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Holocene Sea Level Changes Along the United States' Atlantic Coast

ABSTRACT. Reconstructions of Holocene relative sea level (RSL) have valuable applications in a number of topics within the Earth sciences, including calibrating and constraining geophysical models of Earth's rheology and glacial isostatic adjustment. The usefulness of these reconstructions depends on application of a standardized methodology that fully considers all age and vertical errors. We outline this methodology and provide a detailed example from New Jersey. We describe Holocene RSL reconstructions from the US Atlantic coast that illustrate both spatial and temporal variability. Spatially, rates of Holocene RSL rise were greatest in the Mid Atlantic (New Jersey and Delaware) with decreasing rates of rise to the north and south. Temporally, rates of RSL rise have decreased since the early Holocene due to the combined effects of continued relaxation of the solid Earth in response to deglaciation and reduction in ice melt since 7,000 years ago. A comparison of late Holocene (last 4,000 years) geological reconstructions to long-term tide-gauge measurements reveals that sea level rise increased above background rates by an average of 1.7 mm yr^{-1} during the twentieth century.

PROCESSES AFFECTING HOLOCENE SEA LEVELS

Sea level is far from a constant, planar surface and exhibits spatial and temporal changes at a multitude of scales. To the observer, these changes are manifestations of relative sea level (RSL), a term that reflects the often simultaneous contributions from movements of the ocean surface and land. Eustatic changes are due to transfer of water between the ocean and cryosphere (ice sheets, ice caps, and glaciers). Since the peak of the last glaciation (26,000 years ago), approximately 50 million km^3 of ice melted from land-based ice sheets, raising RSL in regions distant from major glaciation centers (far-field sites) by ~ 120 m (Peltier and Fairbanks, 2006). In contrast, RSL dropped by many hundreds of meters in regions once covered by ice sheets (near-field sites) as a consequence of isostatic rebound (e.g., Shaw et al., 2002). Regional patterns of Holocene (last 11,700 years) RSL changes are produced primarily by the balance between, and interaction of, eustatic and isostatic processes, although other factors (local and tectonic) influence RSL changes preserved in the sedimentary record. These changes can be expressed (Shennan and Horton, 2002) as

$$RSL = E + I + T + L, \qquad [1]$$

where E is eustatic change, I is the total (net) isostatic effect of glacial rebound processes, T is any tectonic effect, and L is the total (net) effect of local processes such as sediment consolidation (e.g., Törnqvist et al., 2008) and changes in tidal range (e.g., Uehara et al., 2006).

Melting (or growth) of land-based ice (mass contribution), ocean water density changes from temperature and salinity variations (steric contribution), and gravitational and rotational changes (geoid contribution) driven by exchange of mass between the cryosphere and the ocean control the eustatic function (e.g., Milne et al., 2009). The eustatic contribution to RSL rise during deglaciation averaged 10 mm yr^{-1}, although peak rates potentially exceeded 50 mm yr^{-1} during "meltwater pulses" at 19,000 and 14,500 years ago (e.g., Alley et al., 2005). A significant reduction in the eustatic contribution to RSL change occurred about 7,000 years ago when ocean volume, on average, changed by only a few meters (Milne et al., 2005).

Glacial isostatic adjustment (GIA) is the process whereby Earth's shape is modified in response to large-scale changes in surface mass load. Growth and thickening of an ice sheet result in subsidence of land beneath the ice mass (termed *glacio-isostasy*), which is compensated for by an outward flow of mantle material that uplifts a peripheral bulge around the ice margin. When an ice sheet melts and loading is diminished, land beneath the melted ice is uplifted at rates that may locally reach 50 to 100 mm yr^{-1} (e.g., Shaw et al., 2002). The peripheral bulge subsides and moves progressively toward the center of the vanishing load as mantle material is once again redistributed. Return of freshwater to ocean basins from melting of continental-scale ice sheets exerts a considerable isostatic load on ocean floors (to the order of 100 t m^{-2} for a sea level rise of 100 m), causing subsidence (termed *hydro-isostasy*). GIA continues to the present day due to a relaxation time scale of several thousand years (e.g., Peltier, 2004). This ongoing effect is seen in North America where land in formerly glaciated areas around Hudson Bay continues to rise, while subsidence persists along the US Atlantic coast due to collapse of the peripheral bulge.

METHODOLOGY TO RECONSTRUCT HOLOCENE SEA LEVELS

Holocene RSL data from the US Atlantic coast published during the past five decades were recently compiled to create a database (Engelhart et al., 2009, in press; recent work of authors Engelhart and Horton). The methodology that is employed to reconstruct RSL is described in *The Manual of Sea-level Research* (van de Plassche, 1986) and other publications (e.g., Tooley, 1982; Shennan, 1986; Gehrels, 1999, Shennan and Horton, 2002; van de Plassche et al., 2002; Engelhart et al., 2009). In brief, this approach uses sediment and fossil analyses. Sediment types are determined from cores or outcrops, which are described in the field and further analyzed in the laboratory. Fossils (plant macrofossils and microfossils such as foraminifera or diatoms) are used as sea level indicators to establish the environment in which sediment accumulated (e.g., salt marsh, freshwater marsh, tidal flat). Sediment age is usually determined by radiocarbon dating. Salt marsh sediments provide the majority of sea level information in the database because they have the most precise indicative meaning for sea level indicators in temperate environments as they are restricted to the upper half of the intertidal zone.

