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Sea level history of the northern Gulf of Mexico coast and sea level rise scenarios for the near future

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Abstract The sea level history of the northern Gulf of Mexico during recent geologic time has closely followed global eustatic sea level change. Regional effects due to tectonics and glacio-isostasy have been minimal. Over the past several million years the northern Gulf coast, like most stable coastal regions of the globe, has experienced major swings of sea level below and above present level, accompanied by major shifts in shoreline position. During advances of the northern hemisphere ice sheets, sea level dropped by more than 100 m, extending the shoreline in places more than 100 km onto the shelf. For much of the period since the last glacial maximum (LGM), 20,000 years ago, the region has seen rates of sea level rise far in excess of those experienced during the period represented by long-term tide gauges. The regional tide gauge record reveals that sea level has been rising at about 2 mm/year for the past century, while the average rate of rise since the LGM has been 6 mm/year, with some periods of abrupt rise exceeding 40 mm/year. During times of abrupt rise, Gulf of Mexico shorelines were drowned in place and overstepped. The relative stability of modern coastal systems is due primarily to stabilization of sea level approximately 6,000 years ago, resulting in the slow rates of rise experienced during historic time. Recent model projections of sea level rise over the next century and beyond may move northern Gulf coastal environments into a new equilibrium regime, more similar to that experienced during the deglaciation than that which has existed during historic time.

1 Introduction

The sea level history of Florida and the northern Gulf of Mexico during recent geologic time has closely followed the path of global sea level. Major swings in sea

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level elevation—and of the regional shoreline—have accompanied the dozens of continental glacial events that have marked the past several million years. During major advances of the ice sheets, sea level dropped by more than 100 m, advancing the shoreline in places more than 100 km onto the Gulf shelf. During interglacial periods, the shoreline has retreated to near today's position, or in some cases even further inland. Approximately 20,000 years ago, when the last ice age was at its peak, waves broke near today's shelf edge in the Gulf of Mexico, at locations that today lie under 120 m of sea water. As recently as 10,000 years ago, as the last remnants of the North American ice sheets were in their final stages of retreat, sea level stood at about 20 m below present, and the earliest human inhabitants of the region foraged and hunted on what is today the inner continental shelf.

The shorelines of the northeastern Gulf, like those of most tectonically stable regions, have retreated as the glaciers melted, but not at a constant rate. Surges and slowdowns in the warming—and even brief periods of cooling—have marked the last 20,000 years. Sea level has at times risen at rates more than 20 times that of today, more than 40 mm/year. At such rates, the regional shorelines would have retreated by as much as 40 m/year, or more than 75 cm/week.

Sea level rise globally and in the northern Gulf slowed by about 8,000 years ago and the sea reached near-present levels about 6,000 years ago. It is this slowdown in the rate of sea level rise that seems to have enabled coastal landforms to develop. The origin of most modern major river deltas, for example, dates from that period (Stanley 1995; Stanley and Warne 1994). The same is true for barriers, estuaries, and coastal wetlands. During the past few millennia, sea level rose slowly and may have fluctuated by a meter or two above or below present levels. As a consequence, shorelines have been relatively stable, especially compared with the rapid excursions experienced during much of the post-glacial period.

Over the past century the rate of sea level rise globally, based on long-term tide gauge data, has averaged 1.7 mm/year (Church and White 2006). This rate is reflected in regional tide gauge data (NOAA 2010a). Global satellite altimetry suggests an increase has taken place over the past approximately 15 years, to about 3.1 mm/year (Jevrejeva et al. 2006). Even at the current relatively slow rates of sea level rise, U.S. shorelines are retreating at an average of 1 m/yr, with northern Gulf of Mexico shorelines exceeding the average, at 1.8 m/year, and exhibiting some of the more extreme local erosion rates (Dolan et al. 1985; Davis 1997).

The Intergovernmental Panel on Climate Change, in its most recent assessment of the potential for future sea level rise, projected a sea level rise by the year 2100 of 18–59 cm, depending on the emissions scenario (IPCC 2007b; Meehl et al. 2007). Several recent studies (Rahmstorf 2007; Horton et al. 2008; Siddall et al. 2009; Vermeer and Rahmstorf 2009; Gregory et al. 2004; Grinsted et al. 2010; Pfeffer et al. 2008; Overpeck et al. 2006) have raised the possibility that the IPCC projections are underestimates, perhaps by more than a factor of two, due to an incomplete understanding of the contribution of large ice sheets—Greenland and Antarctica—to global sea level rise.

Some recent studies have examined indications that global climate may be nearing a tipping point, beyond which natural systems shift to a new equilibrium position. Projections of both greenhouse-induced temperature change and ice-sheet-induced sea level rise raise the possibility that the atmosphere and the oceans may be approaching such a point. Shorelines such as those of the northern Gulf are currently in a dynamic equilibrium with sea level rise. But over the past 6,000 years, global shorelines have not experienced the rates of sea level rise projected for the next century. Overstepping and drowning of shorelines is a possible response if sea level rise accelerates to rates last observed during the deglacial era.

