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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 rigorously quality-controlled database of late Holocene sea-level indices from the US Atlantic Coast, exhibiting subsidence rates of less than 0.8 mm a^{-1} in Maine, increasing to rates of 1.7 mm a^{-1} in Delaware, and a return to rates less than 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}, which is 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 either 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 volume of the ocean, 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. Firstly models of GIA have been constructed and then later employed by a number of authors, which produce global sea-level rise estimates of c. 1.8 mm a^{-1} (Peltier and Tushingham, 1989; Douglas, 1991, 1997; Peltier, 2001; Church and White, 2006), although the US 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; Davis and Mitrovica, 1996; Peltier, 2001). Secondly, global positioning systems (GPS) have been used that suggest a rate of c. 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 US Atlantic Coast. However, this geological database included sea-level index points up to 6 ka BP, 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 (Appendix A). 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 BP 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 the ice-equivalent meltwater input 4 ka to AD 1900 is either zero (Peltier and Tushingham, 1991; Douglas, 1995; Peltier, 1996, 2002) or minimal (Milne et al., 2005; Church et al., 2008). Along the passive margin of the US Atlantic Coast, it is widely accepted that the tectonic component is negligible. We have significantly reduced the influence of compaction by only utilizing basal peat samples (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 AD 1900 and adjusted the sea-level axis to mean sea level in AD 1900 (Appendix B). We estimated the rate of late Holocene RSLR by running a linear regression over the last 4 ka with two sigma errors (Shennan and Horton, 2002).

Tide Gauge Records

We identified 10 suitable tide-gauge records along the US 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 US Atlantic Coast. The validated database contains 212 basal sea-level index points for the last 4 ka BP from 19 locations that stretch from Maine (45ºN) to South Carolina (32ºN) (Fig. 1). There is an absence of index points from Georgia and Florida. Relative sea level has risen along the entire US 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 ka BP), 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 (45ºN) to northern Massachusetts (42ºN), relative sea level has risen less than 3.5 m during the last 4 ka BP, with rates of RSLR lower than 0.8 mm a^{-1} (Fig. 1, Supplementary Table DR1). Along the mid-Atlantic coastline from Cape Cod, Massachusetts (41.5ºN) to the northern Outer Banks, North Carolina (35.9ºN), late Holocene RSLR of 1 mm a^{-1} is met or exceeded at nine of eleven locations. The highest rates of RSLR are recorded in New Jersey, Delaware and Maryland, where all rates are greater than 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 less than 0.9 mm a^{-1} from Beaufort, North Carolina (34.7ºN) to Port Royal, South Carolina (32.4ºN). The southern North Carolina and South Carolina sites all show similar records of RSLR (0.5 - 0.8 mm a^{-1}).

All tide-gauge locations along the US 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, while 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 US 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) propose 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 the "hinge line" separating uplift from subsidence is offshore of the Maine coastline, whereas the geological data from two locations in this study suggest Maine is experiencing 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 within Maine of 1.9 ± 1.0 mm a^{-1} 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 the maximum rate of subsidence (3.1 ± 3.5 mm a^{-1}) 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 US 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 US 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 one sigma level; if two sigma 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 US 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 since AD 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, in press). Rignot et al. (2008) suggested that Greenland is currently losing mass at the equivalent sea-level rise rate of c. 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) propose significant spatial variation in ocean thermal expansion for the upper 700 m along the US 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.

The geological data documents the continued response of the US 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 US 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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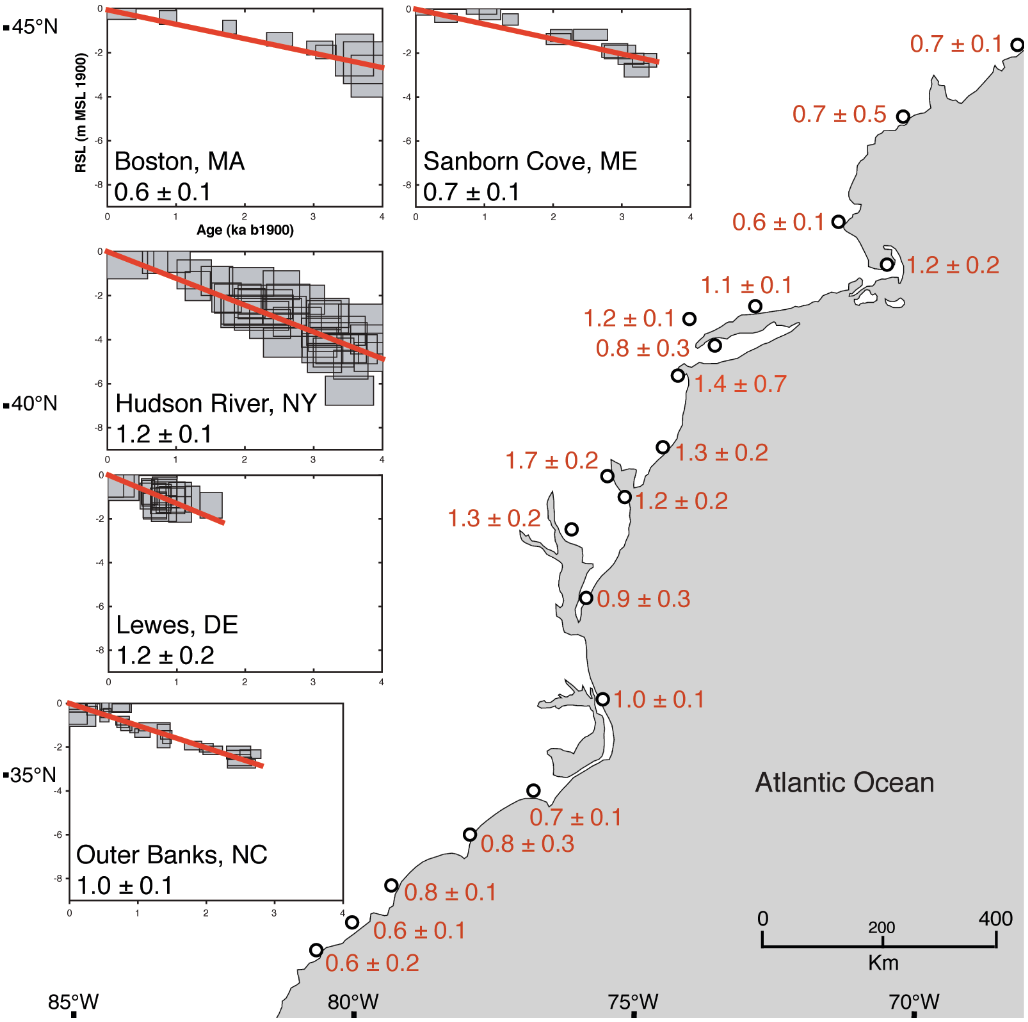
FIGURE CAPTIONS