Sea Level Indicators and the Indicative Meaning

There is a systematic and quantifiable relationship between sea level indicators and elevation in the tidal frame (Shennan, 1986; van de Plassche, 1986). The elevational range of sea level indicators is established from detailed measurement and surveying of modern environments (e.g., Redfield, 1972). This elevational relationship is known as the indicative meaning (Figure 1). Sea level histories can be reconstructed from many types of dated indicators, but each sample is related to the same contemporary tide level such as mean tide level (MTL) or mean high water (MHW). This methodology allows direct comparisons between sea level reconstructions that were produced from different sea level indicators. Indicative

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meanings for the US Atlantic coast database were estimated using published and unpublished data. Within salt marshes, there is a clear vertical division of plants into high marsh and low marsh floral zones (and, in some instances, more) that reflect the varied tolerances of plant species to tidal flooding (e.g., Redfield, 1972; van de Plassche, 1991; Gehrels, 1994; Figure 1). Similarly, salt marsh microfossils display characteristic preferences for particular elevations in the intertidal zone (e.g., Scott and Medioli, 1978; Horton et al., 2006). High salt marsh sediment formed between MHW and HAT (highest astronomical tide), while low salt marsh sediment originated between MTL and MHW (recent work of authors Engelhart and Horton). Dated samples from freshwater or fully marine environments cannot be precisely related to former sea level and are termed *limiting* dates. Reconstructed RSL must fall below freshwater-limiting dates and above marine-limiting dates, providing important constraints on GIA models (e.g., Shennan and Horton, 2002).

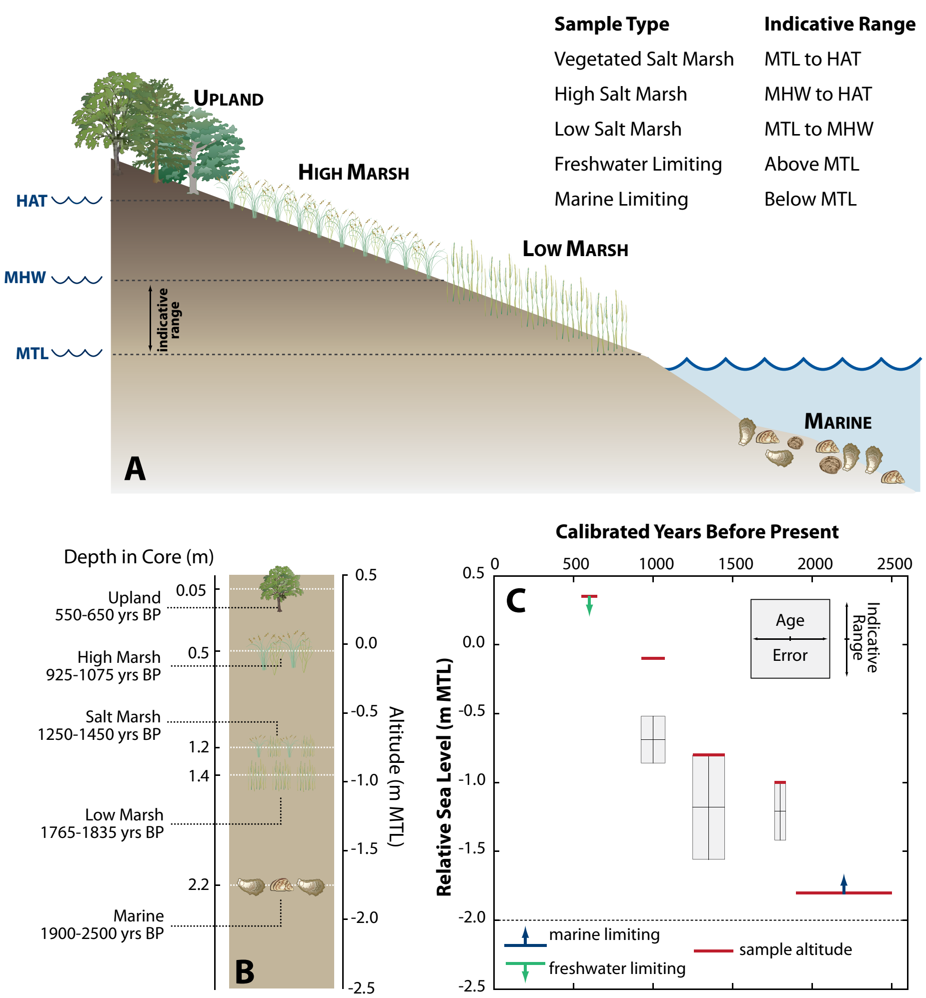

Figure 1. Schematic representation of the indicative meaning and a theoretical example of its application in reconstructing relative sea level (RSL) from radiocarbon-dated salt marsh sediment. (A) Vertical distribution of floral zones (high and low marsh) in the tidal frame typical of salt marshes on the US Atlantic coast. (B) Depth and altitude of dated samples in a core. (C) Production of sea level index points and limiting data. IR = indicative range. RSL = relative sea level. A = altitude. MTL = mean tide level. MHW = mean high water. HAT = highest astronomical tide. *Symbols courtesy of the Integration and Application Network (ian.umces.edu/symbols/), University of Maryland Center for Environmental Science*

