

Last Millennium Relative Sea-level Change on the Western Coast of Southern New Jersey

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Executive Summary

The main goal of this study was to reconstruct last millennium sea-level changes on the western coast of southern New Jersey (Delaware Bay) shore. The project used proven paleoecological techniques (sediment archives/cores) to provide quantitative information on sea level/subsidence in Dennis Creek over the last millennium through analysis of biogeochemical indicators accumulated and preserved in Dennis Creek wetland sediments. Salt-marsh sediment cores were used to understand the underlying stratigraphy, and cores were analyzed using foraminifera, geochemistry, and sediment characteristics. Results from this investigation were used to analyze relative sea-level changes associated with extensive subsidence previously observed at Dennis Creek. The timing of subsidence and relative sea-level change at Dennis Creek were determined with radiocarbon dating and pollution chronomarkers. Changes in fossil foraminifera species abundances isolated from dated core intervals were used to reconstruct relative sea level changes through time.

The results from this project were compared to the available sea-level studies on the east coast of New Jersey to determine whether similar processes are occurring on both the Delaware Bay and a Cape May site located on the Atlantic Ocean-facing coast of New Jersey. Understanding the local and regional physical processes controlling relative sea-level change is crucial for sea-level projections and future mitigation efforts, especially at locations where such high rates of change are documented. Project results revealed that relative sea-level started to accelerate earlier in Delaware Bay's Dennis Creek than sites located along the New Jersey Atlantic coast, and also maintains present day higher rates. This finding underscores that there could be significant differences in local processes contributing to relative sea-level change at individual locations along the New Jersey coast. At Dennis Creek, relative sea-level rise reached a rate of 2 mm/yr by the mid-1600s and 3 mm/yr by 1800 CE, roughly a hundred years earlier than a site located at Cape May Courthouse, around 15km from Dennis Creek. In the 20th century, relative sea-level rise was approximately 3.6 mm/yr at Cape May Courthouse, but 4.2 mm/yr at Dennis Creek. Results from this project have profound implications for understanding local and regional processes controlling relative sea-level change and projections into the future. As the present results suggest, potentially significant local differences in relative sea-level rise could highlight important implications for how individual coastlines respond to accelerating sea-level rise. The protection and mitigation strategies that wetland stakeholders will need to provide at local levels may need to correspond with local conditions.

Introduction

While extensive sea-level research through salt marsh reconstructions has been completed at several locations on the east coast of New Jersey, studies that examine the western coast of southern New Jersey near Delaware Bay are scarce. Anomalous subsidence at Dennis Creek on the west coast of the state was documented by Varekamp and Thomas (1998), at a rate of 6.9 mm/yr since the 17th century, which does not correlate with findings from the east coast of New Jersey (e.g., Cheesequake State Park, Leeds Point, Cape May Courthouse) (Kemp et al., 2013; Walker et al., 2021).

This project fills the gap in knowledge of sea-level change on the western coast of southern New Jersey. The project uses proven paleoecological techniques (sediment archives/cores) to provide quantitative information on sea level/subsidence in Dennis Creek over the last millennium through analysis of biogeochemical indicators accumulated and preserved in Dennis Creek wetland sediments. Salt-marsh sediment cores are used to understand the underlying stratigraphy, and replicate cores will be analyzed using foraminifera, geochemistry, and sediment characteristics to analyze relative sea-level change at Dennis Creek. Since the publication of Varekamp and Thomas (1998), there have been over 20 additional years of sediment deposition in which to study sea-level change.

Knowledge of the rate of sea-level rise on the western coast of southern New Jersey is of the utmost importance. Since the Delaware Bay wetlands lack back-barrier protection, such as those found on the eastern New Jersey coast with the barrier islands, they are especially prone to enhanced erosion effects from the ocean. In addition, New Jersey's west coast suffers from a particular case of social injustice to sea-level rise resilience strategies due to their chronic inability to meet the state and federal cost-benefit thresholds required for shoreline hardening projects that the barrier island municipalities regularly receive. The effects from tidal and storm erosion forces combined with sea-level rise must be considered in coastal management practices for optimal planning and protection of existing wetlands.

Sediment archive utilization to reconstruct historic sea levels

Wetland sediments gradually accumulate layer by layer, incorporating skeletal remains of micro- and macroorganisms, metals, etc. A sediment core collected from the wetland can be sectioned stratum by stratum; each stratum can be analyzed for preserved proxies, providing ecological information that can be read like the pages of a history book when you have the right tool to interpret it. Each sediment interval mirrors the ecosystem characteristic at its time of deposition, going back in time from the surface interval (that represents the most recent, present-day conditions) to its bottom that can extend back decades, centuries or millennia, as a function of the core length and sediment accumulation rates. Different sections of the core containing fossil remains (in this case foraminifera, one of the most used ecological and paleoecological indicators) can be used to reconstruct past sea-level change specific to their deposition times. The core can be sliced continuously to provide a continuum of data to reconstruct sea-level change and quantify the direction and magnitude of change when instrumental records are absent.

Procedure for quantitative reconstruction of sea level

After sediment cores are collected from the sites of interest, they are subsampled in successive intervals; radioisotopes (e.g., C-14) are used to provide core dating for each interval so that proxy-based inferences can be related to specific time periods representing the sediment interval they were extracted from. Typically, quantitative inferences require 2 steps:

- 1) calibration, in which relationships between proxies and environmental parameters of interest are modeled using a large data set consisting of modern sites encompassing large environmental gradients of interest (e.g., elevation) and state of the art numerical analysis techniques. During this step, relationships between biota (e.g., foraminifera) and measured parameters (e.g., elevation) are modeled and quantified.

2) reconstruction ‘down -core’ using the model computed in step 1) (=transfer function) to reconstruct past parameters (e.g., elevation) based upon the composition and abundance of the sediment biological proxy remains (e.g., foraminifera).

