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Spatial variability of late Holocene and 20th century sea-level rise along the Atlantic coast of the United States

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ABSTRACT

Accurate estimates of global sea-level rise in the pre-satellite era provide a context for 21st century sea-level predictions, but the use of tide-gauge records is complicated by the contributions from changes in land level due to glacial isostatic adjustment (GIA). We have constructed a rigorous quality-controlled database of late Holocene sea-level indices from the U.S. Atlantic coast, exhibiting subsidence rates of <0.8 mm a^{-1} in Maine, increasing to rates of 1.7 mm a^{-1} in Delaware, and a return to rates <0.9 mm a^{-1} in the Carolinas. This pattern can be attributed to ongoing GIA due to the demise of the Laurentide Ice Sheet. Our data allow us to define the geometry of the associated collapsing proglacial forebulge with a level of resolution unmatched by any other currently available method. The corresponding rates of relative sea-level rise serve as background rates on which future sea-level rise must be superimposed. We further employ the geological data to remove the GIA component from tide-gauge records to estimate a mean 20th century sea-level rise rate for the U.S. Atlantic coast of 1.8 ± 0.2 mm a^{-1}, similar to the global average. However, we find a distinct spatial trend in the rate of 20th century sea-level rise, increasing from Maine to South Carolina. This is the first evidence of this phenomenon from observational data alone. We suggest this may be related to the melting of the Greenland ice sheet and/or ocean steric effects.

INTRODUCTION

Global sea-level rise is the result of an increase in the ocean volume, which evolves from changes in ocean mass due to melting of continental glaciers and ice sheets, and expansion of ocean water as it warms. To extract the 20th century rates of sea-level rise from satellite altimeters and long-term tide-gauge records, corrections must be applied for vertical land movements that are primarily associated with the glacial isostatic adjustment (GIA) of the solid Earth.

There are various approaches to develop estimates of sea-level rise for the 20th century. First, models of GIA have been constructed, and then later employed by a number of authors, that produce global sea-level rise estimates of ~1.8 mm a^{-1} (Peltier and Tushingham, 1989; Douglas, 1991, 1997; Peltier, 2001; Church and White, 2006), although the U.S. Atlantic coast shows considerable variation in the rate of sea-level rise with respect to this global average, depending upon the GIA model employed (Peltier and Tushingham, 1989; Peltier, 1996, 2001; Davis and Mitrovica, 1996). Second, global positioning systems (GPS) have been used that suggest a rate of ~1.9 mm a^{-1} for the Atlantic coast (Snay et al., 2007), which is essentially identical to the result reported in Peltier (1996), but the errors associated with this technique are currently large due to the short time series of the GPS data. A third method of correcting for land movements is to use geological data. Salt-marsh sedimentary sequences enable the reconstruction of relative sea-level change over a much longer period. This data-based technique improves on model-based approaches, because subtle tectonic effects are incorporated into both the geological and 20th century rates. Gornitz (1995) estimated a 20th century sea-level rise of 1.5 ± 0.7 mm a^{-1} for the U.S. Atlantic coast. However, this geological database included sea-level index points up to 6 kyr B.P., thus sea-level rise rates included meltwater contributions from the remnants of the major ice sheets (Peltier, 2002). Peltier (2001) demonstrated that the Gornitz (1995) result was a significant underestimate because it was based upon a linear least squares fit to the data over a range of time sufficiently long that sea level could not be assumed to be rising linearly.

METHODOLOGY

Construction of a Sea-Level Index Point

To be a validated sea-level index point, a sample must have a location, an age, and a defined relationship between the sample and a tidal level (Shennan, 1986; van de Plassche, 1986). We constrain this relationship, known as the indicative meaning (van de Plassche, 1986), using zonations of modern vegetation (Redfield, 1972; Niering and Warren, 1980; Lefor et al., 1987; Gehrels, 1994), the distribution of microfossils (Gehrels, 1994), and/or $\delta^{13}C$ values from the radiocarbon-dated sediments (Andrews et al., 1998; Törnqvist et al., 2004). We calculate the total vertical error of each index point from a variety of errors that are inherent to sea-level research (Shennan, 1986), including thickness of the sample, techniques of depth measurement, compaction of the sediment during sampling, and leveling of the sample to the nationwide geodetic datum, NAVD 88 (see Appendix A in the GSA Data Repository[1]). These errors exclude any influence of the possible change of tidal range through time. Each validated index point in the database was radiocarbon dated, and we present such assays as calibrated years before present using CALIB 5.0.1 (Stuiver et al., 2005). We used a laboratory multiplier of 1 with 95% confidence limits, and employed the IntCal04 data set (Reimer et al., 2004).

