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Holocene sea-level changes along the North Carolina Coastline and their implications for glacial isostatic adjustment models

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ABSTRACT

We have synthesized new and existing relative sea-level (RSL) data to produce a quality-controlled, spatially comprehensive database from the North Carolina coastline. The RSL database consists of 54 sea-level index points that are quantitatively related to an appropriate tide level and assigned an error estimate, and a further 33 limiting dates that confine the maximum and minimum elevations of RSL. The temporal distribution of the index points is very uneven with only five index points older than 4000 cal a BP, but the form of the Holocene sea-level trend is constrained by both terrestrial and marine limiting dates. The data illustrate RSL rapidly rising during the early and mid Holocene from an observed elevation of -35.7 ± 1.1 m MSL at 11062–10576 cal a BP to -4.2 m $\pm$ 0.4 m MSL at 4240–3592 cal a BP. We restricted comparisons between observations and predictions from the ICE-5G(VM2) with rotational feedback Glacial Isostatic Adjustment (GIA) model to the Late Holocene RSL (last 4000 cal a BP) because of the wealth of sea-level data during this time interval. The ICE-5G(VM2) model predicts significant spatial variations in RSL across North Carolina, thus we subdivided the observations into two regions. The model forecasts an increase in the rate of sea-level rise in Region 1 (Albemarle, Currituck, Roanoke, Croatan, and northern Pamlico sounds) compared to Region 2 (southern Pamlico, Core and Bogue sounds, and farther south to Wilmington). The observations show Late Holocene sea-level rising at 1.14 ± 0.03 mm year^{-1} and 0.82 ± 0.02 mm year^{-1} in Regions 1 and 2, respectively. The ICE-5G(VM2) predictions capture the general temporal trend of the observations, although there is an apparent misfit for index points older than 2000 cal a BP. It is presently unknown whether these misfits are caused by possible tectonic uplift associated with the mid-Carolina Platform High or a flaw in the GIA model. A comparison of local tide gauge data with the Late Holocene RSL trends from Regions 1 and 2 support the spatial variation in RSL across North Carolina, and imply an additional increase of mean sea level of greater than 2 mm year^{-1} during the latter half of the 20th century; this is in general agreement with historical tide gauge and satellite altimetry data.

1. Introduction

The reconstruction of relative sea levels (RSL) during the Holocene has many applications, from investigating spatial and temporal variations in crustal movements and calibrating models of earth rheology and ice sheet reconstructions (e.g., Shennan et al., 2002; Lambeck et al., 2004; Peltier, 2004; Horton et al., 2005; Milne et al., 2005; Lambeck and Purcell, 2005; Wake et al., 2006; Simms et al., 2007; Vink et al., 2007; Yu et al., 2007; Brooks et al., 2008), to studying the development of coastal lowlands and their subsequent occupation by humans (e.g., Stanley, 1988; Day et al., 2007; Turney and Brown, 2007; Törnqvist et al., 2008). Current concerns regarding the potential sea-level rise associated with warming of the atmosphere and oceans have resulted in increased interest in former RSLs (e.g., Alley et al., 2005; Rohling et al., 2008). Holocene rates of sea-level rise represent the fundamental basis for comparison with historical and present-day changes. They provide a benchmark to measure the additional sea-level rise that has

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occurred over the last 100–150 years (e.g., Velicogna and Wahr, 2006; Church and White, 2006; Rahmstorf et al., 2007; Jevrejeva et al., 2008).

RSL data are extremely valuable for constraining the models of the glacial isostatic adjustment (GIA) process (e.g., Peltier, 2002). The need for accurate models of the GIA process is important for the credibility of the global sea-level rise dataset currently being produced on the time dependence of the gravitational field of the planet by the Gravity Recovery and Climate Experiment (GRACE) dual satellite measurement system (e.g., Velicogna and Wahr, 2006). The trends from Greenland or elsewhere must be scaled and corrected for contamination from the influence of the GIA process before they can be interpreted as mass-loss estimates (Peltier, 2004). Fig. 1 illustrates the ICE-4G(VM2) based form of the filter expressed as the time rate of change of geoid height as originally employed in the GRACE program development literature. The predicted structure contains an intense dipolar variation with one center of action located over the Hudson Bay region and a second of opposite sign offshore off the northeastern United States. The ICE-4G(VM2) provided an extremely accurate fit to a database of sea-level observations from the United States Atlantic Coast (Peltier, 1998). The observations, however, had no quality control and there was a notable gap between Virginia and South Carolina. The current version of the GIA model is ICE-5G(VM2) of Peltier (2004), which is commonly used in GRACE investigations, especially regarding North America (e.g., Rangelova and Sideris, 2008; Van der Wal et al., 2008). It differs from the precursor model because a significant redistribution of the Last Glacial Maximum (LGM) ice mass was required to fit data collected since the earlier model was published. The ICE-5G(VM2) has not been validated against any observations along the United States Atlantic Coast, thus it is presently unknown to what extent the modifications to the input files have destroyed the high quality fit of ICE-4G(VM2).

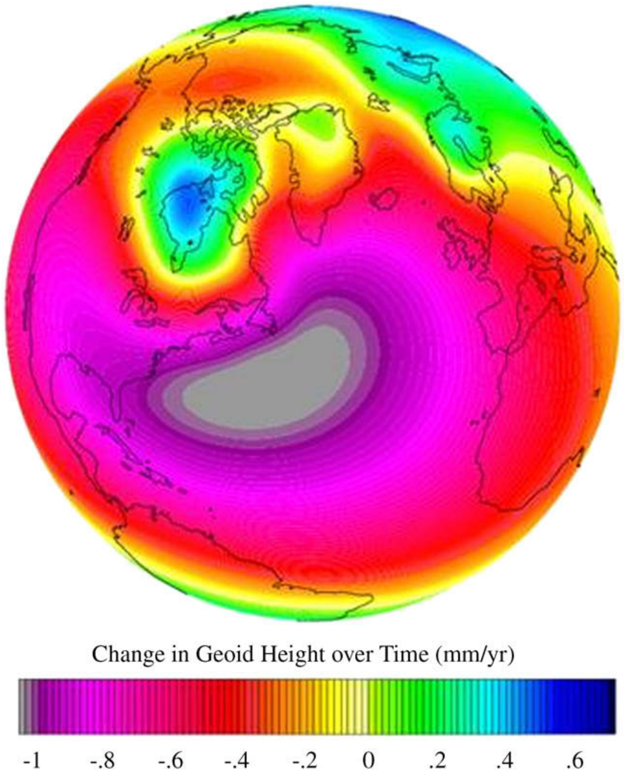

Fig. 1. Prediction of the rate of change of geoid height that is expected to result due to postglacial rebound according to the ICE-4G(VM2) model of Peltier (1996) that has been employed in NASA literature describing the goals of the GRACE satellite program. The prediction of the ICE-5G(VM2) model of Peltier (2004) does not differ significantly from this insofar as the dipolar feature that straddles the United States Atlantic Coast is concerned. It is this feature that makes this region especially interesting from a geodynamic perspective.

There have been several notable attempts to produce a Holocene RSL database for the North Carolina coastline (e.g., Emery and Wigley, 1967; Redfield, 1967; Sears, 1973; Field and Meisburger, 1979; Cinquemani et al., 1981; Riggs et al., 1992). However, the criteria necessary to produce an accurate sea-level database have rarely been met (Vink et al., 2007). The correct interpretation of the elevational relationship of sea-level indicators to sea level is a critical element of reconstructing RSL histories. Different types of sea-level indicators have varying degrees of precision. Mean high water is commonly used as a datum rather than mean sea level (MSL), but this is often not stated. Elevation errors are rarely included in sea-level reconstructions. One common source of error stems from the calibration of radiocarbon dated samples. If ages are calibrated, different calibration programs are often used, and they produce different results. Similar uncertainties are introduced by the application of corrections for the Marine Reservoir Effect.

Our aims for this study are three-fold: (1) produce new sea-level index points based on a suite of paleoenvironmental indices; (2) synthesize new and existing data to produce a quality-controlled, spatially comprehensive database of Holocene RSL changes from the North Carolina coastline; and (3) compare the database of sea-level observations to a GIA model linking RSL, a model of the Earth's radial viscoelastic structure, and a model of ice sheet accumulation and flow.

