



The relative utility of foraminifera and diatoms for reconstructing late Holocene sea-level change in North Carolina, USA

Andrew C. Kemp^{a,*}, Benjamin P. Horton^a, D. Reide Corbett^{b,c}, Stephen J. Culver^b, Robin J. Edwards^d, Orson van de Plassche^e

^a Sea-Level Research Laboratory, University of Pennsylvania, Philadelphia, PA 19104, USA

^b Department of Geological Sciences, East Carolina University, Greenville, NC 27858, USA

^c Institute of Interdisciplinary Coastal Science and Policy, East Carolina University, Greenville, NC 27858, USA

^d Department of Geography, Trinity College Dublin, Dublin 2, Ireland

^e Department of Earth and Life Sciences, VU University, Amsterdam, The Netherlands

ARTICLE INFO

Article history:

Received 3 March 2008

Available online 31 October 2008

Keywords:

Foraminifera

Diatoms

Transfer function

Sea level

North Carolina

ABSTRACT

Foraminifera and diatoms preserved in salt-marsh sediments have been used to produce high-resolution records of Holocene relative sea-level (RSL) change. To determine which of these microfossil groups is most appropriate for this purpose we investigated their relative utility from salt marshes in North Carolina, USA. Regional-scale transfer functions were developed using foraminifera, diatoms and a combination of both (multi-proxy) from three salt marshes (Oregon Inlet, Currituck Barrier Island and Pea Island). We evaluated each approach on the basis of transfer-function performance. Foraminifera, diatoms and multi-proxy-based transfer functions all demonstrated a strong relationship between observed and predicted elevations ($r^2_{\text{jack}} > 0.74$ and $\text{RMSEP} < 0.05$ m), suggesting that they have equal utility. Application of the transfer functions to a fossil core from Salvo to reconstruct former sea levels enabled us to consider relative utility in light of 'paleo-performance'. Fossil foraminifera had strong modern analogues, whilst diatoms had poor modern analogues making them unreliable. This result reflects the high diversity and site-specific distribution of modern diatoms. Consequently, we used foraminifera to reconstruct RSL change for the period since ~AD 1800 using a ^{210}Pb - and ^{14}C -based chronology, and we were able to reconcile this with tide-gauge records.

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Introduction

The need for high resolution sea-level reconstruction has increased with realization that the rate of sea-level rise may be accelerating (Kerr, 2006; IPCC, 2007). To better understand this threat in an appropriate context it is necessary to consider recent trends and future predictions of relative sea-level (RSL) rise in light of late Holocene sea-level records (Donnelly et al., 2004; Gehrels et al., 2005, 2006, 2008). Recently, investigators have begun to extract high resolution (cm- to m-scale vertical resolution and annual- to centennial-scale temporal resolution) records of RSL changes from foraminifera and diatoms preserved in salt-marsh sediments using a transfer-function technique (e.g., Horton and Edwards, 2006). There is interest in understanding which of these sea-level indicators is most appropriate for high resolution reconstruction of RSL. Previous studies of late Holocene RSL change in North America have focused on Maine (e.g., Gehrels, 2000; Gehrels et al., 2002, 2005), Connecticut (e.g.,

Varekamp et al., 1992; Nydick et al., 1995; van de Plassche et al., 1998; Edwards et al., 2004a,b) and Nova Scotia (Gehrels et al., 2005).

In this paper we aim to investigate the relative utility of foraminifera- and diatom-based transfer functions to reconstruct late Holocene RSL at high resolution from salt-marsh sediments. We compare contemporary distributions of foraminifera and diatoms at three sites on the Outer Banks, North Carolina, USA. By collecting and analyzing microfossil data from the same sites, at the same time, it is possible to assess the relative utility of foraminifera, diatoms and a combination of the two. The performance of modern training sets developed from foraminifera, diatoms and multi-proxy data estimates the potential of these proxies. Few other studies have assessed different micropaleontological sea-level indicators (e.g., Gehrels et al., 2001; Patterson et al., 2000, 2005) and these studies did not include a geological application as a means to further the investigation of utility, although Nelson et al. (2008) compared paleo-environmental reconstructions derived from foraminifera and diatoms and discuss their reliability.

We apply three transfer functions to a short core to consider the 'paleo-performance' of diatoms and foraminifera. No previous study has used the strength of analogy between fossil and modern samples

* Corresponding author.

E-mail address: kempac@sas.upenn.edu (A.C. Kemp).

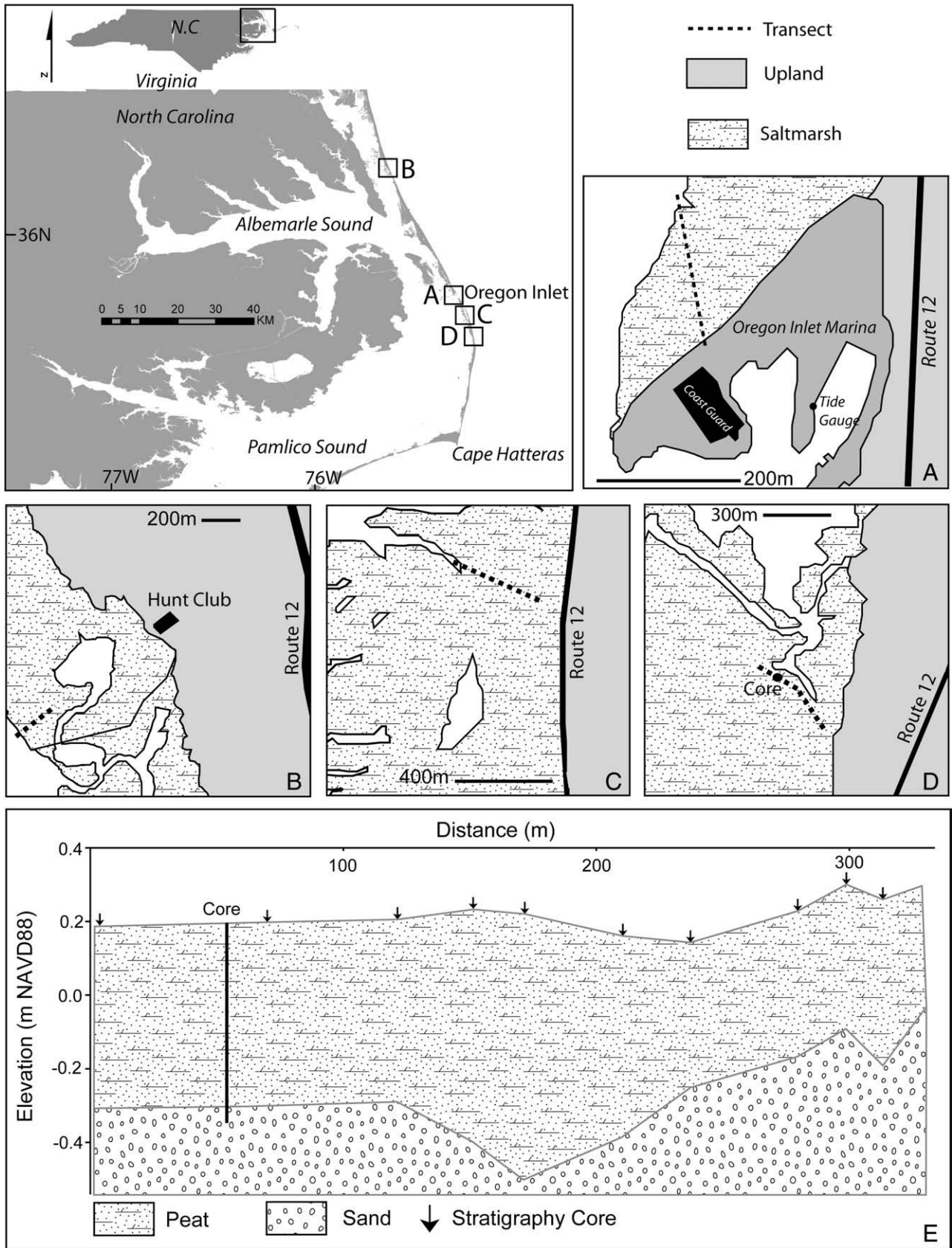


Figure 1. Location of study sites on the Outer Banks barrier islands of North Carolina (NC), USA. Three modern back-barrier marshes were sampled along transects (dashed black lines) at Oregon Inlet (A), Currituck Barrier Island (B) and Pea Island National Wildlife Refuge (C). A core was collected from Salvo (D). A cross section of marsh stratigraphy at Salvo is shown (E).

and RSL reconstructions as an explicit means to consider relative utility of different microfossil groups.

