaciation and the end of a sea level rise (Blum and Roberts, 2009). Before starting with the building of the first

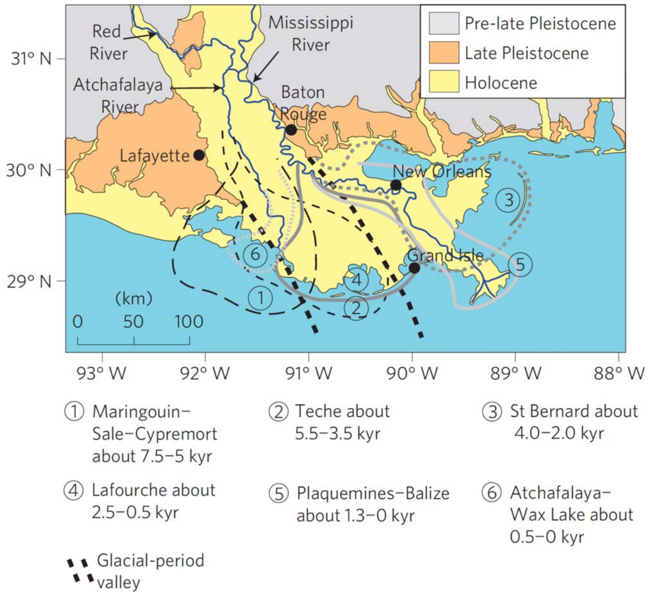

Figure 8. The Late Pleistocene and Holocene Mississippi complex of overlapping deltaic lobes (Blum and Roberts, 2009). (Color for this figure is available in the online version of this paper.)

Holocene delta about 7500 years before present, most of the sediment load was deposited as valley fill. Since then, the river has been quite consistent in building deltas in semipredictable stages. After securing a main channel, flow is most effective when following the maximum gradient. At the macro scale, the cycle continues with steady progradation until the area of the delta reaches about 15,500 km^2 (6000 mi^2) (Coleman, Roberts, and Stone, 1998). In an undisturbed environment, progressive gain in the length of the main channel results in a decreasingly efficient flux and sediment dispersal, which eventually leads to the end of the regressive phase by cutting a new, steeper main channel. During the transgressive phase, while the prograding phase of the new delta is already in progress, dominance of marine over fluvial processes leads to systematic inundation and deterioration by reworking of the delta perimeter, resulting in land loss (Flocks *et al*. 2009; Reed, 2002). At the more local scale, the evolution of bay-fills, crevasse-splays, and marshes follow other shorter cycles lasting from decades to a few centuries (Coleman, Roberts, and Stone, 1998; Roberts, 1997). Lopez (2005) argues for an asymmetric nature to this cycle, whereby the older deltas may persist and exert some morphological control over the development of younger deltaic complexes and spatially adjacent wetlands.

Today, the Plaquemines–Balize delta—also known as the Birdfoot or the Modern delta—is most likely at the end of its regressive phase. The Mississippi River system may have started to abandon the Plaquemines-Balize basin in the 1500s by cutting the Atchafalaya River through the Lafourche and Teche river system deposits, which resulted in the formation of a new delta complex starting in the 1950s after filling in all the lakes and other local depressions along the river, offering for the first time the possibility to observe the evolution of a new delta of the Mississippi River system from its initial stages (Rosen and Xu, 2013). This evolution will not be completely natural because flow through the Atchafalaya River is maintained artificially by U.S. Army Corps of Engineers at 30% (Winer, 2011). If left to Nature, the flow might rapidly grow to 100% because the distance to sea along the Atchafalaya River is about 320 km (200 mi) or 60% shorter than the current main channel of the Mississippi River (Roberts *et al*., 2003; Wang and Adrian, 1998).

Sedimentary Isostatic Adjustment

Sedimentary isostatic adjustment, a common sedimentary basin characteristic, is the continuous adjustment of the lithosphere to the load of the deposited sediments (*e.g.*, Chan and Zoback, 2007). The Gulf of Mexico basement has been sinking since the rifting of Pangea about 175 million years ago (Galloway, 2011) and will continue into an indefinite future. The ancestral Mississippi River has been draining central North America into the Gulf of Mexico since at least the Late Cretaceous (Coleman, Roberts, and Stone, 1998). The modern drainage basin took shape during the Plio-Pleistocene with the capture of the Missouri and Ohio rivers (Galloway, Whiteaker, and Ganey-Curry, 2011). Presently, an average of estimates for total sedimentary column thickness beneath the Mississippi River delta complex is 19,000 m (62,000 ft) (Galloway, 2011; McBride, 1998; Nelson *et al*., 2000).

Mathematical modeling is the only tool available to estimate the magnitude of the adjustments. Ivins, Dokka, and Blom (2007) concluded that the subsidence rate due purely to the load of sediments varies between 1 and 8 mm/y (0.04 and 0.31 in/y) along the Mississippi Valley.

By analogy to isostatic adjustment to ice load, models predict that a decrease in the amount of sediments depositing in the Gulf of Mexico should reduce the rate of subsidence because of the reduction in contributed sediment weight (*e.g.*, Reed and Yuill, 2009; Yuill, Lavoie, and Reed, 2009). Because of the delayed response to such change, we postulate that reduction in sedimentary isostatic adjustment should take several centuries or millennia before having any noticeable effect.

Sediment Compaction

Sediment compaction is the first postdepositional step before lithification (van Asselen, Stouthamer, and van Asch, 2009). When sediments are initially deposited on the seafloor, they consist of approximately 50–75% water, with some clay layers containing up to 90% water. This water is expelled as the load of successive sediments compresses the underlying beds reducing the pore space, and consequently, the height of the sedimentary column shrinks. With aqueous sedimentary processes, 90% of the compaction takes place in the uppermost few meters of the sedimentary column, but the process continues for an extensive time at a decreasing rate with depth (Boesch *et al*., 1994). Figure 9 summarizes the likely compaction rates for southern Louisiana Holocene sediments, which should account for most of the total compaction. For example, if it took 10,000 years to accumulate sediments that today are 50 m (164 ft) thick, there is a 90% probability that the true compaction factor is less than 1.3 mm/y (0.5 in/y) and a 10% probability that it is less than 0.25 mm/y (0.01 in/y). These theoretical values are in agreement with experimental values

