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Review Article

Variable response of coastal environments of the northwestern Gulf of Mexico to sea-level rise and climate change: Implications for future change

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ABSTRACT

The results from nearly three decades of marine geological research in the northwestern Gulf of Mexico are compiled in an effort to understand those factors (e.g., sea-level rise, sediment supply, subsidence, antecedent topography) that influenced coastal evolution during the last eustatic cycle (~120 ka to Present). Armed with this information, we evaluate coastal response to variable sea-level rise of the Holocene and accelerated rise during historical time to gain a better understanding of how the coast is likely to respond to future changes.

The early Holocene evolution of northwestern Gulf of Mexico bays was punctuated by rapid and possibly synchronous flooding events that are interpreted as resulting from episodes of rapid sea-level rise. Two of these events, one between ~8.4 and 8.0 ka and the other between ~7.4 and 6.8 ka, were associated with known episodes of ice sheet retreat in North America and Antarctica, respectively.

During the middle and late Holocene, the east Texas and western Louisiana coasts experienced episodes of stability and growth followed by rapid shoreline retreat, while the central Texas coast remained relatively stable. This variability in coastal response to sea-level rise resulted mainly from differences in sediment supply and the highly irregular antecedent topography on which coastal environments formed. Sand that nourished the evolving east and south Texas, as well as westernmost Louisiana, coasts was derived mainly from transgressive ravinement of deltas that were formed during the falling stage of sea level (MIS5e–MIS2). The loci of these deltas controlled the spatial variability of this offshore sand supply. Sand supply to the central Texas coast has been dominated by converging longshore currents and throughout the middle to late Holocene was large enough to keep pace with sea-level rise. Moreover, sand supply from rivers has varied considerably in response to climate change. During the early Holocene, when the average rate of linear sea-level rise was 4.2 mm/yr, the Brazos, Colorado and Rio Grande Rivers all formed deltas on the inner continental shelf. Today, only the Brazos contributes enough sediment to the Gulf of Mexico to form a delta, but its sand delivery is minimal.

A reversal from late Holocene growth of western Louisiana–east Texas and south Texas barrier islands and peninsulas to erosion occurred during the last ~2.0 ka, after the rate of sea-level rise began to decelerate. The actual timing of this reversal was diachronous across the coast and was caused by a decrease in sediment supply once offshore sand sources were bypassed by the landward-advancing shoreface (transgressive ravinement). Differences in the exact timing and rate of retreat also reflect variability in the offshore profiles of these barriers and their thickness, which results from the underlying relief on the Pleistocene surface. The late Holocene was also the time of chenier plain development in western Louisiana and east Texas that was marked by localized differences in growth and retreat.

The current rate of eustatic sea-level rise in the northern Gulf of Mexico is in the range of 2.0 and 3.0 mm/yr and is approaching rates of the early Holocene. This is on average about five times the long-term rate of the past 4.0 ka. This larger rate is associated with an increase in coastal erosion in historical time relative to long-term rates. Current rates of Gulf shoreline erosion are approaching rates of the early to mid-Holocene and the rate of retreat of some barriers is not sustainable. Core transects off central Texas reflect a late Holocene history of shoreface progradation, but the modern shoreline is currently eroding, albeit at slower rates than elsewhere along the coast.

Overall, the sand supply needed to sustain the Gulf shoreline is lacking. Likewise, baylines are experiencing erosion rates that are faster than the late Holocene average and bayhead deltas are at the tipping point

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of catastrophic retreat. Spatial variability in erosion rates highlights the importance of factors such as sediment supply, subsidence, and anthropogenic influences on coastal evolution. Tropical storms and hurricanes, while exerting the most noticeable coastal change, merely exacerbate overall shoreline retreat and migration.
Along the entire northwestern Gulf Coast, the impact of human intervention to natural processes is particularly evident, primarily due to alterations in river discharge and sediment supply to the coast, interruptions in alongshore and cross-shore sand transport, and increases in rates of subsidence through fluid withdrawal. Compared to natural changes that took place during the Holocene, the impacts of human activity have been virtually instantaneous.
The geological record indicates that the ongoing increase in the rate of sea-level rise, coupled with diminished sediment supply and human intervention, will continue to severely impact the low-gradient coastal environments of the northwestern Gulf of Mexico.