Study areas

We sampled three back-barrier marshes (Oregon Inlet, Currituck Barrier Island and Pea Island National Wildlife Refuge) in the northern part of the Outer Banks, North Carolina, USA (Fig. 1) to provide a regional-scale modern training set of foraminifera and diatoms (Horton and Edwards, 2005). Our approach sought to sample sufficient environments within and between salt marshes to reduce the probability of having a 'no modern analogue' outcome for core samples.

Oregon Inlet, Currituck Barrier Island and Pea Island were chosen because they have differing salinity regimes reflecting their distance from a major barrier inlet (Oregon Inlet). The Outer Banks are a microtidal, wave-dominated environment. Oregon Inlet opened in AD 1864 (Pilkey and Fraser, 2003) and connects Pamlico Sound to the Atlantic Ocean. It is one of three barrier island inlets allowing interchange of waters between Pamlico Sound and the Atlantic Ocean. The Oregon Inlet study site is located <1 km from the waterway on a back-barrier marsh. The marsh is between 100 m and 350 m wide (~200 m at site of transect) and displays a succession from *Spartina alterniflora* at its seaward edge to *Juncus roemerianus* and freshwater shrubs on its landward side. No tidal flat environment is exposed at this site. In August 2002, open-water salinity was measured as 31 ppt (Culver and Horton, 2005); in March 2006 it was 30 ppt.

The Currituck Barrier Island site is located 56 km north of Oregon Inlet. The back-barrier marsh is approximately 200 m wide. There is no tidal flat environment due to negligible astronomical tides. A narrow *J. roemerianus* marsh is succeeded inland by a mixed *J. roemerianus* and *Spartina cynosuroides* marsh. Open-water salinity in Currituck Sound is low: 5 ppt when sampled in August 2002 (Culver and Horton, 2005) and 6 ppt in March 2006.

Pea Island National Wildlife Refuge is 14 km south of Oregon Inlet. The salt marsh is approximately 400 m wide. It displays a succession from *S. alterniflora*, to *J. roemerianus* and then a *Spartina patens*-dominated zone. The marsh is fringed inland by freshwater vegetation. Open-water salinity in Pamlico Sound was 29 ppt when sampled in August 2002 (Culver and Horton, 2005) and 33 ppt in March 2006.

We collected a short core from a salt marsh at Salvo (Fig. 1), which is adjacent to Pea Island. This site was chosen because aerial photography and reconnaissance surveys indicated minimal human modification during the 20th century and no recent overwash from storm surges. Furthermore, stratigraphic investigation (Fig. 1E) revealed a continuous sequence of high marsh *J. roemerianus* peat, which is suitable for high resolution RSL reconstruction (Edwards, 2004; Gehrels et al., 2005; Edwards, 2006). The marsh is about 400 m wide and is dominated throughout by *J. roemerianus*.

Methods

Modern samples

At each of the three sites we established a transect running inland from shallow sub-tidal to freshwater environments. Positioning of surface sample stations along each transect reflected the full range of sub-environments observed on each marsh, as determined by changes in surface elevation and vascular vegetation. In total we sampled 46 stations. At each station we collected two surface samples of ~10 cm³ (10 cm² with a thickness of 1 cm), one for foraminiferal analysis and the other for diatom analysis. To merge data sets from different locations it is necessary to reference them to a common vertical datum (Myers et al., 2005). We standardized the modern elevational data collected at spatially distinct sites by referencing them to a common orthometric datum (NAVD88). We corrected for spatial changes in

MSL by applying the VDatum transformation tool (Hess et al., 2005) generated by NOAA for the North Carolina coast and sound system.

Foraminiferal and diatom analysis

We modified the modern, dead foraminiferal counts of Horton and Culver (in press) by excluding sub-tidal and tidal flat samples because the lithology of the Salvo core is derived from vegetated marsh settings. We used dead assemblages because they are less sensitive to seasonal variations (Horton and Edwards, 2003; Culver and Horton, 2005; Horton and Murray, 2006). Foraminifera newly documented in this study are from the Salvo core.

Sample preparation followed Horton and Edwards (2006). All samples were stored in buffered ethanol and wet sieved to isolate the 63 µm to 500 µm fraction; material larger than 500 µm was discarded after examination. The remaining sample was divided into eight equal parts using a wet splitter (Scott and Hermelin, 1993). Wet counts were completed under a binocular microscope and 200 individuals were counted from a known fraction, or the entire sample was counted in instances where 200 individuals could not be found. The choice to use counts of 200 foraminifera reflects the low species diversity found on salt marshes (Patterson and Fishbein, 1989; Fatela and Taborda, 2002). Identifications of foraminifera were confirmed by comparison with type and figured specimens lodged at the Smithsonian Institution, Washington, DC and The Natural History Museum, London.

Infaunal foraminifera have been documented by researchers on a number of salt marshes (e.g., Ozarko et al., 1997; Goldstein and Watkins, 1998; Patterson et al., 1999; Hippensteel et al., 2000). The presence of foraminifera living (and subsequently dying) in sub-surface sediments may compromise palaeoenvironmental interpretations that are based upon surficial studies of modern populations. The extent of infaunal habitation appears to vary strongly between localities and should be studied as an integral part of understanding modern distributions. In this study we use surface samples (0–1 cm) to describe the modern distribution of salt-marsh foraminifera. This approach is justified by Culver and Horton (2005) who investigated infaunal populations of foraminifera at the Oregon Inlet, Currituck Barrier Island and Pea Island National Wildlife Reserve sites and concluded that the 0–1 cm depth interval provides an adequate and appropriate model upon which to base palaeoenvironmental research.

All diatom counts, including those from the Salvo core, are from Horton et al. (2006). The dataset of modern diatoms is based upon surface (0–1 cm) samples, which represent several seasons of deposition and reduces the possible influence of seasonality and diatom blooms (Zong and Horton, 1999). We excluded all sub-tidal and tidal flat samples because they were redundant (due to the absence of these environments) when applied to the Salvo core.

Chronology

The chronology of the Salvo core is based on ²¹⁰Pb and one ¹⁴C age (Table 1). There has been recent debate about the validity of salt-marsh chronologies derived solely from ²¹⁰Pb dating (e.g., Yang et al., 2001). Marshall et al. (2007) suggest the use of independent chronological markers such as pollen chrono-horizons, bomb spike ¹⁴C and spheroid carbonaceous particles as a means to corroborate age–depth relationships inferred from ²¹⁰Pb dating. We do not have any evidence to suspect problems with our ²¹⁰Pb chronology, but in the absence of such independent age control the chronology of the Salvo core may be treated with some caution. The age–depth model we employ is appropriate given the aim of this study.

