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Reconstructing Common Era Relative Sea-Level Changes on the Gulf Coast of Florida

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RECONSTRUCTING COMMON ERA RELATIVE SEA-LEVEL CHANGES ON THE
GULF COAST OF FLORIDA

BY

MATTHEW GERLACH

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
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OF
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ABSTRACT

Previous research on relative sea-level (RSL) changes in the western North Atlantic identified variations in the timing and magnitude of sea-level oscillations during the past 2,600 years. Quantifying the disparities between these records is reliant upon a robust database of sea-level reconstructions with an appropriate spatial and temporal distribution that can potentially capture a range of ice sheet melt mass balance fingerprints and ocean dynamic processes. To address an absence of high-resolution Common Era sea-level data in the southeastern US, we reconstructed ~ 1.0 m of RSL change encompassing the past $\sim 2,400$ years from the Gulf Coast of Florida. Paleomarch elevation was reconstructed using a regional foraminiferal transfer function trained on 66 modern samples. A composite chronology of radiocarbon dates and pollution and pollen markers of known age were used to build an age-depth model. The geologic reconstruction was combined with a regional set of tide gauge records to create a continuous RSL dataset from ~ 450 BCE to present day. Quantitative trends with formal uncertainties were estimated (95% credible interval) by applying the errors-in-variables integrated Gaussian process (EIV-IGP) model to the combined RSL dataset. RSL fell at a maximum rate of -1.01 mm/yr. (0.65 to -2.68 , 95% credible interval) from ~ 450 BCE to 50 BCE. The trend is consistent with a recent reconstruction of global sea-level variability derived from geological sea-level records. RSL then stabilized and began to rise ~ 0.3 mm/yr. until a change point was identified at 1270 CE (1000 CE to 1430 CE, 95% credible interval) and RSL rose ~ 0.5 mm/yr. until the late 19th century. RSL reconstructions from northern Florida and Louisiana show similar stability throughout the majority of the Common Era. This observation is in contrast to reconstructions north

of Cape Hatteras on the U.S. Atlantic coast that demonstrate positive and negative deviations from the background trend from 0 CE to 1850 CE. Our new data provides further evidence for the absence of these deviations in the records south of Cape Hatteras. This result supports suggestions that an ocean volume change is unlikely to explain them and that changes in the position and/or strength of the Gulf Stream are most likely responsible. Change point analysis reported modern rates of sea-level rise began between 1830 to 1940 CE. This observation is consistent with an overlap in change point timings (1865 to 1873 CE) identified in RSL reconstructions from northern Florida, North Carolina, New Jersey and Connecticut. RSL accelerated continuously from this inflexion until present rates of 2.27 mm/yr. (2.81 to 1.73 mm/yr.; 95% credible interval) were reached in 2014 CE. The consistent timing of this acceleration is in marked contrast to the north-south variation in previous deviations from background sea-level rise during the Common Era, suggesting a global ocean-volume change is the dominant cause.

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PREFACE

This thesis was written in manuscript format in accordance with the requirements of the Graduate School of the University of Rhode Island. The manuscript was modeled after the journal, *Marine Geology*, with the intention to submit for publication.

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**MANUSCRIPT 1: RECONSTRUCTING COMMON ERA RELATIVE SEA-
LEVEL CHANGES ON THE GULF COAST OF FLORIDA**

In preparation for submission to Marine Geology

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CHAPTER 1

INTRODUCTION

The 772 coastal counties of the United States have experienced 20th century population surges and beach-front development (e.g. Hinrichsen, 1998) that coincided with increased rates of global sea-level (GSL) rise (e.g. Church and White, 2006; 2011). In 2013, Florida's shoreline adjacent counties supported ~ 15 million inhabitants and accounted for ~ \$620 billion of the state's gross domestic product; both have increased by ~ 15% since 2005 (NOAA, 2015). It has been projected that under even the most conservative GSL rise scenarios, continued population growth in coastal zones will place millions of additional people at risk to the impacts of relative sea-level (RSL) rise through 2100 CE (Hauer et al., 2016). Such continued, unprecedented coastal expansion necessitates an enhanced understanding of the driving mechanisms of past, present and future RSL change.

Past RSL changes provide insight into the causes and likely magnitude of future changes. The instrumental record (i.e. satellite altimeters and tide gauges) is short (past ~ 150 years), fragmentary, and does not capture the pre-industrial baseline of RSL behavior. In temperate and sub-tropical regions, salt-marsh sediments provide near-continuous and high-resolution RSL reconstructions that capture positive and negative departures of sea level from a stable mean throughout the Common Era (e.g. Kemp et al., 2011b; Kopp et al., 2016). Salt-marshes track RSL rise because they vertically accrete *in-situ* peat in accommodation space linked to a consistent tidal

regime (e.g. Bloom 1964; Redfield and Rubin 1962). The resolution of such records is increased by the use of sea-level indicators (e.g. intertidal foraminifera) which allow for the quantitative estimation of paleomarch elevation (PME; altitude at which a sample was originally deposited) using a transfer function (e.g. Gehrels, 1999; Edwards et al., 2004; Horton and Edwards, 2006). When combined with instrumental records adjusted for interannual variability (e.g. Kopp et al., 2013), proxy-based RSL reconstructions quantify late Holocene (last 4000 years) sea-level trends.

Glacio-isostatic adjustment (GIA) is the primary cause of long-term RSL trends on the U.S. Atlantic coast during the Common Era (e.g. Clark et al. 1978; Farrell and Clark, 1976). Improved estimates of the GIA signal (e.g. Engelhart et al., 2011; Peltier et al., 2015, Keregar et al., 2016) and new statistical methods for removing its contribution to RSL records (e.g. Kopp et al., 2013; Cahill et al., 2015) reveal spatio-temporal sea-level variability that requires further investigation. Changes in the strength and/or position of the Gulf Stream and the fingerprint of Greenland melting cause distinct (but different) spatial patterns of sea-level variability along the Atlantic coast of North America (e.g. Engelhart and Horton, 2012; Kemp et al., 2009; 2013b; 2014; 2015). Identifying these patterns in RSL reconstructions provides a means to draw inferences about the driving mechanisms behind past sea-level changes and to reconstruct prevailing ocean circulation patterns and the configuration of land-based ice in the northern hemisphere. This goal is reliant on the availability of a meridional suite of RSL reconstructions in the western North Atlantic Ocean. However, the current distribution of high-resolution (decimeter and decadal scale) RSL

reconstructions on the U.S. Atlantic and Gulf Coasts is biased toward sites north of Cape Hatteras, NC (Gehrels, 1999; Kemp et al., 2013b; Kemp et al., 2015).

A RSL reconstruction from the Gulf Coast of Florida will extend high-resolution, near-continuous RSL data to the south and provide the additional data needed to identify the pattern and causes of regional-scale sea-level trends during climate phases such as the Roman Warm Period (RWP), Medieval Climate Anomaly (MCA) and Little Ice Age (LIA), all of which are identified in global-, hemispheric- and regional-scale temperature reconstructions (e.g. Moberg et al., 2005; Mann et al, 2008; PAGES 2k Consortium, 2013). We reconstructed ~ 2400 years of RSL change on the Gulf Coast of Florida using foraminifera preserved in a dated core of salt-marsh sediment to answer two questions: (1) did RSL depart from a stable mean prior to ~1850 CE in western Florida? and (2) can we quantify a regional RSL signal with tidal gauge records and existing RSL reconstructions in the southeastern USA? We estimate the rate of Common Era RSL rise by applying the errors-in-variables integrated Gaussian process (EIV-IGP) model to a combined RSL dataset of geological and regional tidal gauge observations. After correction for glacio-isostatic adjustment, we compare our findings to reconstructions elsewhere on the U.S. Atlantic and Gulf Coasts.

CHAPTER 2

STUDY AREA

Tampa Bay is a Y-shaped embayment located on the siliciclastic dominated west-central barrier island coast of the Florida peninsula, USA. The bay covers a water surface area of 1,036 km² with a mean depth less than 4 m (Figure 1A; Brooks and Doyle, 1998). A humid, sub-tropical climate supports an average annual air temperature of ~ 23°C and annual precipitation of ~ 125 cm/yr. The estuary lies near the center of the Jurassic-aged Florida Platform (Hine et al., 2003) overlying an Oligocene-aged karstic sub-basin that collapsed in the Mid-Miocene due to deep-dissolution of the Arcadia fm. (Hine et al., 2009). Newly formed folds, warps and slags produced accommodation space for sediment infill associated with cyclical variations in GMSL since the late-Miocene (e.g. “Siliciclastic Invasion”; Hine, 1997). A variety of paleoenvironments has been identified in the sediment record of the area now occupied by Tampa Bay ranging from relatively low-energy deposition dominated carbonate sediments (mid-Miocene age), to higher energy, siliciclastic fluvio-deltaic deposition of late Miocene to Pliocene sediments, to conditions dominated by marine processes (ebb-tidal delta formation, long shore transport) that reworked spatially mixed carbonate-siliciclastic sediments during the Pleistocene and Holocene (Duncan et al., 2003; Yates et al., 2011). Significant anthropogenic alteration, including dredge and fill, removal of wetlands and groundwater withdrawal associated with the urbanization of the communities surrounding Tampa Bay has

caused degradation of the hydrological and ecological systems within the estuary (Yates et al., 2011).

We investigated the stratigraphy underlying numerous salt marshes throughout the Tampa Bay estuary. The region's thickest and most complete sequences of salt-marsh peat were discovered within the Little Manatee River, a tidal-river estuarine occupying a 575 km² watershed throughout Hillsborough County, Florida (Figure 1A). The river flows ~ 65 km westward from its headwaters to its discharge point in southern Tampa Bay near Ruskin, Florida. Approximately 6 km from the discharge point, Mill Bayou is a 0.065 km² tract of wetland within a meander of the Little Manatee River (Figure 1B). This low-energy, brackish transitional zone features salt-marsh vegetation and mangrove forest growth, typical of tidally influenced rivers in the sub-tropical climate of west-central Florida (FWS, 1999). Northward migration of mangrove forests due to less frequent and extreme winter events has caused salt-marsh loss throughout southern Florida (e.g. Osland et al., 2013; Saintilan et al., 2013). A similar transition was observed at Mill Bayou as red mangrove (*Rhizophora mangle*) trees line the perimeter and tidal inlets of the salt-marsh platform, occupying areas at or around mean tide level (MTL) in the intertidal zone. The salt-marsh platform supports peat forming vegetation at a narrow range of elevations within the tidal frame (MTL to mean higher high water, MHHW), including mono-specific stands of *Juncus roemerianus* (black needle rush) and few mixed-stands of *Juncus roemerianus* and *Achrostichum aureum* (golden leather fern). Upland is largely absent from the Mill Bayou salt-marsh system. Water quality testing completed by the Florida Department of Environmental Protection since 2007 shows that close to the coring site, the Little

Manatee River has a salinity of 18‰. The mixed semi-diurnal tidal regime of the Little Manatee River has a great diurnal tidal range (i.e. mean lower low water, MLLW, to mean higher high water, MHHW) of 0.61 m at the NOAA tidal station (Figure 1A) adjacent to the coring site at Mill Bayou (NOAA Station 8726436). Additional tidal gauges located throughout the Gulf Coast of Florida provide information on historic RSL since 1913 CE for comparison to geologic-based RSL data. Historic data are archived at the Permanent Service for Mean Sea Level (PSMSL; e.g. St. Petersburg: PSMSL Station 520; Naples: PSMSL Station 1107; Fort Myers: PSMSL Station 1106).