Geological Records

We assume that the ice-equivalent meltwater input 4 kyr B.P. to A.D. 1900 is either zero (Peltier and Tushingham, 1991; Douglas, 1995; Peltier, 1996, 2002) or minimal (Milne et al., 2005; Church et al., 2008). It is widely accepted that the tectonic component along the passive margin of the U.S. Atlantic coast is negligible. We have significantly reduced the influence of compaction by only utilizing basal peat samples

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[1]GSA Data Repository item 2009276, Table DR1 (site locations of geological data, rates of relative sea-level rise from geological data, and GPS vertical motions), Figure DR1 (plot of all 212 radiocarbon-dated basal index points), Figure DR2 (individual relative sea-level curves for each of the 19 locations), and Figure DR3 (long-term tide gauge records from Canada to Virginia, demonstrating the methodology used to assess the appropriate error for the tide gauges), is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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(salt-marsh peat that directly overlies uncompressible substrate; Jelgersma, 1961). Therefore, any changes observed in relative sea level are almost entirely from vertical land movements due to GIA. To calculate the late Holocene rate of relative sea-level rise (RSLR) for each location, we excluded the 20th century sea-level contribution by expressing all ages with respect to A.D. 1900 and adjusted the sea-level axis to mean sea level in A.D. 1900 (Appendix B). We estimated the rate of late Holocene RSLR by running a linear regression over the past 4 k.y. with 2σ errors (Shennan and Horton, 2002).

Tide-Gauge Records

We identified 10 suitable tide-gauge records along the U.S. Atlantic coast with a nearby geological record of late Holocene RSLR with minimal influence of non-GIA subsidence, such as groundwater withdrawal (Sun et al., 1999). All records are at least 50 years in length to minimize contamination by interannual and decadal variability (Douglas, 1991). A single standard error was calculated for all the gauges, which included a thorough consideration of tide-gauge record length (Appendix C).

ANALYSIS

We produced a late Holocene database of validated sea-level index points from new, unpublished, and published records of basal peats of the U.S. Atlantic coast. The validated database contains 212 basal sea-level index points for the past 4 kyr B.P. from 19 locations that extend from Maine (45°N) to South Carolina (32°N) (Fig. 1). There is an absence of index points from Georgia and Florida. Relative sea level has risen along the entire U.S. Atlantic coast during the late Holocene, with no evidence of former sea levels above present during this time period within our validated database. There is a large vertical scatter (over 5 m at 4 kyr B.P.), because the entire coastline has been subject to spatially variable GIA-induced subsidence from the collapse of the proglacial forebulge (Peltier, 1994). From eastern Maine (45°N) to northern Massachusetts (42°N), relative sea level has risen <3.5 m during the last 4 kyr B.P., with rates of RSLR <0.8 mm a^{-1} (Fig. 1; Table DR1 in the Data Repository). Along the mid-Atlantic coastline from Cape Cod, Massachusetts (41.5°N), to the northern Outer Banks, North Carolina (35.9°N), late Holocene RSLR of 1 mm a^{-1} is met or exceeded at 9 of 11 locations. The highest rates of RSLR are recorded in New Jersey, Delaware, and Maryland, where all rates are ≥1.2 mm a^{-1}. The maximum RSLR of 1.7 ± 0.2 mm a^{-1} is recorded in the inner Delaware estuary. RSLR decreases to <0.9 mm a^{-1} from Beaufort, North Carolina (34.7°N), to Port Royal, South Carolina (32.4°N). The southern North Carolina and South Carolina sites all show similar records of RSLR (0.6–0.8 mm a^{-1}).