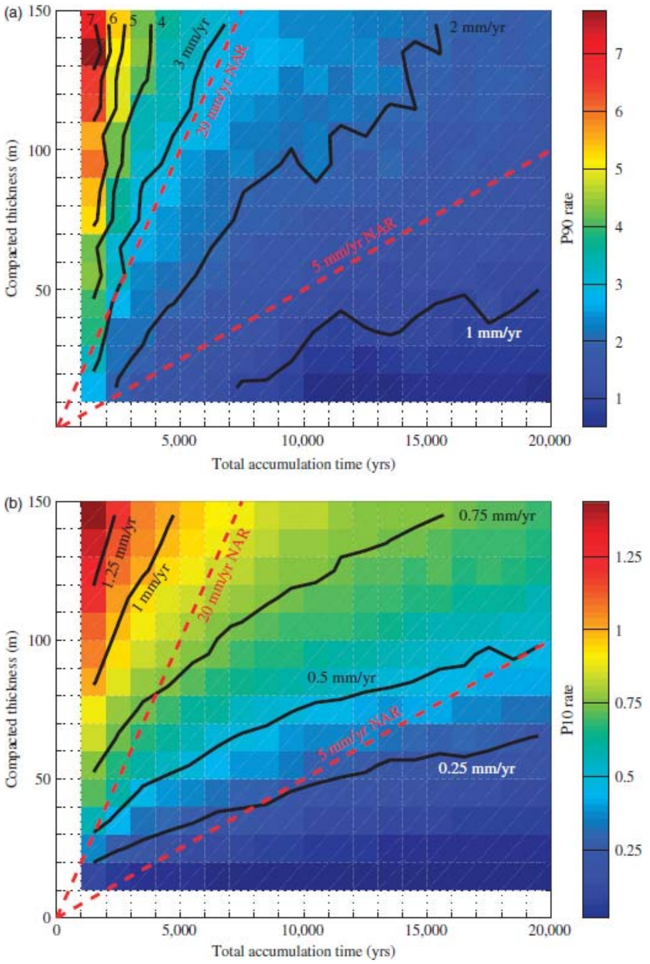

Figure 9. Holocene compaction rates from a probabilistic model. The rates can be read either from the black lines or using the color scales. The net accumulation rate (NAR) is the ratio of compacted thickness over the total accumulation time. (a) Value that has a 90% probability of being less than the real value (90th percentile); (b) 10th percentile (Meckel, ten Brink, and Williams, 2007). (Color for this figure is available in the online version of this paper.)

derived by Törnqvist *et al.* (2008), who, on the basis of chronostratigraphic studies of peat deposits, obtained average values of up to 5 mm/y (0.2 in/y) for sequences comprising about 1400 years of sedimentation.

Much higher rates of sediment compaction have been measured over short periods of time. For example, Cahoon, Reed, and Day (1995) report average compaction rates of 4–24 mm/y (0.16–0.94 in/y) during 2 years for the top 4 m (13 ft) of soils in coastal marshes, where the oxidation of organic matter plays an additional important role. Kuecher (1995); Meckel, ten Brink, and Williams (2006); and Törnqvist *et al.* (2008) consider compaction the dominant component of subsidence in southern Louisiana and the Mississippi River delta complex.

Active Normal Faults

Active normal faults are those extensional fractures between crustal blocks considered to have experienced displacement in the near geologic past and present. Surface geology and seismic profiles indicate the existence of numerous faults in southern Louisiana south of a hinge line intersecting the Mississippi Valley roughly at Baton Rouge (Figures 7 and 10), developed as part of the natural adjustments of the sediment load and of salt migrations (Berman, 2005a; Dokka, 2011; Gagliano, 2005).

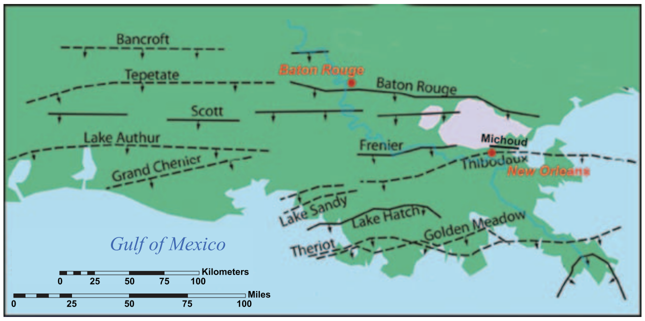

Figure 10. Surface traces of major faults in southern Louisiana (modified from Yuill, Lavoie, and Reed, 2009; Michoud Fault trace generalized from Edrington, 2008). (Color for this figure is available in the online version of this paper.)

Older basement rocks contain faults of late Triassic to Late Jurassic age, which were active during the formation of the Gulf of Mexico basin and are thought to be predominantly inactive today (Reed and Yuill, 2009; Yuill, Lavoie, and Reed, 2009). Current active faults are regarded as an important mechanism for the increasing subsidence seaward as a result of a cascading effect. Normal faults and local faults resulting from diapirism, although present throughout southern Louisiana, are not as significant in creating accommodation space as growth faults associated with the prograding of the sediments toward the south (Figure 4). Most of the displacements along these faults do not generate significant earthquakes (U.S. Geological Survey, 2012) because of the soft, plastic nature of the sediments, which may allow a displacement in slow motion rather than the sudden displacements associated with violent earthquakes occurring from the displacement of rigid rocks (Dokka, Sella, and Dixon, 2006). Sudden displacements that have occurred in the region merely shook windows and rattled doors but did not cause major damage (Stevenson and McCulloh, 2001).

Dokka (2006), Gagliano (2005), and Gagliano *et al.* (2003) believe that faulting is a dominant cause of subsidence in southern Louisiana. Dokka (2006), working in areas away from oil and gas production fields, detected a vertical displacement of up to 23.7 mm/y (0.93 in/y) at the Michoud fault east of New Orleans to which he assigned a tectonic origin (Figure 10).

Peripheral faults around salt domes may create local areas of subsidence as the crestal areas collapse from a combination of relative salt buoyancy causing uplift at the dome crest and hydrologic instability in areas around salt diapirs. Most diapirs, however, are to the south in offshore coastal Louisiana (Figure 4; Garrity and Soller, 2009).

Some authors have postulated that production depressurization of Gulf Coastal Plain hydrocarbon reservoirs may also trigger fault displacements, which may further accelerate local subsidence (Morton, Bernier, and Barras, 2006; Morton, Purcell, and Peterson, 2001; Wang and Nance, 2002; White and Morton, 1997). Hydrocarbon reservoir depressurization and fault displacement have been clearly demonstrated in several Gulf Coast oil and gas fields; however, fault displacement from reservoir depressurization throughout the entire plane of the fault has not been clearly demonstrated (Gagliano, 2005). Directly linking observations of the two phenomena remains conjectural at the present.