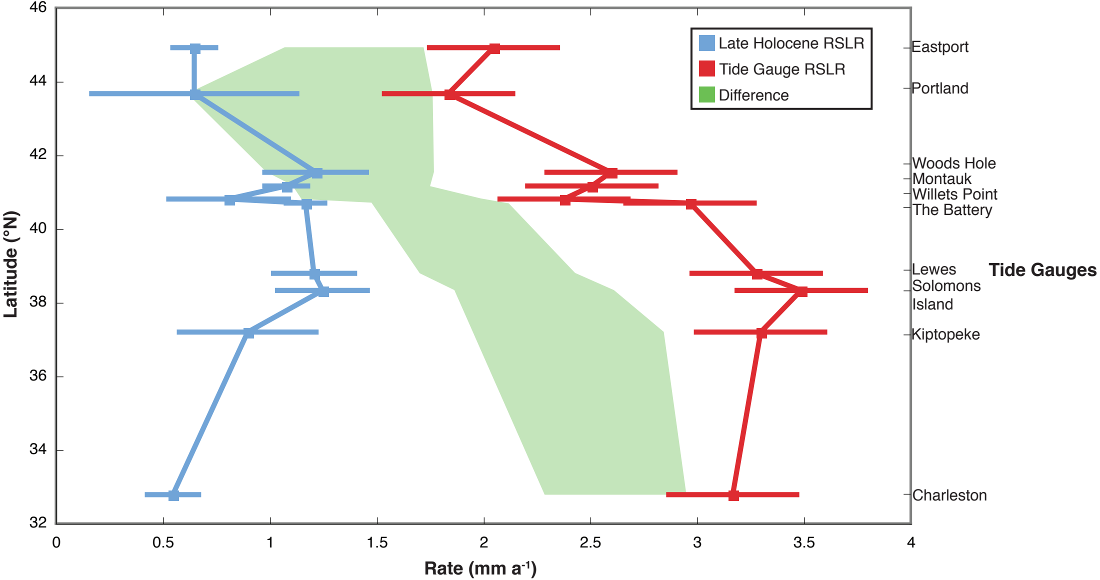
Figure 1. Rate of late Holocene relative sea-level rise with two sigma errors for 19 locations along the U.S. Atlantic Coast. Inset plots are examples of locations with sea-level index points plotted as calibrated age versus change in RSL relative to MSL in 1900 (m). The red line is the linear regression for each site. Rates and errors shown to 1 d.p.

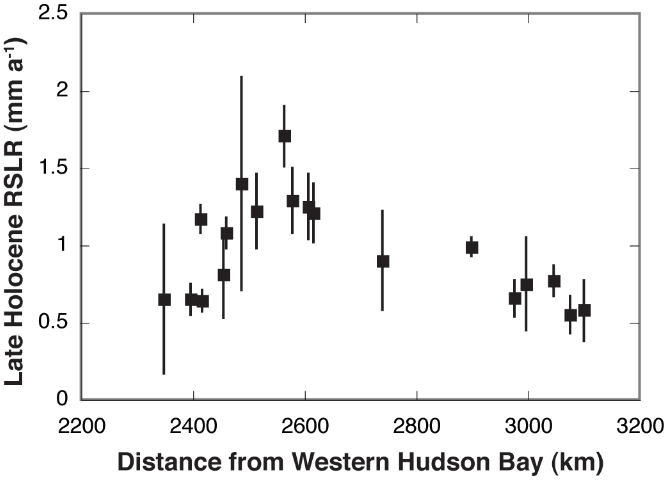
Figure 2. Detrending of 20th century tide gauge relative sea-level rise (RSLR) with rate of late Holocene relative sea-level rise for 10 locations along the US Atlantic Coast. Mean and two sigma error of sea-level trends are plotted against latitude.

Figure 3. Rate of late Holocene relative sea-level rise with two sigma errors for 19 locations along the US Atlantic Coast plotted as a function of distance from western Hudson Bay (km).

[1] GSA Data Repository item 2009xxx, xxxxxxxx, is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.