Core MB9 from Mill Bayou was selected for analysis because it included thickest (~ 1.0 m), most complete accumulation of salt-marsh peat with abundant and *in-situ* salt-marsh plant macrofossils (*Juncus roemerianus*; Figure 1C) Underlying the salt-marsh peat of MB9 was 0.25 m of an organic silt that had sparse *Juncus roemerianus* macrofossils and became less organic with depth. Core MB9 had the smallest accumulation of this organic silt unit, offering a more complete *Juncus* peat accumulation than other cores in Mill Bayou. At the base of recovery was a sand unit serving as the basis for the salt marsh platform.

Figure 1. (A) Location of the Tampa Bay estuary on the southwestern coast of Florida. (B) Location map of the coring transect (X-X') and tidal benchmark (star) within the Mill Bayou study site. (C) Stratigraphic cross-section of coring transect X-X' in Mill Bayou. Core MB9 (bold) was selected for detailed analysis and collected using a Russian hand corer.

CHAPTER 3

METHODS

3.1 CORE SITE SELECTION

We determined the stratigraphy of Mill Bayou by describing 12 gouge cores along two transects. Each core was described in the field using the Troels-Smith (1955) system. The stratigraphy of Mill Bayou was plotted in cross-sectional view (post-survey) to extrapolate the underlying sedimentary sequences. Based on this comparison, we chose core MB9 for analysis because it included the thickest (~ 1.0 m), continuous accumulation of salt-marsh peat with abundant and in-situ salt-marsh plant macrofossils (*Juncus roemerianus*; Figure 1C). Replicates of MB9 were collected using a hand-operated Russian coring device (Jowsey, 1966) to prevent compaction during extrusion, secured in rigid pipe sections with plastic wrap and placed in refrigeration to preserve the sediment record for future laboratory analysis. Altitude (standardized to North American Vertical Datum of 1998 (NAVD 88) post-survey) and GPS coordinates were taken with a Leica GS15 global navigation satellite system (GNSS) system, utilizing a base and rover. Measurements from each core were tied to a local tidal benchmark (NOAA Benchmark: 872 6436 A 1977) with a known elevation expressed relative to NAVD 88. Orthogonal heights were converted to tidal altitudes using previously established relationships between orthometric and tidal datums.

3.2 DEVELOPING A CHRONOLOGY

The accumulation history of Core MB9 was constrained by radiocarbon dating and recognition of historic pollen, ^{137}Cs and pollution markers of known age. In-situ *Juncus roemerianus* macrofossils (i.e. stems and rhizomes) were separated from the sediment matrix throughout the entirety of Core MB9. We selected samples for further preparation by balancing macrofossil quality (i.e. most representative of the depositional environment) with even spacing down core and through depositional time. The chosen samples were cleaned under a binocular microscope to remove any younger in-growing rootlets and older sediment. These macrofossils are accurate indicators of paleo-marsh surfaces because of their close proximity to the surface and their short lifespan (Eleuterius, 1975; Eleuterius 1976). Samples were oven dried for 24 hours (50 °C), weighed and then sent to the National Ocean Science Accelerator Mass Spectrometer (NOSAMS) laboratory at Woods Hole Oceanographic Institute for dating. Each sample underwent standard acid-base-acid pretreatment at NOSAMS.

A plateau on the radiocarbon calibration curve inhibits precisely dating material younger than ~ 300 years. To decipher the recent accumulation history of Core MB9, we therefore identified down-core changes in pollen percent abundance linked to horizons of known environmental change and pollution horizons from changes in the measured activity of ^{137}Cs and elemental concentrations of As and Pb.

Palynomorphs (pollen and fern spores) were isolated from 1-cm thick core samples using standard palynological preparation techniques (Traverse, 2007). To determine palynomorph concentration (grains/g), one tablet of *Lycopodium* spores was

added to 0.5–1.5 g of dry sediment. Samples were treated with HCl to remove carbonates and HF to remove silicates, acetolyzed (1 part H₂SO₄ : 9 parts of acetic anhydride) in a boiling water bath for 10 minutes, neutralized, and treated with 10% KOH for 10 minutes in a 70 °C water bath. After neutralization, the coarse and clay fractions were removed by sieving with 149 µm and 10 µm nylon mesh. Samples were swirled in a watch glass to remove mineral matter as necessary. After staining with Bismarck Brown, palynomorph residues were mounted on microscope slides in glycerin jelly. At least 300 pollen grains and spores were counted from each sample to determine relative abundance.

Prior to elemental analysis by mass spectrometry, the upper 35 cm of Core MB9 was cut into 1-cm thick sections, ground to a fine, homogenized powder and sent to the SGS Mineral Services Canada laboratory for analysis. A 0.25 g subsample of the homogenized powder for each interval was digested in a 2:1 HNO₃/HCl mixed concentrated acid attack. Elemental determinations of As and Pb were made using an ICP-OES instrument (Perkin Elmer Optima Dual View). The instrument was calibrated with multi-element chemical standards of varying concentration to cover the expected range in the sample. The calibration was validated by running additional standards obtained from a separate source to those used in calibration through the same analytical procedure as samples as an additional check. Detection limits (< 3 mg/kg for As; < 2 mg/kg for Pb) were calculated as the 3σ uncertainty of total procedural blanks.

Measurements and interpretations of ¹³⁷Cs isotopic activity were conducted as described by Smoak et al. (2013) and Breithaupt et al. (2014). Prior to analysis, the

upper 15 cm of Core MB9 was sectioned into 1-cm thick intervals, freeze-dried, homogenized and packed in gamma counting tubes for a 21-day equilibration period. Gamma activities were measured at the 661.7 KeV peak using a Small Anode Germanium (SAGE) well detector coupled to a multi-channel analyzer. ^{137}Cs activity was calculated by multiplying the counts per minute by a factor that includes the gamma-ray intensity and detector efficiency determined from standard calibration. Identical geometry were used for all samples.

All the results of our chronological investigation were compiled in *Bchron* (Haslett and Parnell, 2008; Parnell et al., 2008) to produce an age-depth model of the accumulation history of Core MB9. The resulting suite of chronologies is summarized by *Bchron* to estimate sample ages with a 95% uncertainty interval. Chronohorizons established from pollen, ^{137}Cs and pollution markers were treated as having uniform probability distributions, and no weighting was applied to any of the age estimates. We used standard model parameters.

3.3 BUILDING A MODERN TRAINING SET

Foraminifera are commonly employed as sea-level indicators because their distribution is intrinsically related to the frequency and duration of tidal inundation (e.g. Scott and Medioli, 1978; 1980) allowing the analogy between modern surface samples and their associated tidal altitude to be used to estimate PME from fossiliferous counterparts (e.g. Kemp and Telford, 2015). A modern training set was developed by collecting 66 modern surface samples. The modern samples were

collected at regular altitudinal changes from transects across the existing elevational and environmental gradients of seven distinct salt marshes in the Tampa Bay and Charlotte Harbor estuaries. These locations are representative of the ecological and geomorphological spectrum of tidal marshes on the central Gulf Coast of Florida. This sampling regime ensured that a wide array of modern analogues were captured so the modern dataset is representative of any small-scale environmental changes due to natural variability over the Common Era. At each site, 10 cm³ of sediment was taken from an undisturbed area of the marsh surface (0-1 cm) and placed in a plastic vial with 10 cm³ of a Rose Bengal and buffered ethanol mixture to allow differentiation of live and dead specimens (Walton, 1952; Bowser and Murray, 2000). Altitude (standardized to NAVD 88 post-survey) and GPS coordinates were taken with a Leica GS15 GNSS system, utilizing a base and rover. These measurements were tied to a local tidal benchmark with a known elevation expressed relative to NAVD 88. Orthogonal heights were converted to tidal altitudes using previously established relationships between orthometric and tidal datums. All the marshes had similar tidal ranges (~ 0.6 m) eliminating the need to standardize water levels between sites.

3.4 RECONSTRUCTING RSL

Foraminiferal analysis followed Horton and Edwards (2006). Modern foraminiferal samples were sieved through a 500- and 63 µm nylon mesh, retaining the fraction between them after discarding material larger than 500 µm if no large foraminiferal tests were present. The remaining material was counted wet underneath

a binocular microscope to prevent drying of organic residue which may result in consolidation, or “pancaking” of tests (de Rijk, 1995). A total of at least 100 dead individuals was enumerated in each well-mixed sample to ensure a statistically sound representation of the total assemblage at the time of collection (Fatela and Tarboda, 2002; Kemp et al., 2013b). Fossiliferous samples were prepared and analyzed in a manner similar to their modern counterparts. At least 100 individuals were counted in 1-cm intervals from the fossil core at a 3-cm resolution. Additional fossil samples were counted at stratigraphic contacts and intervals where chronohorizons were identified.

We analyzed the modern training set using detrended correspondence analysis (DCA) in *vegan* 2.3-5 (Oksanen et al., 2016) to determine the length of the modern dataset’s environmental gradient, a metric used to decide whether a statistical technique underpinned by a linear or unimodal probability distribution is appropriate (e.g. Kemp and Telford, 2015). Based on a gradient length of 2.6947 standard deviations, we developed a transfer function using weighted averaging, partial least squares (WA-PLS) in the statistical software package “C2” to statistically model the relationship between modern foraminifera and tidal elevation. WA-PLS was used because it is a simple, robust and frequently used approach for dealing with unimodal species-environmental responses (Birks, 2010). Transfer function performance was assessed using cross-validated (10,000 bootstrapping cycles) estimates of root mean squared error of prediction (RMSEP) and correlation between observed and predicted values (r^2_{boot}). We followed the guidelines proposed by Barlow et al., (2013) and

selected component two of the transfer function based on a ~ 5% increase in measured RMSEP from component one.

The WA-PLS transfer function was applied to samples within Core MB9 where foraminifera had been enumerated to determine PME with a sample-specific 1σ estimate of uncertainty (i.e. indicative range; Horton and Edwards, 2006; Kemp and Telford, 2015). Relative sea level was reconstructed from Core MB9 by using the equation:

$$RSL_i = A_i - PME_i. (1)$$

where A_i and PME_i are the altitude and PME of sample i , expressed relative to mean high water respectively. A_i was established by subtracting the depth of each sample in the core from the measured core-top altitude. For a modern (surface) sample, the terms A_i and PME_i are equal, thus RSL is zero. Each interval in core MB9 that has a reconstructed PME was assigned an age estimate from the age-depth model with an associated uncertainty (2σ).