Sediment Supply Reduction and River Confinement

Although construction of minor levees around New Orleans dates back to the 1700s, massive federal engineering efforts to manage the Mississippi River did not start until the early 1900s (*e.g.*, Horowitz, 2010) and expanded after the great flood of 1927 (Barry, 1997). The Mississippi River is the dominant sediment supplier for coastal Louisiana, transporting an estimated 500 million metric tons (550 million short tons) of sediments every year toward the Gulf as recently as 60 years ago (Figure 11) while, in the account of Wang and Adrian (1998), simultaneously experiencing a reduction in mean grain size. Reduction in sediment transport by about 60% and severe interference of its dispersal are the result of engineering modifications throughout the entire basin of the Mississippi River and its tributaries by dams, meander cutoffs, river-training structures, and bank erosion controls (Alexander, Wilson, and Green, 2012; Allison and Meselhe, 2010; Heimann, Sprague, and Blevins, 2011; Meade and Moody, 2010). At the time of these construction projects, the trade-offs of confining the river to its banks and thus decoupling the river from the delta it had created were not properly understood (U.S. Army Corps of Engineers, 2008). As seen in Figure 11, the current suspended sediment load continues to decline and is below the average load responsible for the building of the delta during the Holocene, a factor that contributes to the acceleration of transgressive stages of the delta complex (Coleman, Roberts, and Stone, 1998; Horowitz, 2010). Bedload transport of sediment in the sand particle range in the Mississippi River may account for 4–11% of total load depending on the discharge rate (Allison and Meselhe, 2010).

Confirming sediment starvation, Allison *et al.* (2007) has measured masses of accumulated sediments amounting to one-third to one-half of sediments deposited on the continental shelf southwest of the Birdfoot before about 1946. To worsen the situation relative to past sediment supply (Figure 8), most of the reduced load of sediments flowing through the Birdfoot ends up being deposited in deep waters near or beyond the continental shelf, contributing to the deterioration of existing parts of the delta complex above sea level (Corbett, McKee, and Allison, 2006; National Research Council, 2008; Winer, 2011).

Theoretically, in a subsiding delta environment, the volume of sediment and organic matter accumulating in the deltaic deposits must at least compensate for the subsidence to have a stable wetland. In southern Louisiana, this assumption is confirmed by the Atchafalaya River delta complex, where higher than average sediment supply in recent decades has been creating the only significant coastal prograding area in the entire Mississippi River delta complex (Rosen and Xu, 2013).

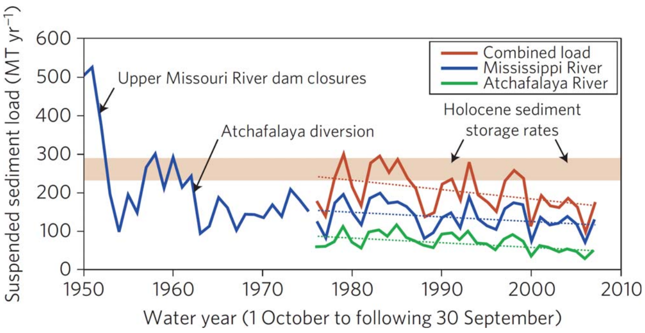

Figure 11. Suspended sediment supply in the Mississippi river (Blum and Roberts, 2009). The Holocene sediment storage rate in this figure is an equivalent historic rate derived by dividing the estimated total load of Holocene sediments in the basin (2530–3130 billion metric tons or 2790–3450 billion short tons) by the length of the period (12,000 y). (Color for this figure is available in the online version of this paper.)

The need to restore the flow from the Mississippi and Atchafalaya rivers into the coastal wetlands of southern Louisiana is becoming an increasingly necessary step to boost the natural capacity needed to build and preserve wetlands (*e.g.*, Boesch *et al.*, 1994; CPRA, 2012; Day *et al.*, 2007; National Research Council, 2008). In the presently controlled system, despite best efforts, most of the sediments that reach the wetlands come in suspension after major continental storms or large volumes of upper drainage spring melt runoff, along with nutrients and freshwater that contribute to increase organic productivity and reduce salinity (Stockstad, 2006; Törnqvist *et al.*, 2007; Turner *et al.*, 2006a, 2007). Unfortunately, major storms also produce significant beach and marsh erosion, offsetting the benefits of this increased sediment load to coastal wetlands (Barras, 2006, 2009; Törnqvist *et al.*, 2007).

Erosion

Erosion is the net removal of the Earth's crustal material, either through physical or biological transport, and may be closely associated with concurrent chemical reactions (weathering). The observed effect of all the putative causes of land loss results primarily in an apparent erosion. Whether losses are indeed the indirect results of eustatic changes, land subsidence, or true erosion can be difficult to nearly impossible to differentiate.

One of the few undisputed causes of true erosion is major storms, particularly hurricanes. Most likely, they have been affecting the region throughout the Holocene, and yet, the coast of southern Louisiana accreted land until recent times (Figure 12) (Britsch and Dunbar, 1993; Dokka, 2011; Ko and Day, 2004). This indicates that storms and hurricanes, as damaging as they can be to communities and infrastructure, are not significant contributors to long-term land loss in the region per se. As mentioned above, impact of major storms and hurricanes is a process producing a redistribution of sediment rather than contributing to long-term land loss. For example, following hurricanes Katrina and Rita of 2005, Turner *et al.* (2006a,b) measured 5–10 cm (2–4 in) of inorganic sediments deposited over 57% of the Louisiana coastal wetlands—8200 km^2 (3200

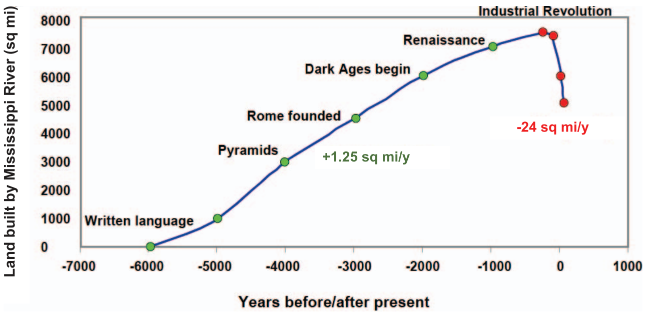

Figure 12. Historical expansion of Louisiana coastal land (after Working Group for Post-Hurricane Planning for the Louisiana Coast, 2006). (Color for this figure is available in the online version of this paper.)

mi^2)—accounting for 131 million metric tons of sediment deposition, equivalent to about 60% of the weight of suspended sediments transported by the Mississippi River during an entire year. The land loss as a direct consequence of these hurricanes was reported to have been 562 km^2 (217 mi^2) (Barras, 2006). The Atchafalaya delta complex offers recent and well-documented evidence supporting the possibility of delta growth despite the effect of storms and hurricanes. Even with partial setbacks, particularly by Hurricane Lili in 2002, adequate sediment supply has allowed a net coastal land gain of 59 km^2 (23 mi^2) between 1989 and 2010 (Rosen and Xu, 2013).

The average frequency of hurricanes of at least Category 3 impacting the Louisiana coast since 1879 has been 7.88 years (Turner *et al.*, 2006a). With no technology in sight to prevent hurricanes, the development of incremental coastal defenses seem to be the only plausible course of action to ameliorate weather related coastal destruction (U.S. Army Corps of Engineers, 2008), although this approach has been declared futile by the National Research Council (2008) and Pilkey and Young (2009) because of the significant influence of ongoing subsidence and eustatic changes affecting southern Louisiana.