Sea Level Index Points

A sea level index point estimates the unique position of RSL in space and time. Where a suite of sea level index points exist for a locality or region, they describe changes in RSL through time and can estimate rates of RSL change. RSL for each index point in the database was calculated using the equation

$$RSL_i = A_i - I_i, \qquad [2]$$

where A_i and I_i are, respectively, the altitude and the midpoint of the indicative range (also known as the reference water level; van de Plassche, 1986; Shennan, 1986) of sample *i*, expressed relative to the same water level (e.g., MTL). A_i is determined by surveying relative to a control point such as a benchmark or estimated (less precisely) from the environment in which the core was collected (e.g., high salt marsh). For a modern (surface) sample, the terms A_i and I_i are equal; thus, RSL is zero.

Each index point in the database has a unique vertical error estimated from the indicative range of the sea level indicator being used (error for I_i in Equation 2) and a variety of factors inherent in the collection and processing of samples for sea level research (such as surveying and coring errors affecting A_i in Equation 2). Total error for each sample (E_i) was estimated from the expression

$$E_i = (e^2{}_1 + e^2{}_2 + e^2{}_n)^{1/2}, \qquad [3]$$

where $e_1 \ldots e_n$ are individual sources of error for sample *i* (Shennan and Horton, 2002).

Another source of vertical error in sea level reconstruction is sediment consolidation from reduction of sediment volume by rearrangement of the mineral matrix and biodegradation (Kaye and Barghoorn, 1964). No error term was estimated for this factor. Sediment consolidation serves to lower the altitude of a sea level index point (A_i in Equation 2) below that at which it was initially deposited. This process can result in an RSL reconstruction that is too low (Figure 2). Methods to estimate (and thus potentially correct for) consolidation (e.g., Brain et al., 2011) require quantitative information about the type of sediment above and below the dated sample, which was not available for many sea level index points.

RSL reconstructions free from the influence of sediment consolidation are derived from index points that are relatively resistant to consolidation (Figure 2). For example, index points from salt marsh sediment in direct contact with an underlying, incompressible substrate (such as Pleistocene sand or a glacial erratic) are termed *base of basal* and usually considered to be unaffected by consolidation (e.g., Donnelly et al., 2004). *Basal* samples are those recovered from within the sedimentary unit that overlies the incompressible substrate, but not directly (within 5 cm) on the contact (Jelgersma, 1961). Basal samples may have undergone some consolidation since deposition. *Intercalated* samples are derived from sediments that were sandwiched between two clastic sedimentary units, neither of which are basal. These samples are the most prone to consolidation (Shennan and Horton, 2002). This classification of index points allows comparison among base-of-basal, basal, and intercalated samples to assess the influence of sediment consolidation on RSL reconstructions. Further, it enables production of regional sea level histories that exclude samples that may have been consolidated, although for most regions there are currently an insufficient number (and distribution) of base-of-basal index points.

All sample ages in the database were estimated using radiocarbon (^{14}C) dating of organic material (contained within saltwater and freshwater marshes), plants, shells, or calcareous foraminifera. Accurately reconstructing sea level from radiocarbon ages requires evaluation of all available information about radiocarbon samples and their stratigraphic or geomorphic context. Because atmospheric radiocarbon varied through geological time, radiocarbon ages were calibrated to provide dates in sidereal years with a 2σ range. When possible, ages for shells were corrected based on the estimated age of seawater (Reimer and Reimer, 2001). Where this

