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Sea-level change and subsidence in the Delaware Estuary during the last ~2200 years

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ABSTRACT

We produced eight new sea-level index points that reconstruct a ~2.5 m relative sea-level (RSL) rise at Sea Breeze in the Delaware Bay from ~200 BCE to 1800 CE. The precision of our reconstruction improved upon existing data by using high-resolution surveying methods, AMS radiocarbon dating of *in-situ* plant macrofossils collected immediately above the basal contact between pre-Holocene sand and salt-marsh sediments, foraminifera as sea-level indicators, and by accounting for tidal range changes through time. Our new data were combined with a database of 65 sea-level index points available for the Delaware Bay to estimate the rate of RSL rise in the upper (1.26 ± 0.33 mm/yr) and lower bay (1.30 ± 0.36 mm/yr) using a spatial-temporal model. Correction for changes in tidal range through time removed the disparity in rate between the upper and lower Delaware Bay that had previously been postulated. After paleotidal correction, the rates of RSL rise estimated for the Delaware Bay (1.25 ± 0.27 mm/yr) correlate with the ~1.3 mm/yr rate reported for New Jersey, Maryland, and Virginia, and confirm that the maximal ongoing forebulge collapse along the U.S. Atlantic coast is focused on the mid-Atlantic.

1. Introduction

Proxy reconstructions are important for understanding the driving mechanisms of past relative sea-level (RSL) trends and for constraining predictions of future sea-level change (e.g., Dutton et al., 2015). On the U.S. Atlantic coast the principal cause of prolonged, regional RSL change during the Common Era (last ~2000 years) was glacio-isostatic adjustment (GIA), driven by collapse of the Laurentide Ice Sheet's proglacial forebulge (e.g., Peltier, 1996). This process causes a change in the geoid height and the local radius of the solid Earth relative to Earth's center of mass (Farrell and Clark, 1976). Despite disintegration of the Laurentide ice sheet by ~7000 years before present (BP; e.g., Carlson et al., 2008), GIA on the U.S. Atlantic coast continues to the present day (e.g., Engelhart et al., 2009), because of the slow response time (~4000 years) of the solid Earth to redistribution of mass during deglaciation (Peltier, 1998). RSL also includes contributions from other processes causing vertical land motion (Kopp et al., 2015) such as sediment compaction (e.g., Miller et al., 2013), dynamic topography (e.g., Rowley et al., 2013), and tectonics (e.g., van de Plassche et al., 2014). For convenience, we use the term “land-level change” to describe the net effect of GIA and these other sources of vertical land motion. Accurate estimates of land-level change are important for generating regional sea-level projections (e.g., Kopp et al., in press), isolating the climate-driven components of RSL trends measured by tide gauges and satellite altimetry (e.g., Church and White, 2011; Nerem et al., 2010), and testing Earth-ice models (e.g., Roy and Peltier, 2015).

In the absence of long-term instrumental measurements, rates of land–land change can be estimated from RSL reconstructions

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spanning the last 1000–4000 years (Engelhart et al., 2009; Shennan and Horton, 2002; Engelhart et al., 2015). This approach assumes that the non-land-level change component of reconstructed RSL over this period was zero or minimal (Bassett et al., 2005; Lambeck et al., 2014; Milne et al., 2005; Peltier, 2002) A standardized database of RSL reconstructions from the U.S. Atlantic Coast demonstrated that spatially-variable rates of land-level change (and RSL rise) during the last 4000 years reflect distance from the former center of the Laurentide Ice Sheet (Engelhart and Horton, 2012; Engelhart et al., 2009). After grouping RSL reconstructions by location, Engelhart et al. (2009) estimated the rate of subsidence for 16 regions from Maine to South Carolina. Maximum subsidence (1.7 ± 0.2 mm/yr) occurred in the upper Delaware Bay. However, the vertical and temporal uncertainties on individual RSL reconstructions from the Delaware Bay were relatively large and were not formally accounted for when estimating rates of RSL change based on linear regression of reconstruction mid points. Furthermore, such estimates did not include the influence of tidal-range change, a process shown to be significant in the Delaware Bay during the Holocene (Belknap, 1975; Belknap and Kraft, 1977; Hall et al., 2013; Leorri et al., 2011). A similar pattern of subsidence was identified by isolating the regionally-coherent linear component of RSL at tide-gauge stations where rates of 1.8 ± 0.5 mm/yr and 1.5 ± 0.4 mm/yr were estimated for Cape May, NJ and Philadelphia, PA respectively (the closest permanent gauges to our site at to Sea Breeze: Fig. 1), but these analyses were limited to the short period of available data (Kopp, 2013).

RSL reconstructions comprise discrete sea-level index points that estimate RSL at a particular time and place. The RSL history of a site or region is described by combining sea-level index points that were generating using a standardized approach where the age of each index point was estimated with uncertainty (usually by radiocarbon dating), its geographic location is known, and the vertical position of former sea level was estimated using a proxy called a sea-level indicator. The indicative meaning (van de Plassche, 1986; Shennan, 1986; Horton et al., 2000; Woodroffe and Barlow, 2015) formalizes the relation between an indicator and sea level by establishing the elevation range (termed the indicative range) across which particular indicators are found. The mid-point of this range is called the reference water level.