2 Long-term sea level change

Global sea level may have stood as high as 200 m above present during the late Mesozoic, about 100 Ma, based on stratigraphic studies (Haq et al. 1987). The high sea levels resulted from high spreading rates on the mid-ocean ridge system, which expands the ridge profile, thus decreasing the volume of the ocean basins. Since that time global sea level has generally decreased, in response to slower spreading rates and, more recently, the onset of continental glaciation. Large ice sheets developed in Antarctica beginning in the late Eocene (~35 Ma), and in the northern hemisphere during the late Miocene (~8 Ma) (Zachos et al. 2001). Figure 1 depicts the last nine million years of global sea level history, derived from marine oxygen isotope records. By 8 Ma global sea level had fallen to approximately 20 meters above the present level (Miller et al. 2005). The northern hemisphere glaciers neared their full extent by late Pliocene time, about 3 Ma, and global sea level had fallen close to present levels. Since that time the advance and retreat of the glaciers has controlled global sea level behavior.

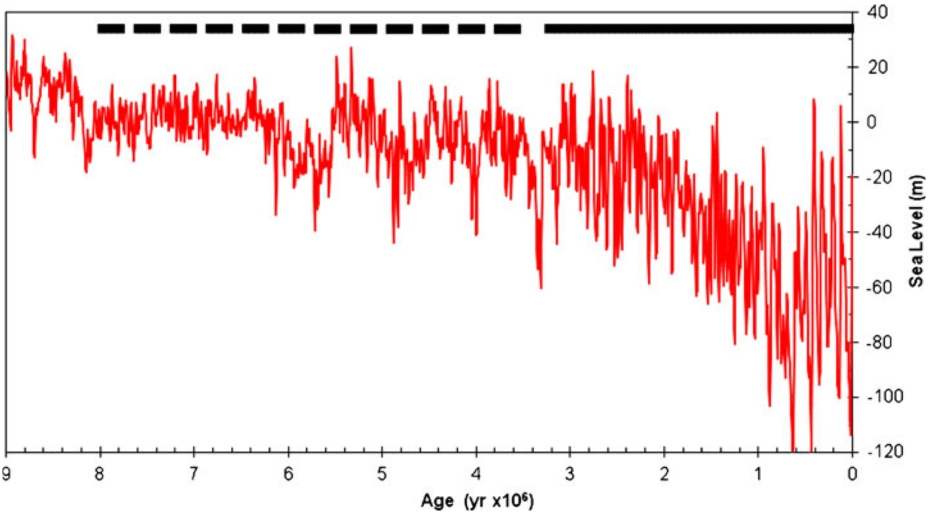

Fig. 1 Global sea level history, 9.0 Ma–present, based on benthic marine oxygen isotope data. *Dashed horizontal bars* represent the development of northern hemisphere ice sheets, beginning in the late Miocene (~8 Ma) and reaching full glacial coverage (*solid bar*) during late Pliocene time (~3 Ma) (Miller et al. 2005; Zachos et al. 2001). Figure adapted from Miller et al. (2005) data, using a three-point moving average

3 Late quaternary sea level change

3.1 Global sea level change, 500 ka to present

Figure 2 presents a sea level history of the last half-million years of the present glacial era. The figure depicts several full glacial-interglacial cycles, demonstrating the 100,000-year cyclicity that has persisted since about 1 Ma, due to the dominant influence of the Milankovitch eccentricity cycle since that time (Rutherford and D'Hondt 2000).

Major glacial advances have removed the equivalent of more than 100 meters elevation of sea water from the world oceans to enable the growth of the ice sheets (Rohling et al. 2009). During some interglacial periods sea level has risen by a moderate amount above present levels. A recent study by Kopp et al. (2009) analyzed evidence of the last interglacial stage (LIG), about 125 ka, examining data from approximately 30 sites around the globe. They concluded that global sea level stood 6–9 m above present sea level at the peak of the LIG, and temperatures were 3–5°C warmer at the poles.

The period immediately prior to the LIG high-stand of sea level—an analog of the present day—was a time of unusually rapid sea level rise. The rates of rise during that period are difficult to determine, but some evidence indicates that sea levels rose as rapidly as 20 mm/year during that time, as indicated in Fig. 2 (McCulloch and Esat 2000; Overpeck et al. 2006). In other words, in the time period leading up to the LIG, global sea level rise was more than 10 times faster than the average rate recorded by tide gauges during the historic period, as discussed below.

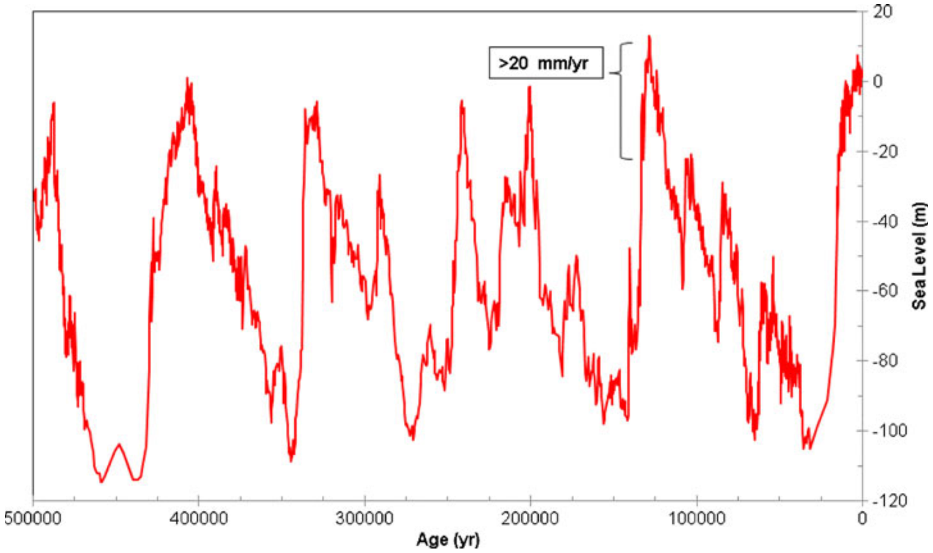

Fig. 2 Modeled global sea level history, showing several glacial-interglacial cycles over the past 500 ka, based on Red Sea benthic foram oxygen isotope data. The *bracket* indicates an estimate of the rate of sea level rise during the period leading up to the last interglacial highstand of sea level, an analog of the present day (McCulloch and Esat 2000; Overpeck et al. 2006). Figure adapted from Rohling et al. (2009) data, using a three-point moving average