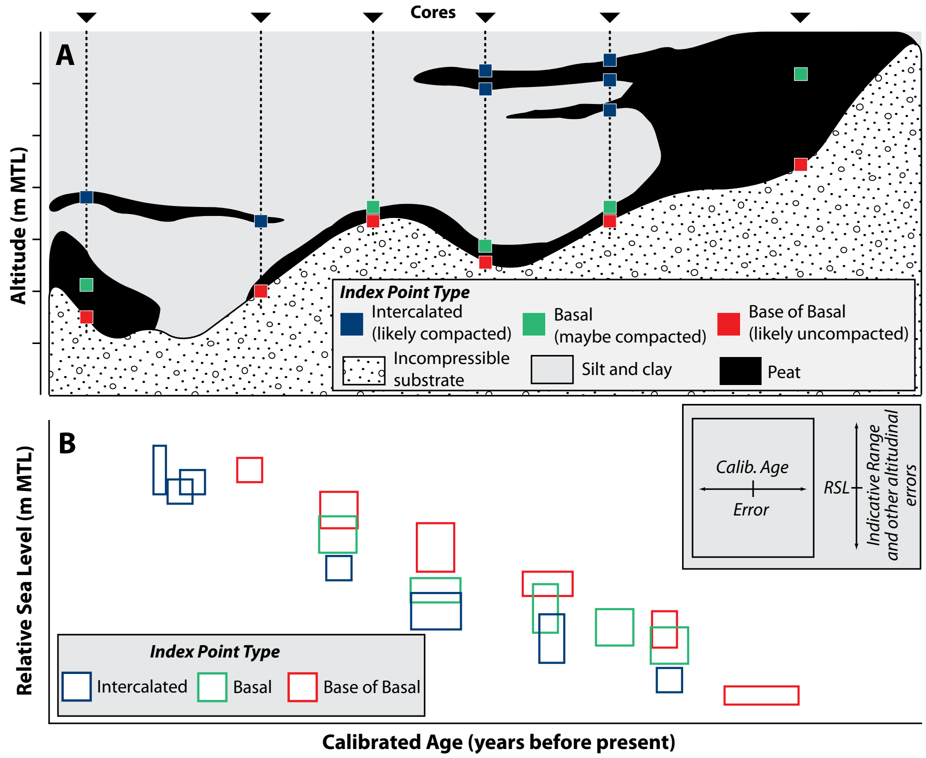

Figure 2. (A) Illustration of the different types of sea level index points and their relative susceptibility to sediment consolidation. Base-of-basal samples (red) are in direct contact with an uncompressible substrate and are consolidation free. Basal samples (green) are within the sedimentary unit overlying an uncompressible substrate but not directly at the base. Intercalated samples (blue) are from organic sediment sandwiched between clastic deposits. (B) Age-altitude graph demonstrating the effect of using these different types of index points for RSL reconstructions. Lowering of samples through sediment consolidation serves to overestimate depth (and therefore altitude). Index points are represented by boxes that incorporate age (from radiocarbon dating and calibration) and total sea level uncertainties.

information was not available, the standard marine reservoir correction value was used (e.g., Hughen et al., 2004). All sea level index points were presented as calibrated years before present (BP), where year 0 is conventionally taken to be AD 1950 (Stuiver and Polach, 1977).

Example of Data Collected: A Late Holocene Basal Sea Level Index Point From New Jersey

We use an example from New Jersey to illustrate the methodology used to create a sea level index point.

Core EF/07/10 (39.49°N, 74.42°W) was collected from a salt marsh at Edwin B. Forsythe National Wildlife Refuge in New Jersey on the US mid-Atlantic coast (Figure 3A). Presently, tidal range (mean lower low water [MLLW] to mean higher high water [MHHW]) at the site is 1.10 m. The modern marsh is dominated by stunted salt marsh cordgrass (*Spartina alterniflora*) with patchy presence of seashore saltgrass (*Distichlis spicata*) and salt meadow cordgrass (*Spartina patens*). Transects of cores across the marsh (Figure 3B) revealed that the organic-rich sediments deposited at the site overlie an incompressible substrate of glacial outwash sands and gravels. The salt-marsh-derived sediment was less than 0.3-m thick at the salt marsh/terrestrial boundary and increased to more than 4 m at the most seaward core.

Core-top altitude was established by leveling (± 0.05-m leveling error using a total station) to a National Geodetic Survey benchmark with first order vertical precision (± 0.10-m benchmark error). Its surface altitude was 0.48 m above North American Vertical Datum (NAVD88; converted to 0.61 m above MTL using data reported for the tide gauge at Atlantic City; Figure 3). The bottom of the core was 3.89 m below MTL. From –3.59 to –2.19 m MTL, the core was composed of organic sediment and contained sparse remains of identifiable plant fossils. In contrast, organic sediment in the upper 2.8 m of the core (–2.19 to 0.61 m MTL) contained large numbers of identifiable high salt marsh plant remains. Agglutinated foraminifera were present in the upper 3.95 m of the core. A *Spartina patens* rhizome with a known relationship (e.g., van de Plassche et al., 1998) to the former marsh surface (0.01 m thick; ± 0.01-m sampling error) was selected for dating. It was found 2.78 m below the surface (± 0.03-m borehole error) at –2.17 m MTL. It yielded a radiocarbon age of 1550 ± 25 ^{14}C years and date of 1521–1383 calibrated years BP (2σ range). Samples were analyzed for foraminifera to verify the environment of deposition (Figure 3D). Samples from –2.39 to –2.22 m MTL were dominated by the agglutinated foraminifera *Miliammina fusca* with occurrences of *Jadammina macrescens*. Foraminifera between –2.20 and –2.09 m were indicative of a high salt marsh environment as illustrated by high abundances of *Tiphotrocha comprimata* and *Trochammina inflata*. The plant remains and foraminifera suggest that the radiocarbon-dated sample formed in a high salt marsh environment. Therefore, the dated sample was assigned an indicative range of MHW to HAT (0.86 m MTL ± 0.25 m). The sample lies within a basal organic sedimentary unit of amorphous and salt marsh peat that overlies an incompressible substrate of sand and gravel. It was not sampled within 0.05 m of the boundary and thus is considered a basal rather than a base-of-basal index point.

