Timing and magnitude of recent accelerated sea-level rise (North Carolina, United States)

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ABSTRACT

We provide records of relative sea level since A.D. 1500 from two salt marshes in North Carolina to complement existing tide-gauge records and to determine when recent rates of accelerated sea-level rise commenced. Reconstructions were developed using foraminifera-based transfer functions and composite chronologies, which were validated against regional twentieth century tide-gauge records. The measured rate of relative sea-level rise in North Carolina during the twentieth century was 3.0–3.3 mm/a, consisting of a background rate of ~1 mm/a, plus an abrupt increase of 2.2 mm/a, which began between A.D. 1879 and 1915. This acceleration is broadly synchronous with other studies from the Atlantic coast. The magnitude of the acceleration at both sites is larger than at sites farther north along the U.S. and Canadian Atlantic coast and may be indicative of a latitudinal trend.

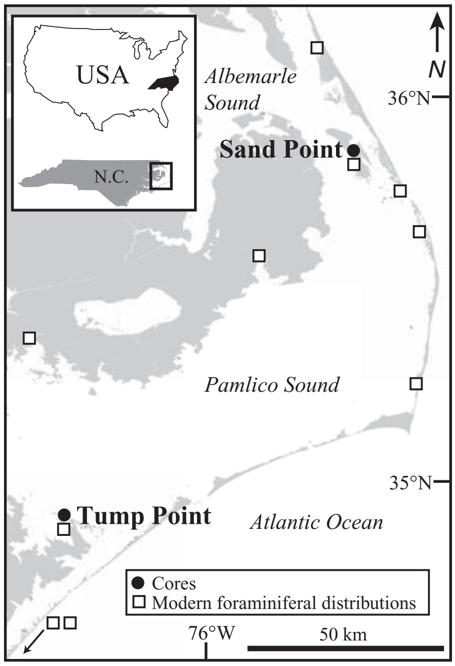

Figure 1. Location of study sites at Sand Point and Tump Point in Albemarle-Pamlico estuarine system of North Carolina, U.S. Atlantic coast (closed circles). Modern foraminiferal distributions were documented at 10 sites (open squares); two are situated in Core and Bogue Sounds south of the area shown.

INTRODUCTION

During the twentieth century the global rate of sea-level rise recorded by tide gauges was 1.7–1.8 mm/a (e.g., Douglas, 1991; Church and White, 2006) greater than the long-term rate of rise that has been inferred from the late Holocene geological record (e.g., Shennan and Horton, 2002; Gehrels et al., 2004). Understanding the timing and magnitude of this apparent acceleration in the rate of relative sea-level rise (RSLR) is critical for testing models of global climate change and providing a context for twenty-first century predictions (e.g., Intergovernmental Panel on Climate Change, 2007; Rahmstorf, 2007). Tide-gauge records are largely inadequate for accurately recognizing the onset of any acceleration of RSLR that occurred prior to A.D. 1900 because too few records exist (Woodworth et al., 2009). Those that are available are concentrated heavily in northwestern Europe, introducing a spatial bias into global analyses of tide-gauge records (e.g., Douglas, 1992; Woodworth et al., 2009). Furthermore, trends inferred from individual records shorter than 50 years are difficult to interpret due to the influence of decadal-scale oscillations (Douglas, 1992, 2008). Geological reconstructions of relative sea level (RSL) and models of glacio-isostatic adjustment often lack sufficient resolution to resolve subtle changes in former sea levels (Horton et al., 2009). High-resolution (decadal and decimeter scale) sea-level reconstructions from salt-marsh sedimentary sequences offer a means to bridge the gap between instrumental records and geological data and identify the onset of accelerated RSLR (e.g., van de Plassche et al., 1998; Gehrels et al., 2005, 2008).

Under a regime of rising sea level, salt marshes form continuous accumulations of organic sediment (Allen, 2000). Foraminiferal assemblages preserved within these sedimentary archives provide an accurate and precise means to reconstruct late Holocene RSL due to a strong relationship with elevation (e.g., Scott and Medioli, 1978), which can be quantified using transfer functions (e.g., Horton et al., 1999). Detailed composite chronologies of salt-marsh sediments can be developed using radiometric isotopes and independent stratigraphic age markers (e.g., Gehrels et al., 2008).