For this project we use a foraminifera-based transfer function developed from new modern samples collected in this study at Dennis Creek in combination with an existing database (Walker et al., 2021) of modern samples from throughout New Jersey. Foraminifera have been extensively used as a sea-level proxy due to their strong relationship with tidal elevation, abundance in salt-marsh sediments, and tests that are well-preserved in sediment (Scott and Medioli, 1978, 1980; Thomas and Varekamp, 1991; Gehrels, 1994, 2007). They can be identified to species level, allowing development of quantitative models and transfer functions that can be applied down-core to reconstruct past environmental parameters (e.g., Kemp et al., 2013; Walker et al., 2021).

Methods

1. Fieldwork and Stratigraphy

Fall 2022

Initial fieldwork was conducted in Fall 2022, which involved stratigraphy analysis with sediment coring (Fig. 1). A transect of 9 cores was taken, ranging from 1 to 6 m in depth, to visually explore the wetlands underlying stratigraphy. The upper 50-60 cm of each core was a brown silty peat. Below was a 1-2 m section of red-brown silty peat. Finally, a dark brown peat overlaid a gray-brown sandy silt at the base. After the visual exploration of multiple cores, one final sediment core was collected from the tidal wetland and preserved for further analyses; however, further examination of this core in the lab revealed that while foraminifera were present in the upper 50-60 cm of the core, they became essentially absent (0-2 tests in a 1-cm slice of sediment) below 60 cm. Due to the absence of foraminifera below 60 cm in the selected core, a new site location was selected to collect a new sediment core to test if foraminifera would be present throughout the entire upper 1.5 m section of the core to allow a complete sea-level reconstruction.



Figure 1. Sediment coring at Dennis Creek with a team of visiting graduate students from the Earth Observatory of Singapore.

30 modern surface samples for foraminifera and stable carbon isotopes were collected. Surface (0-1 cm) sediment samples were used to contribute to a modern training set (dataset used to quantify the relationship between elevation and modern foraminifera and stable carbon isotopes) for the sea-level reconstruction. The modern samples were collected along 2 transects from low marsh to forested upland environments to capture changes in elevation and to include a full range of floral environments.

Spring 2023

The field team returned to Dennis Creek in spring 2023 with a NJDEP boat to access other areas of the tidal wetland environment closer to Delaware Bay and to find a more continuous sequence of brown silty peat that would likely have foraminifera preserved in a sediment core (Fig. 2). Stratigraphy analysis was completed through visual exploration of a transect of sediment cores to find a thick sequence of high salt-marsh sediment. The upper portions of these cores were a brown salt marsh peat, which overlaid a brown silty peat and finally a gray-brown sandy silt at the base. After the visual exploration of these cores was complete, one site was chosen with a thick sequence of high salt-marsh sediment to collect two replicate sediment cores for analysis of at least the upper 1.5 m to produce a sea-level record from the last millennium. The total length of the sediment core was 3 meters.

An additional 15 modern surface samples for foraminifera and stable carbon isotopes were also collected. These surface (0-1 cm) sediment samples were used to contribute to a modern training set (dataset used to quantify the relationship between elevation and modern foraminifera and stable carbon isotopes) for the sea-level reconstruction in addition to the two transects of modern (surface) samples described above. The modern samples were collected along a transect (passing through the collected core location) from the coastal edge of the marsh to a higher marsh interior to capture changes in elevation and to include a full range of floral environments (Fig. 2).

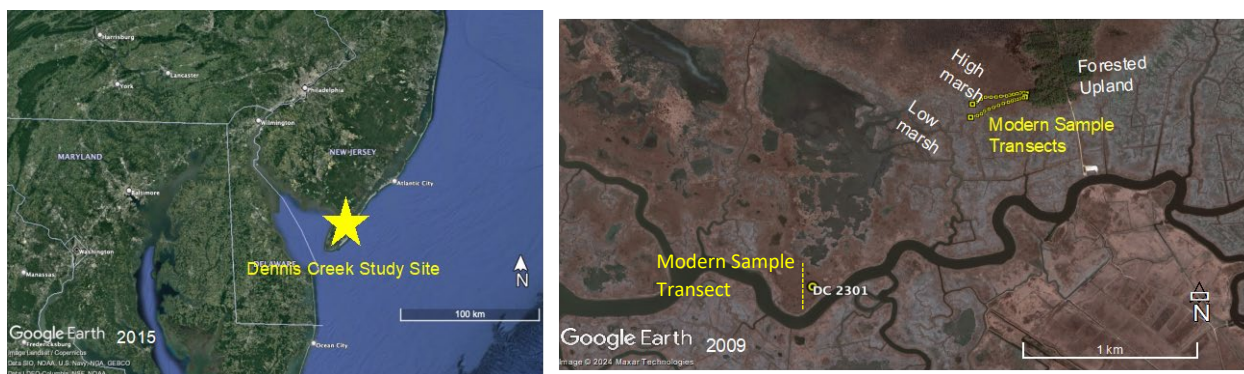


Figure 2. Left: Location of Dennis Creek study site in southern New Jersey. Right: Location of two original modern sample transects and an additional modern sample transect from fieldwork in spring 2023. DC 2301 is the location of the sampled sediment core for analysis (39.1728 N - 74.8698 W).

Spring 2024

The field team returned to Dennis Creek in Spring 2024 with a NJDEP boat to collect additional replicates of the selected DC 2301 core described above. These cores were sampled at a 2 cm resolution for analysis of organic content and bulk density. This information was

used to complete a compaction analysis of the sediment core. Through this analysis, the final sea-level reconstruction can then be corrected for the influence of sediment compaction that occurs naturally in undelaying strata due to sediment accumulation above through time.

2. Labwork

Foraminifera

The original 30 modern surface sediment samples (from fieldwork in Fall 2022 from two 350 meter transects) were prepared and analyzed for foraminifera. Samples were wet sieved to isolate the 63–500 μm size fraction and then split into eight equal aliquots using a wet splitter ([Scott and Hermelin, 1993](#)). In each sample, 100 foraminifera specimens were counted under a binocular microscope while immersed in distilled water and identified to the species level.