3.2 Global sea level change since the last glacial maximum

During the most recent major ice advance, the last glacial maximum (LGM), approximately 20,000 years ago, global sea level dropped more than 100 m below present (Fairbanks 1989; Peltier and Fairbanks 2006). Figure 2 shows the extent of sea level fall during the LGM. By about 20 ka the ice sheets began their retreat and sea level began to rise toward the present level. The rate of sea level rise, however, was not uniform throughout that period. As an example, Blanchon and Shaw (1995) examined dates from shallow-water reef-building corals from throughout the Caribbean-Atlantic region. They found that the deglacial period was punctuated by periods of abrupt sea level rise, which at times exceeded the rate at which corals can build upward, thus drowning reefs. By documenting these events, they found that rates of sea level rise at times exceeded 45 mm/year, more than 20 times the historic rate of sea level rise. The periods of catastrophic rates of rise were found to occur at approximately 14.2, 11.5, and 7.6 ka.

3.3 Northern Gulf of Mexico sea level change, 20 ka to present

A sea level curve for the post-LGM period for the northern Gulf of Mexico is shown in Fig. 3. The curve is a composite of approximately 300 radiocarbon-dated paleoshoreline indicators from the northern Gulf coast and shelf, including samples from Florida, Louisiana, Texas, and Mexico (Balsillie and Donoghue 2004). Samples from the Mississippi Delta coastal region were excluded from the analysis because of the anomalous subsidence associated with the delta complex. All of the dates were converted to sidereal years (cal year BP). The northern Gulf of Mexico sea level

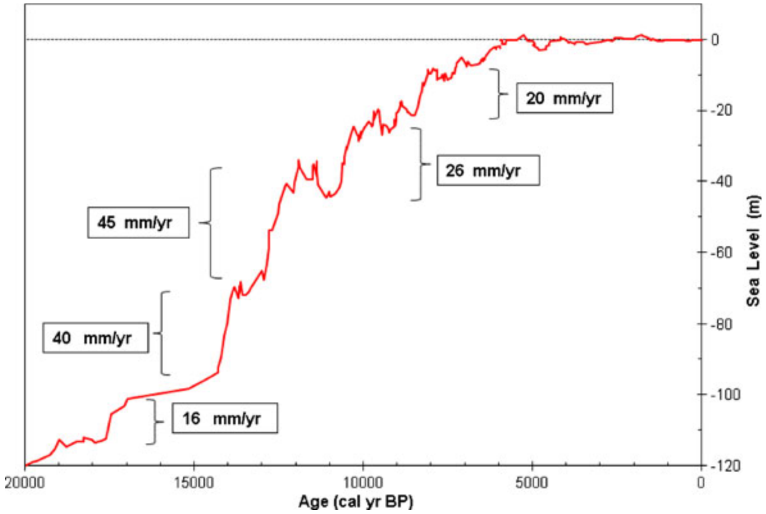

Fig. 3 Sea level history for the northern Gulf of Mexico since the last glacial maximum, based on approximately 300 radiocarbon-dated paleoshoreline indicators. Samples were taken from the coast and shelf of Florida, Louisiana, Texas, and Mexico. Several periods of rapid sea level rise are indicated. Figure adapted from Balsillie and Donoghue (2004)

history is in substantial agreement with global eustatic sea level records, such as those of Blanchon and Shaw (1995), Bard et al. (1990), Fairbanks (1989), and Siddall et al. (2003).

Since the LGM, sea levels in the Gulf have risen 120 m in 20,000 years, or an average of 6 mm/year. The record is highly non-uniform, however. For the first 14,000 years of the deglacial period, higher than average rates of sea level rise prevailed. For the last 6,000 years, rates have been slow and the net change in sea level has been negligible. Examination of Figs. 2 and 3 leads to the observation that during the period of instrumental (tide gauge) records, i.e., the past approximately 150 years, rates of sea level rise have been anomalously low, with few analogs during the glacial era.

Following the LGM, approximately 20,000 years ago, the first abrupt change in sea level began about 17.7 ka, rising nearly 12 m over the next 750 years, or an average of 16 mm/year. The first major excursion in Gulf sea level however, began about 14.3 ka. Sea level then rose more than 24 m over the next 500 years. This rapid rise coincided with a major pulse of meltwater from the Laurentide ice sheet. The meltwater pulse flowed through the Mississippi River drainage system and entered the northern Gulf of Mexico. Flower et al. (2004) observed the signature of the meltwater event in sediment records from the northern Gulf, and dated the event, MWP-1A, as occurring between 15.2 and 13.0 cal year BP. The timing of this event in the Gulf of Mexico sea level record approximately coincides with that reported from the Tahiti coral reef sea level history (Bard et al. 1996) and also from the Barbados reef sea level record (Fairbanks 1989; Bard et al. 1990), as well as the Sunda shelf sea level curve (Hanebuth et al. 2000). The Gulf of Mexico sea level history (Fig. 3) reveals that sea level rise averaged 40 mm/year during that interval, more than 20 times present rates. This rate is similar to those reported in the above studies.