3.5 RSL Trends

Annual tide gauge measurements from Fort Myers, Key West, Naples and St. Petersburg, Florida (Figure 2) were averaged to produce a regional instrumental RSL record. Decadal-scale averages relative to the 2000-2009 CE time period were used to encompass a similar temporal resolution to reconstructed RSL. Vertical uncertainty was estimated by calculating the standard deviation across the tide gauges and averaging them by decade for 1913-2015 CE. A vertical uncertainty (1σ) of ± 0.022 m

was applied to each decadal data point along with an age uncertainty of ± 5 years (1913-1919 was given an age error of ± 4 years; 2010-2015 was assigned an age error of ± 2 years). The regional tide gauge record was combined with the RSL reconstruction to produce a single sea-level dataset for the Gulf Coast of Florida.

Quantitative RSL trends with formal uncertainties were estimated by following the Cahill et al., (2015) approach to apply an error-in-variables integrated Gaussian (EIV-GP) model to the combined RSL dataset from the Gulf Coast of Florida. This method captures the continuous and dynamic evolution of RSL change with full consideration of many sources of uncertainty and resolves the discrepancy between the exploratory variable (sample age) being uncertain when it is assumed to be fixed and known in standard regression (Cahill et al., 2015). We also used change point analysis to provide a best estimate of when modern rates of sea-level rise began following the approach described in Kemp et al., (2013b).

Figure 2. Location map of the Fort Myers, Key West, Naples and St. Petersburg tidal gauges used to create a combined instrumental record spanning the time period since 1913 CE.

CHAPTER 4

RESULTS

4.1 MODERN DISTRIBUTION OF FORAMINIFERA

We identified 12 agglutinated taxa of foraminifera in the dead assemblage of 66 modern surface samples from seven salt marshes in the Tampa Bay and Charlotte Harbor estuaries (Figure 3). Foraminiferal data were grouped utilizing the partitioning around medoids (PAM) method (Kaufman and Rousseeuw, 1990; Kemp et al., 2012) using the ‘cluster’ package in *R* (Maechler et al., 2012). This approach identified four faunal clusters as the best fit to our modern data based on the highest average silhouette width (0.3451) identified in two to twenty groupings. Cluster one occurred between -0.45 to -0.35 m MHW and was dominated by *Ammobaculites* spp. (average 88% of individuals) in two modern samples from the Sand Point (SP) transect. Cluster two was comprised of five samples from the Long Island (LI) transect, three samples from the Long Island Boat (LIB) transect, eleven samples from Little Manatee River (LMR) transect, and one sample each from the South Drift Island (SDI) and Long Island Peninsula (LIP) transects. Surface samples from these locations occurred between -0.25 to 0.06 m MHW and had an approximately equal distribution of *Ammonia* spp., *Miliammina fusca*, *Arrenoporella mexicana* and *Ammobaculites* spp. (average 87% individuals). Cluster three identified samples dominated by *A. inepta*, *A. mexicana* and *Haplophragmoides wilberti* (average 74% individuals)

between elevations of -0.17 to 0.16 m MHW. This group had ten samples from the Harbor Heights (HH) transect, eight from the Drift Island (DI) transect, four from the LI transect, two from the SP transect and one sample each from the SDI, LMR and LIP transects. *A. mexicana* was the most commonly identified taxa in Cluster Four. This faunal group occurred between elevations of -0.12 to 0.13 m MHW and was formed from seven samples from the LIP transect and three samples from each of the LI, SP and SDI transects.

Figure 3. Relative abundances of dead foraminifera from the regional Gulf Coast of Florida modern training set. Samples are grouped into four clusters identified by Partitioning Around Medoids (PAM).

4.2 CHRONOLOGY

Seventeen radiocarbon dates (Table 1) demonstrate that Core MB9 offers a continual archive of RSL change since ~ 300 BCE. Measurements of ^{137}Cs activity, As and Pb concentration and changes in pollen abundance are correlated with historical events including above-ground testing of nuclear weapons, industrial production records and introduction of the exotic plant species *Casuarina equisetifolia*. Each age marker was assigned an age and a depth error. The age error accounted for both the uncertainty in identifying a specific date in historical records and the lag between emission and deposition. The depth error recognizes that horizons could be associated with multiple, adjacent depths in the core. We assumed that industrial emissions were transported to Mill Bayou by consistent prevailing winds and atmospherically deposited on the salt-marsh surface within a few years (Graney et al., 1995) and without further isotopic fractionation (Ault et al., 1970). Trends rather than absolute ages were utilized because emissions rates per unit of production may have changed through time. The onset and peak of ^{137}Cs activity (Figure 4C) linked to the above-ground testing of nuclear weapons was identified and assigned an age of 1954 CE $\pm$ 1 yr. and 1963 CE $\pm$ 1 yr. respectively. Historic As pollution (Figure 4B) was correlated with the onset (1955 CE $\pm$ 5 yrs) of organic arsenical herbicide use in Florida (Whitmore et al., 2008; Escobar et al., 2013). Historic Pb pollution (Figure 4A) was linked to the onset (1930 CE $\pm$ 5 yrs.) and the maximum (1974 CE $\pm$ 5 yrs.) of leaded gasoline use (e.g. USGS, 1998). Changes in pollen percent abundance provided an environmental marker of 1905 CE $\pm$ 5 yrs. (Figure 4D) based on the introduction of

Casuarina equisetifolia at the turn of the 20th century (e.g. Alexander and Crook, 1974; Morton, 1980). All radiocarbon dates and marker horizons were used to develop an age-depth model (Figure 5) for Core MB9 using *Bchron* (Haslett and Parnell, 2008). The model generated an age-estimate (with 95% confidence interval) for each 1-cm thick interval throughout the core with an average uncertainty of ± 68 yrs. for all intervals.

Depth in core (cm)	NOSAMS lab number	Dated material	Age(¹⁴ C years)	Error(¹⁴ C years)	δ ¹³ C (‰, PDB)
20	OS-12298	Wood	175	25	-25.77
37	OS-123299	Wood	400	20	-25.33
42.5	OS-117078	<i>Juncus roemerianus</i> stem	315	15	-26.87
45.5	OS-120430	<i>Juncus roemerianus</i> stem	350	15	-27.25
49	OS-117077	<i>Juncus roemerianus</i> stem	210	20	-26.64
53	OS-122169	Wood	500	15	-26.54
55	OS-122170	Wood	320	15	-25.92
63	OS-120321	<i>Juncus roemerianus</i> stem	1,620	15	-20.83
65	OS-122171	Wood	630	20	-25.92
74	OS-122172	Wood	1,140	15	-26.24
80	OS-122173	Wood	1,240	20	-24.53
80	OS-123300	Wood	1840	20	-26.83
82	OS-117076	<i>Juncus roemerianus</i> stem	1090	15	-28.22
87	OS-123301	Wood	885	25	-26.19
95	OS-122174	Wood	730	20	-25.39
98	OS-123336	Wood	2170	20	-27.91
100	OS-117075	<i>Juncus roemerianus</i> stem	2150	20	-25.85
106.5	OS-120368	<i>Juncus roemerianus</i> stem	2,140	15	-28.02
110	OS-122175	Wood	2120	20	-27.54
120	OS-116955	<i>Juncus roemerianus</i> stem	2100	20	-28.41
120	OS-120322	<i>Juncus roemerianus</i> stem	2,180	15	-27.46

Table 1. Radiocarbon ages from Mill Bayou reported by the National Ocean Sciences Accelerator Mass Spectrometry facility. Reported δ¹³C values are from an aliquot of CO₂ collected during sample combustion.

Figure 4. Down-core profile of (A) Pb concentration (B) As concentration (C) Cs^{137} activity and (D) *Casuarina equisetifolia* abundance from Core MB9. The shaded intervals represents the vertical position of the identified marker with the assigned year (CE) listed beside it.

Figure 5. Age-depth model developed for core MB9. The shaded blue envelope is the 95% credible interval. Calibrated radiocarbon dates represent the probability distribution associated with ages. Inset shows detailed chronology for the last ~ 300 years.

4.3 RECONSTRUCTING PALEOMARSH ELEVATION

PME was estimated using foraminifera enumerated from 74 evenly spaced samples throughout core MB9 (Figure 6). From 124 cm to 108 cm in depth, foraminiferal assemblages from an organic silt unit were dominated by *Ammobaculites* spp. and *M. fusca* (average 67% of individuals). A transition to an assemblage composed primarily of *A. inepta* and *A. mexicana* occurred at 108 cm to 100 cm in depth. This change is associated with a lithologic switch from organic silt to *Juncus roemerianus* peat in the same interval. *A. inepta* and *A. mexicana* remain highly abundant to 85 cm with the addition of *H. wilberti* to form an assemblage dominant at 85 cm to the top of the core (average 89% of individuals). An interval between 59 cm and 48 cm below the core top had increased abundances of *Ammobaculites* spp. and *M. fusca* (average 20% of individuals). To identify samples lacking a modern analogue, dissimilarity between populations of foraminifera preserved in core samples and their modern counterparts was measured using the Bray-Curtis metric (e.g. Kemp and Telford, 2015). The distance between five samples and their closest modern analogue exceeded the 20th percentile of dissimilarity measured among all pairings of modern samples and these samples were excluded from further analysis. We retained all other samples in the RSL reconstruction.

Application of the WA-PLS transfer function provided PME estimates (Figure 7) ranging from -0.34 m to 0.04 m MHW with sample-specific uncertainties ($\sim 1\sigma$) of ± 0.06 m to ± 0.08 m, equivalent to ~ 10 -15 % of the great diurnal tidal range at Mill Bayou. We chose component two of the transfer function (Table 2) because of a ~ 5 %

increase in measured Root Mean Squared Error of Prediction (RMSEP). Estimates of PME consistently increased from the lowest value at the base of recovery (-0.34 m MHW) to -0.10 m MHW at 108 cm in depth. PME values from this depth to the top of Core MB9 generally remained within ± 0.05 m of MHW, except for an interval from 58 cm to 48 cm where the lowest estimates of PME in the top 108 cm of core MB9 (~ -0.10 m MHW) were found. This interval correlates with increased abundances of low marsh foraminiferal species (e.g. *M. fusca*, *Ammobaculites spp.*) found at similar depths.

Figure 6. Relative abundances of the dead benthic foraminifera found in Core MB9.

Paleommarsh Elevation

Figure 7. Paleommarsh elevation (PME) reconstructed using the WA-PLS transfer function. Circles represent mid points and error bars are the sample-specific uncertainty estimated by bootstrapping.