In the 2023 sediment core, foraminifera assemblages were analyzed in 1 cm thick core slices spaced every 10 cm to a depth of 160 cm.

Stable carbon isotopes

The original 30 modern surface sediment samples from the 2022 transects were analyzed for bulk sediment stable carbon isotopes, which can be used as an additional secondary proxy to foraminifera in sea-level reconstructions at the Departments of Geology and Environmental Studies at Bryn Mawr College. We analyzed bulk sediment $\delta^{13}\text{C}$ values because the dominant carbon input to salt marsh sediment is in situ marsh vegetation. Bulk sediment $\delta^{13}\text{C}$ was measured using cavity ring-down laser spectroscopy (CRDS) following the flash combustion technique described by Balslev-Clausen et al. (2013).

Additionally, the 2023 sediment core was sampled every 5 cm for stable carbon isotope analysis to a depth of 300 cm.

Loss-on-ignition and bulk density

Every other cm from the surface to 300 cm in the sediment was analyzed for loss-on-ignition and bulk density on the 2023 sediment core. For analysis, samples were dried in an oven and then ignited in a muffle furnace following the methods of Plater et al. (2015). These measurements were used to estimate post-depositional lowering in the core through a sediment compaction model.

Chronology-2023 sediment core

To build a chronology for the upper portion of the sediment core, sediment samples spaced every other cm in the upper 80 cm were sent to the Meadowlands Research & Restoration Institute for analysis of 19 metals. Downcore abundances of metals were matched to historic pollution production and consumption, assuming that the timing and magnitude of atmospheric emissions and deposition approximately coincided (e.g., Gobeil et al., 2013; Kemp et al., 2013; Lima et al., 2005).

To determine the ages of the sediment core below 80 cm, plant macrofossils were picked from the core and sent for radiocarbon analysis at the National Ocean Sciences Accelerator Mass Spectrometry (NOSAMS) Facility at the Woods Hole Oceanographic Institution. Eleven samples have been analyzed and results returned.

3. Results

Foraminifera

The original 30 modern surface sediment samples (from the two 350 meter transects from the Fall 2022 fieldwork) were prepared and analyzed for foraminifera (Figs 3, 4). In each sample, 100 foraminifera tests were counted and identified.

In this study, higher abundances of the foraminifera *Haplophragmoides* sp. and *Pseudothurammmina limnetis* characterize the low marsh environment, whereas the presence of *Milliamina petila* establishes the high marsh environment. *Tiphotrocha comprimata* dominates the middle of each transect, and *Trochammina inflata* is present in moderate abundances throughout.

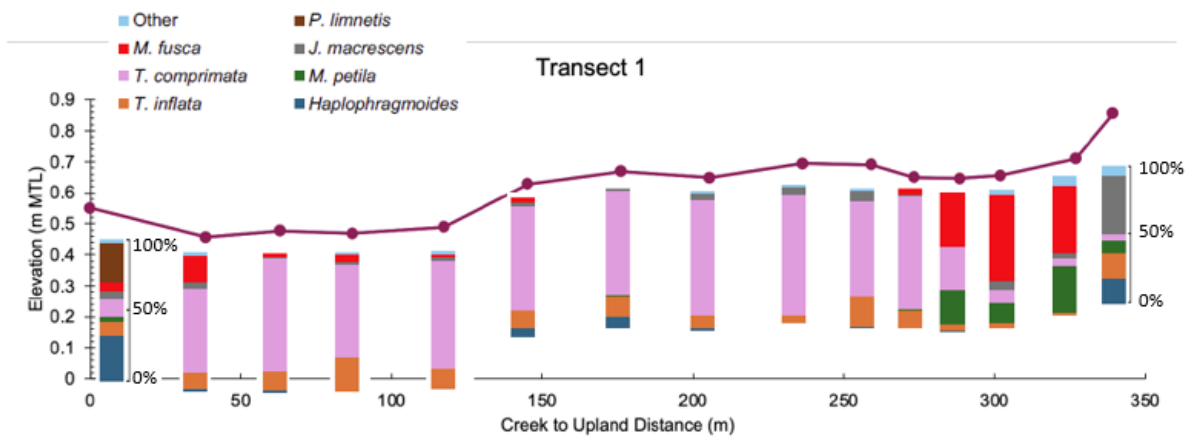


Figure 3. Foraminiferal abundances at each station along Transect 1. Bar graphs show percentages of foraminifera taxa within each sample out of 100%.

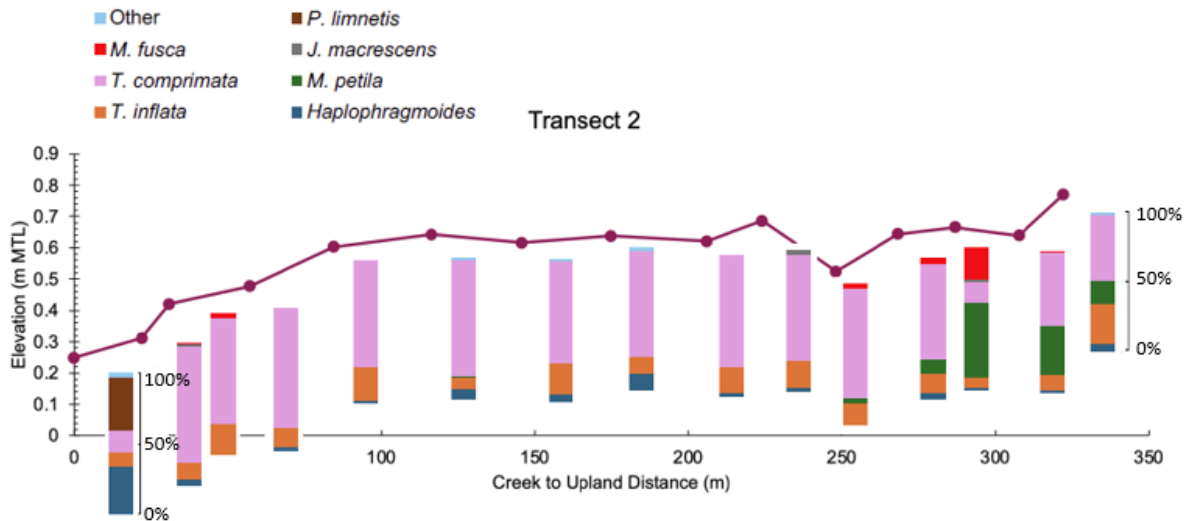


Figure 4. Foraminiferal abundances at each station along Transect 2. Bar graphs show percentages of foraminifera taxa within each sample out of 100%.