A second major excursion of sea level in the Gulf record began about 12.9 ka, rising 27 m in 600 years, an average of 45 mm/year. Smaller-scale events occurred beginning at approximately 11,000 and 8,700 cal year BP, averaging 26 and 20 mm/year respectively.

The average rate of sea level rise in the Gulf of Mexico for the period of rapid deglaciation, approximately 14–8 ka, was over 10 mm/year, with periods of significantly higher rates. This agrees with the Tahiti sea level record for the same period (Bard et al. 1996), which shows global sea level rising an average of 11 mm/year during that time.

By about 8,000 cal year BP the northern hemisphere ice sheets had disappeared (Dyke and Prest 1987), and Gulf of Mexico sea level had approached within 8 m of its present level. Sea level reached present levels by about 6,000 cal year BP. Since that time, sea level rise in the northern Gulf has averaged less than 1 mm/year and has never exceeded 9 mm/year.

4 Sea level change during historic time

The global network of long-term tide gauges provides an instrumental record of sea level over the past approximately 100 years. Various studies of long-term tide

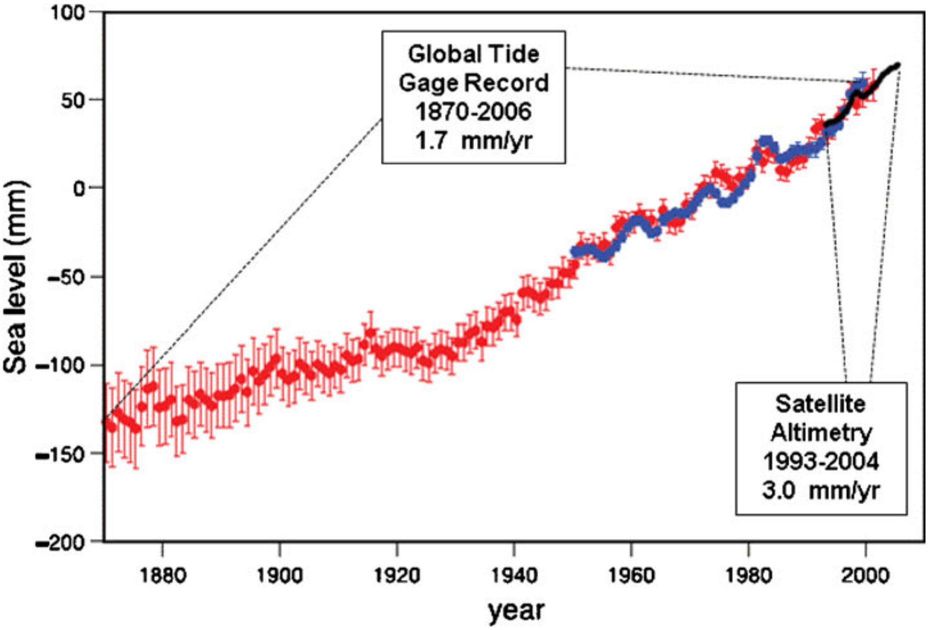

Fig. 4 The instrumental record of global sea level change. Red data points (with 90% confidence limits) show annual tide gauge averages since 1870 (updated from Church and White 2006). *Blue curve* represents coastal tide gauge measurements since 1950 (Holgate and Woodworth 2004). The *black curve* shows satellite altimetry data (Leuliette et al. 2004). The *red and blue curves* are deviations from the 1961–1990 average. The *black curve* is the deviation from the 1993–2001 average for the *red curve*. Figure adapted from IPCC (2007a)

gauge data have produced global averages of 2.4 mm/year (Peltier and Tushingham 1989), 1.84 mm/year (Peltier 2001), 1.8 mm/year (Church et al. 2001), 1.71 mm/year (Douglas 2001), and 1.7 mm/year (Church and White 2006). Figure 4 shows the Church and White (2006) long-term tide gauge data. Table 1 lists all of the tide stations in the northern Gulf region that have records extending longer than 40 years (NOAA 2010a). The table shows that the northeastern Gulf coast (Florida and Alabama) has generally reflected global eustatic sea level change during this period. The long-term average for the Florida stations is 2.1 mm/year. Stations in Louisiana and Texas have generally experienced higher rates of relative sea level rise, reflecting the effects of coastal subsidence due to Mississippi River sedimentation and subsurface fluid extraction.

Since 1993 satellite altimetry has provided an independent and comprehensive measure of sea level, both globally and regionally. Global sea level, based on the TOPEX/Poseidon/Jason satellite data, has averaged 3.0 mm/year from 1993–2010 (NOAA 2010b). Figure 4 shows the global satellite altimetry data in comparison with the long-term tide gauge record. For the Gulf of Mexico, the regional satellite data reflect the global trend: 2.9 mm/year from 1993–2010. For both the Gulf of Mexico and globally, the rate of sea level rise has shown an increase during the past two decades.