²¹⁰Pb and ²²⁶Ra activities were analyzed by direct gamma counting on a germanium detector calibrated via natural-matrix standards (IAEA-300) at each energy of interest. Samples were dried at 60°C, homogenized, packed into standardized vessels, and sealed before counting for at least 24 h. Excess ²¹⁰Pb activities were determined by

Table 1
 ^{210}Pb chronology of the Salvo core

Depth (cm)	Excess Pb-210 (Bq/kg)	Estimated age (yr before AD 2002)	Error (yr)	Year of deposition (AD)
0.5	11.42	Mixed/modern	–	–
2.0	10.37	Mixed/modern	–	–
4.0	11.74	Mixed/modern	–	–
6.0	8.30	11	1.2	1991
8.0	7.71	15	1.6	1987
10.0	6.34	18	2.0	1984
12.0	6.29	22	2.4	1980
14.0	6.00	25	2.8	1977
16.0	4.87	29	3.2	1973
18.0	6.61	33	3.6	1969
20.0	5.33	36	4.0	1966
22.0	3.15	40	4.4	1962
24.0	3.40	44	4.8	1958
26.0	2.52	47	5.2	1955
28.5	2.09	56	6.2	1946
31.5	1.16	75	13.1	1927
34.5	0.39	94	21.1	1908
37.5	0.00	113	31.1	1889
40.5	0.81	131	42.0	1871
43.5	0.04	150	54.2	1852

A chronology for the Salvo core was developed using ^{210}Pb and one radiocarbon date. Sediment-accumulation rates were calculated using the CF-CS model.

subtracting total ^{210}Pb (46.5 keV; corrected for self adsorption after Cutshall et al., 1983 and Cable et al., 2001) from that supported by ^{226}Ra , determined indirectly by the gamma emissions of its granddaughters, ^{214}Pb (295 and 351 keV) and ^{214}Bi (609 keV). Sediment-accumulation rates were calculated using the CF-CS model (Appleby and Oldfield, 1992) and represent a maximum rate for the length of detectable excess ^{210}Pb in the core.

A single AMS radiocarbon age (200 ± 35 ^{14}C yr BP, NOSAMS OS-39370) from salt-marsh plant macrofossil remains is provided from a depth of 0.48 m in the core. This radiocarbon age was calibrated using OxCal 3.10 (Bronk Ramsey, 2005). Its calibrated age range is AD 1640–1960 (95.4% probability).

An age–depth relationship within the core was developed using the method of Heegaard et al. (2005). This enabled the sediment age at all depths in the core to be estimated with an associated error (Fig. 2).

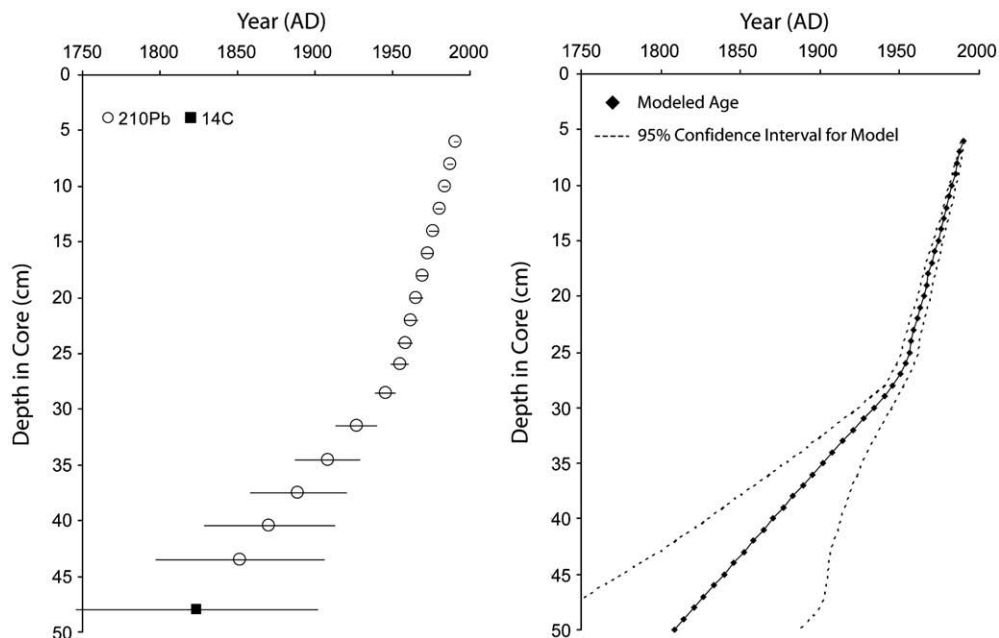


Figure 2. Chronology of the Salvo core was developed using ^{210}Pb and a ^{14}C date (left). The age–depth relationship was modeled after Heegaard et al. (2005) to estimate sample age and error at 1-cm intervals down core (right).

Modern microfossil data

Foraminiferal and diatom distributions are those modified from Horton and Culver (in press) and Horton et al. (2006), respectively. We identified 16 species of foraminifera and 102 species of diatom with an abundance of at least 2% in a single sample (151 in total). Unconstrained cluster analysis and detrended correspondence analysis defined diatom and foraminiferal zones in terms of assemblage constituents and elevational range (Horton et al., 2006; Horton and Culver, in press). Here we summarize these zonations and compare those defined for foraminifera and diatoms at the three study sites (Fig. 3).

At Oregon Inlet, the foraminiferal and diatom assemblages largely correspond with one another and the zones are vertically aligned (Fig. 3). The lowest (shallow sub-tidal) zone (OI-III) consists of calcareous foraminifera such as *Ammonia*, *Elphidium* and *Quinqueloculina* species, and marine/brackish diatom species *Opephora marina* and *Dimeregramma minor*. This zone is found between -1.10 m (lowest sampled elevation) and -0.03 m NAVD88.

Foraminifera in zone OI-II can be subdivided into zone OI-IIa, dominated by *Miliammina fusca* with an elevational range from -0.03 to 0.01 m NAVD88; and zone OI-IIb, dominated by *Arenoparrella mexicana* with an elevational range from 0.01 to 0.04 m NAVD88. Zone OI-II occupies the *S. alterniflora* and *J. roemerianus* marshes. Zone OI-II is dominated by the diatoms *Paralia sulcata* and *Navicula lateropunctata*.

Trochammina inflata and *Haplophragmoides wilberti* dominate the landward zone (OI-I) at Oregon Inlet with *J. roemerianus* and freshwater vegetation. This zone extends from 0.04 to 0.15 m NAVD88 (highest sampled elevation) NAVD88. The diatom assemblage is composed of *P. sulcata* and *Cocconeis scutellum*.

Multivariate analysis of the Currituck Barrier Island transect separates the foraminiferal and diatom assemblages into two zones (Fig. 3). The elevational definition is the same for both foraminifera and diatoms. Zone C-II occupies shallow sub-tidal environments and the *J. roemerianus* low marsh, with an elevational range of -0.56 m (lowest sampled elevation) to 0.06 m NAVD88. The foraminiferal assemblage is dominated by *Ammobaculites subcatenulatus*, *Ammobaculites crassus* and *M. fusca*. The dominant diatoms in zone C-II are *Cocconeis placentula*, *Nitzschia palea*, *Cyclotella meneghiniana* and *Navicula arvensis*.