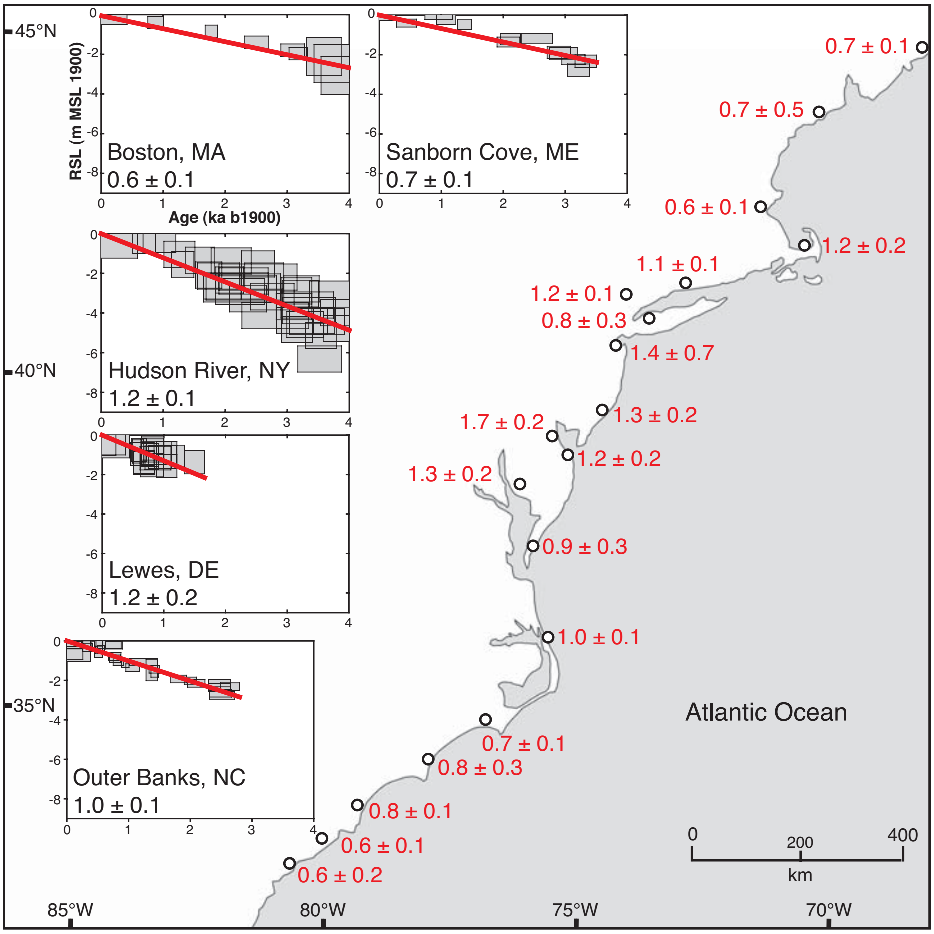

Figure 1. Rate of late Holocene relative sea-level rise with 2σ errors for 19 locations along U.S. Atlantic coast. Inset plots are examples of locations with sea-level index points plotted as calibrated age before A.D. 1900 versus change in relative sea level (RSL) relative to mean sea level (MSL) in A.D. 1900 (m). Red line is linear regression for each site. Rates and errors shown to 1 decimal place. MA—Massachusetts; ME—Maine; NY—New York; DE—Delaware; NC—North Carolina.

All tide-gauge locations along the U.S. Atlantic coast show an acceleration in the rate of RSLR between the late Holocene geological data and the 20th century tide gauges (Fig. 2). Subtracting the late Holocene RSLR from the tide gauges yields an average 20th century sea-level rise rate of 1.8 ± 0.2 mm a^{-1}. This corresponds closely to the global average for the past century (Peltier and Tushingham, 1989; Douglas, 1991, 1997; Peltier, 2001; Church and White, 2006). Despite the errors of the tide gauge and geological data, there is a north to south increase in the rate of 20th century sea-level rise. The lowest rate of 1.2 ± 0.6 mm a^{-1} occurs near the northern end of the study area at Portland, Maine, whereas to the south it doubles to 2.6 ± 0.3 mm a^{-1} (Charleston, South Carolina) (Fig. 2), a range of 1.4 mm a^{-1}.