45°N
40°N
35°N
85°W
80°W
75°W
70°W
RSL (m MSL 1900)
Age (ka b1900)
Boston, MA
0.6 ± 0.1
Sanborn Cove, ME
0.7 ± 0.1
Hudson River, NY
1.2 ± 0.1
Lewes, DE
1.2 ± 0.2
Outer Banks, NC
1.0 ± 0.1
0.7 ± 0.1
0.7 ± 0.5
0.6 ± 0.1
1.2 ± 0.2
1.1 ± 0.1
1.2 ± 0.1
0.8 ± 0.3
1.4 ± 0.7
1.3 ± 0.2
1.7 ± 0.2
1.2 ± 0.2
1.3 ± 0.2
0.9 ± 0.3
1.0 ± 0.1
0.7 ± 0.1
0.8 ± 0.3
0.8 ± 0.1
0.6 ± 0.1
0.6 ± 0.2
Atlantic Ocean
0
200
400
Km


Late Holocene RSLR
Tide Gauge RSLR
Difference
Latitude (°N)
46
44
42
40
38
36
34
32
Rate (mm a-1)
0
0.5
1
1.5
2
2.5
3
3.5
4
Eastport
Portland
Woods Hole
Montauk
Willets Point
The Battery
Lewes
Solomons Island
Kiptopeke
Charleston
Tide Gauges



2.5
2
1.5
1
0.5
0
Late Holocene RSLR (mm a^{-1})
2200
2400
2600
2800
3000
3200
Distance from Western Hudson Bay (km)

APPENDIX A: SEA-LEVEL INDEX POINTS

The standardized methodology for reconstructing former sea levels from low energy, sedimentary environments has been established during the International Geological Correlation Programs (IGCP) (van de Plassche, 1986; Shennan and Horton, 2002; Edwards, 2006). To be a validated sea-level index point (SLI), a sample must have a location, an age and a known relationship between the sample and a known tidal level and the indicative meaning (Shennan, 1986; van de Plassche, 1986). The indicative meaning is constructed of two parameters, the reference water level (e.g. mean higher high water (MHHW)) and the indicative range (the vertical range over which the sample could occur). To constrain the indicative meaning of the index points in the US Atlantic database, we have used published zonations of modern vegetation (Redfield, 1972; Niering and Warren, 1980; Lefor et al., 1987; Gehrels, 1994) and the distribution of microfossils (Gehrels, 1994) supported by $\delta^{13}C$ values from the radiocarbon-dated sediments (Andrews et al., 1998; Törnqvist et al., 2004). As an example, where we have a floral and/or faunal indication that a sample was formed within a salt marsh environment but cannot be identified as specifically high or low marsh, the index point is conservatively estimated to have formed between MHHW and mean tide level (Törnqvist et al., 2004). For samples where we have a positive identification of plant macrofossil species, we can reduce the indicative range. Where authors have used microfossils to quantitatively assess the relationship between the sample and former sea level, these predictions of the indicative meaning have been retained. In practice, over 70% of the samples in the database can only be identified as salt-marsh deposits.

The relative sea level of the sea-level index points is calculated using the equation:

$$\text{Relative Sea Level} = \text{Elevation}_{\text{sample}} - \text{Reference Water Level}_{\text{sample}}$$

where the elevation and reference water level are expressed in meters relative to the national datum, NAVD 88, and subsequently corrected to local mean sea level (MSL).

For each sample, we calculated the vertical error of the index point from a variety of factors that are inherent to sea-level research (Shennan, 1986). Further errors are incorporated including the type of coring equipment used, techniques of depth measurement and the compaction of the sediment during penetration (Woodroffe, 2006). We also included an error estimate associated with the leveling of the sample with respect to NAVD 88. For high precision leveling using modern techniques, this can be as low as ±0.05 m but can rise as high as ±0.5 m for less precise methods. A further error is included due to the leveling of the sample to local tide levels. This is typically ±0.1 m but may be much larger, particularly when samples are collected offshore (Shennan, 1986). The errors in this study do not include the effects of tidal range change through time; we assume that this influence is minimal (Gehrels et al., 1995). The total error (E_h) for each sample is then calculated from the expression:

$$E_h = (e^2{}_1 + e^2{}_2 \ldots + e^2{}_n)^{1/2}$$

Where $e_1 \ldots e_n$ are the individual sources of error.

A further source of error in sea-level reconstruction is sediment consolidation, that is, compression of a sedimentary package by its own weight or the weight from overlying sediment (Kaye and Barghoorn, 1964). The significance of sediment consolidation was recognized from early studies of North American (Bloom, 1964; Kaye and Barghoorn, 1964) and European (Jelgersma, 1961; Streif, 1971; van de Plassche, 1980) salt marshes. If consolidation is not corrected for, then index points will be lowered from their original elevation and the rate and magnitude of relative sea-level rise will be overestimated. However, correcting for the compaction of sediments is a complex process involving many variables (Pizzuto and Schwendt, 1997). Therefore, we have reduced the influence of compaction by only employing basal peat samples, which are deposited directly on the presumed compaction-free substrate (Kaye and Barghoorn, 1964).

Every SLI in the validated database (Figure DR1, Figure DR2) was radiocarbon dated and calibrated using CALIB 5.0.1 (Stuiver et al., 2005). We used a laboratory multiplier of 1 with 95% confidence limits and employed the dataset IntCal04 (Reimer et al., 2004). The database contains samples that were dated by Accelerator Mass Spectrometry (AMS), Gas Proportional Counting (GPC) and Liquid Scintillation Counting (LSC). Sample material in the database varies from dates on bulk peat to dates on identifiable salt marsh rhizomes.