Foraminiferal data from the 2023 sediment core suggest that a high marsh environment below Mean Higher High Water (MHHW) existed when the upper ~140 cm of marsh sediment was being deposited, which corresponds to the time period from the early 1500s to present. From 155-165 cm, lower foraminifera abundances indicate the paleomorph surface at this site may have been above MHHW (Fig. 5), which corresponds to the time period from the mid-1300s to mid-1400s. This change occurs as species associated with the highest marsh elevations such as *Haplophragmoides* and *Jadammina macrescens* become more abundant with depth and species such as *Trochammina inflata* and *Milliamina fusca* are declining, which are more prevalent in low and mid marsh elevations. The overall foraminifera counts also drastically decreased at 160 cm, suggesting that the environment was near or above MHHW and nearing the limits of salt marsh foraminifera viability.

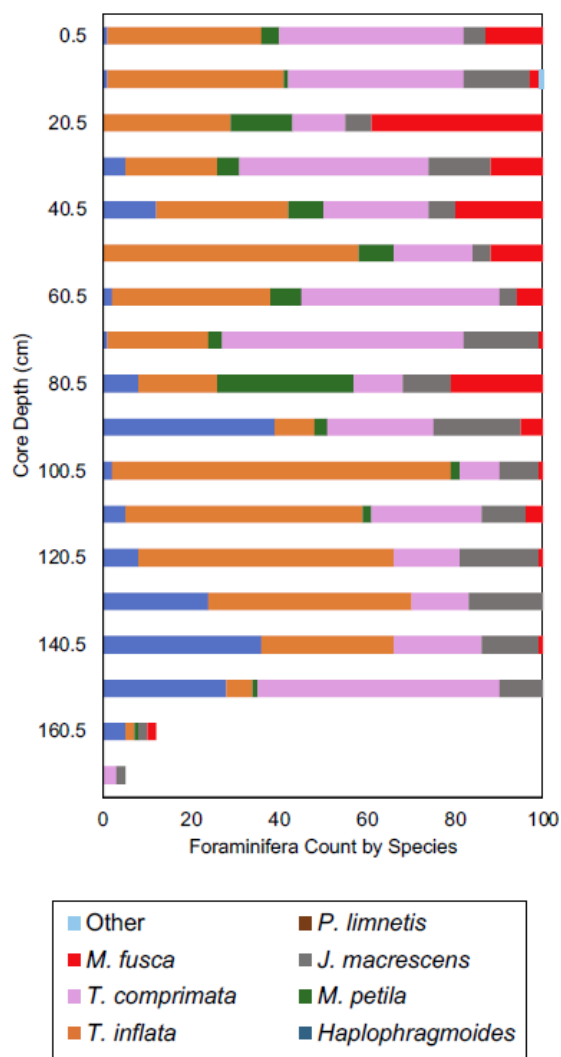


Figure 5. Foraminifera assemblages plotted by depth in the sediment core.

Stable carbon isotopes

The original 30 modern surface sediment samples were also analyzed for bulk sediment stable carbon isotopes, which can be used as a secondary proxy to foraminifera in sea-level reconstructions (Figs 6, 7). For the $\delta^{13}\text{C}_{\text{org}}$ data, values between -27‰ and -22‰ represent the

presence of C₃ vegetation that grow at or above the high marsh. Values between -20‰ and -15‰ indicate C₄ salt marsh plants, indicating low and high salt marsh throughout most of the transect.

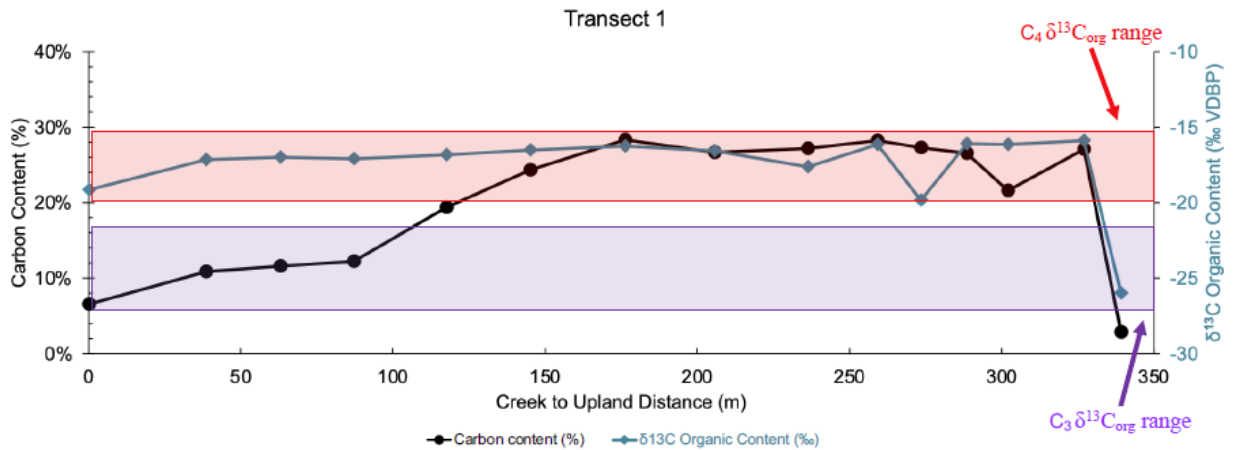


Figure 6. $\delta^{13}\text{C}_{\text{org}}$ (‰ Vienna Pee Dee Belemnite or VPDB) and total carbon content (%) of modern marsh surface samples from Transect 1. VPDB represents the international reference standard for carbon isotopes. In the Carbon Content plot, the greater the carbon percentage, the more plant detritus is present in the sample.