ID	Component 1	Component 2	Component 3	Component 4	Component 5
RMSEP	0.069371	0.066151	0.066968	0.07077	0.07691
r^2_{boot}	0.61765	0.67446	0.68217	0.68159	0.67338
% change r^2_{boot}	N/A	-8.4203	-1.13022	0.08095	-1.21922
% change RMSEP	N/A	4.6414	-1.2346	-5.677	-8.676

Table 2. Performance of the WA-PLS transfer function

4.4 RECONSTRUCTING RELATIVE SEA LEVEL

RSL was reconstructed by subtracting estimated PME from the measured altitude of each sample in Core MB9. A corresponding age with a unique 95% temporal uncertainty was assigned to each interval from the age-depth model (Figure 8). RSL at Mill Bayou was ~ -1.00 m at 350 BCE and rose to ~ -0.10 m at 2001 CE. Annual tide gauge measurements from four locations on Florida's Gulf Coast (Figure 9) show similar trends and variations in 20th century RSL behavior, justifying the creation of a combined instrumental record (Note: Key West is the only location that recorded RSL change from 1913-1947 CE). We produced decadal averages of the tide gauge data (referenced to the 2000-2009 CE average), and compared with the RSL reconstruction (Figure 10). The instrumental record lies within the uncertainties of the proxy-based reconstruction demonstrating the accuracy of our RSL reconstruction and allowing the two records to be fused to quantify Common Era sea-level change on the Gulf Coast of Florida. Application of the EIV-GP model (Figure 11) to the combined dataset shows RSL was falling at a maximum rate of ~ -1.01 mm/yr. (0.65 to -2.68, 95% credible interval) at ~ 450 BCE, before stabilizing at ~ 50 BCE and rising ~ 0.3 mm/yr. until ~ 1000 CE. RSL continued rising, but at an increased rate of ~ 0.5 mm/yr. to ~ 1600 CE, and then accelerated consistently until a rate of 2.27 mm/yr. (2.81 to 1.73 mm/yr.; 95% credible interval) was reached in 2014 CE. Change Point analysis performed on the combined proxy and instrumental dataset revealed two inflexion points in RSL change (95% credible intervals). The first is associated with a slight acceleration in RSL rise occurred between 1000 CE and 1430 CE. The second

identified a sharp acceleration in the onset of modern rates of RSL rise began between 1830 CE and 1940 CE.

Figure 8. Relative sea level (RSL) reconstructed from Mill Bayou. Each box represents a single datapoint with vertical and temporal uncertainty from the transfer function and age-depth

Figure 9. Annual tide-gauge measurements from four locations along the Gulf Coast of Florida referenced to the 2000-2009 CE average.

Figure 10. Relative sea level (RSL) reconstructed from Mill Bayou. Each box represents a single data point with vertical and temporal uncertainty from the transfer function and age-depth model respectively. The average tide-gauge record is expressed with respect to the 2013 CE average to ensure that it can be compared directly to the RSL reconstruction.

Figure 11. (A) Errors-in-variables integrated Gaussian process (EIV-IGP) model fitted to the combined Gulf Coast of Florida regional relative sea level (RSL) dataset. (B) Rate of relative sea-level change estimated by the EIV-IGP model.

CHAPTER 5

DISCUSSION

5.1 MODERN FORAMINIFERA

We used PAM to quantitatively sub-divide 66 modern samples of foraminifera from the Charlotte Harbor and Tampa Bay estuaries into four faunal groupings (Figure 3). PAM identified that clusters two, three and four shared a common elevational range (-0.12 to 0.06 m MHW), while cluster one had just two samples found at the lowest elevations in the modern training set. These observations are likely a reflection of the morphology of the intertidal zone found throughout the Tampa Bay and Charlotte Harbor estuaries. Salt marshes from these regions are formed on remnant karstic features that have often been infilled by siliciclastic material (e.g. Hine et al., 2009). They occur as expansive platforms with minimal topographic relief outside of a step change in elevation to the tidal creek environment. Low marsh and upland floral zones are largely missing from these environments. These conditions are likely to have persisted through time because of the geological control on the marsh geomorphology (e.g. Hine and Belknap, 1986; Rupert 1990).

Cluster one is composed of two samples from the SP transect at the lowest tidal elevations (-0.45 m to -0.36 m MHW); the elevation range of this cluster does not overlap with any others. These two samples were dominated by *Ammobaculites* spp. (average 88% individuals) and occurred in the tidal flat environment. The dominance

of *Ammobaculites spp.* in the tidal flat is consistent with observations from New Jersey (e.g. Kemp et al., 2012) and North Carolina (e.g. Horton and Culver, 2008; Kemp et al., 2009).

Cluster two spanned elevations from -0.25 to 0.06 m MHW, but the majority of the samples occurred below MHW (15 of 21). The samples exhibit an approximately equal distribution of *Ammobaculites spp.*, *M. fusca*, *A. mexicana* and *A. inepta*. *Ammobaculites spp.* and *M. fusca* are found in the highest abundances at the lowest elevations and taper off above MHW. The occurrence of these two species have often been used to sub-divide low-marsh zones below MHW (e.g. Scott, 1976; Scott and Medioli, 1978, Spencer, 2000). *A. mexicana* and *A. inepta* are generally well distributed throughout the entire cluster. *A. mexicana* (e.g. Hippensteel et al., 2000; Horton and Culver, 2008) and *A. inepta* (e.g. Kemp et al., 2009; 2013) have both been frequently identified in the middle marsh environment. However, *A. inepta* has also been observed in the highest marsh environments of northern Florida at sites with low salinities (Kemp et al., 2014). This cluster contains almost the entire distribution of samples from the LMR transect (11 of 12 samples), found upstream of the Tampa Bay estuary in a small tidal creek. However, assemblages from the LMR and other transects in this cluster do not vary substantially.

H. wilberti, *A. mexicana* and *A. inepta* are the three most commonly identified taxa in the 27 samples of cluster three. This cluster captures the highest elevation (0.16 m MHW) found in the modern training set and is predominately composed of samples above MHW (18 of 27). *A. inepta* and *A. Mexicana* are found in consistent abundances throughout all samples of this cluster. However, *H. wilberti* is found in high

abundances ($> 40\%$) in samples from both the highest (0.16 m and 0.06 m MHW) and lowest elevations (-0.13 m MHW) of the cluster. This taxon is also found in abundances of $< 10\%$ in many samples throughout this cluster. *H. wilberti* has been identified at the highest tidal elevations above MHW (e.g. Kemp et al., 2009; Hawkes et al., 2010) but is also a frequent middle marsh occupant (e.g. Gehrels and van de Plassche, 1999; Engelhart et al., 2013). Multiple transects (e.g. LMR, LI, HH) show widespread variation in the distribution of this taxon. Two samples from the Harbor Heights transect demonstrate this variability where a < 0.01 m difference in elevation (i.e. HH 9 and HH 2) is associated with a respective decline in abundance from $\sim 40\%$ to 10% , respectively. Patchiness in foraminiferal distributions from the middle marsh has previously been identified in *J. roemerianus* marshes in North Carolina (Kemp et al., 2011).

A. mexicana was the most commonly identified taxon (average 48% of individuals) in the 16 samples of cluster four. This cluster had an approximately equal distribution of samples both above and below MHW (-0.13 m to 0.13 m MHW). The high abundances of *A. mexicana* found throughout this cluster suggest its ability to thrive in this elevational range (e.g. Hippensteel, 2002; Kemp et al., 2009). Three samples from the SDI transect showed elevated abundances of *A. inepta* ($> 20\%$) which correlated with the three lowest abundances ($\sim 35\%$) of *A. mexicana* found in cluster four.

5.2 ESTIMATION AND REMOVAL OF THE GLACIO-ISOTATIC ADJUSTMENT (GIA) SIGNAL

It is widely accepted that Common Era RSL changes on the U.S. Atlantic and Gulf Coasts are primarily driven by continental-scale GIA (e.g. Engelhart et al., 2012; Yu et al., 2012). Earth-ice models (e.g. Peltier, 2004), existing RSL data (e.g. Engelhart et al., 2009) and GPS data (e.g. Karegar et al., 2016) demonstrate that the amount of GIA varies systematically with distance from the former center of the Laurentide ice sheet. Removal of the GIA signal from high-resolution RSL records standardizes the datasets for identification of sea-level trends and/or anomalies that deviate from the millennial-scale trends. On the centennial scale, this adjustment highlights similarities and differences in the positive and negative departures of sea-level from the Common Era background (e.g. Kemp et al., 2015).

We removed 0.3 mm/yr. of GIA from our RSL reconstruction using the EIV-IGP model to account for the covariance of age and vertical uncertainties introduced by this adjustment (Figure 12; Cahill et al., 2015). We assumed a constant rate of GIA over the duration of the reconstruction, as this period is short relative to the adjustment time of the solid Earth to deglaciation (e.g. Farrell and Clark 1976; Peltier, 1998). Our estimate was based on the GIA contributions from existing RSL data from northern Florida (0.41 mm/yr.; Kemp et al., 2014) and Louisiana (0.45 mm/yr.; Yu et al., 2012), and an estimate of GIA driven RSL change (0.4 mm/yr.) from the ICE6G-VM5a model (Argus and Peltier, 2014; Peltier 2014). This rate was chosen to allow a buffer of 0.1 mm/yr. for processes that may counteract GIA (e.g. uplift from karstification of

the Florida platform; Adams et al., 2010), while also conforming to the existing spatial distribution of GIA rates along the western North Atlantic (e.g. Kemp et al., 2014). Our identified GIA trend is also consistent with the average rates of RSL change over the entire record obtained from core MB9 (0.38 mm/yr.).

Application of the EIV-IGP model to the detrended data reveals RSL departed both positively and negatively from the background rate of rise over our 2,400 year record (Figure 12). Sea level was falling at a maximum rate of -1.25 mm/yr. (0.64 to -3.15 mm/yr.; 95% credible interval) at ~ 450 BCE before stabilizing at ~ 0 CE and rising ~ 0.05 mm/yr. until ~ 350 CE. Sea level subsequently decelerated and began to fall to a maximum rate of -0.21 mm/yr. (0.10 to -0.61 mm/yr.; 95% credible interval) at ~ 700 CE before returning to a stable mean at 1000 CE. Rates of sea-level change consistently accelerated until the current rate of 1.95 mm/yr. (2.49 to 1.41 mm/yr., 95% credible interval) was reached in 2013 CE. This is the fastest century-scale sea-level rise recorded over the ~ 2,400 year period covered by this record.

We used the EIV-IGP and change point models (Figure 13) provided by Kemp et al. (2015) to compare our new detrended dataset to the records from northern Florida (Kemp et al., 2014), North Carolina (Kemp et al., 2011), New Jersey (Kemp et al., 2013) and Connecticut (Kemp et al., 2015). These sites (including Little Manatee River) span a latitudinal gradient from 42° N to 27° N along the U.S. Atlantic coast. Further, we used the GIA-subsidence estimates of 0.45 mm/yr. from Yu et al. (2012) to make inferences on the sea-level history of a high-resolution dataset from Louisiana (Gonzalez and Törnqvist, 2009) covering the time period from 600 CE to 1600 CE.