Canal Construction

Canals have been constructed throughout southern Louisiana for navigation, pipelines, and worksite access by boat or barge since the late 18th century (Ko and Day, 2004). Increasing human presence in Louisiana has resulted in the development of about 16,000 km (10,000 mi) of navigational routes that directly or indirectly have been linked to deterioration of the ecosystem and to subsequent wetland losses (Day *et al.*, 2007). The state of Louisiana, however, did not start keeping track of canal dredging activities until 1982 (Turner, 1997), contributing to the difficultly in assessing the situation (Bjerstedt, 2011).

Barge-mounted draglines were first used in 1938 to construct canals to enable barge-mounted drilling rigs to reach oil and natural gas drilling locations. Each drilling location required its own access canal because high-deviation directional drilling had not been developed and perfected before the peak of coastal Louisiana drilling activities in the 1970s. When the exploration well was successful, additional development wells were drilled in the general area of the established field. Areas around failures, or dry holes, might be abandoned for decades, only to be reoccupied if newly recognized potential was targeted for additional drilling. Once dug, these canals rarely fill in with sediment and remain open for years.

Once a field has been defined and determined to be economically viable, a pipeline canal is usually dug and one or more pipelines are laid connecting the field to main distribution lines, including production coming from offshore (Bauman and Turner, 1990). When pipeline trenches are not backfilled, they can become part of an informal, regional transportation waterway throughout the coastal marshlands (Lopez, 2003). With renewed activity along a canal, dredging may deepen, widen, or lengthen a canal. Studies indicate that annual land loss in Louisiana coastal plain extends 30–150 m (98–490 ft) to either side of pipeline canals, equivalent to 0.1–0.5 km^2 (25–125 acres) of wetland loss per 1.6 km (1 mi) of construction (Johnston, Cahoon, and La Peyre, 2009; Tabberer *et al.*, 1985). In the opinion of Boesch *et al.* (1994), widening, dredging, and opening artificial canals plus improperly disposing spoil materials directly accounted for 16% of the wetland losses between 1955 and 1978.

In general, canals result in intrusion and entrapment of salty water, disruption of the natural dendritic drainage system with an associated impoundment of areas behind the canal spoil banks, and modification of tidal flooding (Day *et al.,* 2000; Ko and Day, 2004). These indirect effects would be responsible for an additional 30–59% of the losses in the period (Boesch *et al.* 1994), which would explain the acceleration of land loss during the 1970s and 1980s (Figure 1). In July 2013, the Southeast Louisiana Flood Protection Authority sued about 100 oil and gas companies to force them to restore the wetlands more aggressively by repairing damage done in the construction and use of well site access roads and pipeline canals since the 1930s, prompting a countermanding reaction from the governor (Mufson, 2013).

Restrictions in canal construction plus technical advancements in drilling technology have resulted in significant reduction in the digging of open trenches in the coastal wetlands of southern Louisiana. In most instances, modern pipeline trenches are required to be backfilled after construction and pipeline installation (Russo *et al.*, 1998). Abandonment of canals tends to be followed by wetland recovery when the reclamation includes not only refilling of the trench but also elimination of the spoil bank levee to promote the restoration of natural water circulation (Turner and Cordes, 1987). Regardless, the recovery of the coastal wetlands from this construction activity is slow (Baustian *et al.*, 2009).

Oil and Gas Production

Oil and gas production in south Louisiana usually comes from reservoirs between depths of about 760 m (2500 ft) and potentially more than 9000 m (30,000 ft). Because of high porosity and permeability in most southern Louisiana reservoirs, fields are produced at the maximum allowable rate until they are no longer economic. The first discovery of Louisiana oil in commercial quantities occurred at Jennings Salt Dome in the Acadia Parish in 1901 (Louisiana Geological Survey, 2001), just nine months after a similar discovery at Spindletop Dome in southeast Texas near the Louisiana border. Since then, at

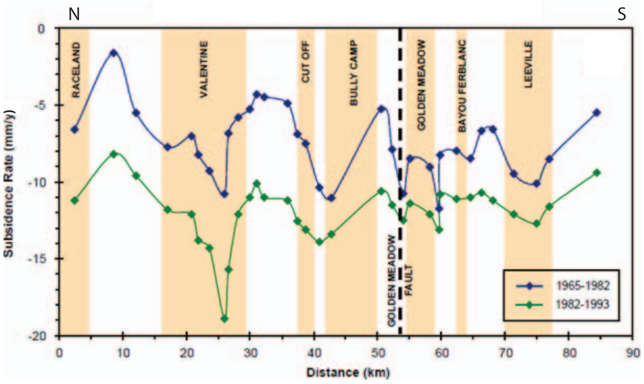

Figure 13. North–south subsidence profile prepared using data by Shinkle and Dokka (2004) along a leveling line following highway LA 1 in Lafourche Parish (Morton *et al*., 2005). Shading denotes vertical projection of an oil and gas field. (Color for this figure is available in the online version of this paper.)

least 1174 fields have been discovered in the south Louisiana onshore and state waters (LOSCO, 2007). Particularly offshore, these fields are on or around salt domes.

As seen in a number of instances, both theory and practice point to the feasibility of inducing fluctuations in land elevation with the injection or production of fluids from the subsurface (*e.g*., Colazas and Strehle, 1995; Hannis, 2010; Mallman and Zoback, 2007). Assuming no intervention is made to maintain reservoir pressures at near original levels, rates of local subsidence over a field should be directly related to production rate and inversely related to the overburden thickness and the mechanical capacity of the overburden to withstand flexure.

Miller (2006); Morton, Bernier, and Barras (2006); Morton, Buster, and Krohn (2002); Morton, Tiling, and Ferina (2003a,b); and Morton *et al*. (2005) have conducted extensive studies to demonstrate that the main cause of loss of land in Louisiana is not erosion but subsidence related to oil and gas production. Miller (2006) examined four fields in southeast Louisiana and concluded that maximum subsidence occurred during the time of greatest petroleum production in the study area (1964–1981). He recognized that "this temporal association does not establish a direct causal relationship between hydrocarbon production and land subsidence" (Miller, 2006, p. 589). On the basis of these assumptions and calculations, Miller (2006, p. 584) concluded that total surface subsidence from petroleum production from fields with stacked reservoirs "could be on the order of a few inches."

Figure 13 is part of several cross sections, maps, and production time series that Morton and others (*e.g*., 2002, 2003a,b, 2005, 2006) have published in the literature as evidence for their conclusions. The entire cross section runs along the Lafourche Parish portion of Louisiana highway LA 1 between Raceland to 8 km (5 mi) past Leeville (see Figure 2). Production comes from moderate depths between 1800 and 3700 m (5900–12,100 ft) (Mallman and Zoback, 2007). The style of subsidence in this selected example is the same on both sides of the fault instead of being larger on the south side of the fault, which is contrary, at least in this case, to the claim that production of oil and gas activates faults (Morton *et al*., 2006).