The calculation of RSL and associated error term for this index point was

$$
\begin{aligned}
\text{RSL} &= -2.17 \text{ m MTL} - 0.86 \text{ m MTL} \\
&= -3.03 \text{ m MTL} \\
\text{Error} &= \Sigma(0.25 \text{ m}^2{}_{\text{indicative range}} \\
&\quad + 0.005 \text{ m}^2{}_{\text{thickness}} \\
&\quad + 0.05 \text{ m}^2{}_{\text{levelling}} \\
&\quad + 0.01 \text{ m}^2{}_{\text{sampling}} \\
&\quad + 0.1 \text{ m}^2{}_{\text{benchmark}} \\
&\quad + 0.03 \text{ m}^2{}_{\text{borehole}})^{1/2} \\
&= \pm 0.28 \text{ m} \\
\text{Age} &= 1550 \pm 25 \ {}^{14}\text{C years} \\
&= 1{,}521\text{–}1{,}383 \text{ calibrated years BP} \\
&\quad (2\sigma \text{ range})
\end{aligned}
$$

THE US ATLANTIC COAST DATABASE OF SEA LEVEL INDEX POINTS

The database included 70 fields of information from which conditional filters (such as possible contamination, erosion of sediment contact, stratigraphical context, and type of radiocarbon measurement) were applied to define sea level index points that we believed to be reliably related to past tide levels. This procedure produced 473 Holocene sea level index points, of which 75 were categorized as base of basal, 267 as basal, and 131 as intercalated. Additionally, 158 freshwater-limiting dates and 189 marine-limiting dates were produced. The database covered more than 1,800 km of coastline from Maine to South Carolina (Figure 4). No validated sea level index points were available for Georgia and Florida. Following Engelhart et al. (in press) and recent work of authors Engelhart and Horton, the Holocene database was divided into 16 regions (Figures 4 and 5). GIA was the principal cause of spatial

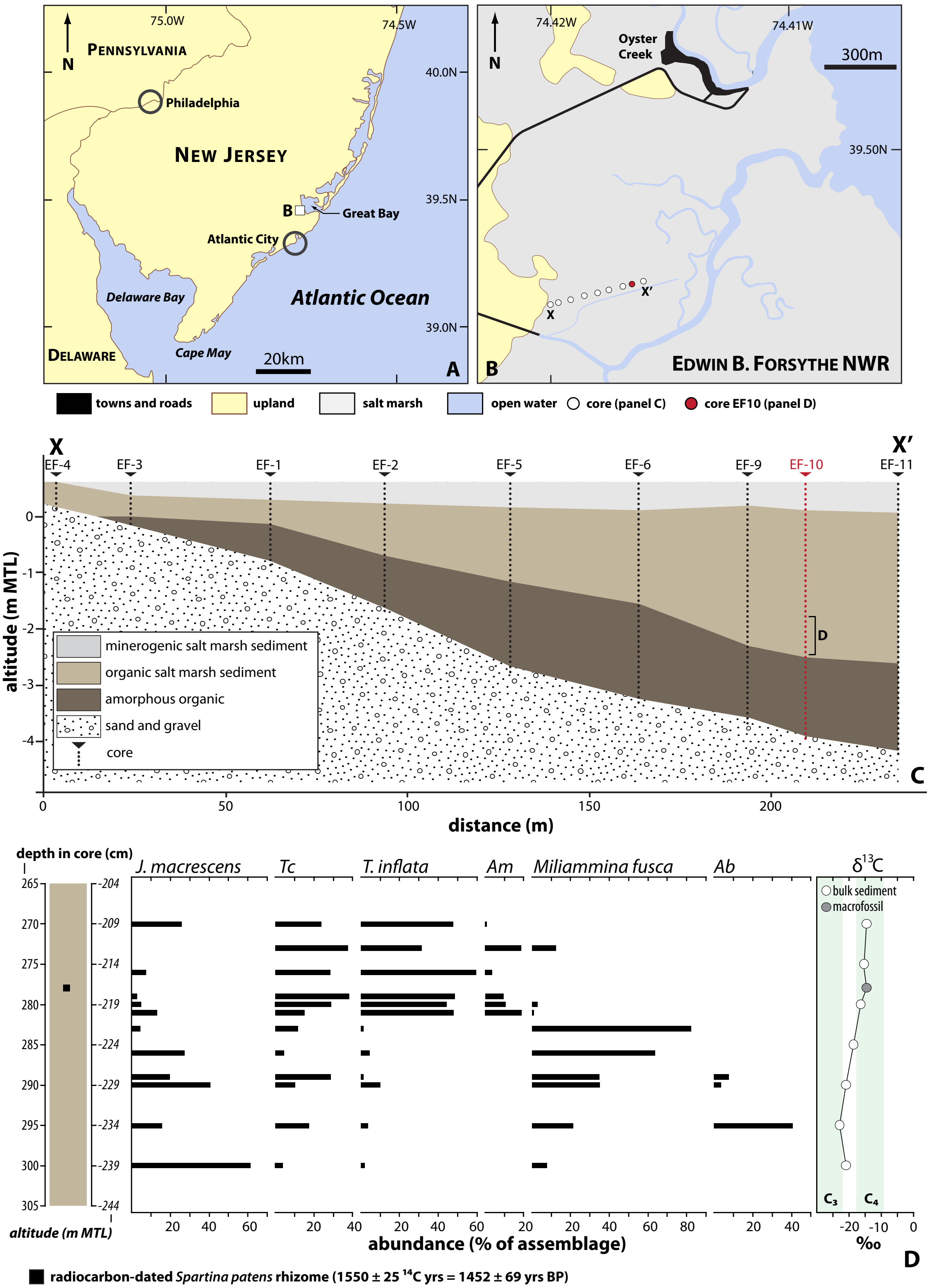

Figure 3. (A) Location of the example site in New Jersey, USA. (B) Map of the study site within the Edwin B. Forsythe National Wildlife Refuge on Great Bay, New Jersey. The locations of cores along a transect (X–X′) used to ascertain the stratigraphy are shown. (C) Summary stratigraphy for transect X–X′ of nine cores across the marsh. (D) Foraminiferal assemblages in 12 samples between 2.65- and 3.05-m depth in core EF/07/10 (Ab = *Ammobaculites* spp.; Tc = *Trochammina inflata*; Am = *Arenoparrella mexicana*). The dated *Spartina patens* rhizome at 2.78-m depth yielded a radiocarbon age of 1550 ± 25 years, which was calibrated to sidereal years (1521 to 1383 calibrated years BP; 2σ range).