2. Relative sea-level observations

A robust method for estimating former sea levels from low-energy sedimentary, temperate coastlines was developed during the International Geological Correlation Programme (IGCP) projects (e.g., van de Plassche, 1986; Shennan and Horton, 2002; Edwards, 2007). The methodology is underpinned by a multiproxy approach, which employs a combination of lithostratigraphy, biostratigraphy, and geochronology to produce a sea-level index point. In this study, lithostratigraphy was observed in a series of sediment cores collected at study sites, which were surveyed to the North American Vertical Datum (NAVD88) geodetic datum using a digital total station, GPS and/or a satellite-based Real Time Kinematic (RTK). The cores were described in the field and laboratory using a modified standard soils stratigraphic nomenclature and the Troels-Smith (1955) method for organic-rich sediments. For the latter method we recorded the upper and lower depths below ground surface; composition; degree of humification of organic horizons; and physical properties.

Biostratigraphy (e.g., relative abundances of pollen, diatoms, and/or foraminifera; see Supplementary material for preparation methodology) was used to establish the nature of the environment in which the index point accumulated and to estimate the relationship of the dated sample to a tidal level. This relationship to a tide level, and hence sea level, is called the 'indicative meaning' (Shennan, 1986; van de Plassche, 1986) and consists 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, we used the zonations of local modern vegetation (e.g., Horton and Culver, 2008), the distribution of local modern microfossils (e.g., Horton et al., 2006; Horton and Culver, 2008; Kemp et al., 2009), which was supported by $\delta^{13}C$ values of ^{14}C dated sediments (e.g., Törnqvist et al., 2004a,b). The RSL of a sea-level index point was calculated by subtracting the reference water level from the elevation of the dated sample. Where the biostratigraphic data indicate deposition in freshwater or marine environments, the sample is classified as a "limiting date". Such samples may be used to test specific hypotheses because freshwater and marine environments must have formed inland or seaward of the paleocoastline and above or below former sea level, respectively.

We calculated the vertical error of an index point from a variety of factors. Shennan (1986) and Woodroffe (2006) identified a number of largely unavoidable errors associated with the use of vibracore, rotary, or hand operated corers, including depth measurement and compaction during penetration. The variability in penetration angle was calculated as 2% of core depth (Törnqvist et al., 2008). We also included an error estimate associated with instrumental leveling of the site to NAVD88 and conversion to MSL. This is usually ±0.05 m for detailed surveying, but may be as much as ±0.5 m for less precise work. The error for relating the leveling datum to local tide levels is typically ±0.1 m, but may be as large as ±1.5 m for offshore sites (Shennan, 1986). These errors exclude any influence of the change of tidal range through time. The total height error, E_h, is calculated from the expression:

$$E_\mathrm{h} = \left(e_1^2 + e_2^2 + \cdots + e_n^2\right)^{1/2}$$

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

Another serious form of vertical 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; Pizzuto and Schwendt, 1997). Sediment consolidation may lower index points from their original elevation and, unless corrected for, will lead to an over-estimate of the rate and magnitude of RSL rise. To provide an initial assessment and suggest whether the influence of sediment consolidation is significant we have separated basal peats from other index points (Shennan et al., 2000; Törnqvist et al., 2008). Basal peats are thought to be compaction-free, because the underlying substrates (e.g., Pleistocene sediment) are typically assumed to be unaffected by compaction.

Every sea-level index point in the North Carolina sea-level database 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), which is confined to 0 to 26,000 cal a BP. In instances where marine samples (such as shells and foraminifera) were dated, the Marine04 dataset was employed (Hughen et al., 2004). The marine calibration dataset incorporates a time-dependent global ocean-reservoir correction of about 400 years, but to account for local effects we have used the ΔR in reservoir age for North Carolina from the Marine Reservoir Correction Database maintained at the University of Belfast ($\Delta R = 170 \pm 50$ years; Reimer et al., 2004; McNeely et al., 2006). Following Wolff (2007) we have expressed the unit for years as "a", both for ages and time spans. The zero in the age scale for radiocarbon and calibrated assays is AD 1950.

3. Predictions of relative sea level

The ICE-5G(VM2) GIA model of Peltier (2004) illustrates the important role that rotational feedback plays in determining the history of postglacial RSL change. Rotational feedback is the consequence of the dominant role polar wandering has for GIA-induced changes in planetary rotation (e.g., Peltier, 1982, 1998, 2002, 2004, 2007a,b; Wu and Peltier, 1984; Milne and Mitrovica, 1996, 1998; Mound and Mitrovica, 1998; Johnston and Lambeck, 1999; Mitrovica et al., 2001). Peltier (1982) and Wu and Peltier (1984) provided the theory to predict changes in the Earth's rotation. The concept for the computation of the sea-level response to these GIA induced changes in Earth rotation was provided in Peltier (1998). His analysis followed that of Dahlen (1976) who considered the problem of the pole-tide raised in the oceans by the Chandler wobble of the Earth's spin axis. The influence of rotational feedback on sea-level history due to the GIA process consists of a quadrupole pattern composed of four "bulls-eyes", two positive and two negatives, which is a consequence of the dominant role of true polar wander.

The new RSL database from the east coast of South America (Rostami et al., 2000) showed that rotational feedback was critical to understanding the very large amplitude mid-Holocene highstands characteristic of the Patagonia coastline of Argentina. Because the southern portion of coastal South America is not in the "near field" of a continental ice sheet, the ice-induced component of the signal reduces in magnitude and the rotational feedback effect is clearly evident (Peltier, 2002). RSL data from two other "bulls-eyes" of the degree-two and order-one pattern (South Pacific and Indian Oceans, and over the islands of Japan) also require the influence of rotational feedback to explain their characteristics (Peltier, 2007a,b). The ICE-5G(VM2) model of Peltier (2004) has been shown to provide an accurate explanation of the influence of rotational feedback at all sites where the direct influence of ice-sheet proximity is irrelevant. Observations from the remaining "bulls-eye", the United States Atlantic Coast, are a combination of both isostatic as well as eustatic influences. The isostatic influence along this coast is especially important as it is associated with the collapse of the pro-glacial forebulge, which was of large amplitude because of the ice load of the vast Laurentide ice sheet (Dyke and Peltier, 2000). Milne and Mitrovica (1996, 1998), and Peltier (1998) suggested that the influence of rotational feedback was too weak for sites along the United States Atlantic coast to be of practical consequence because of the absence of an accurate database of RSL observation. We are now in a good position to reconsider this.

4. Study area

The study area encompasses much of the coastal region of North Carolina (Fig. 2). The northern part of the coastal zone, from the North Carolina/Virginia state border southward to southern Pamlico Sound, occupies the Albemarle Embayment. The Albemarle Embayment is a Cenozoic depositional basin that is bounded to the north and south by the Norfolk Arch (Foyle and Oertel, 1997) and the Cape Lookout High, respectively. The Cape Lookout High is a generally E–W trending Tertiary depositional high that underlies the Carteret Peninsula (e.g., Ward and Strickland, 1985; Popenoe, 1990; Riggs et al., 1995). The southern part of North Carolina's coastal zone, from Cape Lookout to the Cape Fear River, overlies the Carolina Platform, a structural high in the underlying crystalline basement rocks (Riggs and Belknap, 1988). The Carolina Platform consists of shallow (<1 km) Paleozoic crystalline basement rock, and extends from approximately Cape Romain, South Carolina to Cape Lookout, North Carolina (Riggs and Belknap, 1988). A shallow paleo-topographic high on top of the Carolina Platform, the mid-Carolina Platform High (also known as the Cape Fear Arch), is located approximately along the axis of the Cape Fear River.

The different geologic frameworks to the north and south of Cape Lookout result in different physiographic settings (Riggs and Ames, 2003). The southern coastal zone is characterized by an average subaerial land slope of 0.57 m km^{-1} compared to 0.04 m km^{-1} in the northern zone. The southern zone has short, stubby barrier islands with about 18 inlets and narrow back-barrier estuaries. The north has long barrier islands with only about five inlets and an extensive sequence of drowned-river estuaries that form the vast Albemarle-Pamlico estuarine system (Riggs and Ames, 2003). This estuarine system has a low astronomical tidal range (<1 m), minimal saltwater exchange, highly variable salinities (e.g., 0 in the