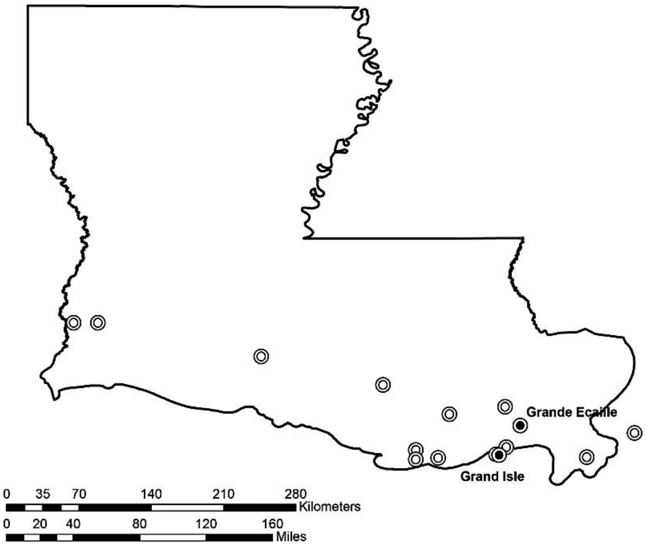

Figure 14. Sulfur extraction locations in Louisiana examined for this study (those sulfur extraction locations mentioned in the text are annotated and highlighted with a solid black inner circle).

Additionally, it is our observation that not all extreme negative values coincide with the fields, the exceptions being Golden Meadow and Bayou Ferblanc. Three of the extreme negative values are above the Raceland, Valentine, and Leeville fields, but an equal number are in between fields, accounting for a less than perfect correspondence between extreme subsidence areas and field locations. The more extreme subsidence rate after 1982 of about 5 mm/y (0.2 in) is fairly uniform across the entire cross section and occurred during a period of declining production. The inconsistency has been explained by invoking a delayed response to the increase in production that took place earlier in the 1960s and 1970s. Although this possibility has been reported in the literature (*e.g*., Hettema, Papamichos, and Schutjens, 2002), such an explanation fails to explain why the curves in Figure 13 basically parallel each other. An increase in subsidence due solely to increase in fluid withdrawal should have resulted in deteriorations only above the fields, leaving the intermediate zones unaltered. The reality is that the entire lower 17 miles of highway LA 1 south of Golden Meadow progressively has been inundating for decades (Eilperin, 2012).

Using mathematical modeling, Chan and Zoback (2007) were able to reproduce surface subsidence of only one-third of the observed subsidence over the Lapeyrouse Field located in the Terrebonne Parish (see Figure 2) and none of the subsidence away from the field. Mallman and Zoback (2007, p. 447) reached similar conclusions, saying that reservoir compaction likely has an effect on the subsidence of the immediate area around the fields studied, "but cannot account for the entire regional subsidence signal."

Currently, a standard procedure in the long-term field management of high–flow rate reservoirs, especially oil reservoirs, is to inject fluids (usually co-produced brines) into the downdip portions of the reservoir to maintain pressure and hydrocarbon fluid composition. This activity substantially

Table 2. *Likely causes of Louisiana coastal subsidence.*

Process	Origin	Rate (mm/y)	Impact	Evidence
Global sea level rise	Under discussion	1.7; 1–19 by 2100	Global	Gauge records
Glacial isostasy	Natural	0–0.55	Basin-wide	Theoretical
Sedimentary isostasy	Natural	1–8	Basin-wide	Theoretical
Sediment compaction	Natural	Up to 5	Basin-wide	Theoretical and empirical
Faulting	Mostly natural	Up to 24	Regional	Seismic profiles
Oil and natural gas production	Anthropogenic	0–20	Local	Theoretical and empirical
Sulfur production	Anthropogenic	0–900	Local	Empirical
Groundwater withdrawal	Anthropogenic	0–20	Local	Empirical

helps to reduce subsidence directly caused by reservoir pressure depletion and reservoir compaction.

Dubiel *et al.* (2007, 2011) have estimated that, in addition to field growth within the existing fields, there are significant amounts of oil, gas and natural gas liquids yet to be discovered in southern Louisiana. Miller (2006) and Morton *et al.* (2006) suggest that most of the subsidence within fields in southern Louisiana has occurred and that future exploitation will likely not induce substantially additional subsidence. However, their conclusions, as well as those of the U.S. Geological Survey's Tertiary oil and gas resource assessment (Dubiel *et al.*, 2007), were established before data were received from the recent, high-pressure, high-temperature gas discoveries in the "Deep Shelf" gas exploration play in shallow waters along the U.S. Outer Continental Shelf (OCS) and Louisiana state waters boundary. This play that is currently being extended onshore into southern Louisiana. Established full production from this new play within Louisiana state waters and wetlands may substantially affect these areas in the event that development does not follow established best management practices.

Groundwater Pumping

As in the case of oil and gas, withdrawal of groundwater in volumes larger than the aquifer recharge may induce land surface subsidence. In general, it takes smaller volumes of water than volumes of oil and gas to induce the same subsidence rates because aquifers are closer to the surface.

The most famous case in the Gulf Coast is that in the greater Houston, Texas, area. Over the last 100 years, an area of 3200 mi^2 (8300 km^2) surrounding Houston and extending to Galveston Bay has subsided at least 0.3 m (1 ft), with a maximum subsidence of 3 m (10 ft) (Stork and Sneed, 2002). Although there are numerous small oil and gas fields in the area, the main cause of the subsidence has been attributed to groundwater pumping (Holzer and Bluntzer, 1984; Holzer and Galloway, 2005).

Dokka (2011) has reported high subsidence rates in the New Orleans area for benchmarks anchored to upper Pleistocene strata that are free of the effects of compaction of the more recent sediments, although still subject to faulting and lithospheric flexure. Based mostly on circumstantial evidence, Dokka (2011) concludes that a land subsidence of 0.8 m (2.6 ft) from 1955 to 1995 was the result of high rate pumping of an aquifer 160–200 m (525–650 ft) deep.

Sulfur Production

Of the 45 onshore salt domes in south Louisiana, 15 have experienced sulfur mining via the Frasch process (Figure 14), a process of drilling into a salt dome caprock and injecting superheated water and hot air to liquefy, froth, and recover the sulfur to the surface (Morse, 1985).

Frasch mining began in Louisiana in 1895 but did not begin to grow into a major industry until 1933 when the Grande Ecaille mine was started in southeast coastal Louisiana (Kyle, 2002). By 1952, the use of salt water for injection in place of scarce fresh water opened up all of southern Louisiana's onshore and offshore salt domes for exploration and economic mining of sulfur. Sulfur mining in coastal Louisiana ceased in 2000 (David Singleton, 2012, *personal communication*).