variability in RSL histories, requiring that samples be grouped geographically based upon distance to the center of the Laurentide Ice sheet.

In the once-glaciated regions northeast of Long Island (regions 1–7), RSL histories are dominated by ice unloading, exemplified by the Holocene record for southern Maine (region 2). Multiple marine-limiting dates indicate an RSL low stand between 11,000 and 8,000 years ago, when RSL must have been above –26 m. Limiting dates combined with middle Holocene index points indicated an RSL change from a falling or low-stand condition to rising sea level (3.5 mm yr^{-1}) at 7,000 years ago.

South of Long Island, regions 8–16 were near the former ice margins and lie now in the area of the peripheral bulge. These regions have a wide continental shelf where there was interplay between postglacial isostatic recovery and hydro-isostatic loading. These processes produced the maximum rates of RSL rise along the US Atlantic coast in New Jersey and Delaware. For example, the Inner Delaware record (region 9) suggests RSL rose at 5.5 mm yr^{-1} from 6,000 to 4,000 years ago and 1.7 mm yr^{-1} from 4,000 years ago to AD 1900. At increasing distances from the Laurentide glacial center, land subsidence reduces in magnitude (e.g., Milne et al., 2005). This reduction can be seen in the RSL history of southern South Carolina (region 16). RSL was –5 m at 7,000 years ago and rose by 0.7 mm yr^{-1} until 4,000 years ago, with little evidence for a change in rate from 4,000 years ago to AD 1900.

Rates of RSL change were greatest during the early Holocene and decreased over time because of continued relaxation of the solid Earth (Peltier, 2004) and reduction of ice melt since 7,000 years ago (Milne and Mitrovica, 2008). For example, in New York (region 6), sea level index points at 6,000 and 4,000 years ago recorded RSL of –11 m and –6 m, respectively, corresponding to a rate of RSL rise in the mid Holocene of 2.5 mm yr^{-1}. The late Holocene data (4,000 years ago to AD 1900) suggest a reduction in the rate to 1.3 mm yr^{-1}. A similar reduction cannot be inferred for all regions because of the scatter of index points (e.g., early Holocene in Long Island, region 7) or their paucity/absence (e.g., Northern Massachusetts, region 3).

BEST ESTIMATES OF LATE HOLOCENE RELATIVE SEA LEVEL CHANGES

To extract twentieth-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 GIA. These land movements explain why US Atlantic coast tide gauges recorded rates as much as double the twentieth-century global average sea

