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Quantifying the contribution of sediment compaction to late Holocene salt-marsh sea-level reconstructions, North Carolina, USA

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ABSTRACT

Salt-marsh sediments provide accurate and precise reconstructions of late Holocene relative sea-level changes. However, compaction of salt-marsh stratigraphies can cause post-depositional lowering (PDL) of the samples used to reconstruct sea level, creating an estimation of former sea level that is too low and a rate of rise that is too great. We estimated the contribution of compaction to late Holocene sea-level trends reconstructed at Tump Point, North Carolina, USA. We used a geotechnical model that was empirically calibrated by performing tests on surface sediments from modern depositional environments analogous to those encountered in the sediment core. The model generated depth-specific estimates of PDL, allowing samples to be returned to their depositional altitudes. After removing an estimate of land-level change, error-in-variables changepoint analysis of the decompacted and original sea-level reconstructions identified three trends. Compaction did not generate artificial sea-level trends and cannot be invoked as a causal mechanism for the features in the Tump Point record. The maximum relative contribution of compaction to reconstructed sea-level change was 12%. The decompacted sea-level record shows 1.71 mm yr^{-1} of rise since AD 1845.

Introduction

Late Holocene relative sea level (RSL) reconstructions supplement and extend spatially and temporally limited tide-gauge records to provide a context for current and projected rates of rise, and to capture multiple phases of sea-level behaviour for calibration of predictive models (Gehrels et al., 2011; Kemp et al., 2011; Bittermann et al., 2013). Sequences of salt-marsh sediment are a valuable archive for reconstructing RSL because salt marshes accrete sediment to preserve their elevation in the tidal frame under regimes of rising RSL where sediment supply is not limited, or where salt-marsh accretion primarily results from organogenic growth (Morris et al., 2002). However, samples of salt-marsh sediment used to reconstruct sea level may have undergone post-depositional lowering (PDL) by compaction of underlying sediment (Jelgersma, 1961; Bloom, 1964; Allen, 1999, 2000; van Asselen et al., 2009). PDL causes an over-estimation of the amount and rate of reconstructed sea-level rise (Horton and Shennan, 2009; Horton et al., 2013). The contribution of compaction must be quantified and removed from sea-level reconstructions to permit fair comparison among records and to ensure that the sensitivity of sea level to forcing factors is not misinterpreted or overstated.

Use of basal salt-marsh samples that directly overlie an incompressible substrate avoids the influence of compaction (Jelgersma, 1961; Donnelly et al., 2004), but compilations of discrete basal RSL reconstructions typically lack the chronological and vertical precision required to identify sub-millennial trends (see Engelhart and Horton, 2012). Therefore, late Holocene RSL reconstructions rely on samples from a single core of salt-marsh sediment (e.g., van de Plassche et al., 1998). One of the most detailed reconstructions of late Holocene RSL is from North Carolina (USA) (Kemp et al., 2009, 2011). It was developed using vertically-ordered samples of salt-marsh peat from two cores—one at Sand Point and one at Tump Point. After adjustment for land-level change, the record shows a sea-level rise in the first millennium and that the modern rate of sea-level rise is the greatest century-scale rise of the past two millennia (Kemp et al., 2011). However, the effect of compaction on these records was only qualitatively assessed and PDL may have contributed to the timing, magnitude and form of reconstructed sea-level trends (cf. Gehrels and Woodworth, 2013). If the key characteristics of the sea-level record are wholly or partially artefacts of sediment compaction, existing conclusions regarding climatic controls on global sea level may be erroneous (cf. Grinsted et al.,

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2011). Consequently, compaction-induced distortions of the sea-level record may have influenced the calibration of semi-empirical models relating sea level to global temperature (Kemp et al., 2011).

Sea-level reconstructions from cores of salt-marsh sediment can be corrected for the effects of compaction using geotechnical modelling (Pizzuto and Schwendt, 1997; Paul and Barras, 1998; see van Asselen et al., 2009, for a detailed summary of previous work). Brain et al. (2011, 2012) developed an empirical framework to estimate the magnitude and effects of compaction in a column of salt-marsh sediment. This model requires calibration by performing geotechnical tests on surface sediments from modern depositional environments analogous to those encountered in sedimentary archives. The model has not previously been applied to, or validated in, a real-world sedimentary succession (cf. Brain et al., 2012). Therefore, the accuracy of the model and ease with which the modern analogue approach can be applied to a particular core are unknown.

Our primary aim is to estimate the degree to which reconstructed sea-level trends in North Carolina result from sediment compaction by applying the Brain et al. (2011, 2012) geotechnical model to the Tump Point core of Kemp et al. (2009, 2011). We detail our calibration approach, outline our assumptions regarding the availability and suitability of modern analogues, and describe a model validation exercise that suggests our assumptions are reasonable. We quantify the contribution of compaction to late Holocene sea-level trends reconstructed in North Carolina and estimate that compaction contributed up to 12% of reconstructed sea-level change (0.03 mm yr^{-1}), but did not generate artificial trends. Following decompaction and adjustment for regional land-level change, the reconstructed rate of sea-level rise since ~AD 1850 was 1.71 mm yr^{-1}. Our study demonstrates that routine 'decompaction' of salt marsh sediments can be undertaken if suitable modern analogues are available. We therefore recommend the development and application of regional datasets that describe the compression properties of sediments from a range of salt-marsh environments.