APPENDIX B: LATE HOLOCENE RATES OF RELATIVE SEA-LEVEL RISE

We have used validated geological observations from basal peat over the last 4 ka (the late Holocene) to reconstruct background rates of sea-level rise. We assume that the ice-equivalent meltwater input over the last 4 ka is either zero (Douglas, 1995; Peltier, 1996, 2002) or minimal (Milne et al., 2005). A meltwater input of 1 m during the late Holocene (Church et al., 2008) would reduce the estimate of subsidence by 0.25 mm yr^{-1}. We also assume that the tectonic component is small, except in close proximity to the Cape Fear Arch, North Carolina, which has experienced uplift (Marple and Talwani, 2004).

When calculating the background rate of relative sea-level rise, it is necessary to remove the modern component, as this will overestimate the background rate due to the sea-level rise experienced during the 20th century (~0.2 – 0.3 m along the US Atlantic coast). In this study, we remove this modern sea level rise by using the nearest reliable tide gauge rate to extrapolate to MSL in 1900 AD. We then express all dates with respect to 1900 AD. At all sites the linear regression is run over the last 4 ka and is forced through zero. Regression errors are at the 95% confidence level. This contrasts with previous work (Gornitz, 1995; Peltier, 1996) that reported the error as the standard deviation and not the standard error.

Table DR1. Location of the 19 sites along the US Atlantic Coast and the rate of late Holocene (last 4 ka) relative sea-level rise (RSLR) derived from geological data. The references for the geological data are shown. GPS rates of vertical motion are from (1) Snay et al. (2007) and (2) Sella et al. (2007). Geological and GPS rates are shown with two sigma errors. Positive and negative values from the geological and GPS data refer to subsidence and uplift, respectively.

Site Number	**Site Name**	**Late Holocene RSLR (mm yr^{-1})**	**Rate from Nearest GPS Station (mm yr^{-1})**	**References**
1	Sanborn Cove, Maine	0.7 ± 0.1	1.9 ± 2.0 (1)	Gehrels and Belknap, 1993; Gehrels, 1999
2	Phippsburg, Maine	0.7 ± 0.5	-0.2 ± 3.2 (2)	Gehrels et al., 1996
3	Boston, Massachusetts	0.6 ± 0.1	2.3 ± 1.2 (2)	Newman et al., 1980; Donnelly, 2006
4	Barnstable, Massachusetts	1.2 ± 0.2	N/A	Redfield and Rubin, 1962; Stuiver et al., 1963
5	Clinton, Connecticut	1.1 ± 0.1	N/A	Cinquemani et al., 1982; van de Plassche, 1991; Nydick et al., 1995; van de Plassche et al., 2002
6	Hudson River, New York	1.2 ± 0.1	0.6 ± 3.0 (2)	Newman et al., 1980; Pardi et al., 1984
7	Northern Long Island, New York	0.8 ± 0.3	1.6 ± 3.0	Cinquemani et al., 1982; Pardi et al., 1984
8	Sandy Hook, New Jersey	1.4 ± 0.7	2.2 ± 1.4 (1)	Cinquemani et al., 1982
9	Atlantic City, New Jersey	1.3 ± 0.2	N/A	Stuiver and Daddario, 1963; Cinquemani et al., 1982; Pardi et al., 1984; Psuty, 1986
10	Inner Delaware Estuary, Delaware	1.7 ± 0.2	2.9 ± 2.0 (2)	Belknap, 1975; Belknap and Kraft, 1977; Nikitina et al., 2000
11	Lewes, Delaware	1.2 ± 0.2	1.1 ± 2.3 (1)	Elliot, 1972; Belknap, 1975; Belknap and Kraft, 1977; Fletcher et al., 1993; Ramsey and Baxter, 1996; Nikitina et al., 2000
12	Blackwater, Maryland	1.3 ± 0.2	2.2 ± 2.3 (1)	Cinquemani et al., 1982
13	Eastern Shore, Virginia	0.9 ± 0.3	3.5 ± 1.6 (2)	Engelhart and Kemp (unpublished)

14	Outer Banks, North Carolina	1.0 ± 0.1	N/A	Horton et al.; 2009 Cinquemani et al., 1982
15	Beaufort, North Carolina	0.7 ± 0.1	N/A	Horton et al. 2009; Cinquemani et al., 1982; Spaur and Snyder, 1999
16	Wilmington, North Carolina	0.8 ± 0.3	N/A	Cinquemani et al., 1982
17	Georgetown, South Carolina	0.8 ± 0.1	N/A	Cinquemani et al., 1982
18	Charleston, South Carolina	0.6 ± 0.1	1.6 ± 1.7 (1)	Cinquemani et al., 1982
19	Port Royal, South Carolina	0.6 ± 0.2	N/A	Cinquemani et al., 1982

APPENDIX C: UNCERTAINTY OF SEA-LEVEL TRENDS FROM TIDE GAUGE DATA

We identified 10 suitable tide gauge records along the US Atlantic Coast from the Permanent Service for Mean Sea Level (Woodworth and Player, 2003) that are at least 50 years in length and where the influence of non-GIA subsidence, such as groundwater withdrawal, is minimal. The tide gauge record at The Battery, New York, is truncated to only include data from the 20th century.

Formal uncertainties of trends of relative sea-level (RSL) obtained from tide gauge data are usually a few tenths of a mm per year for records longer than about 50 years. These formal uncertainties are optimistic, since tide gauge records do not satisfy the criteria for a linear regression, i.e., that the data consist of a trend plus Gaussian random noise. The records also contain interannual and longer variations of high amplitude that can negate the underlying trend of sea level for even many decades in some cases (Douglas, 2001).

As glacial isostatic adjustment (GIA) is considered to be the dominant control on the variation in the tide gauge records, we can assess the appropriate error term by running a linear regression through the rates from long-term tide-gauge records, going from areas of isostatic uplift in Canada to the proposed peak of GIA in the mid-Atlantic (Figure DR3). It is apparent that these rates lie along a straight line with little variation. Therefore, we can run a linear regression through these rates to produce a single estimate of the error for the tide gauges along the US Atlantic Coast of ± 0.3 mm yr^{-1}.