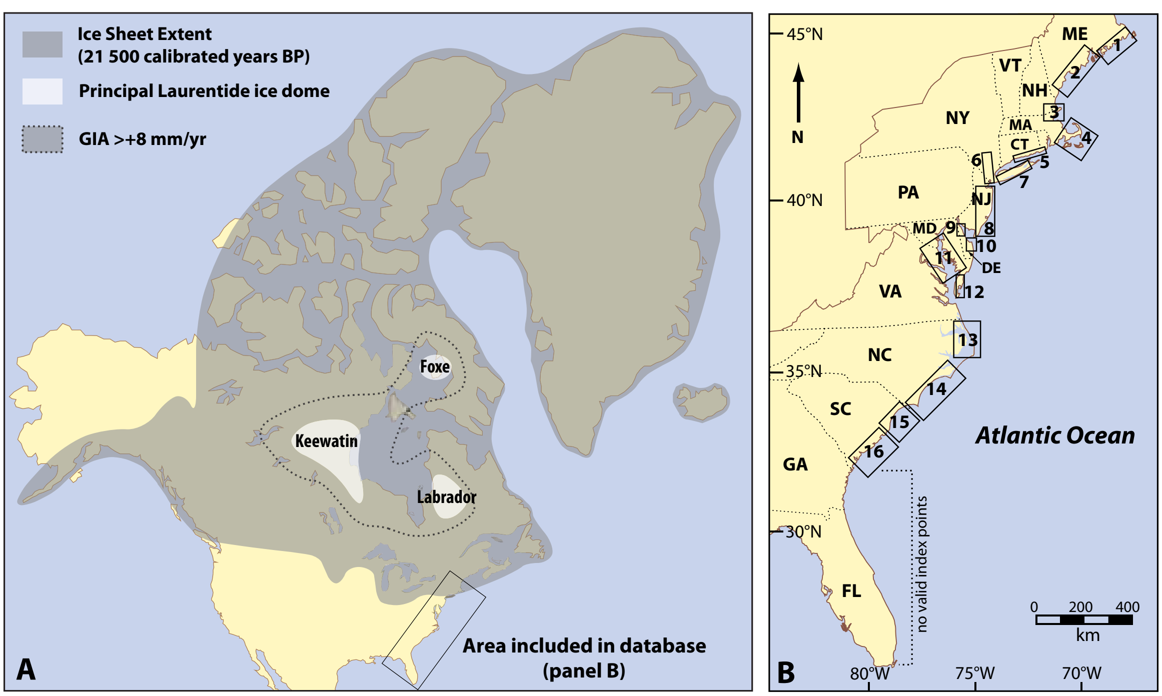

Figure 4. (A) Approximate spatial extent of the Laurentide and Greenland Ice Sheets at 21,500 years ago, redrawn from Dyke et al. (2003). The three principal ice domes (where ice was thickest) are shown as well as areas currently experiencing isostatic uplift in excess of 8 mm yr^{-1}. Sites along the US Atlantic coast approximate a gradient of distance from the ice sheet. (B) Location map of the 16 regions from which individual sea level index points were grouped for analysis.

level rise of 1.7 mm yr^{-1} (e.g., Church and White, 2006; Douglas, 2008). Engelhart et al. (2009) estimated corrections for localities with reliable tide gauges on the US Atlantic coast using late Holocene rates of RSL change from linear regression of regional base-of-basal and basal index points (intercalated data were excluded to reduce the influence of consolidation) from 4,000 years ago to AD 1900. They assumed that most ice sheets had stopped melting by this time (Milne et al., 2005). This assumption is a feature of most GIA models for the late Holocene (Peltier, 2004). Along the passive margin of the US Atlantic coast, it is widely accepted that the tectonic component is zero or small and has been constant. Our analyses reveal that spatial variation in RSL is related to the geometry of the collapsing Laurentide peripheral bulge. RSL rise of < 0.9 mm yr^{-1} was estimated in Maine, increasing to rates of 1.2–1.8 mm yr^{-1}