Study sites

Our primary study site is Tump Point, located in southwestern Pamlico Sound, North Carolina, USA (Figs. 1A–C). Pamlico Sound is a wide, shallow estuarine system that separates the mainland of North Carolina from the barrier island system of the Outer Banks. Tump Point is typical of organogenic salt marshes in this region that are comprised of extensive platforms (often several km wide) of *Juncus roemerianus* salt marsh (Figs. 1B–E) with a narrow (~5 m), seaward fringe of *Spartina alterniflora*, interspersed with occasional patches of *Distichlis spicata*, *Borrichia frutescens* and *Spartina patens* (e.g., Adams, 1963; Eleuterius, 1976; Brinson, 1991; Woerner and Hackney, 1997). The salt-marsh platform at Tump Point is not dissected or flooded/drained by tidal channels.

Levelling transects up to 4 km long show that elevation varies by less than 0.25 m over the majority of the site (Brinson, 1991). This low range in elevation results from the microtidal regime present at the site; the modern diurnal range (mean lower low water to mean higher high water) is 0.13 m (Kemp et al., 2009). The lack of spatial variability in contemporary salt-marsh geomorphology and ecology is reflected in a near-uniform stratigraphy that varied little in a transect of cores covering several hundred metres (Kemp et al., 2009; Figs. 1D, E). The modern salt marsh is underlain by a pre-Holocene sand (assumed incompressible) with a black, amorphous basal unit that transitions upward into 1.2–1.5 m of salt-marsh peat that spans the period since ~AD 1000 and contains abundant and in situ *J. roemerianus* macrofossils. The small tidal range and undisturbed accumulation of salt-marsh peat make Tump Point sensitive to small changes in sea level and ideal for reconstructing late Holocene RSL.

It is worth noting that the physiographic and ecological conditions at Tump Point differ considerably from the minerogenic marshes encountered in northwest Europe that typically have meso- to macrotidal regimes, have large elevational changes and are characterized by deposition of clastic sediment that is distributed by tidal creeks (Allen, 2000). This results in more pronounced variability in sedimentation at

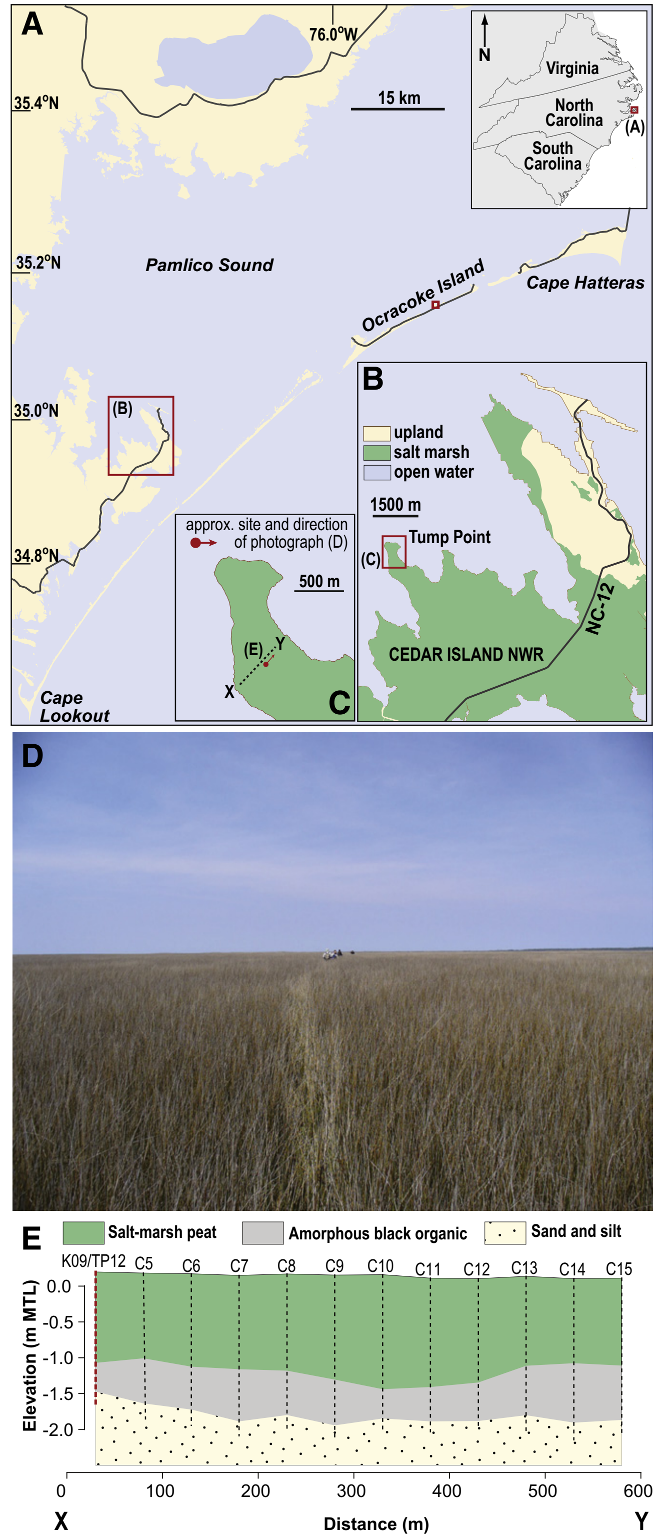

Figure 1. (A–C) Locations of study sites at Tump Point and Ocracoke Island, North Carolina, USA. (D) Photograph of the flat, extensive and ecologically homogeneous salt-marsh platform at Tump Point. Approximate location and direction of view of the photograph are displayed in (C). (E) Simplified stratigraphy underlying the Tump Point site. Adapted from Kemp et al., 2009.