We provide records of RSL change since A.D. 1500 from two salt marshes (Sand Point and Tump Point; Fig. 1) in the Albemarle-Pamlico estuarine system of North Carolina, United States, to identify the timing and magnitude of accelerated RSLR. The reconstructions are validated against twentieth century regional tide-gauge records. The two study sites provide an ideal setting for producing high-resolution records because thick sequences of high marsh sediment are present and the estuarine system is microtidal, which reduces the vertical uncertainty of paleosea-level estimates. While previous such reconstructions of sea-level change were based on single-site analyses (e.g., Donnelly et al., 2004; Gehrels et al., 2005, 2008), this study provides for the first time replicated sea-level reconstructions from two sites ~120 km apart.

ESTIMATING PALEOMARSH ELEVATION

Transfer functions quantify the relationship between biological assemblages and an environmental variable of interest in the modern environment and can be used to estimate past environmental conditions from paleontological data (Sachs et al., 1977). We used the modern elevational distribution of foraminiferal assemblages from 184 samples in 10 North Carolina salt marshes (Kemp et al., 2009; Fig. 1) to develop transfer functions with strong predictive power (r^2 = 0.59–0.63) and small

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errors (0.03–0.05 m). We applied the transfer functions to 73 samples from cores collected at Sand Point and Tump Point (Fig. 1) to provide estimates of paleomarsh elevation (PME) with sample-specific errors.

At Sand Point, ~3 m of salt-marsh peat overlies Pleistocene sand. We identified 10 species of foraminifera in the upper 0.77 m of a core selected for analysis (see the GSA Data Repository[1]). The surface elevation of the core is 0.33 m above present mean sea level (MSL; National Oceanic and Atmospheric Administration, NOAA, datum). Between 0.77 m and 0.33 m core depth the dominant foraminiferal species is *Jadammina macrescens* (average 39% of the total assemblage; Fig. 2A). The interval between 0.33 m and 0.17 m is dominated by *Haplophragmoides wilberti* (average 61%). Both species are indicative of a high marsh environment (Kemp et al., 2009), which supports the transfer function-derived estimates of PME between 0.11 m and 0.29 m above MSL with an average error of ±0.05 m.

The Tump Point site has ~1.5 m of salt-marsh peat overlying Pleistocene sand. We identified 12 species of foraminifera in the upper 0.72 m of a core selected for analysis. The surface elevation of the core is 0.17 m above MSL. The dominant species are *H. wilberti* (average 42%; Fig. 2B) and *Arenoparrella mexicana* (average 34%), which are common high and middle marsh species, respectively (Kemp et al., 2009). PMEs estimated from these assemblages range from 0.06 m to 0.20 m above MSL with an average error of ±0.03 m.