To redress a scarcity of Common Era RSL reconstructions from the New Jersey side of the Delaware Bay we produced eight new sea-level index points from Sea Breeze, New Jersey using foraminifera preserved in radiocarbon-dated, basal sediment. We combined the new reconstruction with an existing database of standardized sea-level index points and corrected for the effect of tidal-range change. Analysis of the resulting regional-scale RSL dataset using a spatio-temporal models showed that the rate of subsidence in the Upper Delaware Bay was previously overestimated. Subsidence in the Delaware Bay is comparable to rates estimated on the Atlantic coasts of New Jersey, Delaware, Maryland, and Virginia.

2. Study region

Sea Breeze, NJ is located on the northeastern shore of the Delaware Bay (Fig. 1). The modern salt marsh at Sea Breeze displays the characteristic regional pattern of floral zonation. Low salt-marsh areas between mean tidal level (MTL) and mean high water (MHW) on the shore of Delaware Bay and along tidal channels are vegetated by *Spartina alterniflora* (tall form). The high marsh is the largest zone by area and lies between MHW and mean higher high water (MHHW). It is vegetated by *Spartina patens*, *Distichlis spicata*, and the short form of *Spartina alterniflora*. The border between salt marsh and freshwater upland at elevations from MHHW to highest astronomical tide (HAT) is a brackish zone vegetated by *Schoenoplectus* spp. and *Phragmites australis*. Great diurnal tidal range (mean lower low water, MLLW to MHHW) measured at the NOAA tide gauge nearest to Sea Breeze (Ship John Shoal; Fig. 1) is 1.79 m. Marine influence reached the region at ~6000 years BP when tidal wetlands began to establish around the Delaware Bay (e.g., Leorri et al., 2006; Nikitina et al., 2003). Continuous RSL rise since then resulted in the Sea Breeze salt marsh being underlain by 2–4 m of salt-marsh and intertidal sediments (Nikitina et al., 2014).

Modern salt-marsh foraminifera in southern New Jersey form at least seven distinctive assemblages (Kemp et al., 2012a, 2013c). The dominant species of foraminifera in low-marsh floral zones are *Miliammina fusca* and *Ammobaculites* spp. High-marsh floral zones are populated by assemblages of foraminifera in which *Trochammina inflata*, *Arenoparrella mexicana*, and *Tiphotrocha comprimata* are the most abundant species. At brackish sites with strong fluvial

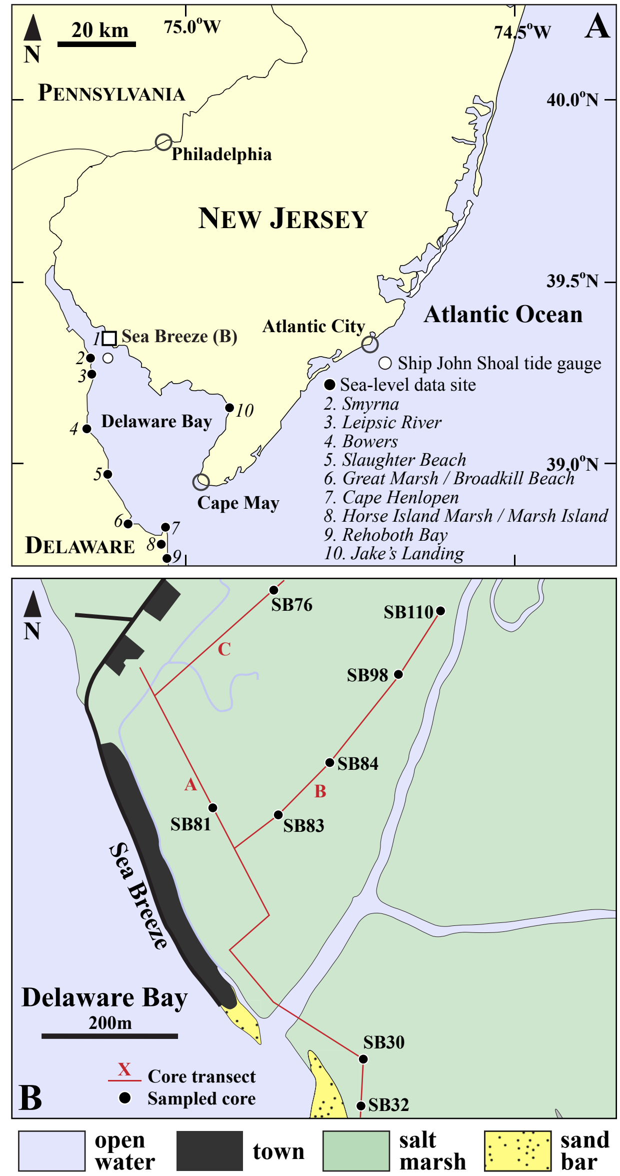

Fig. 1. (**A**) Map of the Delaware Bay and coast of southern New Jersey, USA showing the location of sites referred to in the main text. (**B**) Location of the Sea Breeze, NJ study site on the north coast of the Delaware Bay. The location of cores used to reconstruct relative sea level are shown and the transects used to describe sediment beneath the Sea Breeze salt marsh.