Table 1 Long-term tide-gauge data for all northern Gulf of Mexico stations with more than 40 years of record

Station location	Mean sea-level rise (mm/year)	±	Earliest record
Key West, FL	2.24	0.16	1913
Naples, FL	2.02	0.60	1965
Fort Myers, FL	2.40	0.65	1965
St. Petersburg, FL	2.36	0.29	1947
Cedar Key, FL	1.80	0.19	1914
Pensacola, FL	2.10	0.26	1923
Dauphin Island, AL	2.98	0.87	1966
Grand Isle, LA	9.24	0.59	1947
Sabine Pass, TX	5.66	1.07	1958
Galveston Pier, TX	6.39	0.28	1908
Freeport, TX	4.35	1.12	1954
Rockport, TX	5.16	0.67	1948
Port Mansfield, TX	1.93	0.97	1963
Port Isabel, TX	3.64	0.44	1944
Padre Island. TX	3.84	0.75	1958

NOAA (2010a)

5 Future sea level projections

The most recent Intergovernmental Panel on Climate Change (IPCC) model results for near-future sea level rise predict a rise of 18–59 cm by the year 2100 (IPCC 2007b; Meehl et al. 2007). Figure 5 shows the range of sea level projections for the next century under the various IPCC emissions scenarios. Projections from the earlier IPCC (2001) report are shown in green shading (20–70 cm rise by 2100), while the green solid lines represent an additional rise of as much as 18 cm due to uncertainty concerning changes in the ice sheets. The most recent IPCC (2007b) model projections are shown by the magenta bar (range of model projections, 18–59 cm) and the red bar (range of additional contributions to global sea level from the Greenland and Antarctic ice sheets, 20 cm). The IPCC also left open the possibility that "Larger values cannot be excluded, but understanding of these effects is too limited to assess their likelihood or provide a best estimate or an upper bound for sea level rise" (IPCC 2007b).

Several independent studies have found that the potential exists for significantly higher rates of sea level rise than the IPCC predictions. Rahmstorf et al. (2007) analyzed the recent instrumental trends of global sea level rise and found that the actual rate of rise from 1996 to 2007 was under-predicted by approximately 40% by the IPCC (2001) report. Figure 6 compares the model predictions with the instrumental data for global sea level rise.

Other semi-empirical and modeling studies provide further evidence that the IPCC estimates may be low, and perhaps significantly so, due to an incomplete understanding of the contribution of the large ice sheets—Antarctica and Greenland—to global sea level rise. Some of these reports project as much as 1 m or more of sea level rise by the end of the century, due to the instability of the West Antarctic ice sheet. A few of these recent reports are summarized below.

Rahmstorf (2007) determined that air temperature and global sea level rise have been roughly proportional since the late nineteenth century. He used this proportionality to empirically project sea level into the next century. Based on the

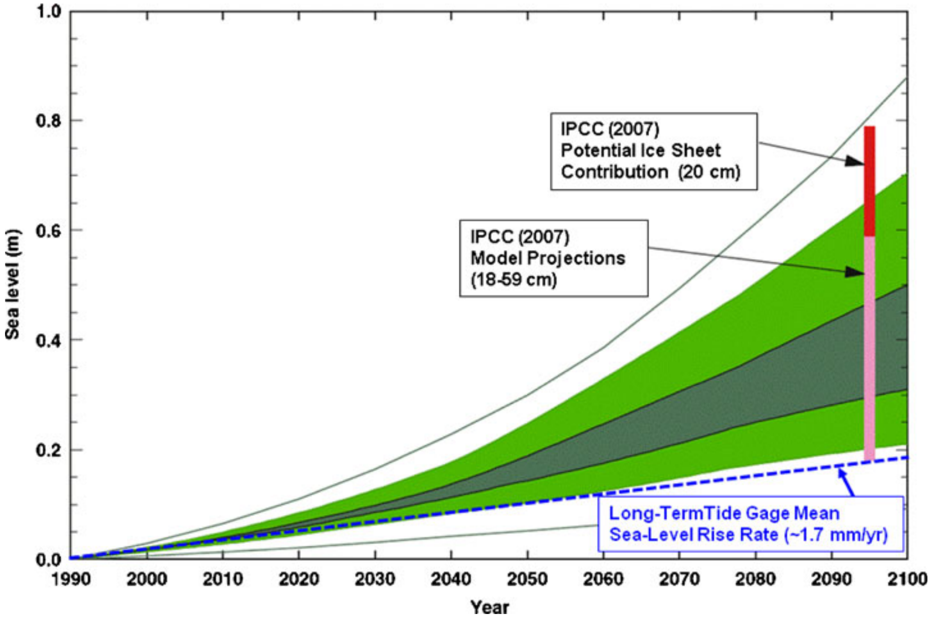

Fig. 5 IPCC sea level rise projections for the next century. *Dashed blue line* is a linear extension of the historic sea level rise rate, based on globally averaged tide gauge data, shown for perspective. The IPCC (2001) model projections for 1990–2100 are shown in *green shading*, with the *green lines* representing additional uncertainty due to land ice changes. The IPCC (2007a) projections are shown as *vertical bars* at the *right*. The *magenta bar* represents the range of model projections, while the *red bar* is the range of estimates for ice sheet contributions to sea level. Figure adapted from Church et al. (2008)

IPCC warming scenarios, he calculated that global sea level will rise 0.5–1.4 m by 2100.

Vermeer and Rahmstorf (2009) updated Rahmstorf's (2007) projections for future sea level change on the basis of the correlation between historic sea level rise and global temperature change. They concluded that the potential sea level rise over the next century is 0.75–1.90 m.

Horton et al. (2008) projected a rise in sea level of 0.62–0.88 m by 2100, also based on an empirical relationship between air temperature and mean sea level. Their projection applied Rahmstorf's (2007) methodology to the Coupled Global Climate Models which were used in developing the IPCC (2007b) predictions.