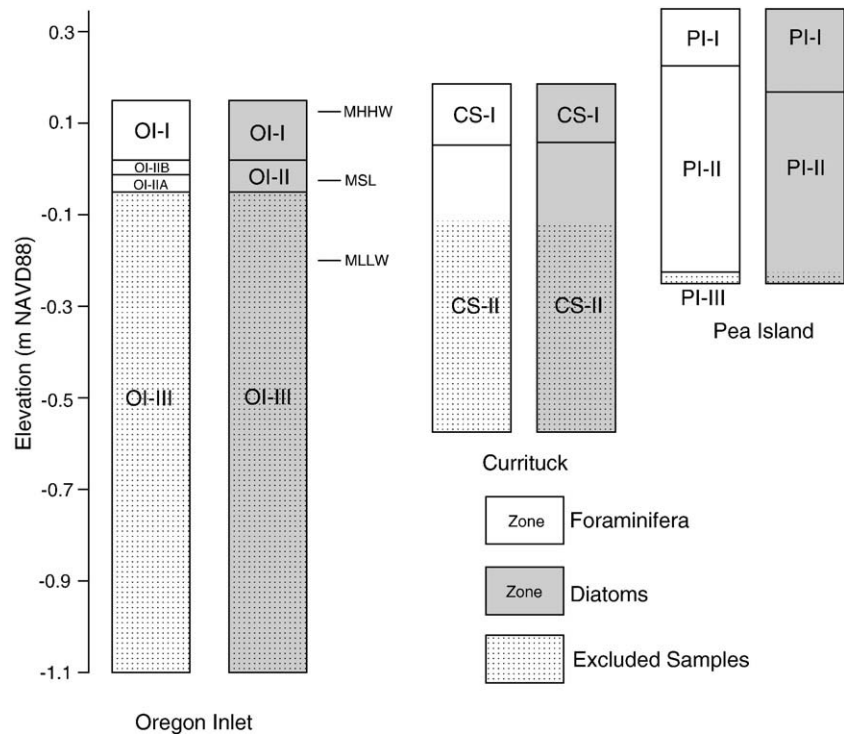


Figure 3. Elevational zonation across three salt marshes of modern foraminifera and diatoms on the Outer Banks. The excluded samples are from shallow sub-tidal and tidal flat environments, which are not represented in the Salvo core.

Zone C-I is found within the mixed *J. roemerianus* and *S. cynosoroides* high marsh and spans an elevational range from 0.06 to 0.18 m (highest sampled elevation) NAVD88, which is above local Mean Higher High Water (MHHW). Zone C-I is dominated by the foraminifer *Jadammina macrescens*. The diatoms consist of oligohalobous species, notably *Navicula tripunctata* and the freshwater epiphyte *N. palea*.

The zonations of foraminifera and diatoms at Pea Island are not congruent as they are at Oregon Inlet and Currituck Barrier Island; there are three foraminiferal zones but only two diatom zones (Fig. 3). Foraminifera zone PI-III occupies a shallow sub-tidal environment and extends from -0.24 m (lowest sampled elevation) to -0.22 m NAVD88 and is composed of *Ammonia* spp. and *Haynesina germanica*. Zone PI-II (-0.22 to 0.20 m NAVD88) is dominated by *T. inflata*. Zone PI-I is identified between 0.20 and 0.33 m (highest sampled elevation) NAVD88; it is dominated by *T. inflata* and *A. mexicana*, this assemblage is found in *S. patens* high-marsh environments.

Diatom zone PI-II (-0.24 to 0.16 m NAVD88) is dominated by *O. marina*, *Mastogloia lanceolata* and *Fragilaria pinnata*. The zone is found in shallow sub-tidal environments, *S. alterniflora* low marsh and *J. roemerianus* middle marsh. Zone PI-I extends from 0.16 to 0.33 m NAVD88. The diatom assemblage is dominated by *Amphora veneta*, *Nitzschia inconspicua*, *Navicula cincta* and *Diploneis smithii*. Zone PI-I is in the *S. patens* high marsh.

Microfossil-based transfer functions

Development

Transfer functions are empirically derived equations for calculating quantitative estimates of past environmental conditions from fossil biological data (Imbrie and Kipp, 1971; Sachs et al., 1977). The equations are constructed from an understanding of the modern, observable relationship between organisms and their environment. Through inverse regression an environmental variable (in this in-

stance elevation) can be expressed as a mathematical function of biological data (Birks, 1995). Elevation is a surrogate variable for the frequency and duration of flooding (Horton and Edwards, 2006). Past environmental conditions are estimated through the application of the modern training set to fossil biological data.

We used statistical measurements to assess the performance of the modern training set. Root Mean Square Error (RMSE) and Root Mean Square Error of Prediction (RMSEP) are measures of predictive ability. RMSE is based upon the difference between observed and predicted values when the sample for which a prediction is made remains in the dataset. Conversely, RMSEP excludes the sample that is being predicted. Thus, RMSEP is considered to be a better measure of a model's true predictive power (Gehrels, 2000). To provide sample-specific error estimates, we used 1000 cycles of bootstrapping to exclude samples. The coefficient of determination (r^2) is used to measure the strength of the relationship between observed and predicted values. The r^2_{jack} statistic excludes the sample being estimated from the training set in estimating a coefficient of determination (Birks, 1995).

We developed three transfer functions from the regional-scale modern training set of foraminifera and diatom data using the computer program C2 (Juggins, 2003). Initially, a transfer function was produced for foraminifera and diatoms, considering each microfossil group separately. The final model merged the foraminifera and diatom data in order to produce a multi-proxy transfer function. The variable of interest, and therefore calibrated for, was elevation. The transfer function was produced using weighted average partial least squares (WA-PLS). According to Birks (1995), WA-PLS is ecologically plausible, has rigorous underlying theory and good empirical predictive power. It does not assume linear biological responses and may be used where the environmental gradient length (established using Detrended Canonical Correspondence Analysis [DCCA]) exceeds two standard deviation units in the modern training set. The length of DCCA axis 1 for foraminifera is 2.155; for diatoms it is 2.679, and for combined foraminifera and diatoms it is 2.704. Therefore, unimodal methods are appropriate (Birks, 1995).

Reconstructions can be evaluated by the use of analogue statistics. We used the modern analogue technique (MAT) based upon chi-square distances to assess the level of analogy between the modern training set and microfossil populations in the Salvo core. For each core sample a minimum distance coefficient was estimated based upon the modern sample most similar to it. Core samples with coefficients below the 10th percentile of the modern training set are considered to have good analogues and therefore provide reliable reconstructions (Birks, 1995; Horton and Edwards, 2006). Samples with coefficients above the 20th percentile are considered to have poor modern analogues and are, therefore, unreliable. We considered samples that fall between the 10th and 20th percentiles to have a fair analogy. Jackson and Williams (2004) noted that distance metrics are a quantitative measure of analogy but that the choice of cut-off or

threshold values remains open to personal selection and should reflect the spatial and temporal scale of the research question(s) being asked. Several authors have used multiple critical values to escape a black-and-white view of analogy in favor of a gray scale (e.g., Overpeck et al., 1985; Anderson et al., 1989; Grigg and Whitlock, 2001).

Performance

The transfer function provides results for five components (progressively more complex models, number 5 being the most complex), each of which has differing statistical attributes. The choice of which component to use is based on the principal of parsimony, that is, selecting the lowest component that gives an acceptable model in terms of RMSEP and r^2_{jack} . Our transfer functions are based upon