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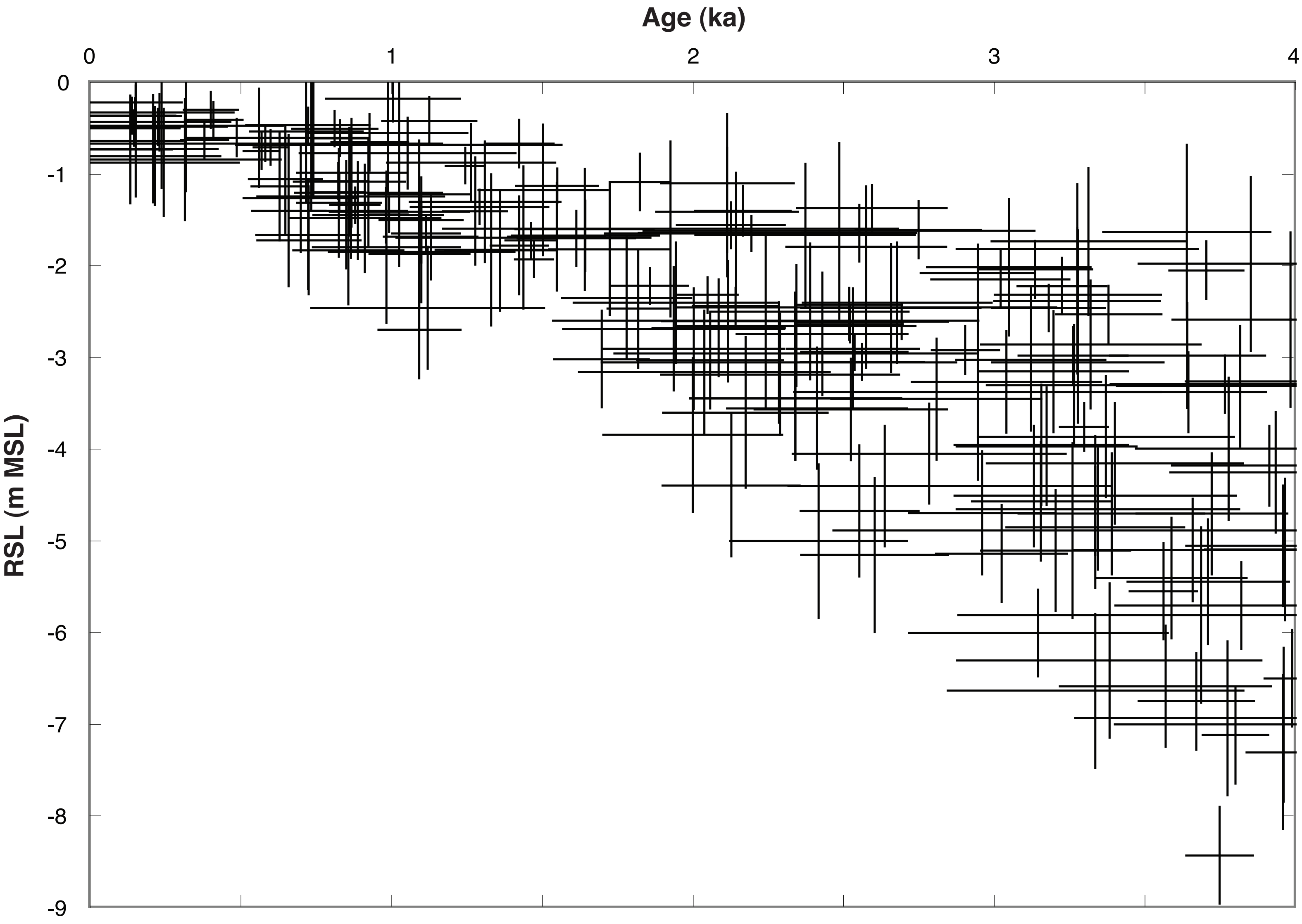
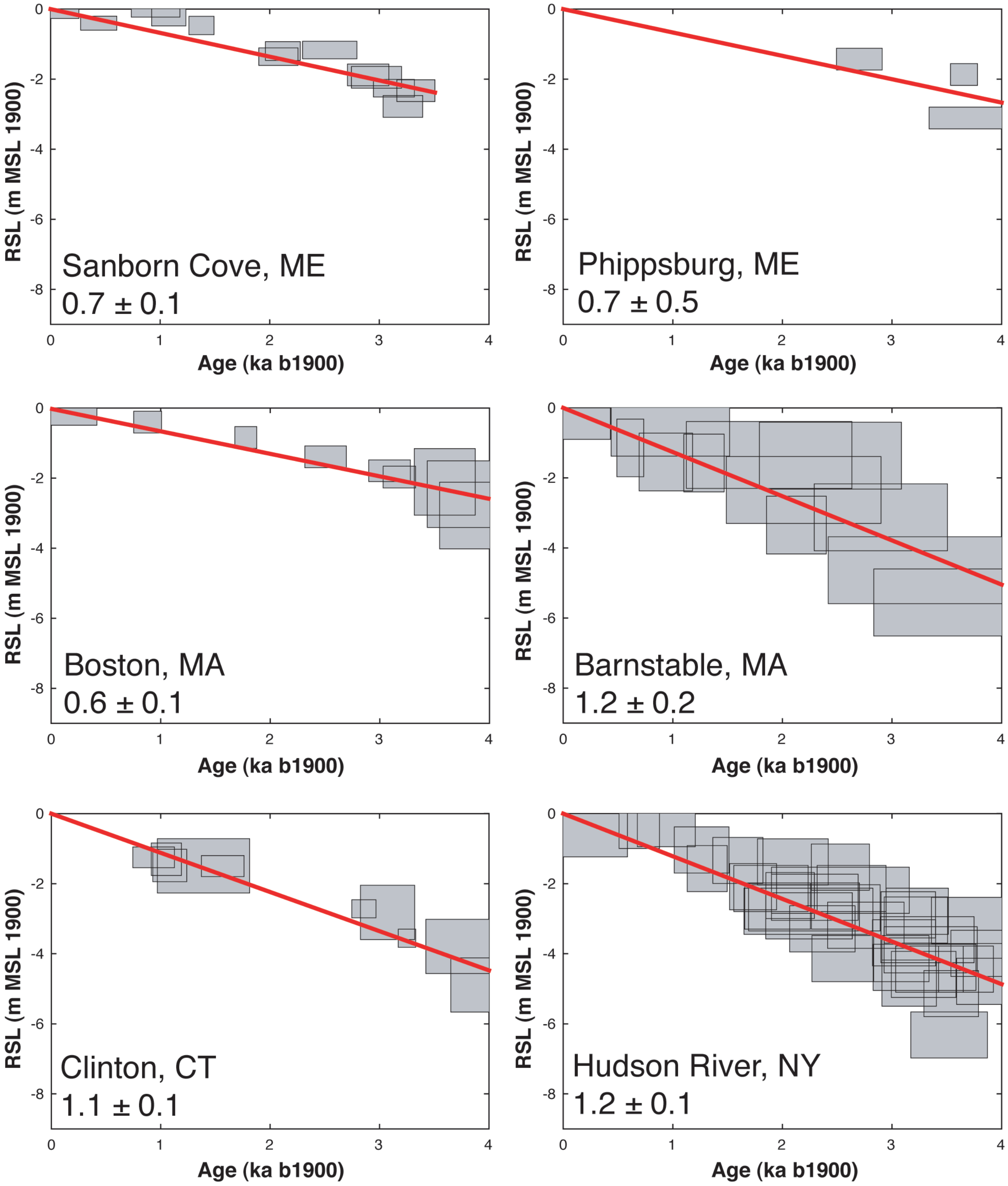
SUPPLEMENTARY FIGURE AND TABLE CAPTIONS