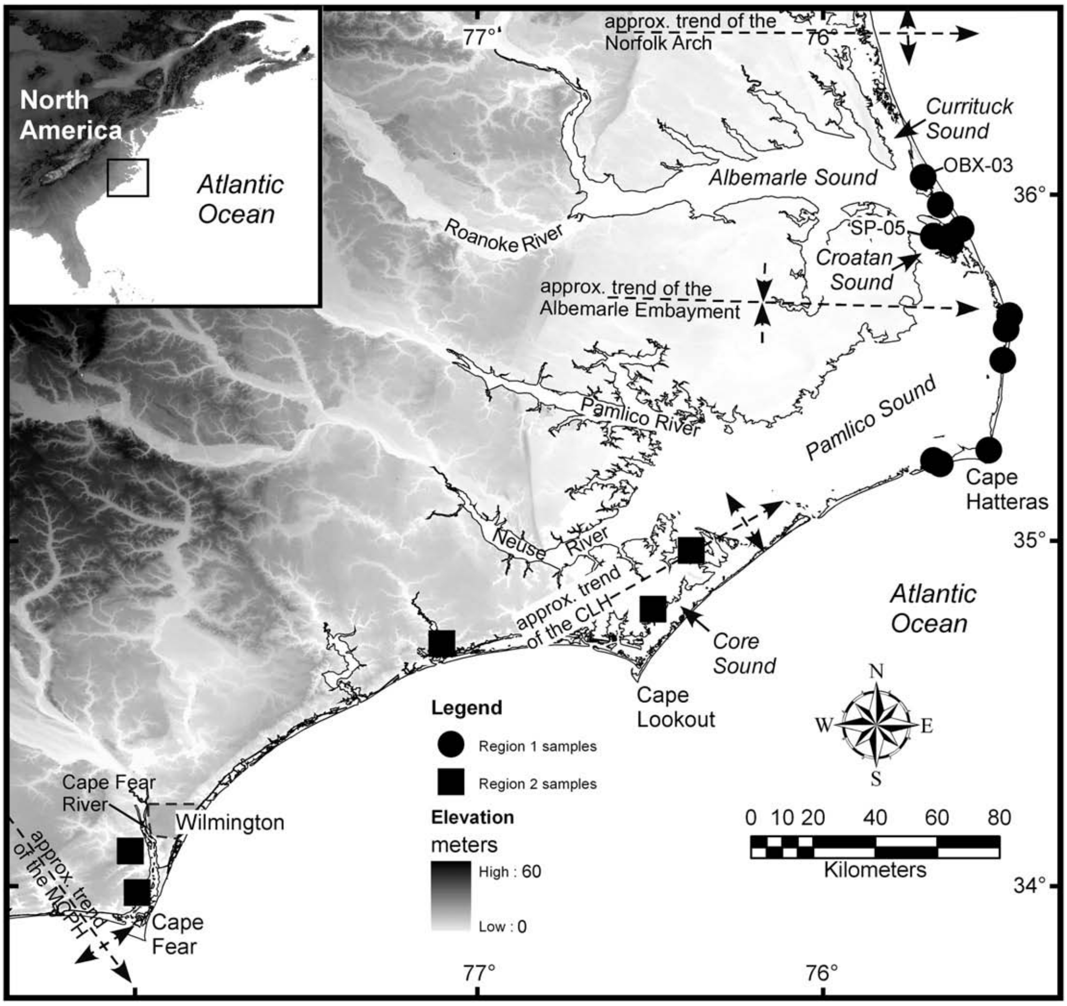

Fig. 2. Location map showing the spatial distribution of sea-level index points, major geomorphic features and trends of structural platforms, arches, and embayments. The circles and squares represent Regions 1 and 2, respectively. Elevations are calculated from LIDAR.

Chowan River and sometimes in northern Currituck Sound; 36 near inlets; average of 20) and is dominated by wind tides (Giese et al., 1985). In contrast, the lagoons and estuaries of the southern zone have higher astronomical tidal ranges (1–2 m), extensive saltwater exchange with generally high brackish salinities, and are fed by smaller drainages, with the exception of the Cape Fear River (Giese et al., 1985; Riggs and Ames, 2003).

5. Examples of data collected

In the following section we present litho-, bio- and chronostratigraphic data from two sites that illustrate the type of sea-level index points used to reconstruct RSL changes.

5.1. An Early Holocene sea-level index point from Core OBX-03

Core OBX-03 is a rotasonic vibracore that was drilled on the northern Outer Banks into six valley-fill units (VF1 to VF6; Mallinson et al., 2005) recognized by seismic-reflection geometry. The core was corrected for compaction due to drilling (Culver et al., 2008). Fig. 3 summarizes the micropaleontological data indicating paleoenvironmental changes at the base of OBX-03.

OBX-03 contains coarse-grained sand and gravel that overlies early Pleistocene silty clay at depths greater than −38 m NAVD88. This sand and gravel interval fills a fluvial channel incised by the paleo-Roanoke River during the Last Glacial Maximum (Mallinson et al., 2005; Culver et al., 2008). Between c. −38 and −29 m NAVD88, a sequence of laminated to interbedded silty clay and sand overly the valley-fill unit. Within this fine grained unit, a thin peat with plant fragments was found between −36 and −35.5 m NAVD88. The pollen assemblage is dominated by varying amounts of *Pinus* and *Quercus* with herbaceous pollen (e.g., Cyperaceae and Poaceae) that have no modern analogues along the modern North American coast, but indicate the presence of local salt marsh conditions, possibly cooler than those of today (Culver et al., 2008). Above the peat, the rare herbaceous pollen is analogous to assemblages found in the modern Chesapeake Bay and at its mouth (Willard et al., 2005). This suggests a conversion from a salt marsh to open water setting. The diatom assemblages in this fine-grained sequence also show a change from a brackish assemblage with notable presence of mesohalobous diatoms (e.g., *Cyclotella striata* and *Trybionella punctata*) and oligohalobous diatoms (e.g., *Cyclotella bodanica* and *Nitzschia amphibian*) to a marine assemblage consisting of polyhalobous species (greater than 75% in all samples) such as *Rhaphoneis amphiceros*, *Rhaphoneis surirella*, *Paralia sulcata*, and *Coscinodiscus nitidus* (Culver et al., 2008).

Undetermined plant macrofossils at the base of the peat at 35.6 m NAVD88 have been dated to 11,062–10,576 cal a BP, which is the oldest index point in our North Carolina sea-level database. The

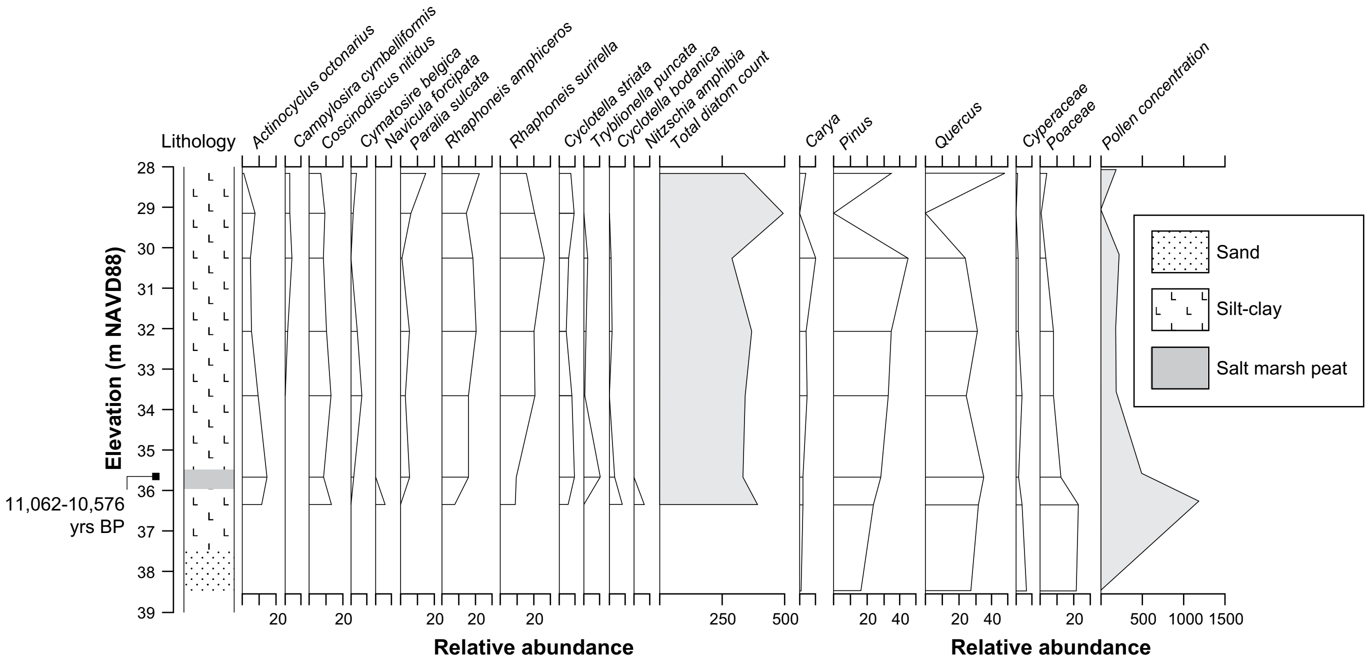

Fig. 3. Microfossil diagram for the Early Holocene sea-level index point from Core OBX-03. Pollen expressed as % total land pollen; spores as % ∑(land pollen + spores); diatoms as relative abundances and grouped according to salinity classes polyhalobous, mesohalobous and oligohalobous. Calibrated radiocarbon age, elevation (m NAVD88) down-core shown to the left of the lithology column. The sediment legend is drawn according to a simplified Troels-Smith (1955).

basal peat represents an index point formed between MHHW and MTL (0.06 ± 0.09 m NAVD88) as pollen and diatoms suggest its deposition within a salt marsh (Table 1). The $\delta^{13}C$ signature (−14.62) is typical of C_4 salt marsh plants such as *Spartina* and *Distichlis*. The alternative C_3 plants, with the Calvin pathway, have low $\delta^{13}C$ values (−24 to −34), while the C_4 plants, with the Hatch and Slack pathway, have high $\delta^{13}C$ values (−6 to −19) (Bender, 1971; Smith and Epstein, 1971).