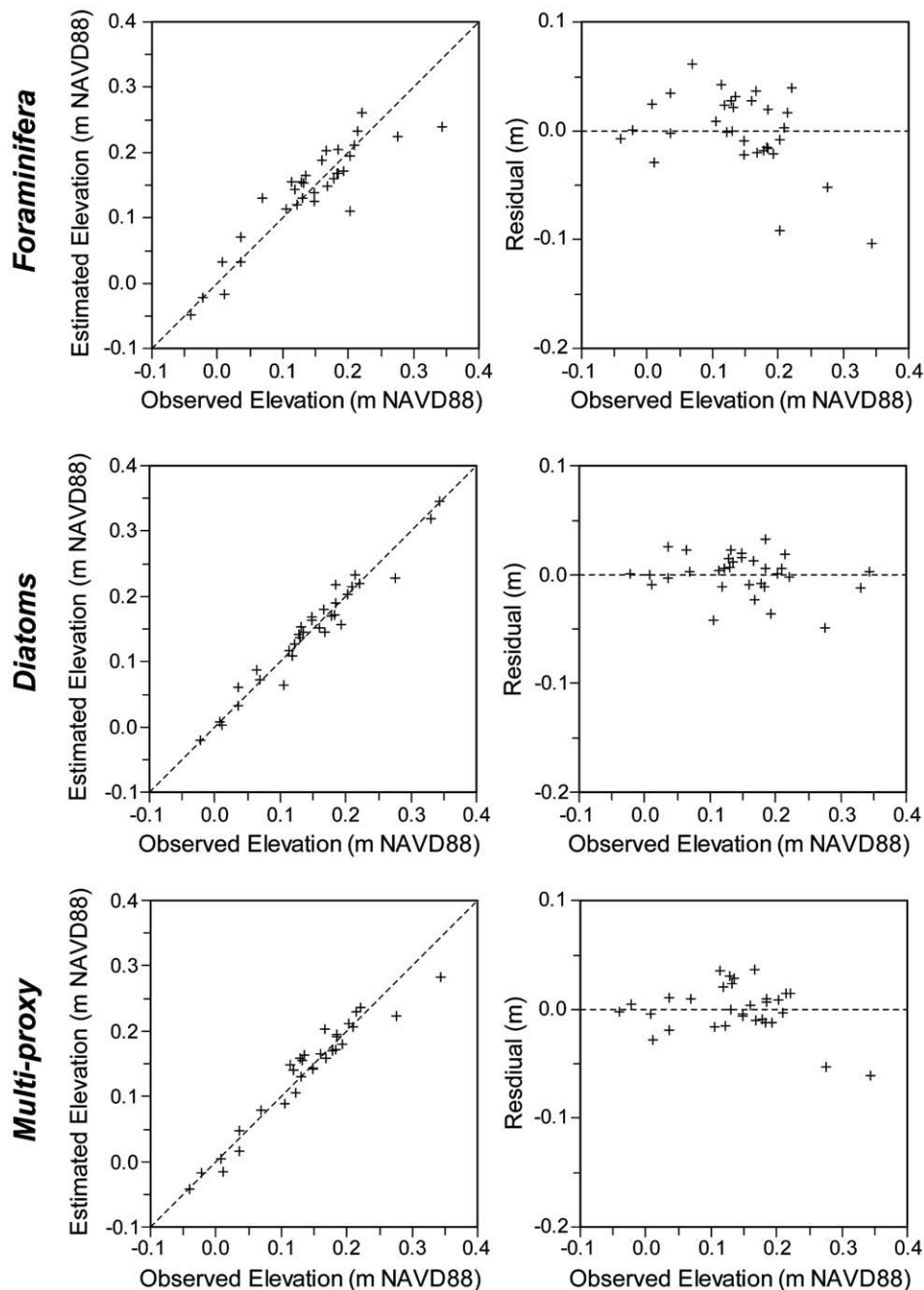


Figure 4. Performance of transfer functions developed using foraminifera (top), diatoms (middle) and a multi-proxy approach (bottom). We excluded sub-tidal and tidal flat samples because peat lithology showed that these environments were absent from the Salvo core.

Table 2
Transfer-function performance

	Foraminifera	Diatoms	Multi-proxy
Component	2	2	2
RMSE (m)	0.035	0.019	0.022
RMSEP (m)	0.042	0.041	0.035
r^2	0.82	0.95	0.93
r^2_{jack}	0.74	0.76	0.83
Max bias (m)	0.103	0.049	0.061

Performance of three WA-PLS transfer functions developed from modern foraminifera, diatoms and a combination of both (multi-proxy) from three salt marshes on the Outer Banks. All results are from component two. The multi-proxy model marginally outperforms the other two in terms of predictive power (r^2_{jack}) and precision (RMSEP). Transfer functions were computed using the C2 program (Juggins, 2003).

component two because it significantly outperformed component one but was not improved upon by more complex models.

All three of the transfer functions show a strong relationship between observed and predicted elevations (Fig. 4, Table 2). The multi-proxy model marginally outperforms the other two in terms of predictive power (r^2_{jack} multi-proxy=0.83; r^2_{jack} diatoms=0.76; r^2_{jack} foraminifera=0.74). The predicted errors are very small for all three models, reflecting the small tidal range of the study area, and the multi-proxy approach again shows a very slight advantage (RMSEP multi-proxy=0.03 m; RMSEP foraminifera=0.04 m; RMSEP diatoms=0.04 m).

Application

We applied the transfer functions developed from a regional dataset to 18 peat samples from a short core at Salvo. The Salvo core is 0.55 m long and consists of 0.50 m of brown salt-marsh peat with

abundant *J. roemerianus* remains, overlying gray sand (Figs. 1 and 5). The surface altitude of the core is 0.19 m NAVD88.

The down-core distribution of selected foraminifera and diatoms from the Salvo core is shown in Figure 5. Foraminifera were abundant throughout the core; 13 species were identified, of which four were dominant and exhibited an oscillating pattern of abundance (Fig. 5). The lowermost section of the core (0.53–0.43 m) was dominated by *T. inflata* (>53%) and *A. mexicana*. Between 0.43 m and 0.27 m there was a significant increase in *H. wilberti* (>25%) and *J. macrescens*. From 0.27 to 0.15 m *A. mexicana* (12–66%) and *T. inflata* (29–56%) were the dominant species, and there was a significant decrease in *H. wilberti* (<1%). The uppermost part of the core recorded a large increase in *H. wilberti* (>32%) and a decline of *A. mexicana* and *T. inflata*.

Polyhalobous diatoms dominated the Salvo core. A total of 53 species were identified. Between 0.53 m and 0.43 m there were high abundances of *Diploneis bombus* (up to 29.4%), *D. smithii* (up to 37.8%) and *P. sulcata* (>15%). At 0.43 m there was an unusually high abundance of *Nitzschia scalaris* (24.6%), a species that did not exceed 1.3% in the other samples. The assemblage became more diverse between 0.39 and 0.27 m, where there was an increase in *O. marina* (from 0% to 19%) and *D. smithii* remained an important constituent (up to 24%). The interval between 0.27 m and 0.15 m was dominated by *D. smithii* (>20%). The uppermost 0.15 m showed a decline in *D. smithii* and *O. marina* became the dominant species.

The transfer function assigned each of the 18 samples a paleo-marsh elevation (PME) and a sample-specific error (Fig. 6). PME is an estimate of the elevation of a marsh surface relative to NAVD88 based upon the modern, observable relationship between marsh-surface elevation and assemblages of foraminifera and diatoms. The foraminifera-based transfer function estimated PME's from 0.08 to 0.22 m NAVD88 (mean of 0.14 m) with an average error of 0.04 m (Table 3). Diatoms produced the largest range of estimated PME's, from 0.03 to