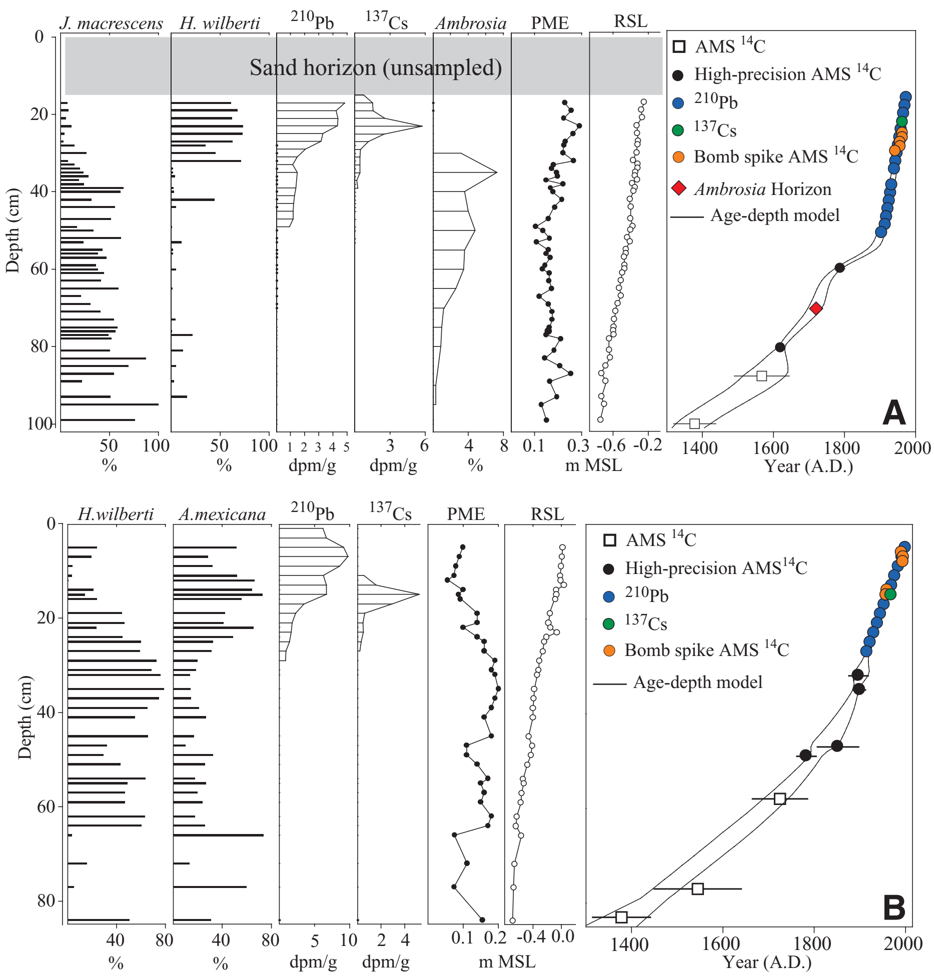

Figure 2. Lithostratigraphy, biostratigraphy, and chronostratigraphy of study sites. A: Sand Point core. B: Tump Point core. Age-depth models (upper and lower estimates shown by solid lines) were developed using ^{14}C dating (accelerator mass spectrometry [AMS], high precision and bomb spike), ^{210}Pb, and ^{137}Cs. In addition, a pollen chronohorizon was identified at Sand Point. Complete foraminiferal assemblages were used to estimate paleomarsh elevation (PME) in meters above mean sea level (MSL); only the two most dominant species are shown for each site (*Jadammina macrescens*, *Haplophragmoides wilberti*, and *Arenoparrella mexicana*). Relative sea level (RSL) is estimated by subtracting PME from sample elevation.

COMPOSITE CHRONOLOGIES

Precise chronological control is critical for identifying changes in sediment accumulation rates. We used a suite of dating methods to constrain the chronology of the Sand Point and Tump Point cores. Ages were estimated using conventional accelerator mass spectrometry (AMS) ^{14}C, high-precision AMS ^{14}C (Marshall et al., 2007), ^{210}Pb, ^{137}Cs, bomb spike AMS ^{14}C (e.g., Goodsite et al., 2001), and a pollen chronohorizon. An age-depth model was developed for both cores following Heegaard et al. (2005), which provides downcore estimates of age and uncertainty.

Conventional AMS and high-precision AMS ^{14}C dates on subsurface stems of *Juncus roemerianus* from the Sand Point core show that the upper 1 m of the core represents the period since ca. A.D. 1500 (Fig. 2A). A pollen chronohorizon at 0.70 m indicating colonial land clearance was identified by an increase (to 2% of the total pollen assemblage) in *Ambrosia* and was assigned an age of A.D. 1720 ± 20 (after Cooper et al., 2004). The upper 0.50 m of the core was dated using ^{210}Pb and is independently supported by a ^{137}Cs spike (A.D. 1963) at 0.23 m and five bomb spike AMS ^{14}C dates.

The upper 0.75 m of the Tump Point core represents the period since ca. A.D. 1500 based on conventional AMS and high-precision AMS ^{14}C dates on *Distichlis spicata* and *J. roemerianus* subsurface stems. The upper 0.3 m of the core was dated using ^{210}Pb. These age estimates were independently corroborated by a spike in ^{137}Cs activity at 0.15 m corresponding to A.D. 1963 and five bomb spike AMS ^{14}C dates (Fig. 2B).

RECONSTRUCTING RELATIVE SEA LEVEL

RSL since A.D. 1500 was reconstructed using 42 and 31 sea-level data points from Sand Point and Tump Point, respectively (Fig. 3). RSL was determined by subtracting the estimated PME from the current elevation of each sample (Fig. 2). The age and error of each data point were estimated by the age-depth model. At Sand Point there is little change in PME from 0.77 m to ~0.5 m depth in the core. The upper 0.5 m shows a trend of increasing PME from ~0.15 m to 0.21 m above MSL (Fig. 2A). This change coincides with a shift in the accumulation rate from ~1 mm/a to ~5 mm/a. In comparison, PMEs increase in the Tump Point core between 0.72 m and 0.35 m (Fig. 2B) and decline in the upper 0.35 m, as evidenced by a change in the foraminiferal assemblages from *H. wilberti* (high marsh) to *A. mexicana* (middle marsh). This shift coincides with a change in the rate of accumulation from ~1 mm/a to 3.5 mm/a. Despite changes in accumulation

[1]GSA Data Repository item 2009260, details of salt-marsh stratigraphy, foraminiferal assemblages, and age-depth data, 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.