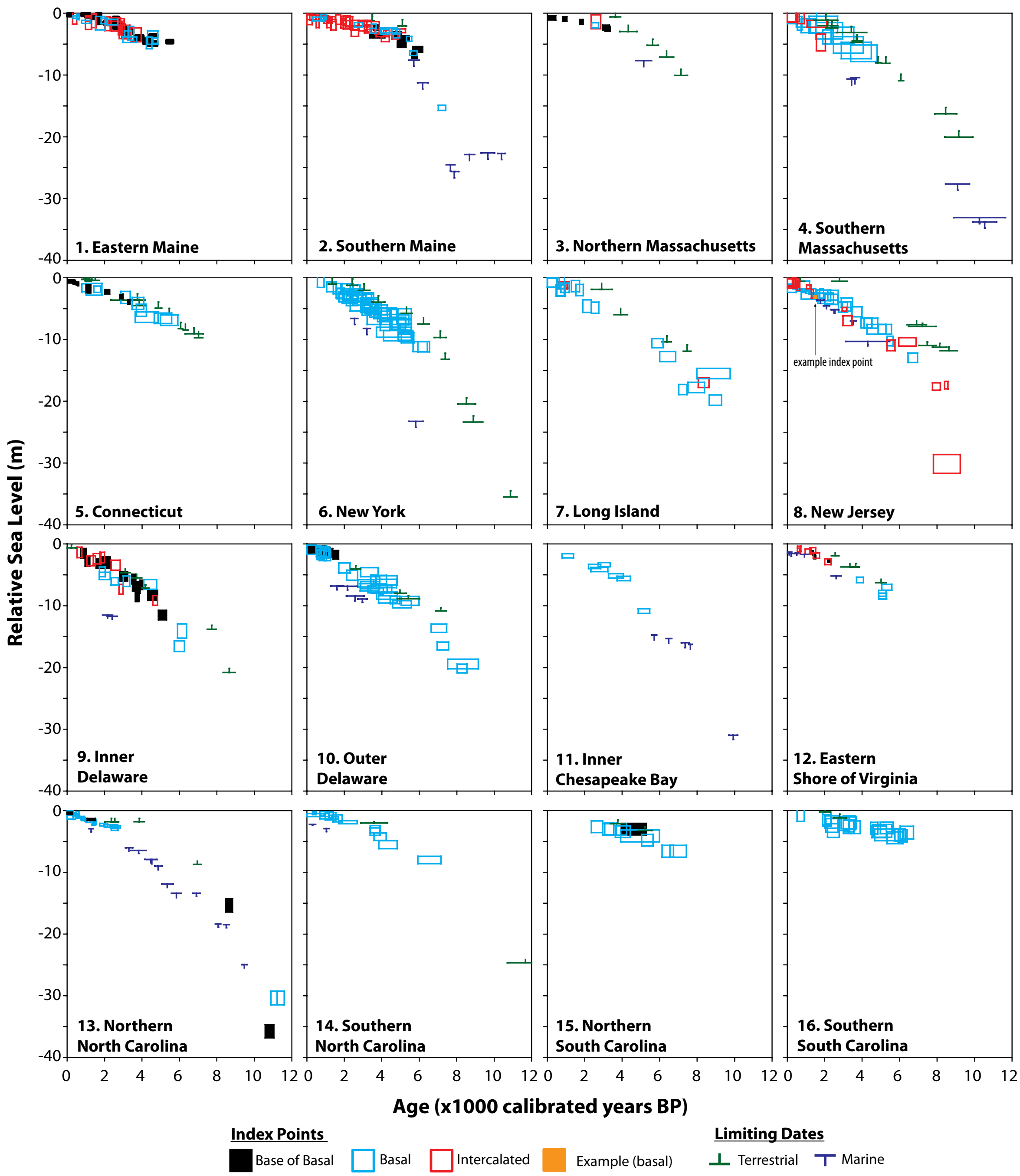

Figure 5. Relative sea level (RSL) reconstructions from the US Atlantic coast database of sea level index points (Engelhart et al., in press). Base-of-basal (filled), basal (blue), and intercalated (red) index points are plotted as boxes with 2σ vertical and calibrated age errors. The example basal index point from New Jersey is shown as a filled orange square in the plot for region 8.

in Delaware, and a return to rates of ≤ 1.0 mm yr^{-1} in the Carolinas. These rates of RSL rise serve as a background against which to compare evidence for a possible twentieth-century increase in the rate of sea level rise (see Woodworth et al., 2011, in this issue, and Woodworth et al., 2009). In addition, these background rates of RSL will be critical for developing regional predictions of future sea level rise. Figure 6 compares late Holocene trends of RSL estimated from geological data with long (> 50 years) tide-gauge records from nearby sites (Douglas, 2008). If late Holocene and twentieth-century rates of sea level rise were different, data points would intersect the 1:1 line. However, all data points show a positive difference of at least 1 mm yr^{-1} up to greater than 2 mm yr^{-1}. We estimate that twentieth-century sea level rise on the US Atlantic coast was (on average) 1.7 mm yr^{-1} greater than the late Holocene background rate, although sea level index points cannot exclude (within their uncertainties) the presence of short periods during the last 4,000 years when sea level rise exceeded the averaged background rate. This figure is in agreement with the Intergovernmental Panel on Climate Change Fourth Assessment Report estimate for global twentieth-century rise of 17 ± 5 cm that was attributed to melting of continental glaciers and ice sheets, and steric effects (expansion of ocean water as it warms).

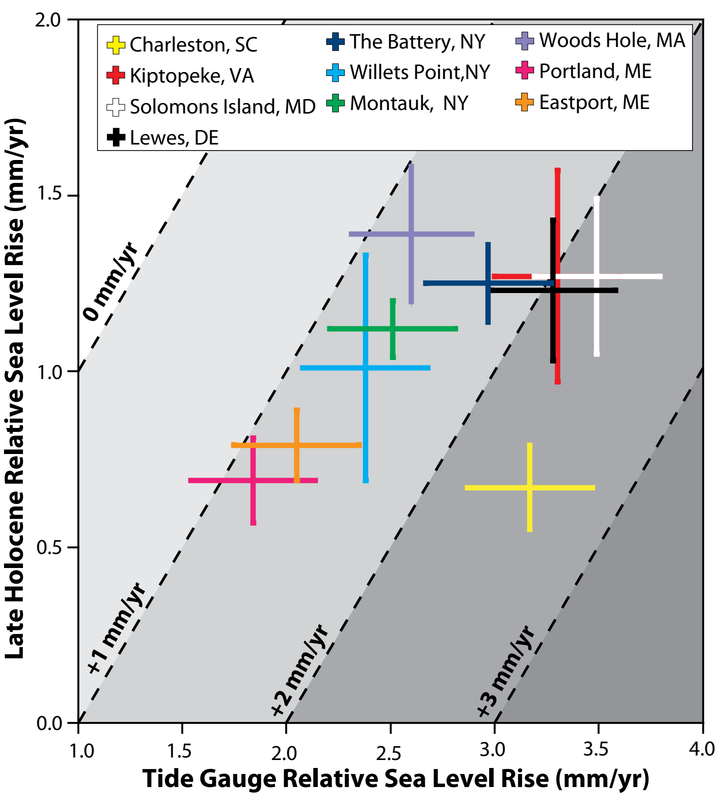

Figure 6. Twentieth and twenty-first century trends in relative sea level (RSL) from tide-gauge data compared with the late Holocene RSL rise. Dotted lines indicate the increase in the rate of sea level rise between the tide-gauge and late Holocene data.

CONCLUDING REMARKS

Over the last decade, there has been a significant increase in the number and distribution (spatial and temporal) of reliable reconstructions of Holocene RSL along the US Atlantic coast. These reconstructions have contributed to better models of GIA processes at global, continental, and regional scales. Analysis of 473 Holocene sea level index points and 347 limiting dates from 16 regions along the US Atlantic coast showed that rates of RSL change were highest during the early Holocene and have decreased over time, due to the continued response of Earth to GIA and reduction of ice equivalent meltwater input. Deglaciation of the Laurentide Ice Sheet was a driving mechanism for spatial variability within the database. The maximum rate of Holocene RSL rise occurred in the mid-Atlantic (New Jersey and Delaware) due to collapse of the Laurentide Ice Sheet's forebulge. Comparisons between geological observations and tide-gauge data reveal a 10–20-cm sea level rise during the twentieth century in addition to long-term changes driven by land level changes.

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