Figure 12. (A) Errors-in-variables integrated Gaussian process (EIV-IGP) model fitted to the combined sea-level (SL) data from the Gulf Coast of Florida with removal of an estimated rate of 0.3 mm/yr. for glacio-isostatic adjustment. (B) Rate of sea-level change estimated by the EIV-IGP model.

Figure 13. Common Era sea-level change on the U.S. Atlantic coast (Kemp et al, 2015). Reconstructions are organized by latitude from north (A) to south (D). Each reconstruction was analyzed using the Errors-in-variables integrated Gaussian process (EIV-IGP) model to ensure fair comparison among records. Left-side panels are sea-level reconstructions after removing an estimated rate of glacio-isostatic adjustment (listed in panel title). Labeled arrows indicate the timing of the primary change in the rate of sea-level estimated using change point regression by applying the same model to all data sets. Right-side panels show estimated rates of sea-level change after detrending.

5.3: SEA-LEVEL CHANGE FROM 450 BCE TO 0 CE

A prominent feature of our new sea-level reconstruction from the Little Manatee River is the potential existence of a 0.05-0.4 m fall in sea level from ~ 450 BCE to 0 CE. This trend is not detected in the existing suite of RSL data from the western North Atlantic. However, only records from New Jersey (Kemp et al., 2013) and northern Florida (Kemp et al., 2014) cover this time period. The sea-level record from northern Florida is tightly constrained during this time and shows no deviation from stable background. In contrast, further examination of the detrended EIV-IGP model from New Jersey shows a lack of coherence in the data points from ~ 500 BCE to 0 CE. Between ~ 350 BCE and 0 CE many of the modeled data points reside outside the lower bounds of the EIV-IGP credible interval. Therefore, a fall in sea-level during this interval is possible, even though the model identifies a persistent period of stability. However, during this time period the data points from New Jersey are at the very limit of this reconstruction, as are our new data at Little Manatee River. Further records that extend beyond 3,000 years may have the potential to provide further clarity on this feature.

However, evidence exists to support an oscillation in sea level during this time period. Kopp et al. (2016) presented a statistical meta-analysis of GSL change over the past ~ 3,000 years tuned by a database of 24 regional-scale RSL datasets that includes the western North Atlantic records as well as other studies across the globe. This study identified a fall of 5-15 cm in GSL that occurred from ~ 350 to 150 BCE. Further evidence for this change in sea level is found in coastal archeological sites ~ 200 km

north of Mill Bayou. Here, recent data indicate the rapid landward movement of human occupation at ~ 0 CE (McFadden, 2016); postulated to be due to a switch from falling to rising sea level.

Further exploration of global-scale mechanisms causing a fall in sea level from 450 BCE to 0 CE is reliant upon a high-resolution temperature record. Currently, a robust high-resolution paleo-temperature database only exists for the past ~ 2,000 years (e.g. Mann et al., 2008; PAGES 2k Consortium). A coarser-resolution temperature reconstruction from Marcott et al. (2013) reconstructed global temperature over the Holocene and showed this interval was in the midst of long-term cooling (0.7°C) over the past 5k years. However, this study is based on an assimilation of 73 records with variations in resolutions and uncertainties. A high-resolution temperature reconstruction spanning the past 3,000 years is needed to serve as a primary comparison point with sea-level data in examining the potential role(s) of ocean dynamic effects and fingerprints of ice sheet mass balance. Further research is needed to confirm or deny any role of these mechanisms to a potential fall in sea level from ~ 450 CE to 0 CE.

We must also consider issues pertaining to our record that could produce this feature. Local factors could be responsible for the fall in observed RSL from ~ 450 BCE to 0 CE on Florida's Gulf Coast. The accumulation history of the bottom ~ 0.25 m of Core MB9 presents lithologic and biostratigraphic evidence of transgression that may explain this feature. At the base of recovery, an organic sand unit was found from 1.25 m to 1.05 m depth before gradually transitioning into 1.0 m of *Juncus roemerianus* peat. Foraminiferal assemblages from this same interval reveal a change

from an assemblage dominated by *Ammobaculites spp.* and *M. fusca* to an assemblage featuring high abundances of *A. mexicana* and *A. inepta*. The bottom intervals of core MB9 had the lowest estimates of PME driven by modern analogues dominated by *Ammobaculites spp.* from the lowest elevations in the modern training set. PME increases rapidly associated with a high sedimentation rate in our age model. This interval likely records the salt marsh vertically accreting sediment at an elevated rate while trying to colonize the intertidal zone. It is possible that because of this evidence, the species of foraminifera found at the bottom of core MB9 do not truly represent the tidal environment at the time of deposition, and estimates of PME are therefore biased low. Rapid accumulation rates could have prevented the replacement of tidal flat species (e.g. *Ammobaculites spp.*) by taxa found in peat forming environments (e.g. *A. mexicana*, *A. inepta*) if species turnover rates are low. Such a lag may have prevented accurate identification of the tidal environment at the time of deposition. A potential misidentification of tidal environment could explain low estimates of PME in this interval and be responsible for the observed sea-level change from 450 BCE to 0 CE.

Other local factors that need to be considered are sediment compaction and tidal range change. It is unlikely that post-depositional lowering from sediment compaction played a role in observed sea-level fall, as a geotechnical study by Brain et al. (2015) found less than 0.03 m of compaction occurred over ~ 1,000 years in a *Juncus roemerianus* salt marsh from North Carolina. Further, the greatest rates of compaction are typically located in the middle of the section, not at the base. Tidal range changes have been shown to induce additional error in RSL reconstructions during the late Holocene (e.g. Nikitina et al., 2015), but this effect is usually strongest at the most

inland portion of estuaries, with tidal range increasing through time (e.g. Hall et al., 2013). A potential test of the role of local factors in causing the sea-level changes observed from ~ 450 BCE to 0 CE would involve the reconstruction of a second RSL record from the Charlotte Harbor estuary. This estuary is geologically similar to Tampa Bay (e.g. Hine et al., 2003) with *Juncus roemerianus* salt marsh growth. While a record from this area will be subjected to its own set of local variables (e.g. differences in tidal regime or salinity), a RSL history that is in agreement with Mill Bayou would suggest that the potential fall in RSL from ~ 450 BCE to 0 CE is regional in nature.

5.4 SEA-LEVEL CHANGE FROM 0 CE TO THE LATE 19TH CENTURY

The sea-level history of the Gulf Coast of Florida reveals that sea level did not significantly depart from the Common Era background from 0 CE until 1830 CE to 1940 CE. Change Point analysis shows an inflexion from slightly falling to slightly rising sea level occurred at 1230 CE (840 CE to 1460 CE; 95% credible interval). This analysis is in general agreement with the pattern of detrended rates of sea-level change predicted by the EIV-IGP model. Comparison with the composite record of high-resolution sea-level reconstructions from the western North Atlantic (Gonzalez and Törnqvist, 2009; Kemp et al., 2009, 2013, 2014, 2015) reveals that the new record is in the best agreement with northern Florida. During the period of 0 CE to 1900 CE the dominant and only identifiable mechanism causing sea-level change in these locations is spatially-variable, long-term GIA. The linearity of sea-level change and lack of

significant departure from a stable mean rule out other mechanisms influencing spatially variable sea-level change in the southern USA.

The records from the Atlantic (Kemp et al., 2014) and Gulf Coasts (this study) of Florida broadly correlate with the record from the Gulf Coast of Louisiana (Gonzalez and Törnqvist, 2009). RSL change in this location is being driven by long term subsidence from GIA (0.45 mm/yr.) and flexural loading (0.15 mm/yr.) from the Mississippi Delta (Yu et al., 2012). The dataset from Gonzalez and Törnqvist (2009) is ambiguous due to high uncertainties. The authors identified a possible sea-level oscillation between ~ 1000 CE and 1200 CE based on a marginally improved r^2 value for a polynomial fit to the data. However, they include the caveat that a completely linear fit to their data cannot be ruled out. It should be noted that change point analysis of our new dataset does indicate a potential small increase in the rate of sea-level rise centered on 1230 CE, but this is hindered by the precision of our age model during this time (95% credible interval: 840 CE to 1460 CE).

The detection of linear rates of rise during the Common Era at our study site provides supporting evidence that the record from Nassau Landing (Kemp et al., 2014) is not due to local effects (e.g. fluvial dominance). The linearity of sea-level change from the Gulf Coast and northern Florida records is in contrast to sea-level reconstructions from further north on the Atlantic coast. These datasets show asynchronous timings and magnitudes of departure from the Common Era background. In North Carolina, sea-level was rising from ~ 1000 CE to 1400 CE and falling from ~ 1500 CE to 1800 CE. A similar pattern is observed in Connecticut and New Jersey, but the timings of departures do not occur simultaneously. Sea level was

rising in New Jersey from ~ 300 CE to 900 CE and falling from ~ 1100 CE to 1700 CE, while sea-level departed positively in Connecticut from ~ 600 CE to 1000 CE and negatively from ~ 1200 CE to 1700 CE. Changes in the strength and/or position of the Gulf Stream have been partially attributed to variability in late Holocene sea-level trends north and south of Cape Hatteras from observations on the Common Era (e.g. Kemp et al., 2014) and instrumental (e.g. Ezer et al., 2013; Yin and Goddard, 2013) time scales. Our data provide further evidence for the absence of these deviations in the records south of Cape Hatteras. This observation supports suggestions that an ocean volume change is unlikely to explain the variability and that changes in the position and/or strength of the Gulf Stream are most likely responsible (e.g. Kemp et al., 2015). Because the understanding of the sensitivity of RSL changes to eastern Gulf of Mexico circulation patterns and/or atmospheric forcing to changes is still in its infancy, further inferences are difficult to draw at this time. This relationship must be quantified before any ocean dynamic effects from the Gulf of Mexico can be correlated to the U.S. Atlantic coast.

5.5: HISTORIC RSL CHANGE

Change point analysis on the detrended sea-level data revealed that modern rates of sea-level rise on the Gulf Coast of Florida began between 1810 and 1950 CE (95% credible interval) on the Gulf Coast of Florida. Comparison of change point analysis (Figure 13) completed by Kemp et al., (2015) from northern Florida, North Carolina, New Jersey and Connecticut reveal that a common inflexion of 1865 to 1873 CE is

shared by all five reconstructions. The reconstructions from northern Florida and the Gulf Coast of Florida have the largest 95% credible intervals of 1834 CE to 1922 CE and 1810 CE to 1950 CE, respectively. Change point analysis models a time series as a piecewise linear section and objectively estimates when/where changes in data occurred (Cahill et al., 2015). The large credible intervals from these reconstructions could be due to a limitation in the change point model. The prolonged, gradual increase in the rate of RSL rise prior to the 19th century could limit the models ability to detect a switch in a linear trend. Conversely, the large credible intervals may be explained by limitations in our data. Increased uncertainty estimates could be caused by the slower accumulation rates at these sites due to low rates (< 0.5 mm/yr.) of GIA, which results in larger estimates for any individual cm of core. A further issue may be the absence of precise chronological markers to constrain the age models between the start of the radiocarbon plateau at ~ 1650 CE and the introduction of *Casuarina equisetifolia* in 1905 CE.