Large volumes of sulfur were extracted at each of the 15 Louisiana sites, with large rates of subsidence during the extraction years. Synthesized data are not available for southern Louisiana, but Mullican's (1988) study of Texas salt domes found that, of the 14 salt domes having Frasch sulfur production, 12 showed evidence of subsidence and collapse. In one instance, the crest of Boling Dome, about 70 km (45 mi) southwest of Houston, Texas, dropped 11 m (35 ft) as a combined result of sulfur production (83% attributed subsidence) and oil and gas production (11–12% attributed subsidence) for an average of almost 890 mm/y (35 in/y) (Mullican, 1989). At Grand Isle Sulphur Mine, offshore Grand Isle, state waters, Louisiana, approximately 21 m (70 ft) of subsidence occurred between initial production in 1960 and 1988 for an average rate of about 760 mm/y (30 in/y) (Hunt, 1988). Other empirical evidence shows that substantial subsidence has occurred over a number of other southern Louisiana salt domes as well (see Morton *et al.*, 2005). This subsidence is restricted to the area above and peripheral to the mined salt domes. By and large, the effect of salt dome sulfur mining may be significant in subsidence magnitude, but it was quite local in extent.

Table 3. *Wetland loss causes not directly causing subsidence.*

Process	Origin	% of Total	Impact	Evidence
Canal construction	Anthropogenic	16–75	Local	Empirical (air photos)
Flood control	Anthropogenic	High	Basin-wide	Theoretical and empirical
Delta relocation	Natural	None	Local	Historical and empirical
Storms and hurricanes	Natural	Net of 0	Coastal	Historical and empirical

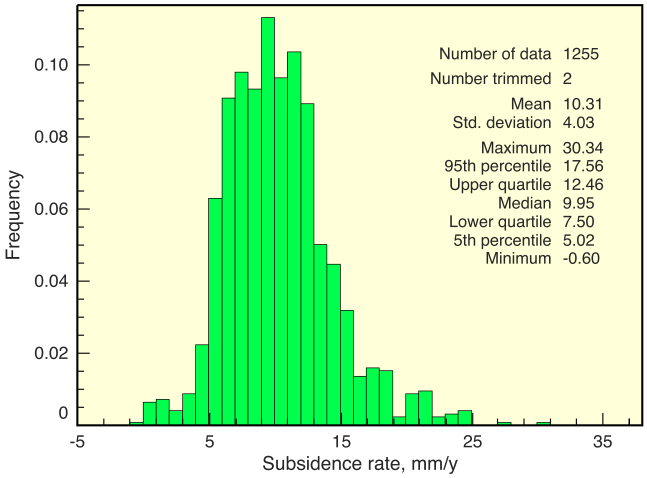

Figure 15. Subsidence rates in southern Louisiana from 1980 to 1996 according the geodetic survey conducted by Shinkle and Dokka (2004). (Color for this figure is available in the online version of this paper.)

MONTE CARLO SIMULATION OF COASTAL SUBSIDENCE IN LOUISIANA

Tables 2 and 3 summarize the opinions mentioned above by the leading experts in the different processes, separating wetland loss causes into subsidence and other factors. In these tables, a sea level moving away from the center of the Earth is a positive increase, whereas a subsidence rate is positive when the land surface moves toward the center of the planet. Subsidence and sea level rising have been the land loss causes with continuous effect through time and space at least for the last 80 years with better records. Other factors seem to have had a more local or temporary influence.

Validation of Historical Subsidence Rates

Given the dominant influence that multiple sources of subsidence have had on land losses in southern Louisiana, clarifying their magnitude and relative importance is an important step toward understanding the ultimate causes of the observed consequences.

Comparison of all causes of subsidence against the measurements by Shinkle and Dokka (2004) allow a good check for consistency between partial causes and total recorded effect. Subsidence associated with sulfur extraction, although quite significant when present, has too local an expression to be a significant factor in subsidence at the state level. The fact that the survey did not detect the high values of subsidence typical of sulfur extraction is another reason to exclude this factor from the comparison. Subsidence by excessive pumping of groundwater is also localized and a factor with a less certain significance. Canal construction has been directly and indirectly associated with wetland loss, but not to subsidence.

Figure 15 summarizes subsidence for southern Louisiana using a subset of the data in Figure 5 after reversing the sign convention. Southern Louisiana was defined as the portion of the state south of 31° N, the parallel that is the east–west boundary between Mississippi and Louisiana (Figure 2), thus coinciding with the definition for south Louisiana in the production data by Nehring Associates, Inc. (2011), necessary for the comparison. Additionally, the subsidence rates were restricted to those base years post-1979 to avoid potentially less reliable earlier leveling, to minimize the temporal fluctuation in the rates (Shinkle and Dokka, 2004), and to operate with the values that should be the most similar to the rates in recent years.

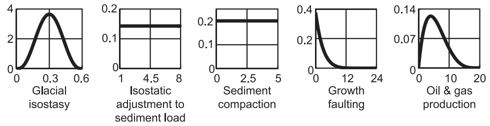

Figure 16. Probability distributions for the likely causes of subsidence. All rates in the abscissae are in mm/y; the units for probability density function in the ordinates are the inverse of those of the variables (y/mm).

A stochastic aggregation of multiple sources is the most convenient form of validation when all the intervening factors are vaguely defined. Figure 16 shows the probability distributions characterizing the likely ranges of subsidence rates in Table 1. The forms of the distributions were determined according to the expected style of variation. In the case of glacial isostasy, we consider that the extreme values are equally less likely than the intermediate values; we regard all values as equally plausible for sedimentary isostasy and compaction, whereas we perceive the other two factors (faulting and oil and gas production) as being positively skewed; that is, small values are relatively more frequent than large ones. The Monte Carlo method is an increasingly popular approach for numerically modeling processes involving probability distributions, as an alternative to the traditional but more demanding analytical approach (*e.g.*, Kalos and Whitlock, 2008). The Monte Carlo method was used to generate subsidence values synthetically by drawing one value from each distribution and adding them together. The process was repeated as many times as the number of measurements to have datasets of the same size (Figure 17). Data extracted from Nehring Associates, Inc. (2011), indicate that the area of the onshore oil and gas fields in south Louisiana by 2004 was 9% of the geographical extent of onshore south Louisiana as defined in the previous paragraph. Thus, subsidence due to the existence of an oil and gas field in the subsurface was considered in only 9 out of 100 draws.

The possibility to reproduce synthetically the subsidence rate according to geodetic surveys implies that (1) the likelihood that the agreement in rates between the postulated subsidence factors and measurements is coincidental is quite low, (2) the ranges of variations established by the experts for each factor appear to be realistic, (3) the geodetic survey of Shinkle and Dokka (2004) is consistent with the subsidence mechanisms independently postulated by other scientists, and (4) the likelihood that all factors in Figure 16 are components of the total subsidence cannot be rejected.