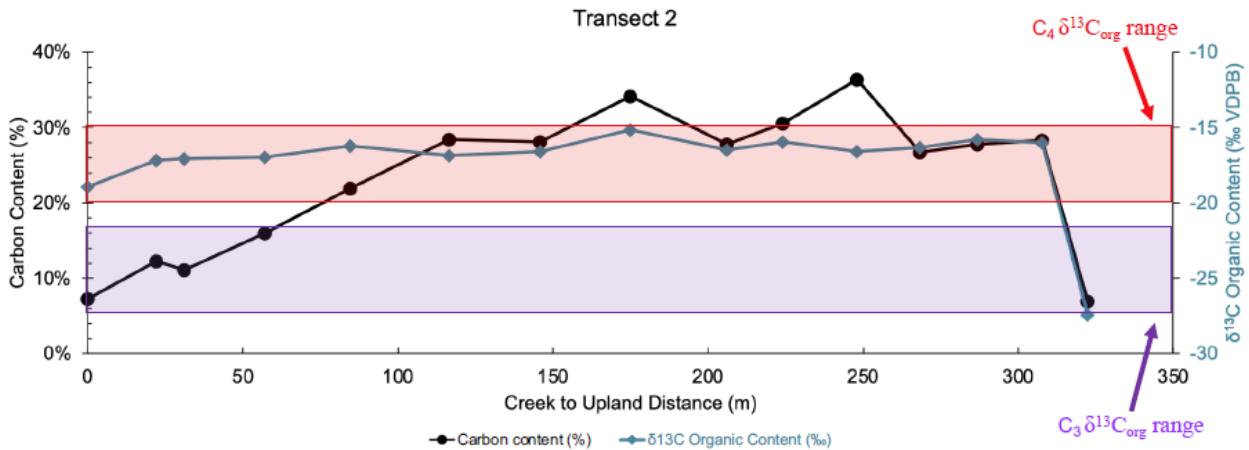


Figure 7. $\delta^{13}\text{C}_{\text{org}}$ (‰ Vienna Pee Dee Belemnite or VPDB) and total carbon content (%) of modern marsh surface samples from Transect 2. VPDB represents the international reference standard for carbon isotopes. In the Carbon Content plot, the greater the carbon percentage, the more plant detritus is present in the sample.

In the sediment core, $\delta^{13}\text{C}$ data suggest that a high marsh environment below MHHW existed while the upper ~140cm of marsh sediment was deposited (Fig. 8). Below 155cm, lower $\delta^{13}\text{C}$ values indicate the paleommarsh surface at this site may have been above MHHW. These results appear to corroborate the results from the foraminiferal assemblages with a transition to an environment at or above MHHW beginning around 160 cm depth. Below a depth of 175 cm, the carbon isotopes clearly suggest an environment dominated by C₃ vegetation, which would occur above MHHW.

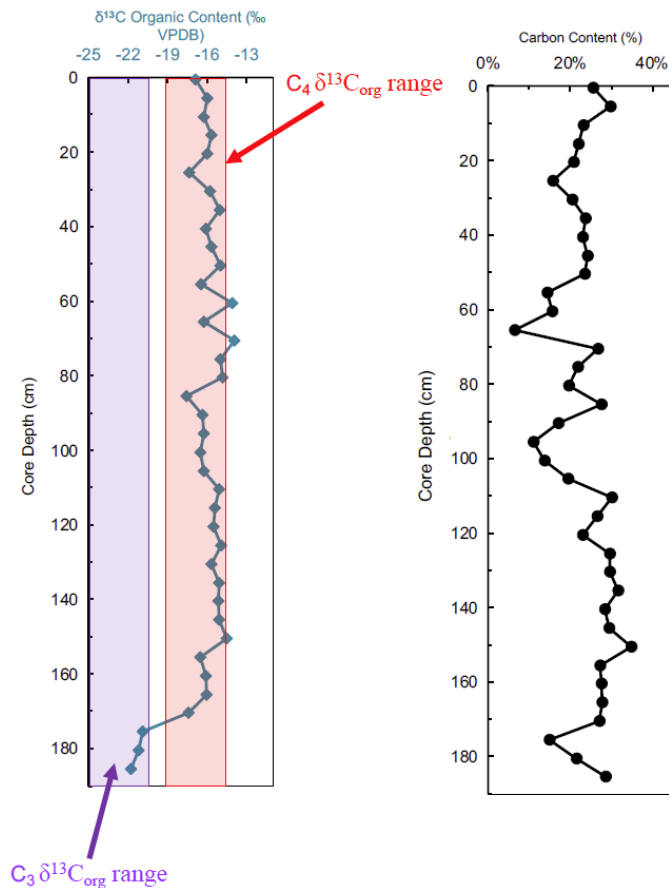


Figure 8. $\delta^{13}\text{C}_{\text{org}}$ (‰ Vienna Pee Dee Belemnite or VPDB) and total carbon content (%) plotted by depth in the sediment core.

Loss-on-ignition and bulk density

Loss-on-ignition (%) had rapid fluctuations in the upper 300 cm, with an average of 44%. Below 300 cm to the base of the core at 325 cm, the LOI rapidly decreased to an average of 8% in the bottom 15 cm (Fig. 9). The fluctuations in organic content are typical of sediment cores from salt-marsh environments as subtle tidal level and regional climate fluctuations affect organic matter accumulation through time. The distinctive decline in organic matter content at the base of the core likely corresponds to an environment prior to the salt marsh formation at this location and may indicate terrestrial sediment deposits.