The commonality between the shared overlap in timing of late 19th century acceleration across the existing western North Atlantic reconstructions is likely the local to regional expression of changes in ocean mass and volume (Church et al., 2013, Kemp et al., 2015). The consistency of this acceleration is striking given the variation in sea-level oscillations between sites during the Common Era (e.g. Kemp et al., 2015; Kopp et al., 2016). Our reconstruction is in good agreement with the timing of GSL rise determined from global tide gauge compilations by Church and White (2006; 2011). Our new data provide further evidence that the magnitude of 20th century sea-level rise was greater along the U.S. Atlantic coast than the 20th century

global average of 1.2 mm/yr. (Hay et al., 2015). Our data are consistent with the findings of Kopp et al. (2016), demonstrating that the 20th century rate of rise at our site was faster than at any time during the past ~ 2,400 years.

CHAPTER 6

CONCLUSIONS

We addressed a spatial gap in high-resolution Common Era RSL reconstructions along the Gulf Coast of the United States of America. We reconstructed ~ 1.0 m of RSL change encompassing the past 2,400 years from the Little Manatee River, Florida. Paleomarch elevation was estimated using a foraminiferal-based transfer function calibrated by a regional training set of 66 modern samples from the Charlotte Harbor and Tampa Bay estuaries. A composite chronology of radiocarbon dates, and pollution and pollen markers of known age was used to build an age-depth model in *Bchron*. Comparison of our geological reconstruction to the instrumental record over their shared time periods indicates that our method is accurate as well as precise. We combined our geological reconstruction with a suite of regional tide gauge records from the Gulf Coast of Florida to create a combined RSL dataset. Application of the error in variables integrated Gaussian process (EIV-IGP) model to the combined RSL dataset was used to quantitatively estimate centennial-scale persistent trends of Common Era sea-level variability with full consideration of uncertainty and the temporal distribution of data. After correction for long term glacio-isostatic adjustment (0.3 mm/yr.), sea level fell at a maximum rate of ~ -1.25 mm/yr. at ~ 450 BCE before stabilizing at ~ 0 CE and rising ~ 0.05 mm/yr. until ~ 350 CE. Sea-level rise subsequently decelerated and began to fall to a maximum rate of ~ -0.21 mm/yr. at ~ 700 CE before returning to a stable mean at 1000 CE. Sea level then consistently

accelerated from a change centered at 1230 CE until the current rate of 1.95 mm/yr. was reached in 2014 CE. This rate is the fastest century-scale sea-level rise over the last ~ 2,400 years, which likely began at 1810 CE to 1950 CE in response to global changes in ocean volume. Prior to the late 19th century, sea-level trends from Florida's Gulf and Atlantic coasts were similar throughout the Common Era. However, these two records may differ from ~ 450 BCE to 0 CE, when a potential fall in sea-level at the Little Manatee River correlates with the timing of a reconstructed fall in global sea level. Lack of sea-level variability in our record through the pre-industrial Common Era provides further geologic evidence for the recent suggestion of a dominant role for ocean dynamics in Common Era sea-level change.

APPENDIX

This supplementary data includes the altitude of each sample (given in depth below surface) from Core MB9 where fossiliferous foraminifera were enumerated, along with the corresponding results of the regional-scale transfer function (i.e. PME and RSL error) and the age-depth model (i.e. Median Age and Age Error) used to reconstruct RSL at each sample depth.

Sample ID	Altitude (m MHW)	PME (m MHW)	RSL (m)	RSL Error (m)	Median Age (CE)	Age Error (yrs.)
0-1cm	-0.120	-0.047	-0.073	0.065	2001.0	15.0
1-2cm	-0.130	-0.039	-0.091	0.066	1996.0	13.5
4-5cm	-0.160	0.000	-0.160	0.065	1983.0	10.5
7-8cm	-0.190	-0.025	-0.165	0.065	1967.0	7.5
10-11cm	-0.220	-0.004	-0.216	0.066	1942.0	9.5
13-14cm	-0.250	-0.029	-0.221	0.065	1930.0	11.0
16-17cm	-0.280	-0.007	-0.273	0.082	1919.0	11.5
17-18cm	-0.290	-0.015	-0.275	0.072	1916.0	11.5
18-19cm	-0.300	-0.002	-0.298	0.073	1913.0	11.5
21-22cm	-0.330	-0.072	-0.258	0.068	1891.0	39.5
22-23cm	-0.340	-0.016	-0.324	0.075	1878.0	46.0
25-26cm	-0.370	-0.001	-0.369	0.072	1843.0	61.0
28-29cm	-0.400	-0.006	-0.394	0.076	1810.0	64.6
34-35cm	-0.460	-0.003	-0.457	0.067	1726.0	65.5
37-38cm	-0.490	-0.009	-0.481	0.068	1693.0	57.0
40-41cm	-0.520	-0.044	-0.476	0.064	1661.0	49.0
41-42cm	-0.530	0.003	-0.533	0.065	1649.0	43.5
42-43cm	-0.540	-0.039	-0.501	0.067	1638.0	39.0
43-44cm	-0.550	0.001	-0.551	0.069	1629.0	33.5
45-46cm	-0.570	-0.014	-0.556	0.066	1608.0	27.5
46-47cm	-0.580	-0.019	-0.561	0.065	1598.0	30.0
48-49cm	-0.600	-0.057	-0.543	0.065	1588.0	35.0
49-50cm	-0.610	-0.067	-0.543	0.066	1583.0	36.5

ID	Altitude (m MHW)	PME (m MHW)	RSL (m)	RSL Error (m)	Median Age (CE)	Age error (yrs.)
52-53cm	-0.640	-0.095	-0.545	0.064	1568.0	41.5
53-54cm	-0.650	-0.030	-0.620	0.064	1559.0	44.5
54-55cm	-0.660	-0.061	-0.599	0.064	1543.0	39.0
55-56cm	-0.670	-0.072	-0.598	0.066	1524.0	45.5
56-57cm	-0.680	-0.020	-0.660	0.064	1496.0	47.0
57-58cm	-0.690	-0.033	-0.657	0.065	1470.0	43.5
58-59cm	-0.700	-0.064	-0.636	0.067	1443.0	40.5
59-60cm	-0.710	-0.007	-0.703	0.065	1417.0	34.5
61-62cm	-0.730	-0.018	-0.712	0.074	1386.0	38.5
63-64cm	-0.750	-0.011	-0.739	0.069	1358.0	44.5
64-65cm	-0.760	-0.021	-0.739	0.066	1339.0	46.0
65-66cm	-0.770	-0.035	-0.735	0.065	1311.0	78.0
66-67cm	-0.780	-0.006	-0.774	0.065	1270.0	114.1
67-68cm	-0.790	-0.017	-0.773	0.066	1227.0	134.5
70-71cm	-0.820	-0.016	-0.804	0.068	1105.0	145.5
72-73cm	-0.840	-0.067	-0.773	0.066	1019.0	142.5
74-75cm	-0.860	-0.018	-0.842	0.082	931.0	81.5
79-80cm	-0.910	0.001	-0.911	0.072	767.0	75.0
80-81cm	-0.920	-0.005	-0.915	0.070	724.5	109.1
81-82cm	-0.930	-0.004	-0.926	0.072	655.0	162.6
83-84cm	-0.950	-0.005	-0.945	0.076	513.5	190.0
84-85cm	-0.960	0.008	-0.968	0.066	445.5	189.5
85-86cm	-0.970	-0.006	-0.964	0.079	376.0	185.5
86-87cm	-0.980	-0.021	-0.959	0.066	303.0	172.5
87-88cm	-0.990	-0.043	-0.947	0.065	227.0	129.6
88-89cm	-1.000	-0.002	-0.998	0.065	195.0	60.0
91-92cm	-1.030	-0.003	-1.027	0.065	137.0	70.5
94-95cm	-1.060	0.002	-1.062	0.069	82.5	60.0
95-96cm	-1.070	0.035	-1.105	0.068	56.0	64.0
97-98cm	-1.090	-0.022	-1.068	0.070	-9.0	70.5
98-99cm	-1.100	-0.005	-1.095	0.066	-39.5	73.0
100-101cm	-1.120	-0.016	-1.104	0.067	-112.0	74.5
102-103cm	-1.140	-0.029	-1.111	0.069	-132.0	56.0
104-105cm	-1.160	-0.012	-1.148	0.067	-144.0	48.0
106-107cm	-1.180	-0.048	-1.132	0.066	-161.0	38.0
108-109cm	-1.200	-0.101	-1.099	0.065	-176.0	33.5
109-110cm	-1.210	-0.217	-0.993	0.066	-180.0	31.5

ID	Altitude (m MHW)	PME (m MHW)	RSL (m)	RSL Error (m)	Median Age (CE)	Age error (yrs.)
110-111cm	-1.220	-0.124	-1.096	0.065	-188.0	39.5
111-112cm	-1.230	-0.149	-1.081	0.064	-199.0	49.5
113-114cm	-1.250	-0.192	-1.058	0.065	-217.5	62.5
115-116cm	-1.270	-0.193	-1.077	0.065	-239.0	70.5
117-118cm	-1.290	-0.265	-1.025	0.070	-263.0	76.0
120-121cm	-1.320	-0.332	-0.988	0.076	-316.0	98.0
121-122cm	-1.330	-0.266	-1.064	0.071	-341.0	109.0
122-123cm	-1.340	-0.327	-1.013	0.075	-352.0	124.6
123-124cm	-1.350	-0.342	-1.008	0.076	-363.0	139.6

BIBLIOGRAPHY

- Adams, P.N., Opdyke, N.D. and Jaeger, J.M., 2010. Isostatic uplift driven by karstification and sea-level oscillation: Modeling landscape evolution in north Florida. *Geology* 38, 531-534.
- Alexander, T.R. and Crook, A.G., 1974. Recent vegetational changes in southern Florida. In Gleason, P.J., ed., *Environments of South Florida: Present and Past*, 61-72. Miami Geological Society, Miami.
- Argus, D.F., Peltier, W.R., Drummond, R. and Moore, A.W., 2014. The Antarctica component of postglacial rebound model ICE-6G_C (VM5a) based on GPS positioning, exposure age dating of ice thicknesses, and relative sea level histories. *Geophysical Journal International* 198, 537-563.
- Ault, W.U., Senechal, R.G., Erlebach, W.E., 1970. Isotopic composition as a natural tracer of lead in the environment. *Environmental Science & Technology* 4, 305–313.
- Barlow, N.L.M., Shennan, I., Long, A.J., Gehrels, W.R., Saher, M.H., Woodroffe, S.A., Hillier C., 2013. Salt marshes as late Holocene tide gauges. *Global and Planetary Change* 106, 90-100.
- Birks, H.J.B., 2010. Numerical methods for the analysis of diatom assemblage data, in: Smol, J.P., Stoermer, E.F. (Eds.), *The Diatoms: Applications for the Environmental and Earth Sciences*, Second ed. University Press, Cambridge, UK, 23-54.