Figure 18 displays the contribution of each subsidence factor to the simulation histogram in Figure 17. As expected, the least influential factor is glacial isostasy. Sediment

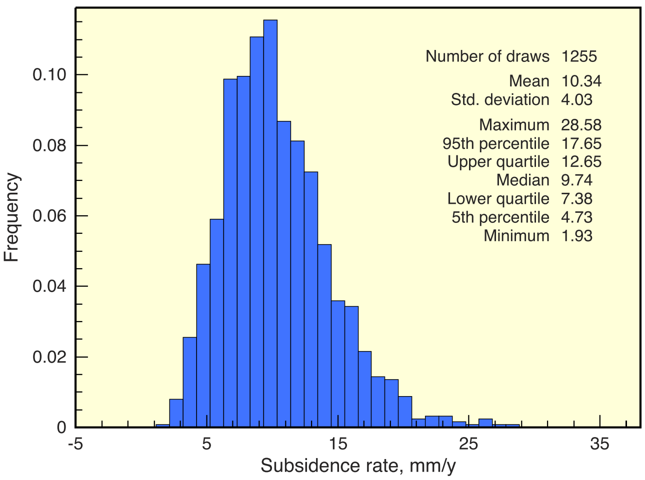

Figure 17. Simulated ground subsidence according to the distributions in Figure 16. (Color for this figure is available in the online version of this paper.)

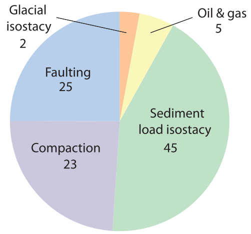

Figure 18. Percentage of relative contribution by factors to subsidence in southern Louisiana. (Color for this figure is available in the online version of this paper.)

compaction and growth faulting, on the other hand, are significant subsidence factors. Based on the modeling results by Ivins, Dokka, and Blom (2007), isostatic adjustment to sediment load has come up as the dominant factor. Interestingly, this was the very first cause of subsidence postulated in the pioneering work of Russell (1936). Finally, despite its second largest maximum rate, depletion of oil and gas fields comes second to last with a contribution of 5%. This is primarily a consequence of the fact that only 9% of southern Louisiana is over hydrocarbon fields, which dilutes the overall regional influence of this factor.

Lithostratigraphic flexure (sediment load isostacy) and faulting, the two main causes of regional subsidence (Figure 18), are independent of surface conditions and also are four out the five factors. Consequently, subsidence along highways should not be much different from that of the surrounding terrain, thus making a minor consideration the fact that the geodetic survey of Shinkle and Dokka (2004) was mainly conducted along roadways. Figure 19 illustrates the point for an area around the southern end of Louisiana Highway 1.

Epilog: Extrapolations into the Future

Attention above is on the past. In addition to the scientific curiosity about the possible future effects of ongoing processes, there is a pressing need to formulate scenarios of possible land loss outcomes for the southern Louisiana coastal area at least until the end of the 21st century. Extrapolation of temporal data into the future can be accomplished through the use of time series analysis (*e.g.*, Box, Jenkins, and Reinsel, 2008). This widely accepted and applied mathematical method presumes that the data, such as that shown in Figure 1, contains a structure that is used to expand the series beyond the last measurement. In applying time series analysis to the results presented in this paper, except for the period of 1974–1988, we determined that the decadal rate of land loss has remained fairly stable at between 39 and 52 km^2/y (15–20 mi^2/y) during 1932–2011. At those rates, additional coastal land loss in southern Louisiana by 2100 could total as much as an additional 3367–4532 km^2 (1300–1750 mi^2).

The accuracy of such time series forecasts may become compromised when changes occur in the behavior of factors controlling the time series (*e.g.*, Silver, 2012). With the exception of the anthropogenic oil and gas production, the natural causes of land subsidence in Figure 18 are known to act at scales of thousands to millions of years. Consequently, no major changes affecting subsidence rates are expected from this category of causes during the 21st century.

With respect to the effect of anthropogenic causes of subsidence on coastal land loss, there is potential for improvement. There have been favorable improvements in terms of minimizing the number of well sites needed to develop oil and gas fields and in terms of pressure maintenance, which has become a paramount consideration for maximizing production efficiency. In terms of impact at the state level, even if subsidence related to oil and gas production were completely eliminated, according to Figure 18, complete elimination of this form of subsidence will likely result in no more than a 5% reduction of subsidence and coastal land loss. Canal construction associated with oil and gas field developments has slowed significantly in recent years. Sulfur mining and groundwater pumping, never significant contributors to regional land loss, are substantially in decline or have ceased in coastal Louisiana.

We have left two factors for the end because they are the ones with the greatest potential to make a difference in extrapolating the past into the future: sediment load and sea level rise. According to Figure 12, land aggradation in central and eastern coastal Louisiana was consistent until the end of the 18th century, with an average gain of 3.2 km^2/y (1.25 mi^2/y). This implies that it would be necessary to restore the quantity, quality, and dispersion of the Mississippi River sediments to predevelopment levels to compensate for land subsidence and sea level rise with sediment filling capable of at least halting land loss across south Louisiana (Alexander, Wilson, and Green, 2012; Blum and Roberts, 2009, 2012; Paola *et al.*, 2011). Intermediate solutions might have intermediate effects. For example, in general terms, after restoring 50% of the loss predevelopment sediment load of 272 metric tons (300 million short tons) per year (Figure 11) and eliminating half the delta levees, revetments, and all other engineered structures, coastal

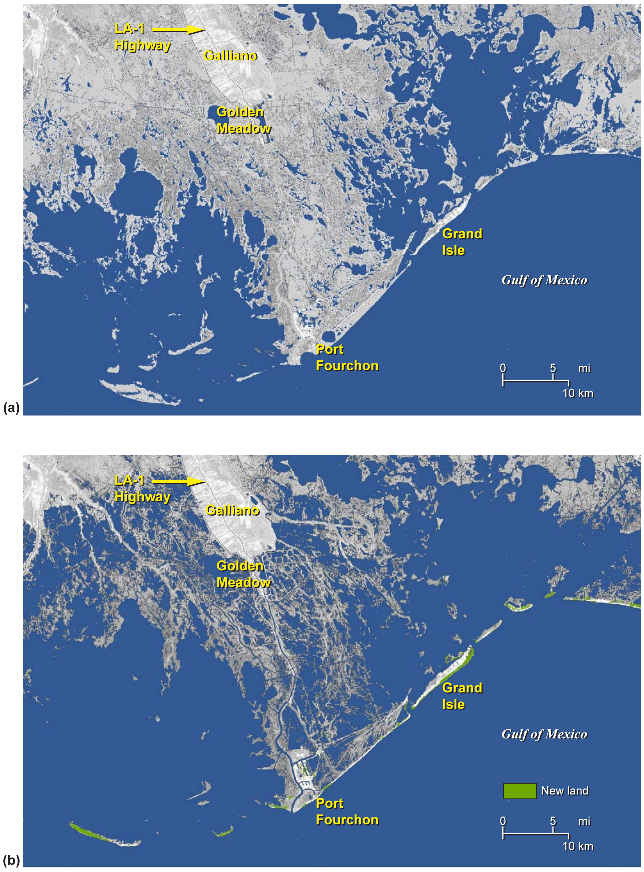

Figure 19. Aerial view around the southern end of Louisiana highway 1 to Port Fourchon: (a) 1932, (b) 2011 (after Gill, 2013). (Color for this figure is available in the online version of this paper.)

losses still would be on the order of 18–26 km^2/y (7–10 mi^2/y), all other factors remaining constant. A restoration of such magnitude is unlikely to take place.