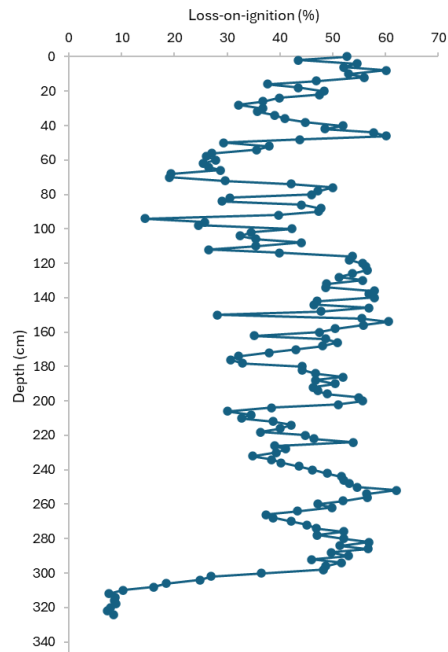


Figure 9. Loss-on-ignition (%) plotted by depth in the sediment core.

Dry bulk density fluctuated between 0.04 and 0.58 g/cc in the upper 300 cm, with an average of 0.19 g/cc (Fig. 10). Below 300 cm to the base of the core at 325 cm, the dry bulk density rapidly increased to 0.93 g/cc at 316 cm and then decreased to 0.49 g/cc at the base of the core.

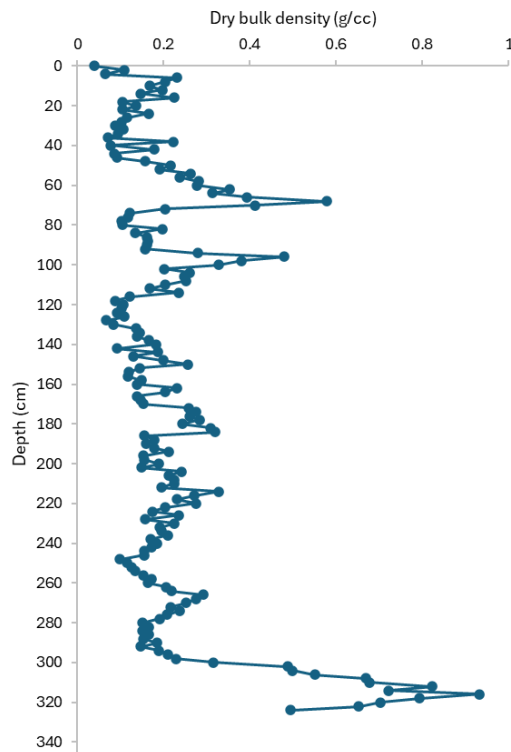


Figure 10. Dry bulk density plotted by depth in the sediment core.

The LOI and bulk density results are used in a geotechnical model (Brain et al., 2011, 2012, 2015) to model post-depositional lowering in the sediment core. The final relative sea-level record can then be corrected for sediment compaction using the results from the geotechnical model.

Chronology

The following changes in downcore abundances of metals (Fig. 11) were used to determine the chronology of the sediment core. The onset of Pb pollution was assigned an age of 1875 CE \pm 20 years (at ~68 cm) (e.g., Kemp et al., 2012), while a peak in Pb pollution is associated with the introduction of the Clean Air Act and was assigned an age of 1974 CE \pm 5 years CE (at ~28 cm) (e.g., Kemp et al., 2012). In addition, a decline in Cd occurred in 1962 CE \pm 5 years (at ~36 cm) (USGS Minerals Yearbook, accessed 2024).

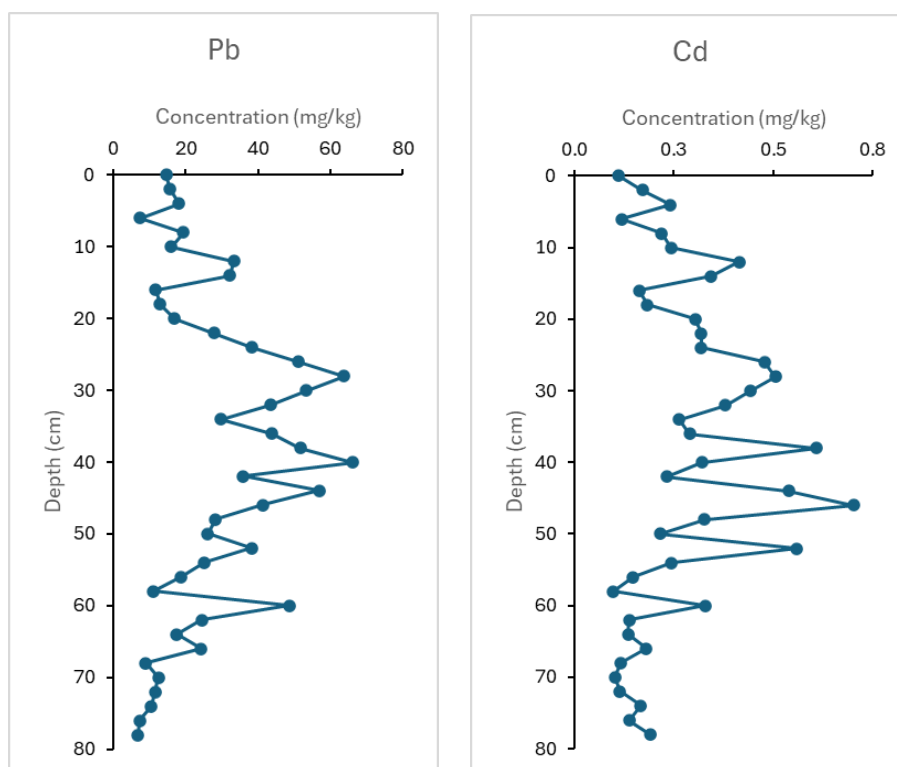


Figure 11. Concentrations of lead (Pb) and cadmium (Cd) plotted by depth in the sediment core.

Eleven plant macrofossil specimens were selected from the core for radiocarbon analysis (as shown in Table 1 below). The radiocarbon ages were corrected using Calib 8.20.