5.2. A Late Holocene sea-level index point from Core SP-05

Core SP-05 was extruded with a Russian corer from Sand Point on Roanoke Island. There was no compaction during coring. This site was selected after extensive stratigraphic investigation (vibracore, rotary, or hand operated coring) in the Albemarle-Pamlico estuarine system showed that it contained one of the thickest continuous sequences of salt marsh peat in this region.

The core is 3.3 m long (0.3 m NAVD88 to −3.0 m NAVD88) and consists of organic sediment overlying coarse-grained sand (Fig. 4). The uppermost 2.7 m contains abundant remains of the common salt marsh plants *Juncus roemerianus* and *Distichlis spicata*. Toward the base of the peat (−2.4 m NAVD88) a well-preserved sub-surface stem of *Distichlis spicata* was identified and prepared for radiocarbon dating by removing younger, invasive root material under a binocular microscope. It returned an age of 2120 ± 25 ^{14}C a (2287–2003 cal a BP). $\delta^{13}C$ measurement on this sample of −13.78 is consistent with that of modern *Distichlis spicata* at Sand Point (Kemp, 2009). Foraminifera are present in the core from −2.6 m NAVD88 upwards (Table 1). The assemblage associated with the dated sample is dominated by salt marsh species such as *Ammoastuta inepta*, *Miliammina petila* and *Jadammina macrescens*, which suggested it formed between MHHW and MTL (Culver and Horton, 2005; Horton and Culver, 2008).

6. Holocene sea-level reconstructions for North Carolina

We have developed a sea-level database for North Carolina from new, published, and unpublished records (Fig. 2, Table 2). The database consists of 54 sea-level index points quantitatively related to a past tide level together with an error estimate, and a further 33 data points that provide limits on the maximum and minimum elevation of RSL (Fig. 5a). The temporal distribution of the index points is very uneven; only five index points are older than 4000 cal a BP (Fig. 5b). There is a great need to extend the observational data into the Early Holocene. Nevertheless, the form of the Holocene sea-level trend is constrained by both terrestrial and marine limiting dates, illustrating their importance for sea-level reconstructions. The plot of all data confirms the upward trend of Holocene RSL. Sea level rapidly rises from an observed value of −35.7 ± 1.1 m MSL at 11062–10576 cal a BP to −4.2 ± 0.4 m MSL at 4240–3592 cal a BP,

Table 1
The calculation of relative sea level (RSL) for two sea-level index points from the North Carolina study area. Relative sea level (RSL) is calculated as elevation minus the reference water level, which is then converted from NAVD88 to mean sea level (MSL), shown to 1 decimal place. The RSL error range is calculated as the square root of the sum of squares of indicative range, sample thickness, elevational error, tide-level error and coring error, shown to 1 decimal place.

Index point	RSL	Error
OBX-03	$-35.62\ \mathrm{m}_{\text{elevation}} - 0.06\ \mathrm{m}_{\text{RWL}} - 0.03\ \mathrm{m}_{\text{NAVD88 to MSL}} = -35.7$ m MSL	$\Sigma(0.09\ \mathrm{m}^2_{\text{indicative range}} + 1.00\ \mathrm{m}^2_{\text{sample thickness}} + 0.20\ \mathrm{m}^2_{\text{leveling}} + 0.02\ \mathrm{m}^2_{\text{depth}} + 0.12\ \mathrm{m}^2_{\text{datum}} + 0.36\ \mathrm{m}^2_{\text{angle of borehole}})^{½} = 1.1$ m
SP-05	$-2.36\ \mathrm{m}_{\text{elevation}} - 0.06\ \mathrm{m}_{\text{RWL}} - 0.03\ \mathrm{m}_{\text{NAVD88 to MSL}} = -\ 2.5$ m MSL	$\Sigma(0.09\ \mathrm{m}^2_{\text{indicative range}} + 0.05\ \mathrm{m}^2_{\text{sample thickness}} + 0.05\ \mathrm{m}^2_{\text{leveling}} + 0.02\ \mathrm{m}^2_{\text{depth}} + 0.12\ \mathrm{m}^2_{\text{datum}} + 0.04\ \mathrm{m}^2_{\text{angle of borehole}})^{½} = 0.2$ m

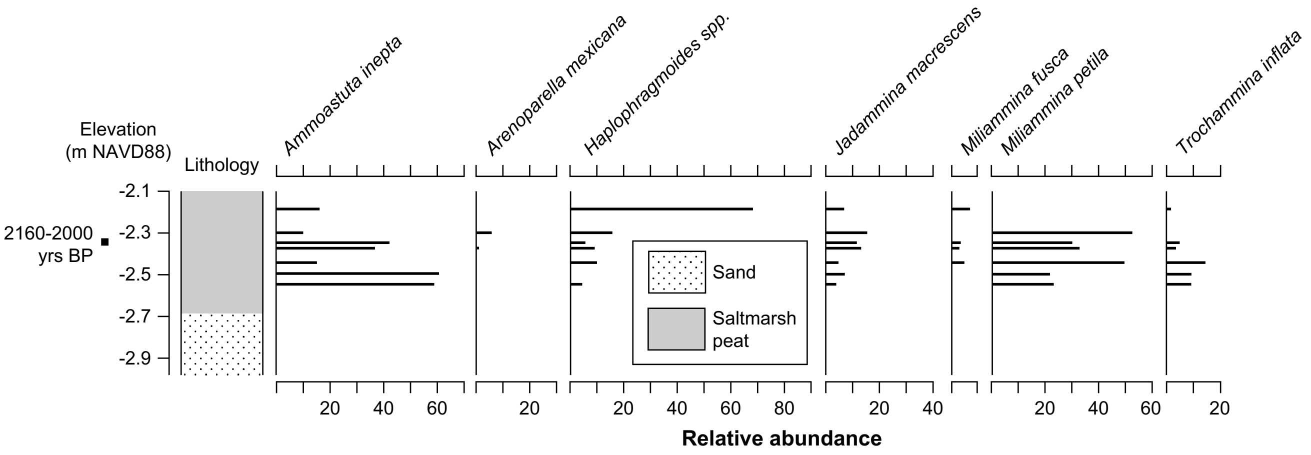

Fig. 4. Foraminiferal diagram for the Late Holocene sea-level index point from Core SP-05. Foraminiferal abundance is calculated as a percentage of total tests (species >5% are shown). Calibrated radiocarbon age, elevation (m NAVD88) down-core shown to the left of the lithology column. The sediment legend is drawn according to a simplified Troels-Smith (1955).

which equates to an average rate of rise during the Early and Mid Holocene of c. 5 mm year^{-1}.

Studies elsewhere along the mid-Atlantic coast of the United States reveal similar sea-level histories. These include several studies from the New Jersey coast that suggest rapidly rising sea level during the Early and Mid Holocene (e.g., Stuiver and Daddario, 1963; Bloom, 1967; Meyerson, 1972; Psuty, 1986; Miller et al., 2009). Miller et al. (2009) illustrated that RSL rose from −18 m at c. 8500 cal a BP to −7 m at 5000 cal a BP. Thereafter, the rate of rise was steady at 1.7–1.9 mm year^{-1}. There is a long history of sea-level research in Delaware (e.g., Kraft, 1971; Belknap and Kraft, 1977; Fletcher et al., 1993; Nikitina et al., 2000), which suggests that RSL rose 3 mm year^{-1} during the Early Holocene until it reached −11 m at approximately 5000 cal a BP. Subsequently, the rate of rise was 2 mm year^{-1} from 5000 to 2000 cal a BP. Further south along the United States Atlantic coast, studies have suggested the presence of a Mid Holocene high stand, which is contrary to our observational data. In South Carolina, an oscillating RSL history during the Holocene has been proposed (e.g., Gayes et al., 1992; Scott et al., 1995). Relative sea level rose from −3 m at 5200–4600 cal a BP to −1 m by c. 4300 cal a BP. Most studies from the Florida Keys showed continual rise of RSL during the Holocene with no indication of an emergence (e.g., Robbin, 1984; Toscano and Lundberg, 1998). Toscano and Lundberg (1998) suggested RSL rose from −13.5 to −7 m between 8900 and 5000 cal a BP, whereas Froede (2002) suggested Late Holocene sea level was at least 0.5 m higher than at present in Key Biscayne, Florida.