Overpeck et al. (2006) examined the history of the Antarctic ice sheet during the last interglacial (LIG), plus future temperature scenarios. They found that peak rates of sea level rise during the LIG were greater than 1 m/century (see Fig. 2) in response to modest warming, and noted that projected warming rates could result in a similar rise over the next century. They also concluded that many meters of sea level rise are possible if anthropogenic soot triggers more rapid melting of the ice sheets.

Gregory et al. (2004) developed a model showing that, at CO_2 levels likely to be exceeded by 2050, the Greenland ice sheet will disappear in the next millennium, raising sea levels by 7 m.

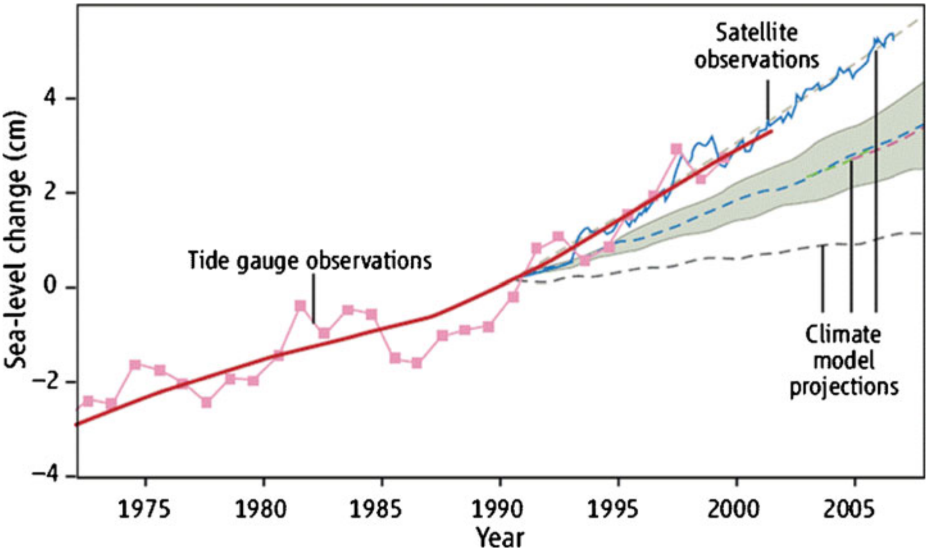

Fig. 6 Observational record of global sea level rise compared with model projections. Data are plotted in terms of deviations from the trendline value for 1990, the base year for the IPCC scenarios. Annual tide gauge data are shown in *magenta*, with trendline in *red*. Satellite altimetry data (quarterly data, 1993–2006) are shown in blue. IPCC (2001) climate model projections are shown with *dashed lines and gray ranges*. Figure from McCarthy (2009). Original data from Rahmstorf et al. (2007)

Siddall et al. (2009) presented a model based on surface ocean thermal expansion and decrease in continental ice volume, in response to global warming over the next century. Based on a maximum warming of 6.4°C, their model predicted a maximum sea level rise of 82 cm by the year 2100.

Grinsted et al. (2010) constructed a model linking global temperature and sea level change, using both historic data and longer-term geologic proxies. They concluded that the IPCC projections may underestimate the sea level rise by the end of the century by approximately a factor of 3. They predicted a total rise of 90–130 cm by the end of the century.

Pfeffer et al. (2008) determined, based on ice-flow dynamics, that a sea level rise of 0.8 m is likely by 2100. Their modeling indicated that the range of potential sea level rise over the next century is 0.8–2.0 m.

Using a different approach, Jeverjeva et al. (2010) modeled volcanic, solar and greenhouse gas forcings for the next century, using the standard IPCC scenarios. After calibration with historic data, the model projected a sea level rise of 0.6–1.6 m by 2100, with most of the effect due to increased atmospheric concentration of greenhouse gases.

As an example of one of the above studies, Fig. 7 presents the Rahmstorf (2007) projections for sea level rise over the next century, based on the IPCC emissions scenarios and an empirical relationship between global air temperature and sea level. The projections show sea level rising during the 2050–2100 period at a rate of approximately 8 mm/year under the IPCC B1 emissions scenario, 14 mm/year under the IPCC A1F1 emissions scenario, and as much as 21 mm/year under the worst