1. Introduction

The most recent scientific results from satellite altimetry indicate that the rate of global sea-level rise averages ~3.0 mm/yr, although the actual rate varies regionally (Church et al., 2004; Rahmstorf et al., 2007; Carlson, 2011; Church and White, 2011; NRC, 2012). However, within the northwestern Gulf of Mexico, subsidence exacerbates relative sea-level rise with rates as high as ~10 mm/yr, although the current rate of rise is hard to constrain because of considerable variability in subsidence across the region (Paine, 1993; Kolker et al., 2011; Simms et al., 2013). Regardless of the actual value, this is a significant increase over the long-term rate of the past few thousand years of ~0.40 to 0.60 mm/yr (Törnqvist et al., 2004a, 2004b, 2006; Simms et al., 2007b; Milliken et al., 2008a; Livsey and Simms, 2013). The evidence for accelerated sea-level rise in the northwestern Gulf of Mexico is consistent with results from the east coast of the US, which show that the rate of rise since the 19th century has significantly increased relative to the past few millennia (Engelhart et al., 2011; Kemp et al., 2011). It is generally accepted that the rate will continue to accelerate during the 21st century, but the actual magnitude of rise remains problematic due to uncertainty about the contribution of water from the Greenland and Antarctic Ice Sheets. An increased contribution appears more and more likely as our understanding of the state of these ice sheets increases (e.g. Rignot et al., 2011).

Current predictions about the impact of rising sea level on coasts rely largely on simple inundation models where the landscape elevation is flooded as sea level rises (e.g. NOAA, EPA). These models fail to capture the complex response of coastal systems to sea-level rise because they ignore changes in sediment accommodation, accretion, and erosion. There is general agreement among coastal scientists that we are still ill prepared to predict coastal response to accelerated sea-level rise and to other factors related to Global Climate Change, such as variations in sediment supply and changes in the frequency and magnitude of severe storms (Anderson et al., 2013a).

Here, we use results from marine geological research conducted during the past three decades that investigated the nature of Holocene sea-level rise and climate change and their impacts on the Northwestern Gulf Coast (NGC) (Fig. 1). We describe the spatial and temporal variability in coastal response to different rates of sea-level rise and provide context to changes that are occurring along the coast today. We further address the evidence for punctuated sea-level rise and its impacts. While this is a regional study, our message is that the response of coastal systems to Global Climate Change is controlled by multiple factors, and thus exhibits considerable spatial and temporal variability. We use the operational definition of the Holocene as the period of geologic time after the Younger Dryas cold event (~11.5 ka to present).

2. Data set

Over the last three decades, we have acquired over 10,000 km of high-resolution seismic data from the continental shelf using the Rice University research vessel *R/V Lone Star* and within area bays using the *R/V Matagorda*, *R/V Trinity* and the University of North Carolina's *R/V Jenny* (Fig. 1). Seismic data from the bays are augmented by data collected by the United States Geological Survey, mostly during the 1970s. The majority of the high-resolution seismic profiles from the continental shelf were digitally collected using a 15 in^3 water gun, with limited post-cruise processing (see Anderson et al., 2004 for details). Chirp and boomer profiles were taken within bays. Several hundred pneumatic-hammer cores and vibracores were collected and analyzed. More than 70 rotary drill cores (up to 25 m long) were acquired within the bays using the *R/V Trinity* (see Anderson and Rodriguez, 2008; Simms et al., 2010; Troiani et al., 2011).

A robust chronostratigraphic framework consisting of several hundred radiocarbon dates, mostly AMS, were used to constrain the ages of sediment and timing of events. More details about the methods used, including calibration of radiocarbon ages, can be found in Simms et al. (2007b, 2009a) and Milliken et al. (2008a, 2008b, 2008c).

3. Physiographic, oceanographic and climatic setting

For about 600 km along the northwestern Gulf of Mexico, the modern shoreline includes extensive coastal wetlands and bays, chenier plains, barrier islands and peninsulas, the Brazos wave-dominated delta and several tidal inlet/delta complexes (Fig. 1).

The shoreline is sculpted by fair-weather waves in the near shore that typically range from 30 to 60 cm high, with periods of 2 to 6 s and a diurnal, microtidal range (<1 m) (Morton, 1994). Prevailing winds are out of the southeast with more variable winds during the passage of low-pressure systems from the west and north. Because of the curved shape of the coastline, prevailing southeasterly winds cause longshore currents to flow from east to west in east Texas and from south to north in south Texas. This results in a longshore current convergence zone offshore of central Texas (Lohse, 1955; Curray, 1960; Morton, 1979). The area is subject to frequent severe storms. Over the late Holocene, intense hurricanes (likely category 3 and higher) have impacted the Texas coast at a time-averaged rate of 0.46% (annual landfall probability) (Wallace and Anderson, 2010).

From onshore to offshore, the low-gradient coastal plain transitions to a continental shelf that exhibits variable physiography in terms of width and gradient (Fig. 1). The shelf physiography is largely controlled by order-of-magnitude differences in long-term river sediment supply, which can be linked to differences in river drainage-basin area and climate variability (Anderson et al., 2004).

The area currently includes four major climate regimes (Thornthwaite, 1948): humid (western Louisiana and far east Texas), wet subhumid (east central Texas), dry subhumid (central Texas), and semiarid (south Texas). Holocene climate records indicate that these climate zones have shifted in the past between warm-arid and cool-moist at millennial time scales, although the exact cause(s) of these climate changes is not fully known (Toomey et al., 1993).

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