6.1. *Implications for glacial isostatic adjustment models*

There are sufficient observations of former sea levels in North Carolina during the Late Holocene (last 4000 years) to justify comparisons with the ICE-5G(VM2) with rotational feedback GIA model of Peltier (2004). The ICE-5G(VM2) model predictions have a 500-year time step and are based on a spherically symmetric, self-gravitating and compressible Maxwell visco-elastic Earth model with a lithosphere thickness of 90 km. The radial variation of elastic properties is fixed to the Preliminary Reference Earth Model (PREM) of Dziewonski and Anderson (1981). For each spherical harmonic degree, these spectra are characterized by a discrete set of inverse relaxation times, which appear in the Dirichlet series expansions for the time-dependent Love numbers in terms of which the theory is expressed (see Peltier, 2004, Fig. 1 for further details).

The spatial variation in the predicted sea-level signal from the ICE-5G(VM2) model across North Carolina is illustrated in Fig. 6a for 4000 cal a BP. The results show a variation in RSL of c. 2 m across the region. Based upon these predictions and the spatial distribution of the RSL observations, we have split the data into two regions: Region 1 includes sites within the Albemarle, Currituck, Roanoke, Croatan and northern Pamlico sounds; Region 2 contains sites from southern Pamlico, Core and Bogue sounds, and farther south to Wilmington (Fig. 2).

Index points younger than 4000 cal a BP from Regions 1 and 2 illustrate a rising RSL due to the strong influence of the pro-glacial forebulge collapse. The ICE-5G(VM2) model predicts an increase in the rate of sea-level rise in Region 1 compared to Region 2. This is clearly shown in Fig. 6b; RSL observations from Region 1 clearly plot below Region 2 until c. 1000 cal a BP when the errors begin to overlap significantly. In Region 1 the observations show Late Holocene sea-level rising from −2.6 ± 0.2 m MSL at 2849–2543 cal a BP to present at a rate of 1.14 ± 0.03 mm year^{-1} (Fig. 6c). The observations from Region 2 illustrate RSL rising at a slower rate of 0.82 ± 0.02 mm year^{-1} from −3.4 ± 0.4 m MSL at 3905–3389 cal a BP (Fig. 6d).

The ICE-5G(VM2) shows a close correspondence to observations from Region 1. The fit is superior to the ICE-4G(VM2) precursor model (Fig. 6c). There is also an accord between the ICE-5G(VM2) model and observations younger than 2000 cal a BP in Region 2. The older observations, however, lie between both models (Fig. 6d). The variance in Region 2 is expected because the orientation of the coastline diverges from the trend of predicted isostatic adjustment south of Cape Hatteras (Fig. 6a). More importantly, most of these older data points in Region 2 are located in the Wilmington, near the most prominent structural feature of the North Carolina Coastal Plain, the mid-Carolina Platform High. Regional stratigraphic studies have identified broad areas of uplift (e.g., Winker and Howard, 1977; Markewich, 1985; Soller and Mills, 1991; Marple and Talwani, 2004). Marple and Talwani (2004) infer the uplift to be between 0.14 and 1.8 mm year^{-1} based upon incision of the Cape Fear River. Similarly, Braatz and Aubrey (1987) estimate the uplift to be 0.6 mm year^{-1}. Applying an uplift of between 0.5 and 1 mm year^{-1} to the index points from the Wilmington region would remove the difference between the ICE-5G(VM2) model predictions and observations. The observations from North Carolina suggest an improved fit with the ICE-5G(VM2) model compared to its precursor, and the spatial variation in RSL may be explicable when rotational feedback is included. We have further supported

Table 2
Summary of sea-level index points and limiting data from the North Carolina study area.