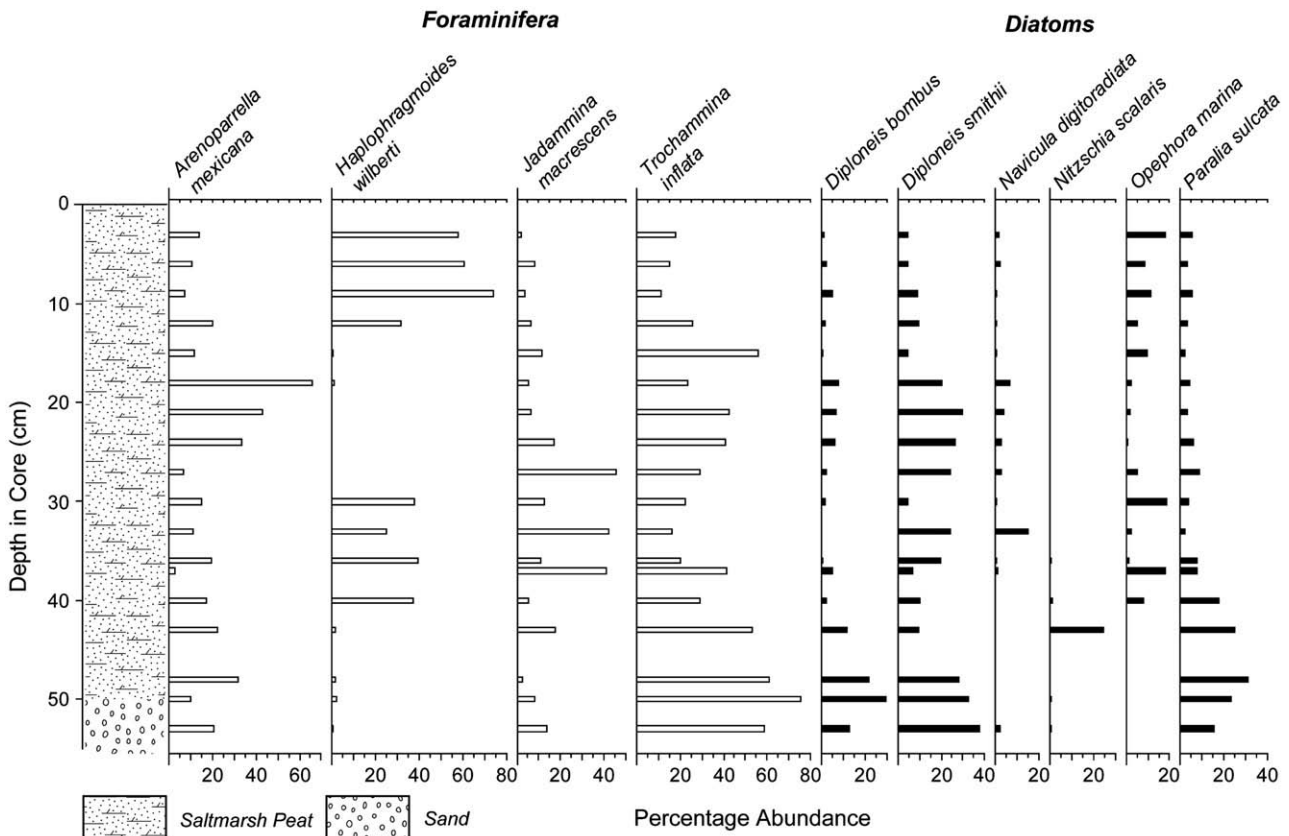


Figure 5. Abundance (shown as a percentage of total individuals) of foraminifera and diatoms from the Salvo core. Only the most abundant species are shown.

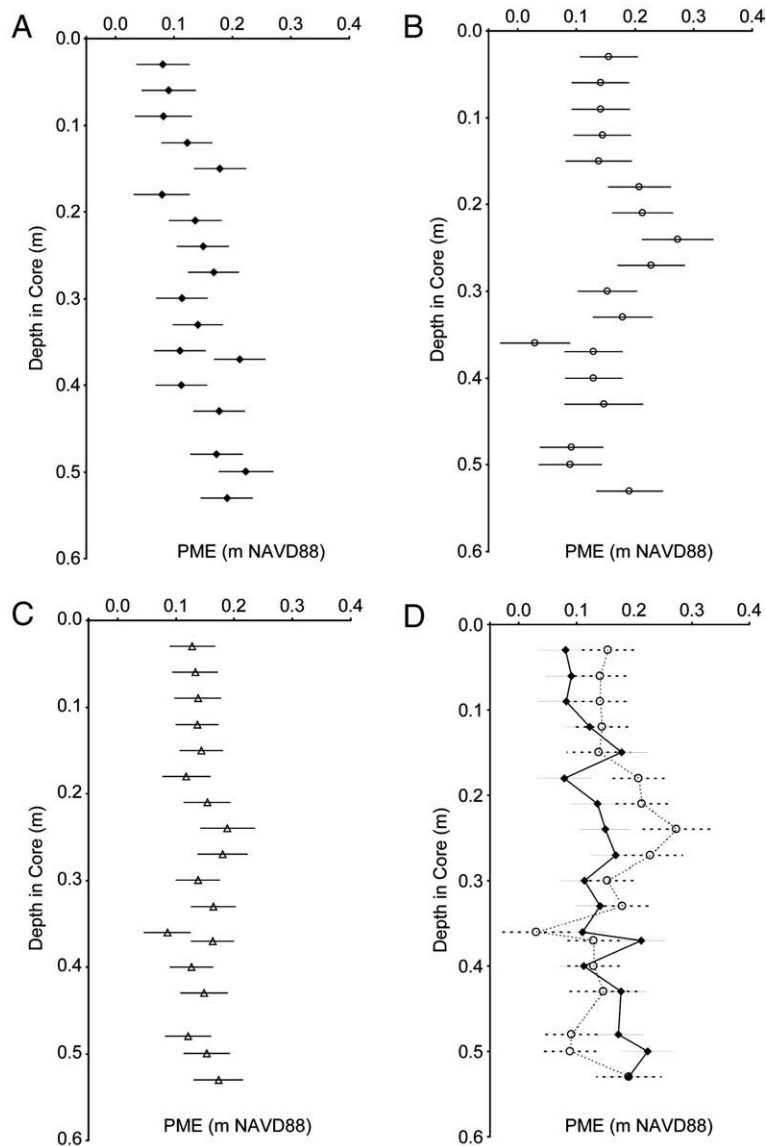


Figure 6. Paleo-marsh elevations (PME) estimated using WA-PLS transfer functions including foraminifera (A), diatoms (B) and a combination of both (C). Foraminifera and diatom-based estimates are both shown in (D). Sample-specific errors were estimated by bootstrapping.

0.27 m NAVD88 with a mean of 0.15 m (Table 3). The average error for diatoms is 0.05 m. The multi-proxy-based transfer function exhibited the smallest range of estimated PME, from 0.09 to 0.19 m NAVD88 (mean of 0.14 m) with an average error of 0.04 m (Table 3). At depths of 0.18 m, 0.24 m and 0.50 m in the Salvo core there was no overlap of foraminifera and diatom-based estimates of PME when errors are included (Fig. 6, Table 4), and so they are considered to be significantly different.

Table 3
Summary of paleo-marsh elevations estimated for samples within the Salvo core

	Foraminifera (n=18)	Diatoms (n=18)	Multi-Proxy (n=18)
Maximum PME (m NAVD88)	0.22	0.27	0.19
Minimum PME (M NAVD88)	0.08	0.03	0.09
Range of PMEs (m)	0.14	0.24	0.1
Average PME (m NAVD88)	0.14	0.15	0.14
Average error (m)	0.04	0.05	0.04

Summary of paleo-marsh elevations (PMEs) estimated from 18 samples within the Salvo core using transfer functions developed from foraminifera, diatoms and a combination of both (multi-proxy). The Salvo core is 55 cm long and consists of 50 cm of salt-marsh peat with abundant *Juncus roemerianus* remains overlying sand.

There was a striking contrast between dissimilarity coefficients (with 10th and 20th percentile cut-offs) for foraminifera, diatoms and multi-proxy-based reconstructions (Fig. 7). Foraminifera had a strong analogy to the modern training set whilst diatoms demonstrated a pronounced dissimilarity. The foraminifera-based reconstruction had one sample exceeding the 20th percentile (at 0.27 m depth) and 12 samples below the 10th percentile. In contrast, the diatom-based model had no samples below the 10th percentile and 12 samples exceeding the 20th percentile. The multi-proxy-based reconstruction showed four samples below the 10th percentile and nine exceeding the 20th percentile.