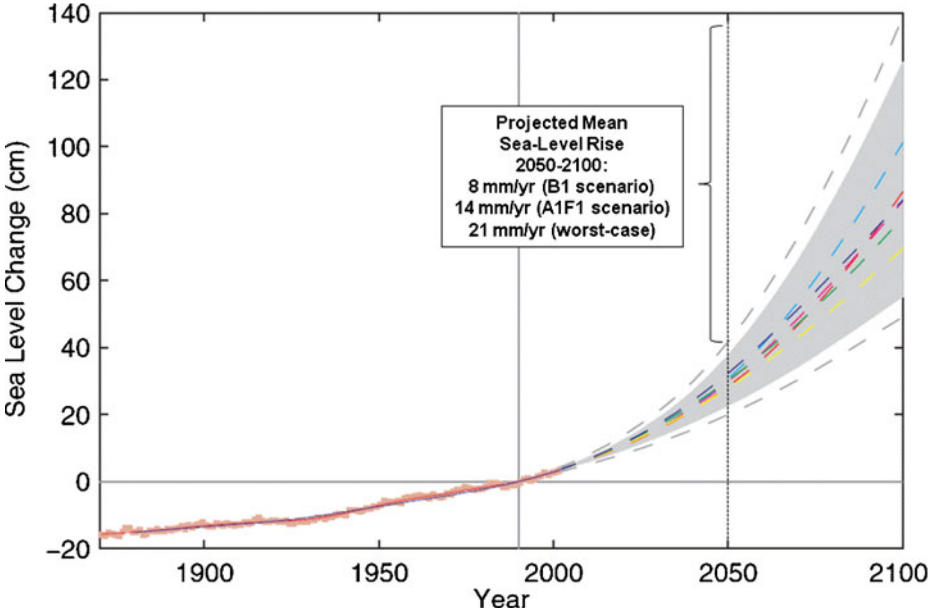

Fig. 7 Past sea level from global tide-gauge data, 1881–2001, and sea level projections to 2100 from Rahmstorf (2007). Sea level projections are based on a linear relationship between sea level and global mean temperature change. Projected sea levels, with gray uncertainty band, span the range of IPCC (2001) future temperature rise, from 1.4°C to 5.8°C. *Colored dashed lines* are the individual IPCC scenarios: the *light blue dashed line* is the A1FI emissions scenario, and the *yellow dashed line* is the B1 emissions scenario. Figure adapted from Rahmstorf (2007)

case. Even at the lowest range, sea level would be rising at a pace faster than global coastlines have experienced over the past 6,000 years.

In what can be considered a mid-range sea level scenario among the model projections described above, Fig. 8 depicts an example of the potential effects on Florida of a 1-m rise over the next century. Nearly ten percent of the state's land area would be inundated, including nearly all of the Florida Keys. Nearly 10% of the state's population, 1.5 million people, would be displaced. Approximately US$130 billion in property losses would result, including half of Florida's existing beaches and 99% of its mangroves (Stanton and Ackerman 2007). Other coastal regions of the United States will be similarly affected by abrupt sea level change, but Florida will experience the greatest effect as a result of its 3,660 km of tidal shoreline.

6 Effects of rapid sea level change on northern Gulf of Mexico shorelines

Several studies have identified some well-preserved drowned shorelines on the northern Gulf of Mexico shelf. These features, combined with the record of sea level change (Fig. 3) can be used to better understand the potential effect of the rapid rates of sea level rise that have been projected for the next century.

Under recent rates of sea level rise—1.7 mm/year based on long-term tide gauge data (Fig. 4)—U.S. shorelines are retreating on average about 1 m/year (Dolan

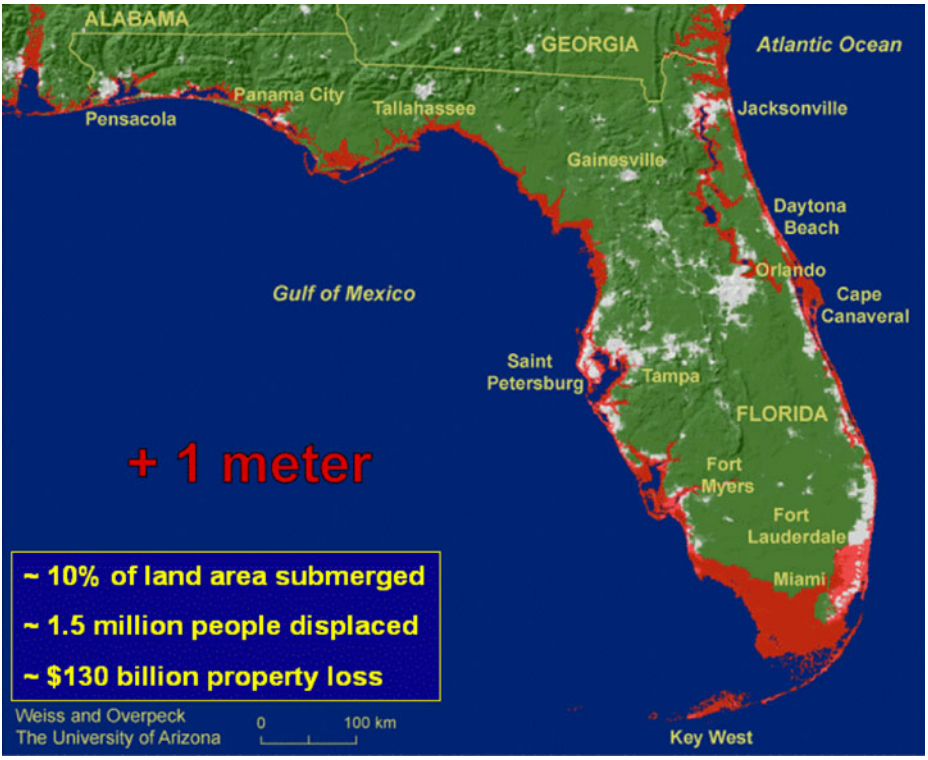

Fig. 8 Effect of inundation of Florida by a 1-meter sea level rise. Adapted from Weiss and Overpeck (2003) and Stanton and Ackerman (2007)

et al. 1985). There is evidence that coastal morphologic systems—barrier islands, deltas, estuaries, wetlands—move into a different equilibrium mode at higher rates of sea level change. Rather than increasing the rate of coastal retreat, at some point shorelines are overstepped by rapid rates of sea level rise. Many of the scenarios for near-future sea level change described above involve rates of rise that far exceed those experienced over the past 6,000 years, and approach those that prevailed during the recent deglacial era (Fig. 3) or those that occurred in the lead-up to the last interglacial high-stand of sea level (Fig. 2).