Location	Region	Labcode	Material dated	^{14}C age ± 1σ	δ^{13}C	Calibrated age range	Macro/-microfossil data	RSL (m MSL)	Citation
Index points									
Buxton, BX0254C1	1	Beta-183551	Peat	160 ± 30	−25.10	0–286	Yes	−0.4 ± 0.2	Unpublished
Frisco, Fri02s1pc1	1	OS-39722	Peat	205 ± 40	–	0–310	No	−0.7 ± 0.6	Unpublished
Hatteras, DrtPt03-S1	1	Beta-187692	Peat	250 ± 40	−26.10	0–436	No	−0.8 ± 0.5	Unpublished
Hatteras, SalIn-05-VC1B	1	OS-54058	Peat	265 ± 35	−22.49	0–456	No	−0.5 ± 0.2	Unpublished
NHW03S2	1	Beta-187694	Peat	1580 ± 40	−23.00	1382–1548	No	−1.7 ± 0.2	Unpublished
Kitty Hawk, OBX1	1	Beta-168060	Peat	7830 ± 50	−28.00	8455–8853	Yes	−15.5 ± 1.1	Mallinson et al., 2005
Kity Hawk, OBX-03	1	OS-36174	Peat	9460 ± 40	−14.64	10576–11062	Yes	−35.7 ± 1.1	Mallinson et al., 2005
Kitty Hawk, OBX5	1	Beta-168063	Peat	9720 ± 40	−24.60	10889–11231	Yes	−30.5 ± 1.1	Mallinson et al., 2005
Kitty Hawk, OBX5	1	OS-36176	Peat	9930 ± 45	−24.48	11235–11603	Yes	−30.5 ± 1.1	Mallinson et al., 2005
Pamlico Sound, Clam03s1	1	Beta-187689	Peat	500 ± 40	−26.60	496–630	No	−0.6 ± 0.5	Unpublished
Salvo, SAL02s1pc1	1	OS-39790	Peat	200 ± 35	−27.43	0–306	Yes	−0.4 ± 0.2	Unpublished
Sand Point, Roanoke Island	1	OS-43066	Peat	185 ± 30	−24.28	0–300	Yes	−0.5 ± 0.2	Unpublished
Sand Point, Roanoke Island	1	OS-43067	Peat	900 ± 50	−27.27	727–927	Yes	−1.1 ± 0.2	Unpublished
Sand Point, Roanoke Island	1	OS-43068	Peat	1520 ± 40	−25.55	1333–1521	Yes	−1.8 ± 0.5	Unpublished
Sand Point, Roanoke Island	1	OS-43069	Peat	1920 ± 45	−21.98	1734–1986	Yes	−2.2 ± 0.2	Unpublished
Sand Point, Roanoke Island	1	OS-43070	Peat	2090 ± 35	−22.92	1951–2151	Yes	−2.3 ± 0.2	Unpublished
Sand Point, Roanoke Island	1	OS-43071	Peat	2420 ± 35	−26.52	2349–2699	Yes	−2.7 ± 0.2	Unpublished
Sand Point, Roanoke Island	1	OS-43266	Peat	2470 ± 45	−25.47	2363–2715	Yes	−3.0 ± 0.2	Unpublished
Sand Point, Roanoke Island	1	OS-58902	Peat	315 ± 25	−27.33	305–461	Yes	−0.6 ± 0.2	Unpublished
Sand Point, Roanoke Island	1	OS-58897	Peat	535 ± 30	−26.67	512–632	Yes	−0.8 ± 0.2	Unpublished
Sand Point, Roanoke Island	1	OS-58901	Peat	910 ± 30	−27.00	743–917	Yes	−1.2 ± 0.2	Unpublished
Sand Point, Roanoke Island	1	OS-58896	Peat	1000 ± 25	−14.08	800–964	Yes	−1.4 ± 0.2	Unpublished
Sand Point, Roanoke Island	1	OS-58713	Peat	1080 ± 30	−13.26	933–1057	Yes	−1.5 ± 0.2	Unpublished
Sand Point, Roanoke Island	1	OS-58712	Peat	1190 ± 30	−13.40	1006–1230	Yes	−1.7 ± 0.2	Unpublished
Sand Point, Roanoke Island	1	OS-58711	Peat	1600 ± 25	−13.28	1413–1539	Yes	−1.9 ± 0.2	Unpublished
Sand Point, Roanoke Island	1	OS-58710	Peat	2120 ± 25	−13.78	2003–2287	Yes	−2.5 ± 0.2	Unpublished
Sand Point, Roanoke Island	1	OS-63287	Peat	2550 ± 70	−26.26	2360–2770	Yes	−3.1 ± 0.2	Unpublished
Sand Point, Roanoke Island	1	OS-62716	Peat	2620 ± 45	−20.65	2543–2849	Yes	−2.6 ± 0.2	Unpublished
Sand Point, Roanoke Island	1	OS-64687	Peat	615 ± 35	−26.65	546–658	Yes	−0.7 ± 0.2	Unpublished
Sand Point, Roanoke Island	1	OS-64688	Peat	2410 ± 35	−27.45	2346–2698	Yes	−2.4 ± 0.2	Unpublished
Sand Point, Roanoke Island	1	OS-64813	Peat	1390 ± 110	−27.97	1067–1523	Yes	−1.4 ± 0.2	Unpublished
Sand Point, Roanoke Island	1	OS-64689	Peat	2410 ± 40	−28.58	2345–2699	Yes	−2.6 ± 0.2	Unpublished
Broad Creek	1	Teledyne18999	Peat	320 ± 95	–	0–534	Yes	−0.4 ± 0.5	Benton, 1980
Broad Creek	1	Teledyne18989	Peat	320 ± 80	–	0–518	Yes	−0.4 ± 0.5	Benton, 1980
Broad Creek	1	Teledyne19181	Peat	810 ± 80	–	573–921	Yes	−1.0 ± 0.5	Benton, 1980
Broad Creek	1	Teledyne19206	Peat	1765 ± 85	–	1424–1888	Yes	−2.3 ± 0.5	Benton, 1980
Tump Point, Cedar Island	2	OS-59677	Peat	350 ± 30	−14.35	315–493	Yes	−0.3 ± 0.2	Unpublished
Tump Point, Cedar Island	2	OS-59728	Peat	385 ± 35	−26.16	317–509	Yes	−0.4 ± 0.2	Unpublished
Tump Point, Cedar Island	2	OS-59676	Peat	915 ± 35	−25.60	743–921	Yes	−0.6 ± 0.2	Unpublished
Tump Point, Cedar Island	2	OS-59675	Peat	1350 ± 30	−26.80	1183–1313	Yes	−0.9 ± 0.2	Unpublished
Tump Point, Cedar Island	2	OS-59697	Peat	1650 ± 35	−14.15	1417–1689	Yes	−1.1 ± 0.2	Unpublished
Jarrett Bay	2	SC-VI-53-1	Peat	701 ± 230	−25.00	0–1170	No	−0.7 ± 0.2	Spaur and Snyder, 1999
Jarrett Bay	2	SC-VI-53-2	Peat	2130 ± 161	−23.00	1712–2682	No	−1.7 ± 0.2	Spaur and Snyder, 1999
Croatan National Forest	2	QC-801	Peat	1180 ± 190	–	698–1414	No	−0.8 ± 0.4	Cinquemani et al., 1982
Croatan National Forest	2	QC-802	Peat	1735 ± 110	–	1402–1890	No	−1.3 ± 0.2	Cinquemani et al., 1982
Wilmington	2	QC-799	Peat	1385 ± 130	–	988–1546	No	−0.9 ± 0.4	Cinquemani et al., 1982
Wilmington	2	QC793A	Peat	3390 ± 110	–	3387–3901	No	−3.0 ± 0.6	Cinquemani et al., 1982
Wilmington	2	QC-793B	Peat	3395 ± 110	–	3389–3905	No	−3.4 ± 0.4	Cinquemani et al., 1982
Wilmington	2	QC-794	Peat	3600 ± 115	–	3592–4240	No	−4.2 ± 0.4	Cinquemani et al., 1982
Wilmington	2	QC-796	Peat	3870 ± 175	–	3845–4821	No	−5.5 ± 0.5	Cinquemani et al., 1982
Wilmington	2	QC-797	Peat	5675 ± 250	–	5922–7156	No	−8.0 ± 0.4	Cinquemani et al., 1982
Southport	2	I-1576	Peat	2310 ± 130	–	2009–2721	No	−1.9 ± 0.6	Redfield, 1967
Southport	2	I-1577	Peat	3100 ± 120	–	2963–3573	No	−2.5 ± 0.6	Redfield, 1967
Southport	2	I-1579	Peat	3720 ± 140	–	3695–4497	No	−3.7 ± 0.6	Redfield, 1967
Marine limiting									
Albemarle Sound, AS-12	1	Beta-90661	*Crassostrea*	6140 ± 80	–	6204–6612	Yes	−14.6 ± 1.2	Unpublished
Albemarle Sound, AS-18	1	Beta-90671	*Crassostrea*	2880 ± 60	–	2245–2689	Yes	−6.2 ± 1.1	Unpublished
Albemarle Sound, AS-18	1	Beta-90672	*Cyrtopleura*	4200 ± 100	–	3759–4383	Yes	−8.6 ± 1.1	Unpublished
Albemarle Sound, AS-23	1	Beta-90674	*Cyrtopleura*	4810 ± 40	–	4679–5049	Yes	−8.9 ± 1.0	Unpublished
Albemarle Sound, DC88	1	Teledyne	*Mercenaria*	5225 ± 105	–	5066–5642	Yes	−11.8 ± 1.0	Unpublished
Albemarle Sound, DC88	1	Teledyne	*Ensis*	5600 ± 110	–	5566–6104	Yes	−13.3 ± 1.0	Unpublished
Nags Head	1	W-1402	*Crassostrea virginica*	8130 ± 400	–	7657–9419	Yes	−33.6 ± 1.2	Emery and Wigley, 1967
Pea Island	1	Core1LayerB	*Donaz*	5618 ± 100	–	5584–6090	Yes	−23.6 ± 1.1	Sears, 1973
Pamlico Sound, Gull04s17	1	Beta-201772	*Chione cancellata*	1760 ± 40	0.10	990–1282	Yes	−3.6 ± 1.0	Unpublished
Pamlico Sound, Gull04s7	1	Beta-205450	*Chione cancellata*	2070 ± 40	−0.10	1301–1595	Yes	−4.5 ± 1.1	Unpublished
Roanoke Sound, RS-VC-09	1	Beta-95296	*Crassostrea virginica*	1900 ± 60	–	1116–1468	Yes	−4.1 ± 1.0	Unpublished
Salvo, SalIn-05-VC1B	1	OS-53608	*Chione cancellata*	1900 ± 30	1.62	1161–1399	Yes	−2.4 ± 1.1	Unpublished
Croatan Sound, CS-01	1	Beta-115591	*Crassostrea*	4480 ± 80	–	4155–4767	Yes	−7.8 ± 1.0	Unpublished
Croatan Sound, CS-03	1	Beta-115593	*Macoma*	3610 ± 50	−5.30	3120–3486	Yes	−5.5 ± 1.1	Unpublished
Croatan Sound, CS-22	1	Beta-115595	*Cyrtopleura*	4010 ± 150	–	3403–4225	Yes	−6.0 ± 1.1	Unpublished

(*continued on next page*)

Table 2 (*continued*)