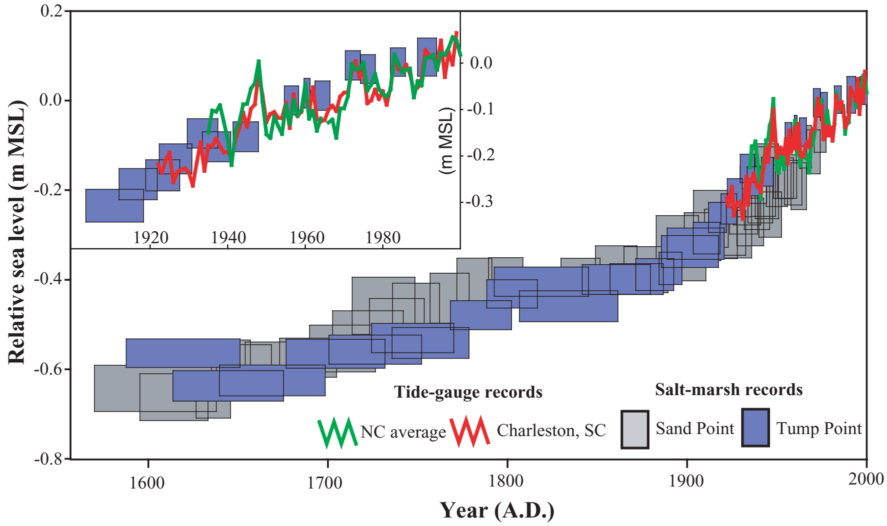

Figure 3. Reconstructions of relative sea level (meters above mean sea level, MSL) at Sand Point (gray boxes) and Tump Point (blue boxes) for the period since A.D. 1500. Average tide-gauge record from North Carolina (NC, green) and record from Charleston, South Carolina (SC, red), are also shown. Inset: Twentieth century relative sea level reconstructed at Tump Point is compared to tide-gauge records.

rate, the RSL records from Sand Point and Tump Point are comparable because of variations in PME associated with the response of foraminiferal assemblages.

Sea-level data points are represented by boxes (Fig. 3) that incorporate the elevational (derived from the transfer functions) and age uncertainties (estimated by the age-depth model). Both cores are considered to be free of compaction because of consistent downcore bulk density (e.g., Gehrels et al., 2008) and agreement between the age and altitude of basal and nonbasal samples at Sand Point. Furthermore, Horton et al. (2009) compared the age and altitude of basal and nonbasal samples throughout this region, and showed that late Holocene salt-marsh sediments were not significantly affected by compaction.

We compare the two salt-marsh records against an independent, observational record of sea-level change provided by tide-gauge data (an average North Carolina record from seven gauges and the record from Charleston, South Carolina, provided by NOAA's National Ocean Service). The detailed twentieth century salt-marsh record from Tump Point shows that the highest rate of RSLR occurred between A.D. 1900 and 1956 (3.8 mm/a), which was followed by a reduced rate of RSLR that began between A.D. 1960 and 1970 and persisted for ~30 years (Fig. 3). These trends are apparent in the local tide gauges and are prominent features of the instrumental record in the northwest Atlantic (e.g., Douglas, 2008; Woodworth et al., 2009). The agreement between these records validates the approach employed in reconstructing RSL at high resolution from salt marshes and justifies its application to time periods prior to tide-gauge observations.

HIGH-RESOLUTION RECORDS OF RELATIVE SEA-LEVEL CHANGE

We subtracted late Holocene (background) rates of 1.1 mm/a and 0.8 mm/a from the sea-level reconstructions at Sand Point and Tump Point, respectively, following Horton et al. (2009). The difference between sites is a consequence of ongoing, spatially variable, glacio-isostatic adjustment in response to collapse of the pro-glacial forebulge (Peltier, 2004; Horton et al., 2009).

Using Bayesian change point linear regression (Carlin et al., 1992), we identify a 2.2 mm/a increase in the rate of sea-level rise in excess of the background rate at Sand Point and Tump Point that began between A.D. 1879 and 1915. A small number of other salt-marsh studies have similarly investigated the timing and magnitude of this acceleration (Fig. 4). The onset of accelerated RSL rise in North Carolina appears to be broadly synchronous with published records from Connecticut and Nova Scotia. Donnelly et al. (2004) inferred an acceleration to have taken place in Connecticut between A.D. 1850 and 1900 from the