- Bloom, A.L., 1964. Peat accumulation and compaction in Connecticut coastal marsh. *Journal of Sedimentary Research* 34, 599–603.
- Blum, M.D., Misner, T.J., Collins, E.S., Scott, D.B., Morton, R.A., Aslan, A., 2001. Middle Holocene sea-level rise and highstand at +2 m, central Texas Coast. *Journal of Sedimentary Research* 71, 581–588.
- Brain, M. J., Kemp, A. C., Horton, B. P., Culver, S. J., Parnell, A. C., & Cahill, N., 2015. Quantifying the contribution of sediment compaction to late Holocene salt-marsh sea-level reconstructions, North Carolina, USA. *Quaternary Research* 83, 41-51.
- Brooks, G.R., Doyle, L.J., 1998. Recent sedimentary development of Tampa Bay, Florida: A microtidal estuary incised into tertiary platform carbonates. *Estuaries* 21, 391-406.
- Breithaupt, J.L., Smoak, J.M., Smith, T.J. and C.J. Sanders, C.J., 2014. Temporal variability of carbon and nutrient burial, sediment accretion, and mass accumulation over the past century in a carbonate platform mangrove forest of the Florida Everglades, *Journal of Geophysical Research: Biogeosciences* 119, 2032-2048.
- Cahill, N., Kemp, A.C., Horton, B.P. and Parnell, A.C., 2015. Modeling sea-level change using errors-in-variables integrated Gaussian processes. *The Annals of Applied Statistics* 9, 547-571
- Church, J.A., White, N.J., 2006. A 20th century acceleration in global sea-level rise. *Geophysical Research Letters* 33, doi: 10.1029/2005GL024826.

- Church, J.A., White, N.J., 2011. Sea-level rise from the late 19th to the early 21st century. *Surveys in Geophysics* 32, 585-602.
- Church, J.A., Monselesan, D., Gregory, J.M., Marzeion, B., 2013. Evaluating the ability of process based models to project sea-level change. *Environmental Research Letters* 8, 014051.
- Clark, J.A., Farrell, W.R., Peltier, W.R., 1978. Global changes in postglacial sea level: a numerical calculation. *Quaternary Research* 9, 65–287.
- De Rijk, S., 1995. Agglutinated foraminifera as indicators of salt marsh development in relation to late Holocene sea level rise (Great Marshes at Barnstable, Massachusetts). *Fabo, Utrecht, The Netherlands*.
- Duncan, D.S., Locker, S.D., Brooks, G.R., Hine, A.C., Doyle, L.I., 2003. Mixed carbonate-siliciclastic infilling of a Neogene carbonate shelf-valley system: Tampa Bay, west-central Florida. *Marine Geology* 200, 125–156.
- Edwards, R.J., Van De Plassche, O., Gehrels, W.R. and Wright, A.J., 2004. Assessing sea-level data from Connecticut, USA, using a foraminiferal transfer function for tide level. *Marine Micropaleontology* 51, 239-255.
- Eleuterius, L., 1975. The life history of the salt marsh rush, *Juncus roemerianus*. *Bulletin of the Torrey Botanical Club* 102, 135–140.
- Eleuterius, L., 1976. Vegetative morphology and anatomy of the salt-marsh rush *Juncus roemerianus*. *Gulf Research Reports* 5, 1–10.
- Engelhart, S.E., Horton, B.P., Douglas, B.C., Peltier, W.R., Törnqvist, T.E., 2009. Spatial variability of late Holocene and 20th century sea-level rise along the Atlantic coast of the United States. *Geology* 37, 1115-1118.

- Engelhart, S.E., Peltier, W.R. and Horton, B.P., 2011. Holocene relative sea-level changes and glacial isostatic adjustment of the US Atlantic coast. *Geology* 39, 8751-754.
- Engelhart, S.E., Horton, B.P., 2012. Holocene sea-level database for the Atlantic coast of the United States. *Quaternary Science Reviews* 54, 12-25.
- Engelhart, S.E., Horton, B.P., Nelson, A., Hawkes, A.D., Witter, R.C., Wang, K., Wang, P.L., and Vane, C.H., 2013. Testing the use of microfossils to reconstruct great earthquakes at Cascadia. *Geology* 41, 1067–1070.
- Escobar, J., Whitmore, T.J., Kamenov, G.D. and Riedinger-Whitmore, M.A., 2013. Isotope record of anthropogenic lead pollution in lake sediments of Florida, USA. *Journal of paleolimnology* 49, 237-252.
- Ezer, T., Atkinson, L.P., Corlett, W.B. and Blanco, J.L., 2013. Gulf Stream's induced sea level rise and variability along the US mid-Atlantic coast. *Journal of Geophysical Research: Oceans* 118, 685-697
- Farrell, W.E., Clark, J.A., 1976. On postglacial sea level. *Geophysical Journal of the Royal Astronomical Society* 46, 647-667.
- Fatela, F., Taborda, R., 2002. Confidence limits of species proportions in microfossil assemblages. *Marine Micropaleontology* 45, 169-174.
- Gehrels, W.R., 1994. Determining relative sea-level change from the salt-marsh foraminifera and plant zones on the coast of Maine, U.S.A. *Journal of Coastal Research* 10, 990-1009.
- Gehrels, W.R., 1999. Middle and late Holocene sea-level changes in eastern Maine

reconstructed from foraminiferal saltmarsh stratigraphy and AMS C-14 dates of basal peat. *Quaternary Research* 52, 350-359.

Gehrels, W.R. and van de Plassche, O., 1999. The use of *Jadammina macrescens* (Brady) and *Balticammina pseudomacrescens* Brönnimann, Lutze and Whittaker (Protozoa: Foraminiferida) as sea-level indicators. *Palaeogeography, Palaeoclimatology, Palaeoecology* 149, 89-101.

Gonzales, J.L., Törnqvist, T.E., 2009. A new Late Holocene sea-level record from the Mississippi Delta: Evidence for a climate/sea-level connection?. *Quaternary Science Reviews* 28, 1737-1749.

Graney, J.R., Halliday, A.N., Keeler, G.J., Nriagu, J.O., Robbins, J.A., Norton, S.A., 1995. Isotopic record of lead pollution in lake sediments from the northeastern United States. *Geochimica et Cosmochimica Acta* 59, 1715–1728.

Hall, G.F., Hill, D.F., Horton, B.P., Engelhart, S.E. and Peltier, W.R., 2013. A high-resolution study of tides in the Delaware Bay: Past conditions and future scenarios. *Geophysical Research Letters* 40, 338-342.

Haslett, J., Parnell, A., 2008. A simple monotone process with application to radiocarbon-dated depth chronologies. *Journal of the Royal Statistical Society: Series C: Applied Statistics* 57, 399–418.

Hauer, M.E., Evans, J.M., Mishra, D.R., 2016. Millions projected to be at risk from sea-level rise in the continental United States. *Nature Climate Change*, doi:10.1038/nclimate2961.

Hawkes, A.D., Horton, B.P., Nelson, A.R. and Hill, D.F., 2010. The application of intertidal foraminifera to reconstruct coastal subsidence during the giant

- Cascadia earthquake of AD 1700 in Oregon, USA. *Quaternary International* 221, 116-140.
- Hay, C.C., Morrow, E., Kopp, R., Mitrovica, J.X., 2015. Probabilistic reanalysis of twentieth-century sea-level rise. *Nature* 517, 481-484.
- Hine A.C., Belknap D.F., 1986. Recent geological history and modern sedimentary processes of the Pasco, Hernando, and Citrus county coastline: West-Central Florida. *Florida Sea Grant Report* 79. Florida Sea Grant, Gainesville, Florida.
- Hine, A. C. 1997. Structural, stratigraphic, and paleoceanographic development of the margins of the Florida Platform, in *Geology of Florida* (eds. A. F. Randazzo and D. S. Jones), University Press of Florida, Gainesville, Florida, USA, 169-194
- Hine, A.C., Brooks, G.R., Davis, R.A., Jr., Duncan, D.S., Locker, S.D., Twichell, D.C., Gelfenbaum, G., 2003. The west-central Florida inner shelf and coastal system: A geologic conceptual overview and introduction to the special issue. *Marine Geology* 200, 1–17.
- Hine, A.C., Suthard, B., Locker, S.D., Cunningham, K.J., Duncan, D.S., Evan, M., Morton, R.A., 2009. Karst subbasins and their relation to the transport of Tertiary siliciclastic sediments on the Florida Platform, In Swart, P.K., Eberli, G.P., and McKenzie, J.A., (Eds), *Perspectives in sedimentary geology: A tribute to the career of Robert N. Ginsburg*. Wiley-Blackwell, International Association of Sedimentologists, Special Publication 41, 179–197.

- Hinrichsen, D., 1998. *Coastal waters of the world: trends, threats, and strategies*. Island Press, Washington, DC, 275 pp.
- Hippensteel, S.P., Martin, R.E., Nikitina, D. and Pizzuto, J.E., 2000. The formation of Holocene marsh foraminiferal assemblages, middle Atlantic coast, USA: implications for Holocene sea-level change. *The Journal of Foraminiferal Research* 30, 272-293.
- Hippensteel, S.P., Martin, R.E., Nikitina, D. and Pizzuto, J.E., 2002. Interannual variation of marsh foraminiferal assemblages (Bombay Hook National Wildlife Refuge, Smyrna, DE): Do foraminiferal assemblages have a memory?..*The Journal of Foraminiferal Research* 32, 97-109.
- Horton, B.P., Edwards, R.J., 2006. Quantifying Holocene Sea Level Change Using Intertidal Foraminifera: Lessons from the British Isles. *Cushman Foundation for Foraminiferal Research, Special Publication* 40, 1-97.
- Jowsey, P. C., 1966. An Improved Peat Sampler. *New Phytologist* 65, 245–248.
- Karager, M., Dixon, T.H., Engelhart, S.E., 2016. Subsidence along the Atlantic Coast of North America: Insight from GPS and late Holocene relative sea level data. *Geophysical Research Letters* 43, doi: 10.1002/2016GL0685015.
- Kaufman, L., Rousseeuw, P.J., 1990. *Finding Groups in Data: An Introduction to Cluster Analysis*. Wiley-Interscience.
- Kemp, A.C., Horton, B.P., Culver, S.J., 2009a. Distribution of modern salt-marsh foraminifera in the Abermarle-Pamlico estuarine system of North Carolina, USA; implications for sea-level research. *Marine Micropaleontology* 72, 222-238.