The tipping point in response to sea level rise, i.e., the drowning of a shoreline that has been undergoing retreat, will vary depending on local conditions, including sediment supply and coastal subsidence. However, some near-future sea level scenarios hold the potential for coastal drowning. Evidence for this comes from examination of drowned paleo-shorelines in the northern Gulf of Mexico. Many previous morphologic studies have identified paleoshoreline features, such as deltas and barrier islands, on the northern Gulf of Mexico mid- to outer shelf. The depths and degree of preservation of these features indicate that many of these coastal landforms were drowned in place when sea level rise overstepped them during a marine transgression. Some examples are described below.

Locker et al. (1996) investigated sub-bottom seismic and sidescan sonar records of sedimentary bodies identified as transgressive shorelines and subtidal shoals. The paleoshorelines were observed at depths between 80 m and 65 m on the SW Florida margin, south of the Marquesas Keys. Radiocarbon ages for the paleoshorelines ranged 14,500–13,800 year BP. Figure 3 indicates that, when Gulf of Mexico sea level was at these depths, waters were initially rising slowly, enabling the coastal landforms to develop. Subsequently, however, Gulf sea level began rising at a rate as 20 times present rates, which was sufficient to overstep the shorelines and drown them in place.

Jarrett et al. (2005) also investigated a drowned paleoshoreline complex off SW Florida. They used seismic and sidescan imagery to identify it as a drowned barrier island. The feature, which has the morphology of a drumstick barrier, lies in 60–75 m water depth in the Pulley Ridge region of the Gulf shelf, NW of the Dry Tortugas. Although no dates were obtained for the barrier complex, it was said to be contemporaneous, based on similar depths, with the paleoshorelines described by Locker et al. (1996), and thus was apparently drowned in place by the rapid sea level rise near the beginning of the deglaciation.

Sager et al. (1992) reported on morphologic features of the Mississippi–Alabama continental shelf with bases at 105–120 and 74–82 m. They attributed the depth clustering to non-uniform rises in sea level in the Gulf during the deglaciation. They identified the features as nearshore reefs, which formed during periods of slow sea level rise and then became inactive when the rate of sea level rise increased. It can be inferred from the Gulf sea level history (Fig. 3) that the overstepping may have occurred during the early periods of abrupt rise, approximately 17,500 and 14,000 years ago, when sea level was rising as much as 16 mm/year, more than eight times faster than at present.

The Florida Middle Ground lies at mid-shelf in the eastern Gulf of Mexico, approximately 200 km NW of Tampa. Jordan (1952) first described it as an old river delta with the seaward end divided into passes. Lying 40–50 m below present sea level, it has the appearance of a paleo-delta of the Apalachicola River of NW Florida, to which it has been connected (Donoghue 1993). As a former river-mouth feature, it may have been drowned and overstepped during the period of abrupt rise in sea level that began about 11,000 years ago, as shown in Fig. 3.

A younger paleo-delta of the Apalachicola River has also been identified beneath the Cape St. George Shoal, on the inner Gulf of Mexico shelf approximately 20 km offshore from the eastern Florida panhandle coast (Donoghue 1993). The deltaic deposits lie at a depth of approximately 16 m below present sea level. This paleoshoreline feature may have been overstepped by the last abrupt rise in sea level in the Gulf, which began approximately 8,500 years ago, as shown in Fig. 3.

Gardner et al. (2005) identified several well-preserved paleoshorelines on the mid- to outer shelf of the northern Gulf of Mexico shelf off NW Florida. High-resolution multibeam sidescan imagery enabled identification of the six features as relict deltas, each with an accompanying barrier island complex. Beach ridges and cuspate shorelines can be observed in the imagery. The paleoshorelines lie at present water depths of 65–85 m. Based on the water depth and sea level history, the time of origin of the features was inferred to be marine isotope stage 3 (MIS-3), approximately 58–28 ka, when the rate of sea level change may have slowed sufficiently (Fig. 2) to allow the building of delta and barrier complexes. However, sea level was generally falling during that period and ultimately fell to more than 100 m below present sea level by about 20 ka. Thus, the features would have been subaerially exposed for several thousand years, making it unlikely they would be in the state of preservation in which they are presently found. An alternative scenario is that the delta/barrier complexes formed early in the deglacial era, after the LGM. At least one lengthy period of sea level stasis occurred in the Gulf, beginning about 17 ka, and ending about 14.3 ka (Fig. 3). At that time, sea level was at -90 m and began a rapid rise. The drowning of the deeper paleoshoreline features could have occurred during that time. The shallower features may have developed during a shorter period of sea level slowdown from approximately 13.8–12.8 ka, after which Gulf sea level again resumed a rapid rate of rise, drowning those shorelines.

7 Conclusion

An increasing number of climate scientists warn that global climate may be approaching a tipping point, beyond which natural systems may not return to the current equilibrium for many millennia, and perhaps not at all. Some models, for example, show CO_2 levels staying at elevated levels for a millennium or more even after greenhouse emissions end (Solomon et al. 2009). The same may hold true for coastal systems. Current rates of sea level rise, on the order of 2 mm/year, have changed little over the past 6,000 years. Global shorelines have generally been in equilibrium with sea level rise during that period. Prior to that time, however, during the period of rapid deglaciation after the LGM, global sea level at times has been rising more than 20 times the present rate.

The geologic record of the northern Gulf of Mexico provides evidence that mobile shorelines such as those of the northern Gulf coast can equilibrate to sea level rise rates higher than present. But at some point overstepping occurs and coastal systems are inundated. Such was the case with the periods of abrupt rise during the deglacial era. That record implies that rates of sea level rise as low as 16 mm/year may be sufficient to cause in-place drowning and overstepping of shorelines. Several of the recent model projections for sea level rise would result in a similar outcome over the next century.

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