Figure 1. All 212 radiocarbon dated basal index points, covering the last 4 kyr. The data demonstrates the considerable scatter caused by the differential GIA along the Atlantic Coast.

Figure 2a-d. 19 locations along the US Atlantic Coast with 3 or more basal sea-level index points and the late Holocene rates of RSL rise. Sea-level index points are plotted as calibrated age versus change in RSL relative to MSL in AD 1900 (m). The red line is the linear regression for each site. Rates and errors shown to 1 d.p. Data sources for sea level index points are referenced in Table DR1.

Figure 3. Long-term tide gauge records from Canada to Virginia, USA, plotted against distance from Churchill, Canada. The regression line demonstrates the methodology used to ascertain an appropriate error for the tide gauges.


Age (ka)
0
1
2
3
4
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
RSL (m MSL)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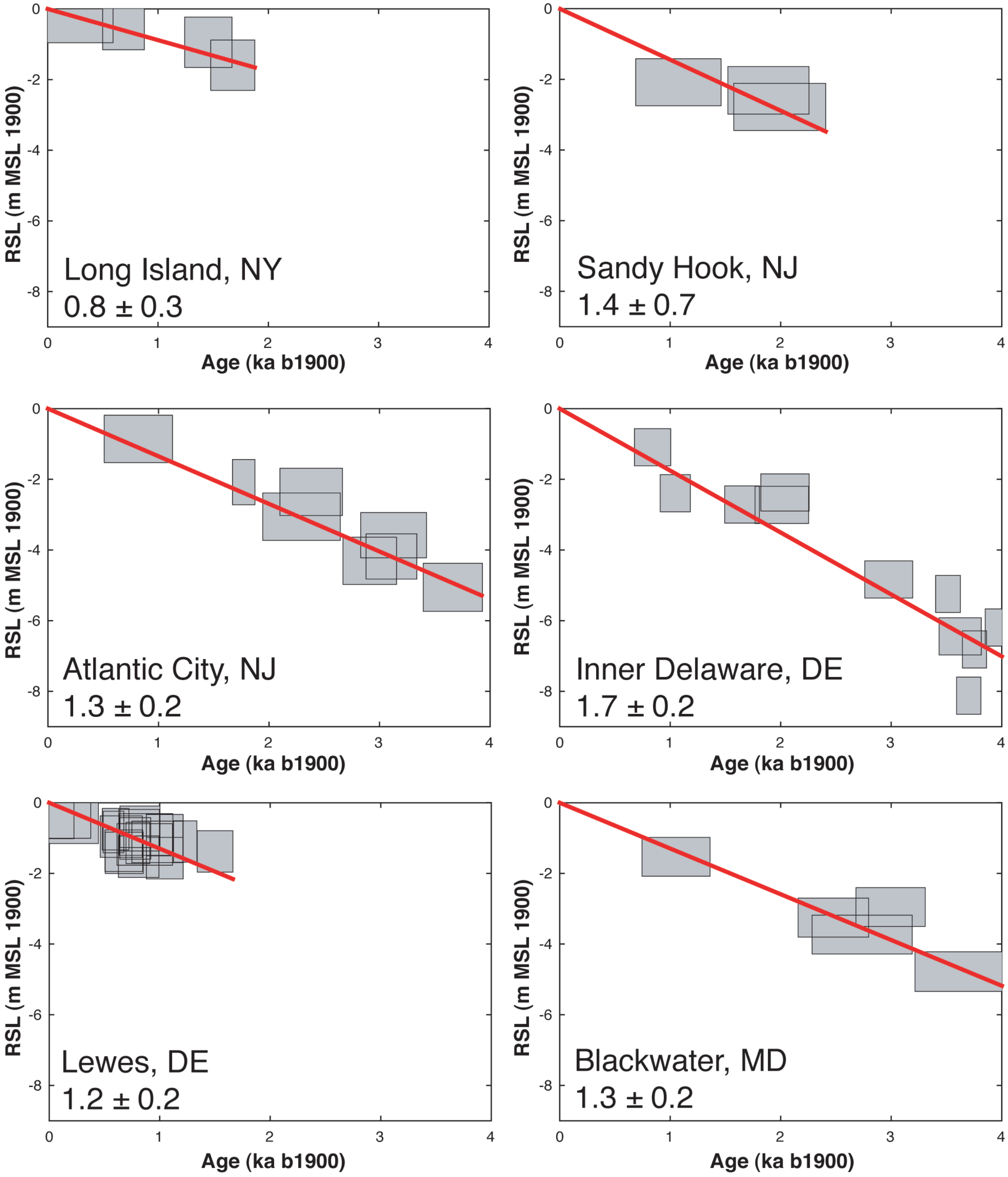
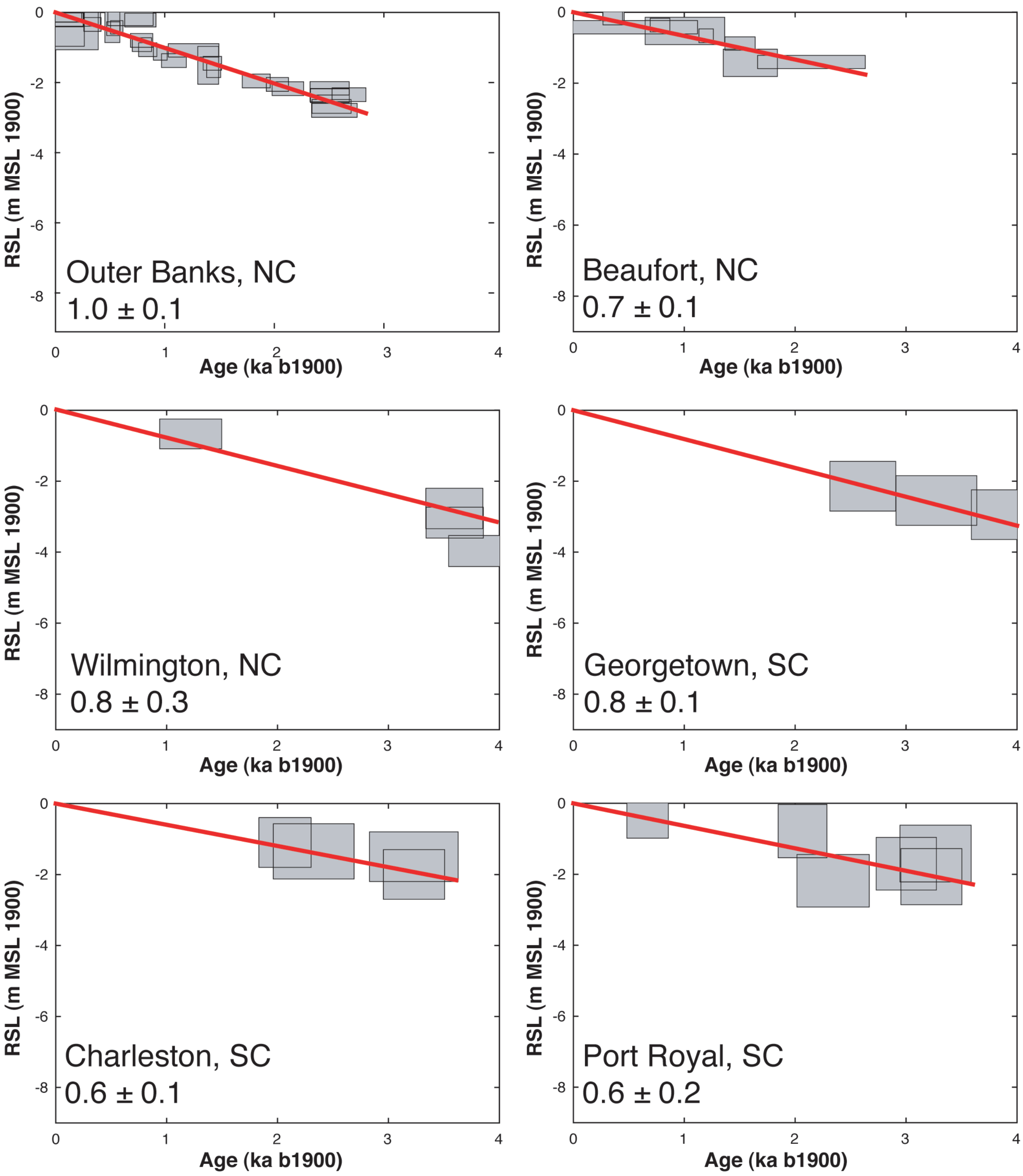
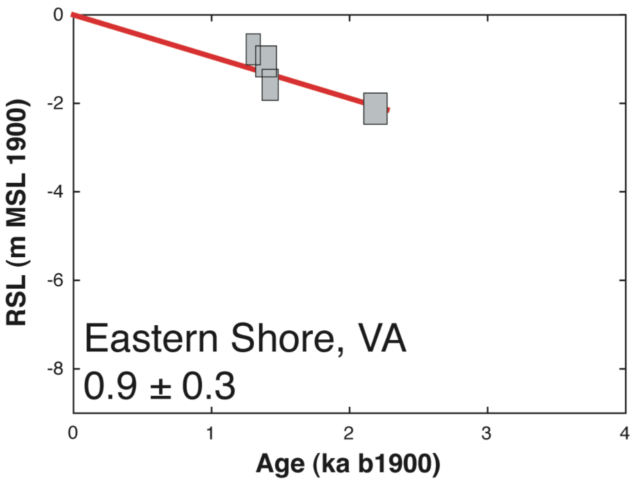
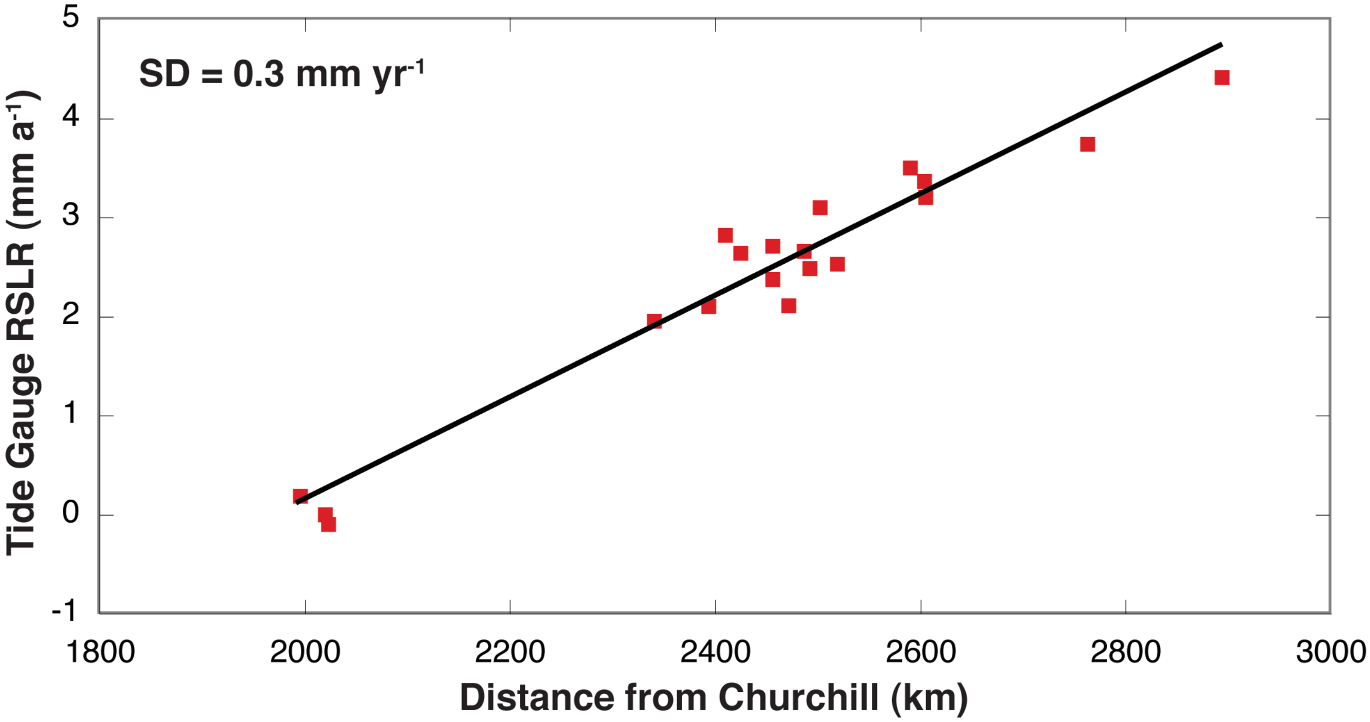
0.7 ± 0.1
Phippsburg, ME
0.7 ± 0.5
Boston, MA
0.6 ± 0.1
Barnstable, MA
1.2 ± 0.2
Clinton, CT
1.1 ± 0.1
Hudson River, NY
1.2 ± 0.1
RSL (m MSL 1900)
0
-2
-4
-6
-8
Age (ka b1900)
0
1
2
3
4


Long Island, NY
0.8 ± 0.3
Sandy Hook, NJ
1.4 ± 0.7
Atlantic City, NJ
1.3 ± 0.2
Inner Delaware, DE
1.7 ± 0.2
Lewes, DE
1.2 ± 0.2
Blackwater, MD
1.3 ± 0.2
RSL (m MSL 1900)
Age (ka b1900)
0
-2
-4
-6
-8
0
1
2
3
4


Outer Banks, NC
1.0 ± 0.1
Beaufort, NC
0.7 ± 0.1
Wilmington, NC
0.8 ± 0.3
Georgetown, SC
0.8 ± 0.1
Charleston, SC
0.6 ± 0.1
Port Royal, SC
0.6 ± 0.2
RSL (m MSL 1900)
0
-2
-4
-6
-8
Age (ka b1900)
0
1
2
3
4


0
-2
-4
-6
-8
RSL (m MSL 1900)
Eastern Shore, VA
0.9 ± 0.3
0
1
2
3
4
Age (ka b1900)



SD = 0.3 mm yr^{-1}
Tide Gauge RSLR (mm a^{-1})
5
4
3
2
1
0
-1
1800
2000
2200
2400
2600
2800
3000
Distance from Churchill (km)