- Kemp, A.C., Horton, B.P., Culver, S.J., Corbett, D.R., van de Plassche, O., Gehrels, W.R., Douglas, B.C., Parnell, A.C., 2009b. Timing and magnitude of recent accelerated sea-level rise (North Carolina, United States). *Geology* 37, 1035-1038.
- Kemp, A.C., Buzas, M.A., Horton, B.P. and Culver, S.J., 2011a. Influence of patchiness on modern salt-marsh foraminifera used in sea-level studies (North Carolina, USA). *The Journal of Foraminiferal Research* 41, 114-123.
- Kemp, A.C., Horton, B.P., Donnelly, J. P., Mann, M.E., Vermeer, M., Rahmstorf, S., 2011b. Climate related sea-level variations over the past two millennia. *Proceedings of the National Academy of Science* 108, 11017-11022.
- Kemp, A.C., Horton, B.P., Vann, D.R., Engelhart, S.E., Grand Pre, C.A., Vane, C.H., Nikitina, D., Anisfield, S.C., 2012. Quantitative vertical zonation of salt-marsh foraminifera for reconstructing former sea-level; an example from New Jersey, USA. *Quaternary Science Reviews* 54, 26-39.
- Kemp, A.C., Nelson, A.R., Horton, B.P., 2013a. Radiocarbon Dating of Plant Macrofossils from Tidal-Marsh Sediment. In: John F. Schroder (Editor in Chief), Switzer, A.D., Kennedy, D.M. (Volume Editors). *Treatise on Geomorphology, Vol 14, Methods in Geomorphology*, San Diego: Academic Press, 370-388.
- Kemp, A.C., Horton, B.P., Vane, C.H., Bernhardt, C.E., Corbett, R., Engelhart, S.E., Anisfield, S.C., Parnell, A.C., Cahill, N., 2013b. Sea-level change during the past 2500 years in New Jersey, USA. *Quaternary Science Reviews* 81, 90-104.

- Kemp, A.C., Bernhardt, C.E., Horton, B. P., Kopp, R.E., Vane, C.H., Peltier W.R., Hawkes, A.D., Donnelly, J.P., Parnell, A.C., Cahill, N., 2014. Late Holocene sea-and land-level change on the US southeastern Atlantic coast. *Marine Geology* 357, 90-100.
- Kemp, A.C., Hawkes, A.D., Donnelly, J.P., Vane, C.H., Horton, B.P., Hill, T.D., Anisfield, S.C., Parnell, A.C., Cahill, N., 2015a. Relative sea-level changes in Connecticut (USA) during the last 2200 years. *Earth and Planetary Science Letters* 428, 217-229.
- Kemp, A.C., Telford, R.J., 2015b. Transfer functions, in *Handbook of Sea-Level Research* (eds I. Shennan, A. J. Long and B. P. Horton), John Wiley & Sons, Ltd, Chichester, UK, pp. 470-499. doi: 10.1002/9781118452547.ch1
- Kopp, R.E., 2013. Does the mid-Atlantic United States sea level acceleration hot spot reflect ocean dynamic variability? *Geophysical Research Letters* 40, 3981–3985.
- Kopp, R.E., Kemp, A.C., Bittermann, K., Horton, B.P., Donnelly, J.P., Gehrels, W.R., Hay, C.C., Mitrovica, J.X., Morrow, E.D., Rahmstorf, S., 2016. Temperature-driven global sea-level variability in the Common Era. *Proceedings of the National Academy of Sciences*, 201517056.
- Horton, B.P., Culver, S.J., 2008. Modern intertidal foraminifera of the Outer Banks, North Carolina, USA, and their applicability for sea-level studies. *Journal of Coastal Research*, pp.1110-1125.
- Maechler, M., Rousseeuw, P., Struyf, A., Hubert, M., 2012. cluster: cluster analysis basics and extensions. R Package Version 1.14.3.

- Mann, M.E., Zhang, Z., Hughes, M.K., Bradley, R.S., Miller, S.K., Rutherford, S., Ni, F., 2008. Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia. *Proceedings of the National Academy of Sciences* 105, 13252–13257.
- Marcott, S.A., Shakun, J.D., Clark, P.U. and Mix, A.C., 2013. A reconstruction of regional and global temperature for the past 11,300 years. *Science* 339, 1198-1201.
- McFadden, P.S., 2016. Coastal Dynamics and Pre-Colombian Human Occupation in Horseshoe Cove on the Northern Gulf Coast of Florida, USA. *Geoarchaeology*, doi 10.1002/gea.21549.
- Moberg, A., Sonechkin, D. M., Holmgren, K., Datsenko, N. M., & Karlén, W., 2005. Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. *Nature* 433, 613-617.
- Morton, Julia F. 1980. The Australian pine or beefwood (*Casuarina equisetifolia* L.), an invasive "weed" tree in Florida. *Proceedings, Florida State Horticultural Society* 93, 87-95.
- Murray, J. W., and Bowser, S. S., 2000. Mortality, protoplasm decay rate, and reliability of staining techniques to recognize 'living' foraminifera: a review. *Journal of Foraminiferal Research* 30, 66–70.
- Nikitina, D., Kemp, A.C., Engelhart, S.E., Horton, B.P., Hill, D.F. and Kopp, R.E., 2015. Sea-level change and subsidence in the Delaware Estuary during the last ~ 2200 years. *Estuarine, Coastal and Shelf Science* 164, 506-519.

- National Ocean and Atmospheric Administration - Economics: National Ocean Watch (ENOW). Online. 2016. Available:
<http://www.csc.noaa.gov/digitalcoast/data/enow>: Accessed: 1 May 2016.
- Osland, M.J., Enwright, N., Day, R.H., Doyle, T.W., 2013. Winter climate change and coastal wetland foundation species: salt marshes vs. mangrove forests in the southeastern United States. *Global Change Biology* 19, 1482-1494.
- PAGES 2k Consortium, 2013. Continental-scale temperature variability during the past two millennia. *Nature Geosciences* 6, 339–346.
- Parnell, A.C., Haslett, J., Allen, J.R.M., Buck, C.E., Huntley, B., 2008. A flexible approach to assessing synchronicity of past events using Bayesian reconstructions of sedimentation history. *Quaternary Science Reviews* 27, 1872–1885.
- Oksanen, J., F., Blanchet, G., Kindt, R., Legendre, P., Minchin, P.R., O'Hara, R.B., Simpson, G.L., Solymos, P., Stevens M.H., Wagner. H., 2016. vegan: Community Ecology Package. R package version 2.3-5. <http://CRAN.R-project.org/package=vegan>
- Peltier, W.R., 1998. Postglacial variations in the level of the sea: Implications for climate dynamics and solid-earth geophysics. *Reviews of Geophysics* 36, 603-689.
- Peltier, W.R., 2004. Global glacial isostasy and the surface of the ice-age Earth: the ICE-5G (VM2) model and GRACE. *Annual Review of Earth and Planetary Sciences* 32, 111-149.

- Peltier, W.R., Argus, D.F., Drummond, R., 2014. Space geodesy constrains ice-age terminal deglaciation: the ICE-6G_C (VM5a) model. *Journal of Geophysical Research, Solid Earth* 120, 450–487.
- Peltier, W. R., D. F. Argus, and R. Drummond (2015), Space geodesy constrains ice age terminal deglaciation: The global ICE-6G_C (VM5a) model, *Journal of Geophysical Research Solid Earth* 120, 450–487.
- Redfield, A.C., Rubin, M., 1962. The age of salt marsh peat and its relation to recent change in sea-level at Barnstable, Massachusetts. *Proceedings of the National Academy of Sciences* 48, 1728-1735.
- Rupert, F., 1990. *The geology and geomorphology of Florida's coastal marshes*. Tallahassee, Florida: Florida Geological Survey.
- Saintilan, N., Wilson, N.C., Rogers, K., Rajkaran, A., Krauss, K.W., 2014. Mangrove expansion and salt marsh decline at mangrove poleward limits. *Global Change Biology* 20, 147-157.
- Scott, D.B., 1976. Brackish-water foraminifera from southern California and description of *Polysaccamina ipohalina*. *The Journal of Foraminiferal Research* 6, 312-321.
- Scott, D.B., Medioli, F.S., 1978. Vertical zonations of marsh foraminifera as accurate indicators of former sea-levels. *Nature* 272, 528-531.
- Scott, D.B., Medioli, F.S., 1980. Living vs. total foraminiferal populations- Their relative usefulness in Paleoecology. *Journal of Paleontology* 54, 814-831.

- Smoak, J.M., Breithaupt, J.L., Smith III, T.J. and C.J. Sanders 2013. Sediment accretion and organic carbon burial relative to sea-level rise and storm events in two mangrove forest in Everglades National Park. *Catena* 104, 58-66.
- Spencer, R.S., 2000. Foraminiferal assemblages from a Virginia salt marsh, Phillips Creek, Virginia. *The Journal of Foraminiferal Research* 30, 143-155.
- Törnqvist, T.E., Hijma, M.P., 2012. Links between early Holocene ice-sheet decay, sea-level rise and abrupt climate change. *Nature Geoscience* 5, 601-606.
- Traverse, A., 2007. *Paleopalynology*. Springer.
- Troels-Smith, J. 1955. Karakterisering af løse jordarter (Characterization of unconsolidated sediments) Danmarks *Geologiske Undersøgelse, Række IV* 3, 1-73.
- U.S. Fish and Wildlife Service. 1999. South Florida multi-species recovery plan. Atlanta, Georgia. 2172 pp.
- Walton, W. R., 1952, Techniques for recognition of living foraminifera: *Contributions of the Cushman Foundation for Foraminiferal Research* 3, 56–60.
- Whitmore, T.J., Riedinger-Whitmore, M.A., Smoak, J.M., Kolasa, K.V., Goddard, E.A. and Bindler, R., 2008. Arsenic contamination of lake sediments in Florida: evidence of herbicide mobility from watershed soils. *Journal of Paleolimnology* 40, 869-884.
- Yates, K.K., Greening, Holly, and Morrison, Gerold, eds., 2011. Integrating Science and Resource Management in Tampa Bay, Florida: *U.S. Geological Survey Circular* 1348, 280 p., available at <http://pubs.usgs.gov/circ/1348/>.

- Yin, J. and Goddard, P.B., 2013. Oceanic control of sea level rise patterns along the East Coast of the United States. *Geophysical Research Letters* 40, 5514-5520.
- Yu, S.Y., Törnqvist, T.E., Hu, P., 2012. Quantifying Holocene lithospheric subsidence rates underneath the Mississippi Delta. *Earth and Planetary Science Letters* 331-332, 21-30.