Table 1. Reported radiocarbon ages and uncertainties from the Dennis Creek core with corrected ages using Calib 8.20 and 2 sigma error (95% confidence interval).

Depth (cm)	Radiocarbon Age (radiocarbon years before present)	Age Error (years)	Corrected Age (Common Era)	2s Error (years)
89	120	15	1847	118
111	180	15	1764	143
120	285	15	1555	132
131	325	20	1563	73
150	370	15	1501	83
189	855	15	1197	56
212	965	15	1102	124
233	1030	20	1009	146
255	1250	15	725	144
271	1260	15	721	37
296	1580	15	483	56

An age-depth model (Fig. 12) was constructed using the initial radiocarbon samples and changes in downcore abundances of metals using the Bchron package in R (Haslett and Parnell, 2008; Parnell et al., 2008). The model shows that the 300 cm sediment core spans the last 1500 years. The rate of accumulation is fairly linear through time before increasing in the last several hundred years.

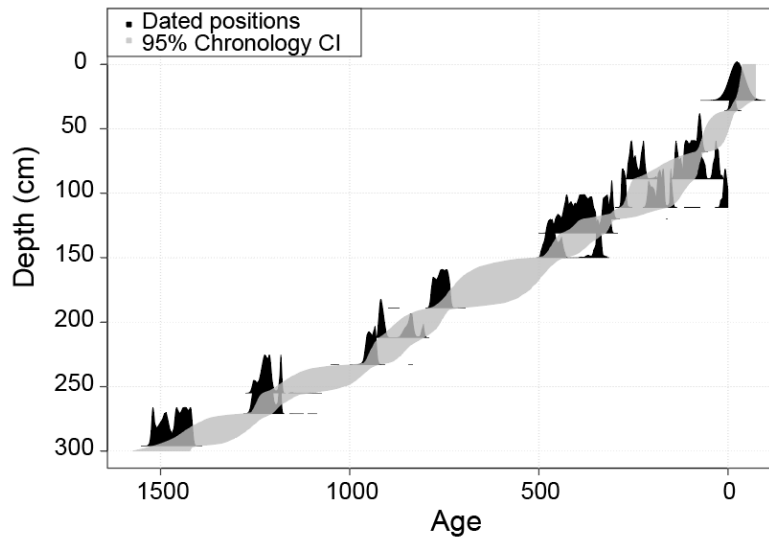


Figure 12. Age-depth model for the sediment core showing position (depth in cm) by age (years BP).

Relative sea-level reconstruction

A Bayesian transfer function (Cahill et al., 2016) was used to provide paleommarsh elevation estimates for each sample within the sediment core. Combined with the chronology from the core, a preliminary record of relative sea-level change over the last 800 years was produced for Dennis Creek (Fig. 13).

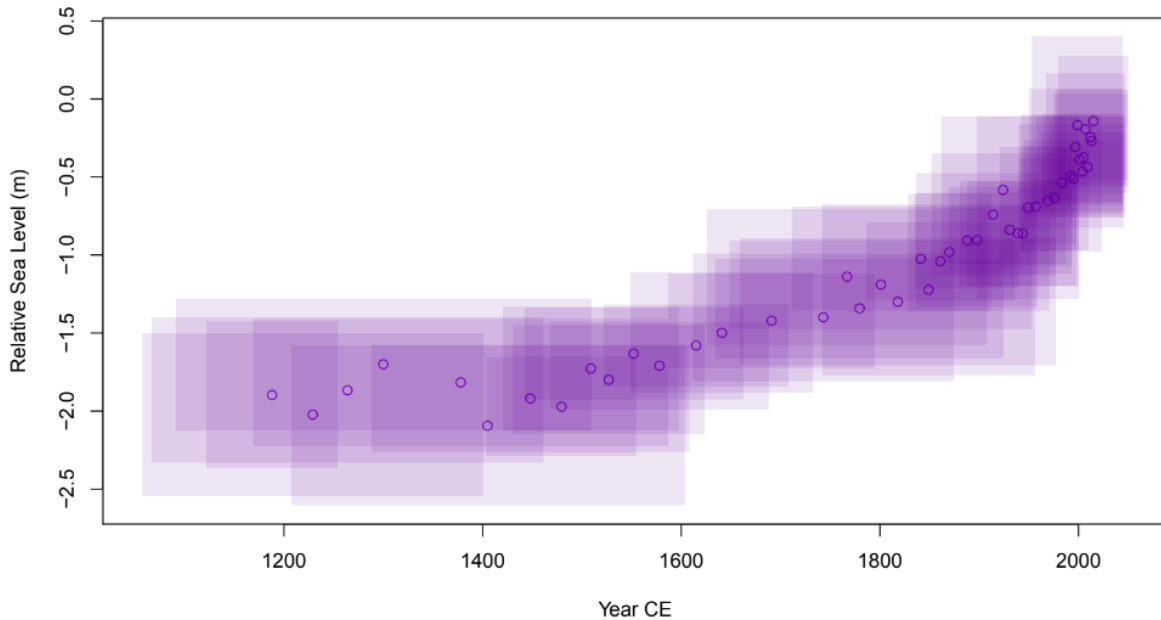


Figure 13. Relative sea-level record from Dennis Creek over the last 800 years. Each purple rectangle represents the vertical and chronological uncertainties, with the midpoint shown by the circle.

Using an Errors-in-Variables Integrated Gaussian Process model (Cahill et al., 2015), quantifications of magnitude and rates of relative sea-level change can be examined (Fig. 14). From 1200 to the present, relative sea level at Dennis Creek rose approximately 1.5 m at a mean rate of 1.8 ± 0.2 mm/yr. The rate of rise appears to continually increase throughout the record until present (Table 2).