This leaves eustatic change as the land loss cause with the highest potential to invalidate extrapolations of the rates in Figure 1. According to some of the predictions in Table 1, by the middle of the century, sea level rise may become a dominant cause of inundation, more critical than all other adverse factors combined together. The most favorable rates call for an increase slightly below a linear increase at a rate of 1.75 mm/y (0.07 in/y) (Houston and Dean, 2011a), which is basically equivalent to accepting without any correction the extrapolation of 3367–4532 km^2 (1300–1750 mi^2) of additional land loss by the end of the century. If any of the other predictions involving accelerated rates materialize, land loss will be higher. Figure 20 shows the fluctuations in areas under and above open water 50 years from 2012 assuming a sea level rise of 0.45 m (1.5 ft) and remedial action no more drastic than being undertaken at the present. The additional coastal losses would be comparable to those already reported in Figure 1 for the last 80 years (CPRA, 2012).

CONCLUSIONS

We have demonstrated in this paper that the observed subsidence in southern Louisiana can be reproduced synthetically using independently postulated subsidence factors. Results of the analysis indicate that the agreement between these factors and measurements can hardly be coincidental. The ranges of variations cited for each factor appear to be realistic. Most likely, all of the factors discussed herein and illustrated in Figure 16 are components of the total subsidence and no one factor controls the entire suite of subsidence effects.

Land loss along the coasts of Louisiana is the result of complex interactions between a combination of natural and anthropogenic factors. The main natural factors contributing to coastal land loss in southern Louisiana are lithosphere flexure as a reaction to sediment loading, faulting, and sediment compaction. All three causes result in subsidence that is of such large magnitude that its mitigation is beyond present technological capabilities. Despite these factors being active through the Holocene, southern Louisiana had a regressive coast up until the 1800s because the coastal subsidence was offset by deposition of sediment from the Mississippi River. As a result of the extensive engineering work completed along the entire Mississippi River catchment throughout the 20th century, there has been a severe reduction of sediment load and particle size reaching the coast of southern Louisiana, resulting in a reversal of this trend. The difficult task of increasing the sediment load reaching the coastal wetlands is at the core of all proposals to mitigate coastal subsidence in southern Louisiana. Conceivably, the positive side to this reduced sediment load from the Mississippi River is that the reduction in sediment weight should result in a decrease in subsidence due to isostatic adjustment. However, because of inertia, we are centuries to millennia away from observing such an effect.

In addition to the reduction of the sediment load delivered by the Mississippi River during the 20th century, the other most consequential factor affecting the stability of the Louisiana coast is the potential rise in sea level during the present century. According to middle-of-the-road predictions, by 2062 Louisiana will double the coastal land losses incurred from 1932 to the present mainly through a combination of geologic and eustatic causes.

According to our review and analysis, extraction of geologic resources has not been a dominant cause of the regional subsidence experienced along the Louisiana coast. Locally, the most impressive subsidence rates have been those associated with the extraction of sulfur, which ceased in 2000. Several sites of coastal Louisiana sulfur production were either far enough inland so as not to bring land under water per se, or located already in open waters. Oil and gas fields in south Louisiana cover a total area that is larger than that of sulfur mines but still represent only 9% of the area of southern Louisiana not covered by water. Several developments have contributed to reduce significantly threats by oil and gas production to wetland stability: (1) interest to maximize recovery has incentivized producers to inject fluids in the subsurface to preserve reservoir pressure until the field is abandoned, thus eliminating the primary cause of surface collapse; (2) most fields have production in decline; and (3) advancements in drilling now favor the practice of drilling

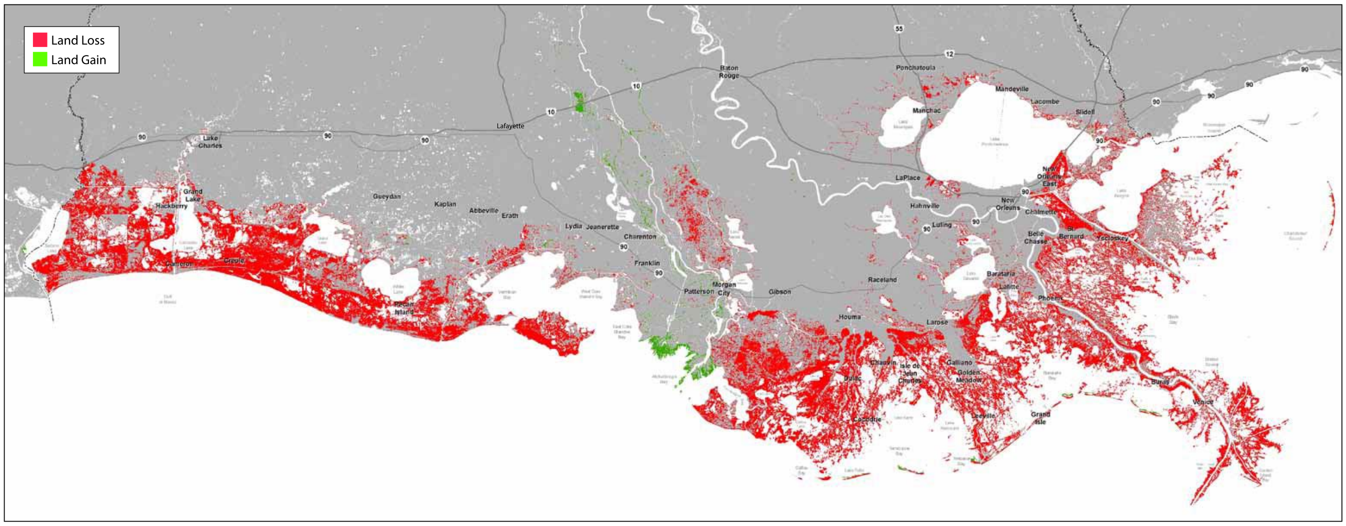

Figure 20. Coastal land changes by 2062 assuming a sea level rise of 0.45 m (1.5 ft) and no additional efforts to curve down present trends (modified from CPRA, 2012). Red = forecast land loss; green = forecast land gain. (Color for this figure is available in the online version of this paper.)

multiple wells from a single drill site, which significantly reduces the need for constructing canals. Pumping of groundwater for municipal and industrial uses remains as a miscellaneous cause of subsidence but is deserving of continued monitoring and evaluation to avoid creating a new locally significant form of subsidence.

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