Discussion

Patterson et al. (2000; 2005) and Gehrels et al. (2001) investigated the relative utility of foraminifera and diatoms for sea-level reconstruction. They concluded that each of these groups, or combinations of them, all produced similar results. We also show that performance ($r^2_{\text{jack}} > 0.74$ and $\text{RMSEP} < 0.05$ m) of modern training sets of foraminifera, diatoms or a combination of them are almost identical. A multi-proxy approach to sea-level reconstruction was cited by

Table 4

Estimated paleo-marsh elevations for 18 samples in the Salvo core

Depth(m)	Foraminifera		Diatoms	
	PME (m NAVD88)	Error (m)	PME (m NAVD88)	Error (m)
0.03	0.08	0.05	0.15	0.05
0.06	0.09	0.05	0.14	0.05
0.09	0.08	0.05	0.14	0.05
0.12	0.12	0.04	0.15	0.05
0.15	0.18	0.04	0.14	0.05
0.18	0.08	0.05	0.21	0.05
0.21	0.14	0.04	0.22	0.05
0.24	0.15	0.04	0.28	0.06
0.27	0.17	0.04	0.23	0.05
0.30	0.11	0.04	0.15	0.05
0.33	0.14	0.04	0.18	0.05
0.36	0.11	0.04	0.03	0.06
0.37	0.21	0.04	0.13	0.05
0.40	0.11	0.04	0.13	0.05
0.43	0.18	0.04	0.11	0.05
0.48	0.17	0.04	0.09	0.05
0.50	0.22	0.05	0.09	0.05
0.53	0.19	0.04	0.19	0.05

Down-core paleo-marsh elevations (PMEs) estimated by the application of foraminifera- and diatom-based transfer functions to 18 samples in the Salvo core. Sample-specific errors were derived by bootstrapping. The gray depth intervals represent those samples where there is no overlap of PME estimates when the errors are included.

Gehrels et al. (2001) as very slightly out-performing transfer functions using a single microfossil group. Similarly, the performance of our transfer functions shows that combining foraminifera and diatoms offers minimal statistical improvement. Furthermore, transfer-function performance (high r^2_{jack} and low RMSEP) is comparable to results documented by other researchers using foraminifera- and diatom-based transfer functions to study sea level (e.g., Foraminifera: Gehrels, 2000; Edwards et al., 2004a,b; Patterson et al., 2004; Horton and Edwards, 2006; Massey et al., 2006. Diatoms: Zong, 1997; Zong and Horton, 1999; Gehrels et al., 2001; Ng and Sin, 2003; Sawai et al., 2004; Szkornik et al., 2006).

No previous study however, has looked beyond modern training set performance of different microfossil groups and considered down-core PME estimates as a means of making an assessment of relative utility. Intuitively there should be no difference because of the almost identical performance of the models. Indeed, only three of the 18 samples in the Salvo core show significantly different PME estimates depending on whether foraminifera or diatoms were used (Table 4).

To investigate paleo-performance further we analyzed the dissimilarity between samples in the Salvo core and the modern training set. Only one sample lacks a modern foraminifera analogue (at 0.27 m), while 12 of 18 diatom samples are seen as unreliable because they have a poor modern analogue (Fig. 7). As a consequence of the poor modern analogues for diatoms in the Salvo core, there are nine multiproxy samples with poor analogues and nine with fair or good analogues.

At first it appears contradictory that diatoms in the Salvo core lack modern analogues yet are able to estimate PMEs, which for most samples are comparable to those from the foraminifera-based transfer function (which have good modern analogues). This is probably a product of the small tidal range of the Outer Banks (at Oregon Inlet, for example, the difference between MHHW and MLLW is 0.36 m; Fig. 3) and a modern sampling regime that uses transects across salt marshes. As such, the transfer functions included modern samples covering an elevational range of 0.52 m (−0.18 to 0.34 m NAV88). This elevational range effectively sets the limits of any transfer-function-based estimate of a PME. Even with little analogy between diatoms in the Salvo core and the modern training set, the transfer-function-derived estimate of PME will largely be restricted to the elevational range of the modern data set. These differences should be considered

in light of the range of estimated PMEs (0.24 m) in the Salvo core. The diatom-based transfer-function estimates the minimum (0.03 m) and maximum (0.27 m) PME.

However, there does not appear to be a consistent relationship between PMEs estimated from foraminifera and those estimated from diatoms. In the upper section of the Salvo core (0–0.33 m) diatoms estimate a higher PME in 10 of 11 samples (the exception is at 0.15 m). Conversely, in the lower section (0.33 to 0.53 m) foraminifera provide estimated PMEs greater than that from diatoms in six of seven samples. The difference between foraminifera and diatom-derived estimates of PME at a single depth in the Salvo core varies from 0 to 0.13 m.

There are a number of possible reasons why diatoms in the Salvo core lack good analogues in the modern training set. In the Salvo core there are 14 species of diatoms that do not appear in the modern training set of 151 species. This does not necessarily cause a no- or poor-analogue outcome for environmental reconstruction, but in the case of the Salvo core these species represent a significant proportion of the assemblage at some depths. At 0.15 m (poor analogue; Fig. 7), for example, 21.7% of the diatoms found in the core are not represented in the modern training set. *Diploneis suborbicularis*, *Mastogloia elliptica* and *Rhabdonema adriaticum* each make up more than 4% of diatoms in this sample.

In addition to diatom species that are absent from the modern training set, there are species that make up significant proportions of assemblages in the core but are relatively minor components in the modern environment. *Actinocyclus octonarius*, for example, has a maximum abundance of 2% in the modern training set but represents 49% of diatoms at a depth of 0.36 m (poor analogue; Fig. 7) in the core (Fig. 5). This is responsible for the sharp decrease in estimated PME at depths between 0.33 m and 0.36 m (Fig. 6, Table 4). *D. bombus* also makes up a significant proportion of some core samples but is relatively scarce in the modern training set. At a depth of 0.50 m (poor analogue; Fig. 7) it constitutes 29% of the assemblage (Fig. 5) whilst the maximum abundance of this species in the modern training set is 9%.

Hill's N2 defines the effective number of species in a sample and is a measure of assemblage diversity (Hill, 1973). Transfer-function output provides an N2 value for each sample in the core. The average N2 value for diatoms in the core is 10.4 (ranging from 3.2 to 19.9), and for foraminifera the average is 2.9 (ranging from 1.7 to 4.6). Foraminifera in the Salvo core are much less diverse than diatoms; a few species of foraminifera are dominant throughout the core. The transfer function also provides an N2 value for each species in the modern environment, which is an estimate of the number of samples in which a species has an effective occurrence (i.e., is a significant component of the assemblage). Modern foraminifera on the three sampled salt marshes occur in assemblages with much less diversity than diatoms from the same sites.

To investigate community composition further, we employed detrended correspondence analysis (DCA). We applied this method to the modern training sets of foraminifera, diatoms and a combination of both (Fig. 7). The modern diatoms are grouped very distinctively by site. Each of the three sites (Oregon Inlet, Currituck Barrier Island and Pea Island) form mutually exclusive groups; there is no overlap of samples from different sites and the samples from a single site plot very close to one another, implying that species composition differs markedly between sites. The diatoms from the Salvo core may lack good modern analogues in most instances because of the site-specific nature of modern diatom distributions on the Outer Banks. In comparison, samples of foraminifera from two of the three sites (Oregon Inlet and Pea Island) overlap with one another and form diffuse groups (Fig. 7). Low-salinity Currituck Barrier Island foraminifera plot separately from the two higher salinity sites but as a diffuse group.