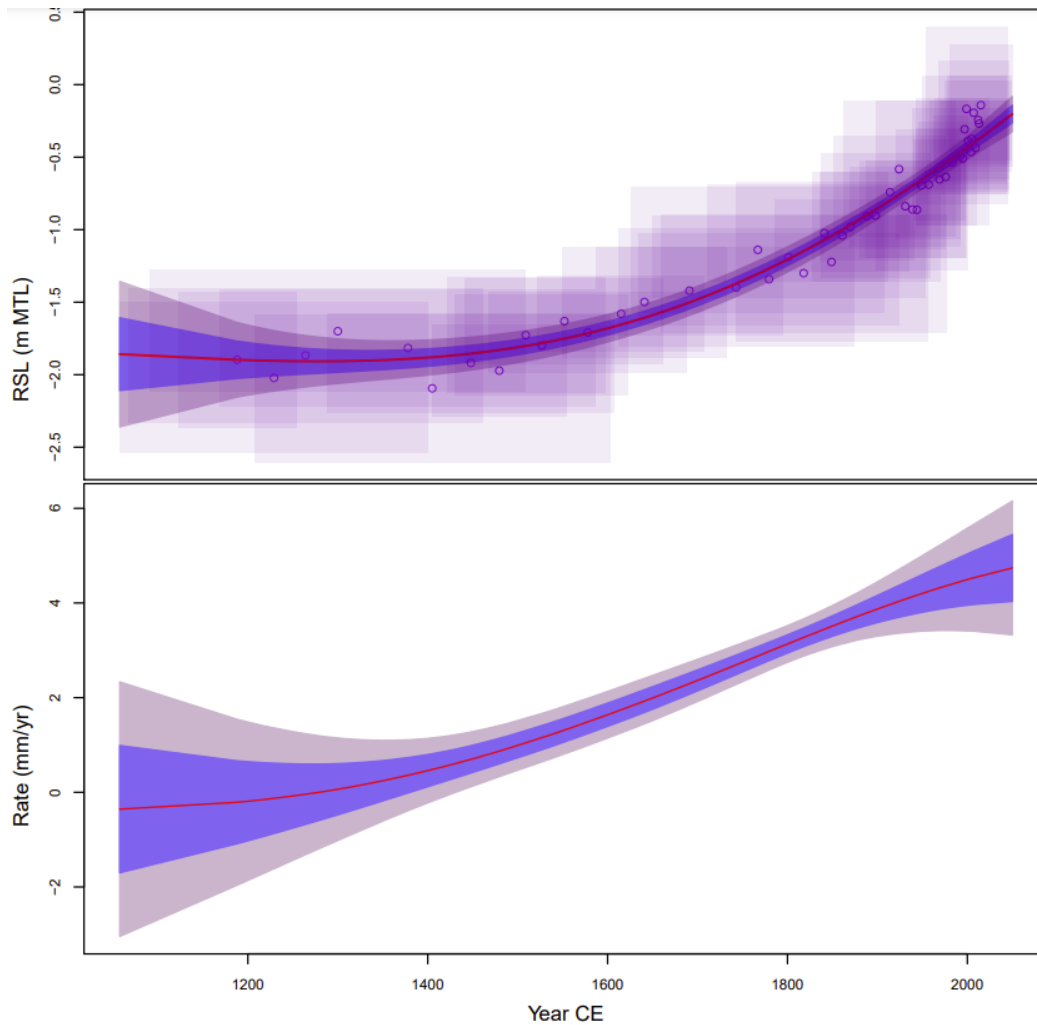


Figure 14. Errors-in-Variables Integrated Gaussian Process model results for Dennis Creek. Top shows the change in relative sea level (m) from 1200 CE to present. Bottom shows the rate (mm/yr) of relative-sea level change from 1200 CE to present.

Table 2. Rates of sea-level change (mm/yr) over various time intervals at Dennis Creek (this study) compared to Cape May Courthouse (Kemp et al., 2013). *Note that the Cape May reconstruction stops at 2008 when the sediment core was collected restricting the comparison after this year.*

Time Interval (year Common Era)	Rate (mm/yr)	
	Dennis Creek (this study)	Cape May Courthouse (Kemp et al., 2013)
Entire study period (1188-2008)	1.8 ± 0.2	1.8 ± 0.2
Rates per century		
1508-1608	1.4 ± 0.3	1.4 ± 0.3
1608-1708	2.1 ± 0.2	1.9 ± 0.3
1708-1808	2.8 ± 0.2	2.5 ± 0.2
1808-1908	3.6 ± 0.2	3.1 ± 0.3
1908-2008	4.2 ± 0.4	3.6 ± 0.5
Rate for last decade		
1998-2008	4.5 ± 0.5	3.8 ± 0.6

Summary Discussion

This record from Dennis Creek provides a unique local understanding of relative sea-level change from the Delaware Bay region of New Jersey. In particular, the Dennis Creek relative sea-level record can be compared with previously published records from the Atlantic coast of New Jersey to analyze varying rates and magnitudes of sea-level in the Common Era. Based on the results shown here, relative sea-level in Dennis Creek started rising more quickly earlier than on the Atlantic coast of New Jersey and at present, has higher rates of relative sea-level rise than some areas of the Atlantic coast. Considering that one of the previously published records (Kemp et al., 2013; Cape May Courthouse) is from a site less than 15 km from the Dennis Creek field site, it is likely that there are significant differences in local processes contributing to relative sea-level change at individual locations. For example, at Cape May Courthouse, relative sea-level rise likely reached a rate of 2 mm/yr by the 1700s and 3 mm/yr by 1900 CE; at Dennis Creek, relative sea-level rise reached a rate of 2 mm/yr by the mid 1600s and 3 mm/yr by 1800 CE. In the 20th century, relative sea-level rise was approximately 3.6 mm/yr at Cape May Courthouse, but 4.2 mm/yr at Dennis Creek. It is crucial to understand local and regional physical driving processes controlling relative sea-level change to produce the most accurate sea-level projections into the future.

As the present results suggest potentially significant local differences in relative sea-level rise (even within a region of southern New Jersey), there could be important implications for how individual coastlines continue to respond to accelerating sea-level rise from human-induced climate change.

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