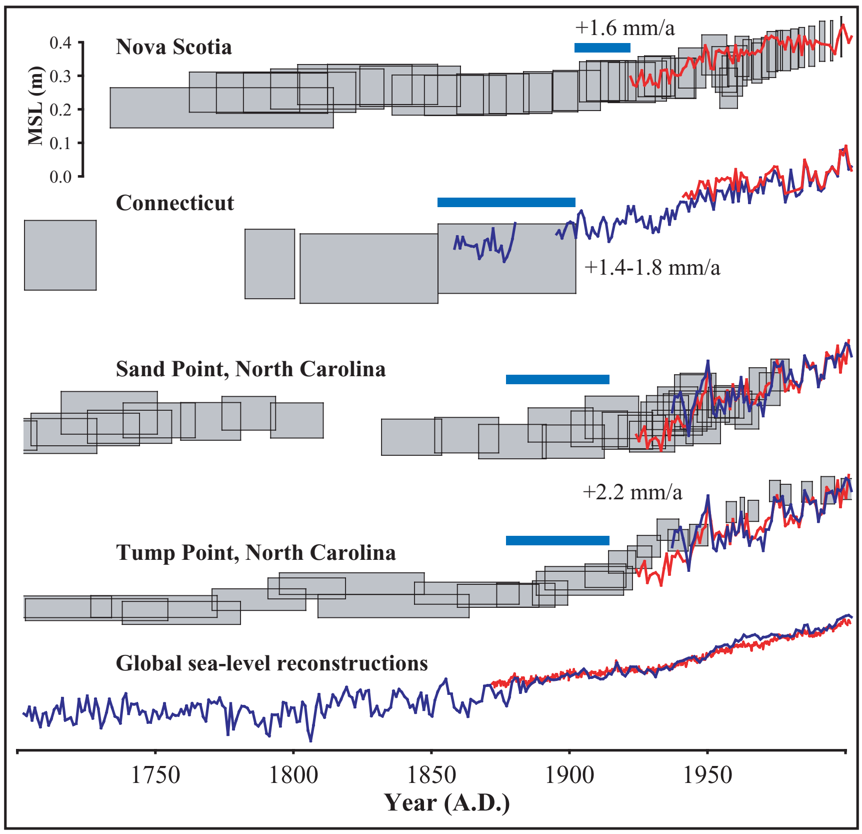

Figure 4. Records of mean sea level (MSL) from eastern North America and reconstructions of global sea level based on instrumental records (red—Church and White, 2006; blue—Jevrejeva et al., 2008). Scale for all plots is identical and regional late Holocene background rates of sea-level rise were subtracted. For salt-marsh reconstructions, sea-level data points are represented by gray boxes encompassing age and elevation errors. Tide-gauge records are shown for comparison and were matched with salt-marsh records (Nova Scotia [Halifax]; Connecticut [New London in red and New York City in blue]; North Carolina [Charleston, South Carolina, in red and North Carolina average in blue]). Timing (blue bars) and estimated magnitude (rate in excess of background) of accelerated sea-level rise are shown for each study.

difference between local tide-gauge records (2.4–2.8 mm/a) and a late Holocene salt-marsh record (1 mm/a). Gehrels et al. (2005) showed modern rates of RSLR in Nova Scotia to be 1.6 mm/a above the background rate, and dated this acceleration to A.D. 1900–1920.

Comparison of the Sand Point and Tump Point records (2.2 mm/a above background rate) with these other salt-marsh studies suggests that the magnitude of accelerated RSLR may exhibit a latitudinal trend. Tide-gauge records support this inference (e.g., Douglas, 1991; Peltier, 2001; Wake et al., 2006); gauges north of New York City show rates (average 1.5 mm/a) lower than those to the south (average 2.5 mm/a; Douglas, 1991). Wake et al. (2006) attributed this latitudinal variation to ocean thermal expansion. In contrast, this latitudinal trend could also be a fingerprint of mass loss from the Greenland Ice Sheet because water migrates away from the ice sheet as its gravitational attraction is diminished (Conrad and Hager, 1997; Mitrovica et al., 2001).

CONCLUDING REMARKS

We reconstructed RSL using salt-marsh foraminifera and composite sediment chronologies at two sites in North Carolina to identify the onset and magnitude of accelerated sea-level rise. Comparison with twentieth century tide-gauge records validates the use of this approach and suggests that salt-marsh records with decadal and decimeter resolution can supplement tide-gauge records by extending record length and compensating for the strong spatial bias in the global distribution of longer instrumental records. We identify a 2.2 mm/a increase in the rate of RSLR that was initiated between A.D. 1879 and 1915 in data from North Carolina salt marshes. This change is broadly synchronous with similar salt-marsh records from the Atlantic coast. The magnitude of the acceleration suggests a latitudinal variation, which may be indicative of ocean thermal expansion or a fingerprint of mass loss from the Greenland Ice Sheet.

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