DISCUSSION

The geological data constrain the form of the ongoing forebulge collapse along the U.S. Atlantic coast. This is apparent when the rates of late Holocene RSLR are plotted against the distance from the center of mass loading of the Laurentide Ice Sheet (Fig. 3). Vertical motions from continental North America GPS measurements (Sella et al., 2007) and GIA models (Peltier, 2004) suggest that the center of ice loading is west of Hudson Bay. Sella et al. (2007) calculated maximum vertical velocities of +10 mm a^{-1}, with rates generally decreasing with distance away from Hudson Bay. Interpolation of the GPS observations suggest that the hinge line separating uplift from subsidence is offshore of the Maine coastline, whereas the geological data from two locations in this study suggest that Maine is undergoing GIA-related subsidence of 0.7 mm a^{-1} (with a maximum uncertainty of 0.5 mm a^{-1}). Snay et al. (2007) also identified subsidence rates of 1.9 ± 1.0 mm a^{-1} within Maine using coastal GPS stations, but with significant spatial variation; two GPS measurements from Maine suggest uplift (+1.0 ± 1.2 mm a^{-1} and +0.3 ± 1.0 mm a^{-1} vertical velocity).

Snay et al. (2007) estimated that the maximum rate of subsidence (3.1 ± 3.5 mm a^{-1})

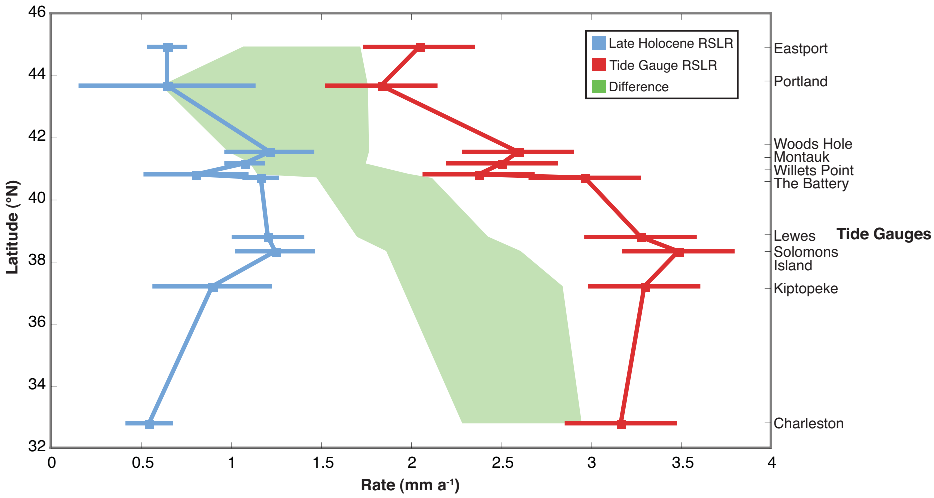

Figure 2. Detrending of 20th century tide-gauge relative sea-level rise (RSLR) with rate of late Holocene relative sea-level rise for 10 locations along the U.S. Atlantic coast. Mean and 2σ error of sea-level trends are plotted against latitude.

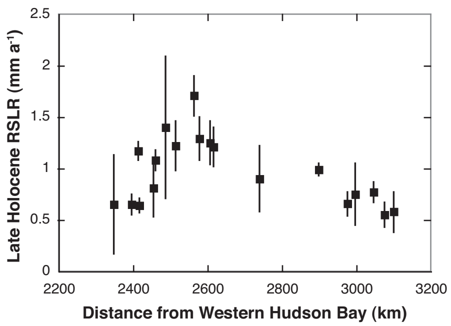

Figure 3. Rate of late Holocene relative sea-level rise (RSLR) with 2σ errors for 19 locations along the U.S. Atlantic coast plotted as function of distance from western Hudson Bay (km).