Location	Region	Labcode	Material dated	^{14}C age ± 1σ	δ^{13}C	Calibrated age range	Macro/-microfossil data	RSL (m MSL)	Citation
Croatan Sound, CS-23	1	Beta-115596	*Crassostrea*	4540 ± 80	–	4275–4799	Yes	−7.9 ± 1.0	Unpublished
Croatan Sound, CS-25	1	Beta-115597	*Cyrtopleura*	3670 ± 50	−0.60	3211–3559	Yes	−6.7 ± 1.1	Unpublished
Croatan Sound, CS-25	1	Beta-115598	*Nassarius*	3810 ± 50	–	3364–3722	Yes	−7.2 ± 1.1	Unpublished
Croatan Sound, CS-41	1	Beta-119895	*Mya*	4130 ± 60	–	3721–4173	Yes	−7.1 ± 1.1	Unpublished
SNL-113A-63	1	OS-39293	*Petricola*	7780 ± 45	−2.40	8217–7927	Yes	−17.9 ± 1.1	Stanton, 2008
SNL-161C-90	1	OS-39198	*Crassostrea virginica*	6580 ± 40	−2.34	7084–6720	Yes	−12.9 ± 1.1	Stanton, 2008
SNL-163B-28	1	OS-39195	*Crassostrea virginica*	8210 ± 40	−2.70	8650–8360	Yes	−18.0 ± 1.1	Stanton, 2008
Kitty Hawk, OBX2	1	Beta-168061	*Crassostrea virginica*	97200 ± 40	−3.40	11105–10209	Yes	−30.6 ± 1.1	Mallinson et al., 2005
SNL-164D-93	1	OS-39196	*Crassostrea virginica*	8980 ± 35	−1.41	9776–9527	Yes	−24.5 ± 1.1	Stanton, 2008
Southern Pamlico, NCB05S30	2	OS-54866	*Argopecten irradians concentricus*	835 ± 30	0.16	146–450	Yes	−2.2 ± 1.0	Unpublished
Southern Pamlico, NCB05S30	2	OS-53604	*Elphidium excavatum*	1670 ± 30	−1.57	919–1187	Yes	−2.4 ± 1.1	Culver et al., 2007
Freshwater limiting									
Albemarle Sound, AS-16	1	Beta-90666	Wood	6060 ± 60	−30.70	6749–7157	No	−9.3 ± 1.1	Unpublished
Buxton, BX02s1	1	OS-39792	Peat	315 ± 35	−27.77	302–472	No	−0.1 ± 1.1	Unpublished
Kitty Hawk, OBX5	1	OS-36101	Peat	10950 ± 45	−25.30	12840–12958	Yes	−31.5 ± 1.1	Mallinson et al., 2005
Broad Creek	1	Teledyne18988	Wood	2505 ± 90	–	2356–2750	No	−2.3 ± 1.1	Benton, 1980
Broad Creek	1	Teledyne19208	Wood	3545 ± 100	–	3577–4141	No	−2.3 ± 1.1	Benton, 1980
Broad Creek	1	Teledyne18990	Wood	5315 ± 110	–	5770–6312	No	−2.5 ± 1.1	Benton, 1980
Broad Creek	1	Teledyne19253	Peat	2290 ± 110	–	2009–2703	No	−2.3 ± 1.1	Benton, 1980
Jarrett Bay	2	SC-VI-53-3	Peat	3330 ± 263	−27.00	2880–4282	No	−2.2 ± 1.0	Spaur and Snyder, 1999
Jarrett Bay	2	SC-VI-53-4	Peat	5710 ± 142	−28.00	6214–6856	No	−2.7 ± 1.0	Spaur and Snyder, 1999
Cape Fear Arch	2	GX-2965	Peat	10000 ± 300	–	10701–12637	No	−25.3 ± 1.2	Field and Meisburger, 1979

See Fig. 1 for details of Regions 1 and 2. Macro-/microfossil data may include plant rhizomes, diatom, foraminifera and/or pollen information. Relative sea level (RSL) is calculated as elevation minus the reference water level, which is then converted from NAVD88 to mean sea level (MSL), shown to 1 decimal place. The RSL error range is calculated as the square root of the sum of squares of elevational error, sample thickness, tide-level error, and indicative range, shown to 1 decimal place. The indicative range (given as a maximum) is the most probable vertical range in which the sample occurs, but for limiting dates the sample could occur above this range. Every index point for the North Carolina sea-level database has been age dated using radiocarbon techniques and the CALIB 5.0.1 calibration model (Stuiver et al., 2005). We used a laboratory multiplier effect of 1 with 95% confidence limits and employed the dataset IntCal04 (which is confined to 0–26 ka cal BP). In instances where marine samples (such as shells and foraminifera) have been dated, the dataset Marine04 has been employed (Hughen et al., 2004). The marine calibration dataset incorporates a time-dependent global ocean-reservoir correction of about 400 years but to accommodate local effects, we have determined the Δ*R* in reservoir age for North Carolina (Δ*R* = 170 ± 50 years, Reimer et al., 2004).

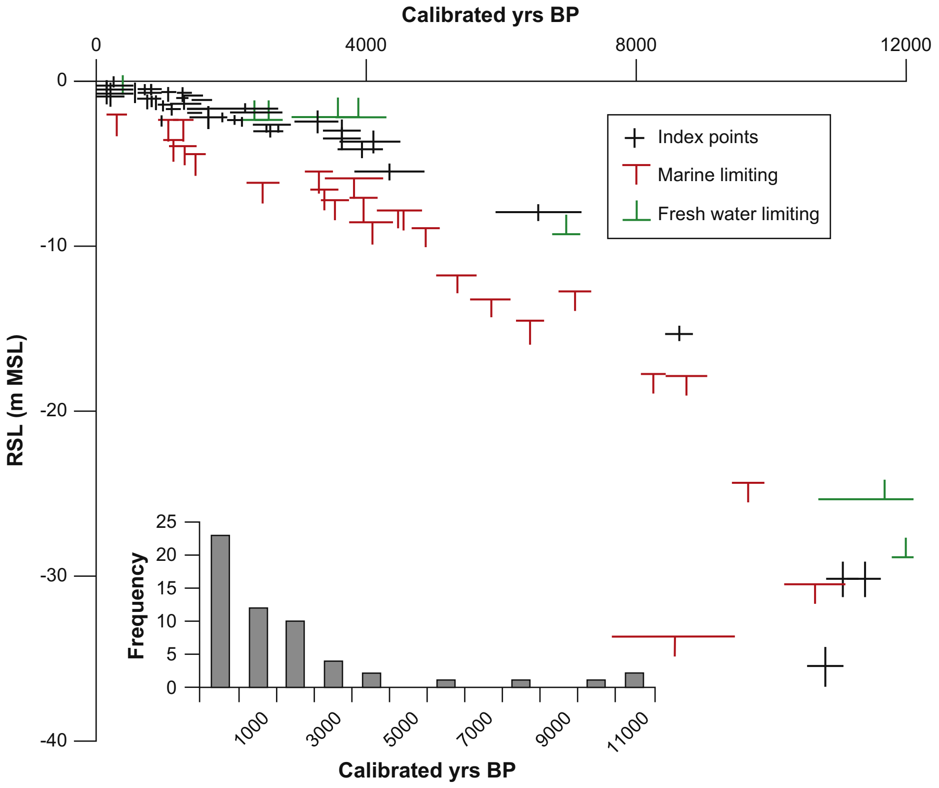

Fig. 5. (a) North Carolina relative sea-level index points and limiting data. (b) Histogram illustrates the temporal distribution of index points.

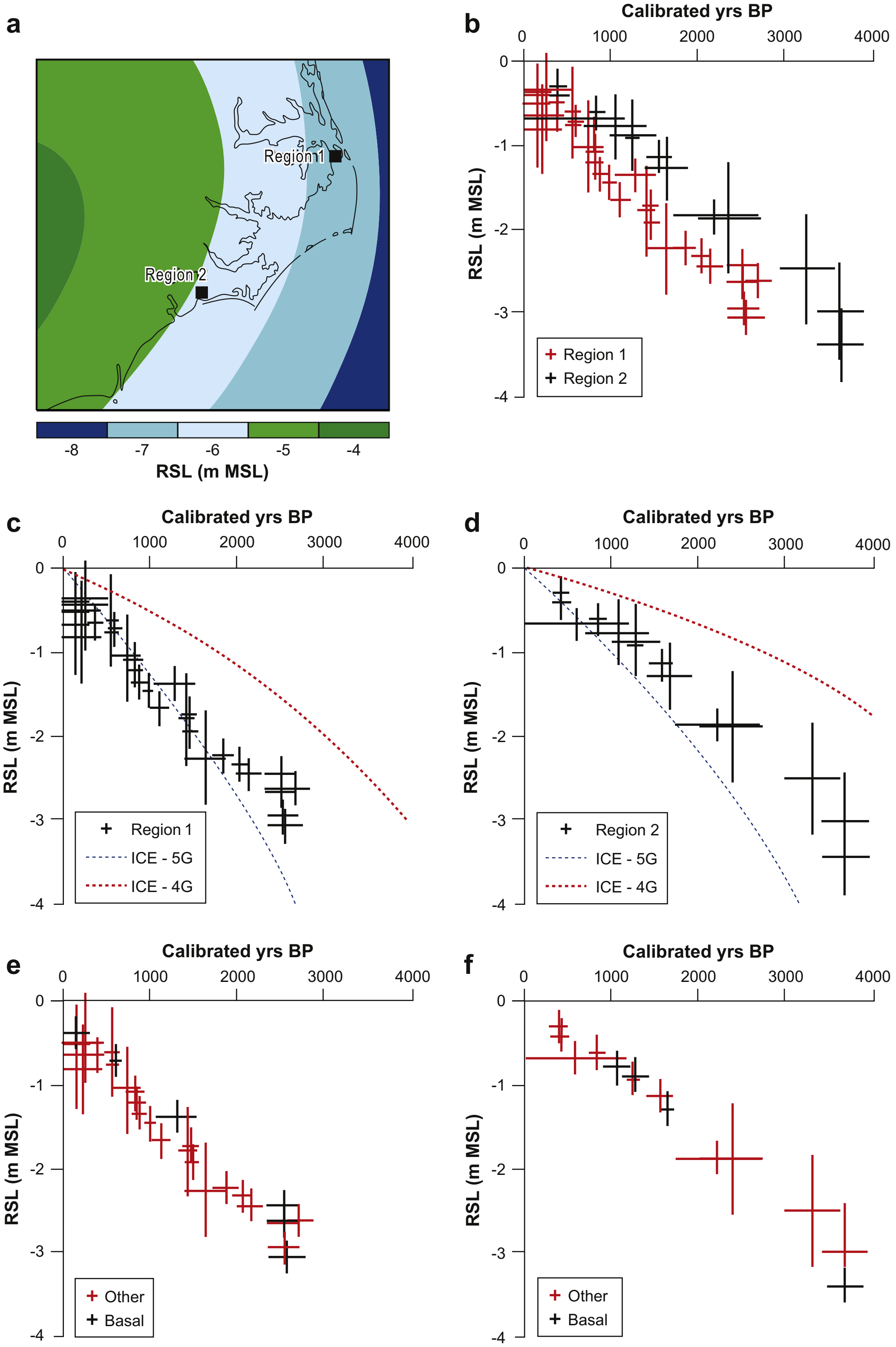

Fig. 6. (a) Map showing ICE-5G(VM2) with rotational feedback Glacial Isostatic Adjustment (GIA) model predictions of relative sea level for North Carolina at 4000 cal a BP. The location of Late Holocene predictions from the ICE-5G(VM2) for Region 1 (Albemarle, Currituck, Roanoke, Croatan, and northern Pamlico sounds) and Region 2 (southern Pamlico, Core, and Bogue sounds, and further south to Wilmington) are shown; (b) North Carolina Late Holocene relative sea-level index points from Regions 1 and 2; (c) Sea-level index points from Region 1 with ICE-5G(VM2) and ICE-4G(VM2) predictions; (d) sea-level index points from Region 2 with ICE-5G(VM2) and ICE-4G(VM2) predictions; (e) sea-level index points from Region 1 with subdivision between basal and all other index points; and (f) sea-level index points from Region 2 with subdivision between basal and all other index points.

Table 3
Mean sea-level trends for North Carolina water-level stations in mm year^{-1}.

Station number	Station name	Region	MSL trend	Period of data
8651370	Duck	1	4.27 ± 0.74	1978–2002
8652587	Oregon Inlet Marina	1	2.55 ± 1.21	1977–1980, 1994–2002
8654400	Cape Hatteras	1	3.46 ± 0.75	1978–2002
8656483	Beaufort	2	3.20 ± 0.54	1973–2002
8656590	Atlantic Beach	2	2.48 ± 1.99	1977–1983, 1998–2000
8658120	Wilmington	2	2.12 ± 0.23	1935–2002
8659084	Southport	2	2.04 ± 0.25	1933–1954, 1976–1988
8659182	Yaupon Beach	2	2.92 ± 0.77	1977–1978, 1996–1997

All results are displayed with a 95% confidence interval which is ±1.96 times the standard error.

the model's accuracy in an area proximal to the Laurentide Ice Sheet.

We must also consider the role that sediment consolidation may play in Late Holocene RSL change. Subdivision of the Late Holocene RSL data into basal and all other index points for Regions 1 and 2 (Fig. 6e,f), suggests that the influence of sediment consolidation may be minor during this time period. Most of the basal peats samples lie among those from other peats of the same age. Gehrels et al. (2002, 2006) compared Late Holocene index points of peat overlying compaction-free substrates with those from within the sedimentary packages in Iceland and the Gulf of Maine. In the former site, compaction was minimal for the past ~1900 years and the latter site showed a maximum amount of sediment consolidation of only 0.2 m. In contrast, Shennan and Horton (2002) showed an over-estimate of the rate of Late Holocene RSL rise in areas of the UK with thick sequences of Holocene sediments of 0.5–1.1 mm year^{-1}. Similarly, Törnqvist et al. (2008) found that Late Holocene compaction rates of the Mississippi Delta, primarily associated with peat, can reach 5 mm year^{-1}. These contrasting results are not wholly unexpected, and further analyses will be needed to investigate the effects of tremendous variability in the total amount and rate of porosity loss, decomposition of plant remains within sedimentary sequences, and differing land use histories (Pizzuto and Schwendt, 1997).

North Carolina has eight stations with water-level data tied to established tidal bench marks spanning a period of at least 20 years. The tide-gauge records extend as far back as 1933 for Southport, and 1935 for Wilmington. The records are good candidates for the determination of mean sea level (MSL) trends with reasonable confidence intervals to further test the ICE-5G(VM2) with rotational feedback GIA model (Zervas, 2004; Kolker and Hameed, 2007). The MSL trends range from 2.04 mm year^{-1} at Southport to 4.27 mm year^{-1} at Duck (Table 3). There appears to be a regional gradient with the trends increasing from Region 2 to Region 1; tentatively supporting the spatial variation in RSL across North Carolina. The average for all eight North Carolina stations is 2.88 mm year^{-1} (Zervas, 2004). A comparison with the Late Holocene observations implies an additional rate of mean sea-level change of c. 2 mm year^{-1}, which is in general agreement with historical tide gauge and satellite altimetry data. Tide gauge records longer than 50 years have suggested global sea-level rise to be c. 1.8 mm year^{-1} (range 1.7–2 mm year^{-1}; e.g., Peltier and Tushingham, 1989, 1991; Peltier, 1996, 2001; Douglas, 2001; Church and White, 2006).

7. Conclusions

Re-assessment of RSL records has increased our understanding of the driving mechanisms and spatially variable expression of the Holocene sea-level history for North Carolina. The data have been compared to a dynamical model of the GIA process that is currently employed to filter tide-gauge and satellite records of secular sea-level change in order to isolate the contribution to this signal due to climate warming.

We produced a RSL database consisting of 54 sea-level index points that are quantitatively related to a past tide level with error estimates, and 33 data points that provide limits on the maximum and minimum elevation of RSL. The distribution of index points is uneven and warrants a further investigation into Early and Mid Holocene sea-level observations. The current resolution of the index points and limiting data show RSL rapidly rising (c. 5 mm year^{-1}) from −35.7 ± 1.1 m MSL at 11062–10576 cal a BP to −4.2 ± 0.4 m MSL at 4240–3592 cal a BP, which is typical of an area at or beyond the margins of the Laurentide ice sheet.

We compared observations of former sea levels with predictions from the ICE-5G(VM2) with rotational feedback GIA model during the Late Holocene. The ICE-5G(VM2) differs from precursor models because a significant redistribution of the LGM ice mass was required to fit data collected since earlier models were published. The ICE-5G(VM2) has not been validated against observations along the United States Atlantic Coast. Index points younger than 4000 cal a BP illustrate a rising sea-level record due to the influence of the pro-glacial forebulge collapse predicted by the ICE-5G(VM2) model. The observational data may be explained when rotational feedback is included in the ICE-5G(VM2) model. The model suggests an increase in the rate of sea-level rise in Region 1 (Albemarle, Currituck, Roanoke, Croatan, and northern Pamlico sounds), compared to Region 2 (southern Pamlico, Core, and Bogue sounds, and farther south to Wilmington). The observations from Region 1 show Late Holocene sea level rising from −2.6 ± 0.2 m MSL at 2849–2543 cal a BP to present at 1.14 ± 0.03 mm year^{-1}. In Region 2, the observations illustrate RSL rising at 0.82 ± 0.02 mm year^{-1} from −3.4 ± 0.4 m MSL at 3905–3389. The ICE-5G(VM2) predictions capture the general trend of the observations, thus we have further supported the model's accuracy in an area proximal to the Laurentide Ice Sheet. However, there is an apparent misfit for index points older than 2000 cal a BP. It is presently unknown whether these misfits are caused by possible tectonic uplift associated with the mid-Carolina Platform High or a flaw in the GIA model. A comparison of local tide-gauge data with the Late Holocene RSL trends from Regions 1 and 2 supports the spatial variation in RSL across North Carolina, and implies an additional increase of mean sea-level rise of 2 mm year^{-1} during the latter half of the 20th century. This generally agrees with global historical tide-gauge and satellite-altimetry data.

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Appendix A. Supplemental material

Supplementary information for this manuscript can be downloaded at doi: 10.1016/j.quascirev.2009.02.002.

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