occurs within Maryland. Similarly, the geological data show late Holocene RSLR increasing from eastern Maine to a maximum within the mid-Atlantic but of a smaller magnitude (Maryland, 1.3 ± 0.2 mm a^{-1}; Delaware, 1.7 ± 0.2 mm a^{-1}; New Jersey, 1.4 ± 0.7 mm a^{-1}). The geological rates of subsidence decline rapidly with distance from Hudson Bay along the U.S. Atlantic coast compared to the GPS observations. The GPS observations suggest that high rates of subsidence from the collapse of the forebulge extend into Virginia and the Carolinas (Sella et al., 2007; Snay et al., 2007). For example, the geological data within Chesapeake Bay, Virginia, estimate subsidence of 0.9 ± 0.3 mm a^{-1} compared to nearby GPS observations of 3.5 ± 1.6 mm a^{-1} (Sella et al., 2007) and 2.6 ± 1.2 mm a^{-1} (Snay et al., 2007). Although the GPS data agree with the general form of the forebulge collapse revealed by the geological data, there are significant spatial variations. The GPS data are limited by the short time series with a maximum length of eight years on the U.S. Atlantic coast between Maine and South Carolina (Snay et al., 2007), which results in large errors. The errors of the GPS data quoted above are at the 1σ level; if 2σ errors are used, the geological and GPS rates concur. Furthermore, it has been noted elsewhere that continuous GPS measurements may be systematically biased (too positive), potentially due to inadequate modeling of antenna phase center variations and/or the use of current terrestrial reference frames (Teferle et al., 2009).

Removing the GIA signal from the tide-gauge records with our geological observations of subsidence reveals a significant amount of spatial variability in the rate of 20th century sea-level rise that increases from north to south. A similar slope has been identified by GIA modeling (Peltier, 1996), but this is the first evidence from observational data alone. There may be a significant contribution to the 20th century sea-level changes from Greenland Ice Sheet mass-balance changes (Marcos and Tsimplis, 2007) and/or ocean steric effects (Domingues et al., 2008). The effects of Greenland mass loss on the U.S. Atlantic coast would result in a north to south increase in sea-level rise (Conrad and Hager, 1997). Estimates of Greenland mass loss from GRACE (Gravity Recovery and Science Experiment; http://www.csr.utexas.edu/grace/ since A.D. 2002 vary between 100 and 270 Gt a^{-1}, which is equivalent to a sea-level rise of ~0.4–0.7 mm a^{-1} (Velicogna and Wahr, 2006; Peltier, 2009). Rignot et al. (2008) suggested that Greenland is currently losing mass at the equivalent sea-level rise rate of ~0.6 mm a^{-1}. Steric effects may also play an important role in 20th century sea-level change (Miller and Douglas, 2004; Wake et al., 2006; Church et al., 2008). Church et al. (2008) proposed significant spatial variation in ocean thermal expansion for the upper 700 m along the U.S. Atlantic coast with areas possessing negative and positive thermal contributions to sea-level rise over the period 1993–2003. Wake et al. (2006) analyzed hydrographic data sets of the Atlantic coast and identified a large steric effect for the southern portion of the coastline that would influence 20th century RSLR, but Miller and Douglas (2006, 2007) concluded that there were only minor steric contributions to sea-level rise during the 20th century, north of Cape Hatteras, North Carolina.

The geological data document the continued response of the U.S. Atlantic coast to the collapsing Laurentide forebulge at a significantly improved resolution. Furthermore, we have demonstrated that the removal of the variation imposed on the tide gauges by this ongoing deformation cannot fully explain the spatial variations seen within the tide-gauge records. Therefore, care should be taken when employing tide-gauge records as a validation of GIA models (Davis and Mitrovica, 1996; Davis et al., 2008). The database of late Holocene sea levels provides a new tool both for testing hypotheses relating to this spatial variability, as well as refining models of ocean dynamical effects. From analyzing climate models, Yin et al. (2009) found that a dynamic regional rise in sea level is induced by a weakening meridional overturning circulation in the Atlantic Ocean (superimposed on the global mean sea-level rise). The application of a comparable methodology to de-trend relative sea-level records from Canada (e.g., Gehrels et al., 2004), the U.S. Gulf coast (e.g., Törnqvist et al., 2004), and the Caribbean (e.g., Toscano and Macintyre, 2003) using geological data will further elucidate the spatial variability of 20th century sea-level rise.

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