Few studies have provided modern data sets of both salt-marsh or mangrove foraminifera and diatoms. Where these studies are

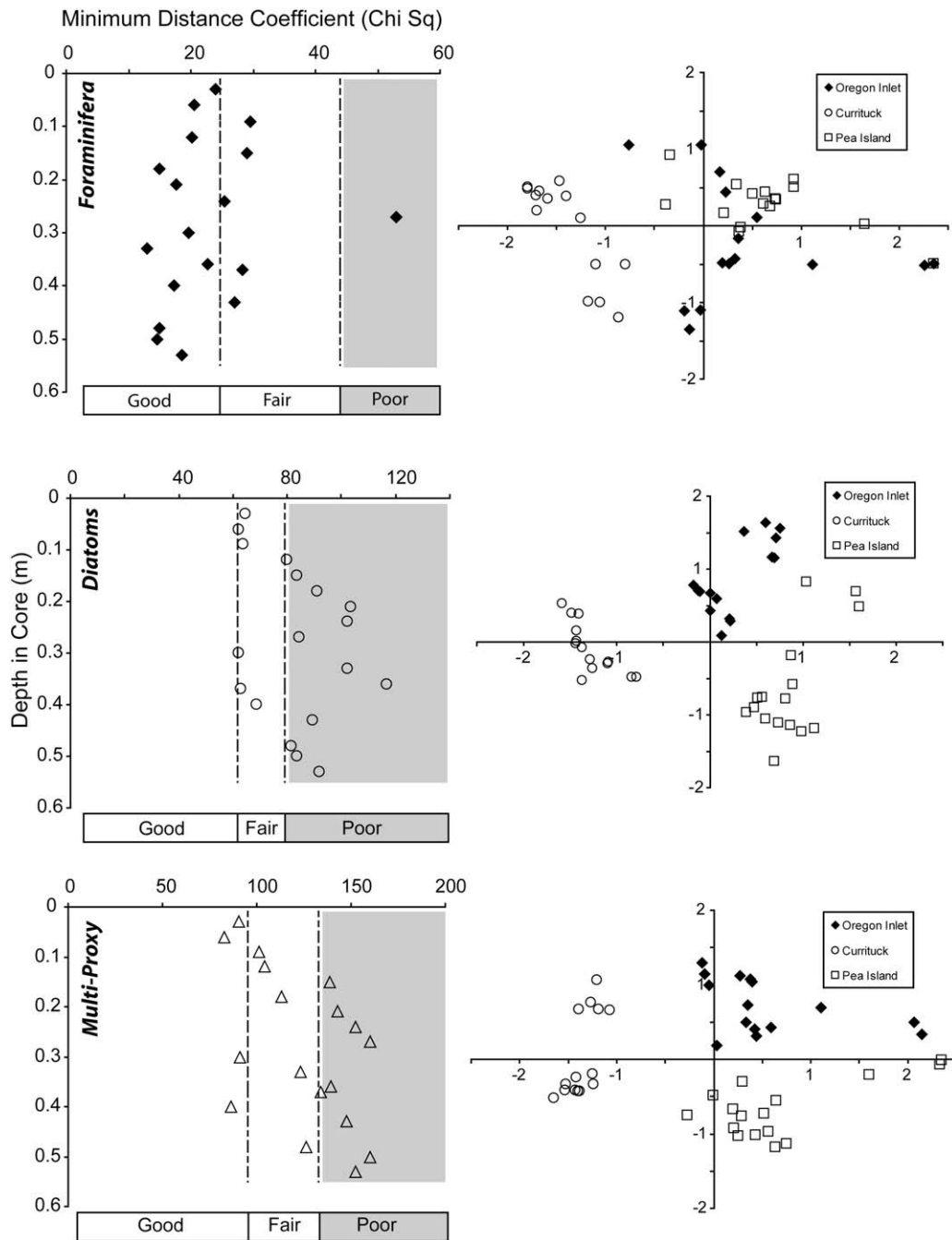


Figure 7. Estimates of dissimilarity and strength of analogy for samples in the Salvo core (left). Foraminifera have good analogies in the modern training set but diatoms do not. Detrended correspondence analysis (right) of modern foraminifera (top), diatoms (middle) and a combination of both (bottom).

available they demonstrate that diatoms form high-diversity assemblages that vary significantly in composition between sites. Foraminifera, however, form low-diversity assemblages, frequently composed of the same ubiquitous taxa globally (Sen Gupta, 1999). Gehrels et al. (2001) collected modern foraminifera and diatoms from three salt marshes in the United Kingdom. A total of 361 species of diatoms were recorded of which 35 occurred in more than half of the samples. Only two species of diatom (*Navicula pusilla* and *Navicula peregrina*) were important constituents at all three sites. In contrast, a total of 29 species of foraminifera were recorded. The dominant agglutinated foraminifera were *M. fusca*, *T. inflata*, *J. macrescens* and *Haplophragmoides* spp. at all three sites. In Indonesia, Horton et al. (2007) identified 73 and 62 species of diatoms from two intertidal transects on the small island of Kaledupa. The dominant taxa at these

two sites are not consistent in presence or relative abundance. One of these transects (Ambeua) was also sampled for foraminifera (Horton et al., 2005); six species of agglutinated foraminifera were identified; the dominant taxa were *M. fusca*, *T. inflata* and *A. mexicana*. Nelson and Kashima (1993) reported the distribution of diatoms in four salt marshes in southern Oregon, USA and compared them to the foraminifera identified by Jennings and Nelson (1992) at three of the same sites. In total, 79 species of diatom were identified (17 of these compose 99% of individuals). Ten species of agglutinated foraminifera were present; the dominant species (*M. fusca*, *T. inflata*, *J. macrescens*, *Haplophragmoides* spp., *Ammotium salsum*, *Ammobaculites exiguus* and *Reophax nana*) were the same at the three sites.

Unfortunately, the dominant species of diatoms identified in these examples cannot be directly compared between studies because of the

difference in taxonomic keys used by investigators. Our modern training set confirms previous findings that salt-marsh diatoms are highly diverse and exhibit significant variation in assemblage composition between sites. In order to construct a more applicable regional-scale modern training set of diatoms, it appears necessary to collect additional modern transects from multiple marshes. Alternatively, diatom-based transfer functions should use local distributions and apply them to core material from the same locality. In contrast, foraminifera form low-diversity communities consisting of many of the same species at all sites. Thus, we find them to be the most useful sea-level indicator on the Outer Banks.

The final test of salt-marsh foraminifera from the Outer Banks as RSL indicators is to validate the sea-level history they produce against instrumental records of historical sea-level change (Donnelly et al., 2004). By reconciling geologically derived estimates of former sea level with tide-gauge records it is possible to consider the accuracy of a transfer-function-based methodology (e.g., Gehrels, 2000; Donnelly et al., 2004; Gehrels et al., 2005, 2006, 2008). To be confident in sea-level reconstructions derived from microfossils for the period prior to instrumental records, it is critical to demonstrate that they are providing a record that is accurate.

We produced a RSL reconstruction from the Salvo core using the transfer function developed for foraminifera (Fig. 8). An estimate of paleo-sea level is made for each foraminiferal sample within a core by subtracting the PME (m NAVD88) of the sample, as estimated by the transfer function, from its present altitude (m NAVD88). When each sample is assigned an age it becomes possible to plot a sea-level curve as a time–height diagram (Gehrels, 2000). Sample ages are estimated using the age–depth model (Fig. 2). Each sample has a unique elevation error provided by the transfer function and a temporal error associated with the age model. In combination, these errors produce an ‘envelope’ of former RSL defined by a series of ‘boxes’. The age errors increase systematically as samples get older and coalesce prior to ~AD 1900 (Fig. 2).

RSL reconstructed using foraminifera in the Salvo core (including all sampled depths and the radiocarbon date) shows a rate of sea-level rise of 2.6 mm/yr \pm 0.1 mm (95% confidence interval 2.1 mm/yr to

3.0 mm/yr) between AD 1790 and 2002. Since 1934, the rate of sea-level rise estimated from foraminifera in the Salvo core is 4.6 mm/yr \pm 0.8 mm (95% confidence interval 2.7 to 6.5 mm/yr). For the period since 1963 the estimated rate is 4.5 mm/yr \pm 1.5 mm (95% confidence interval 0.5 to 8.4 mm/yr). The wide confidence interval is a factor of the small number of data points in this time interval. These rate estimates are based upon regression of the mid-point of each sample and its associated errors. Within the RSL envelope it is possible to offer a number of alternative interpretations and contrasting RSL histories with widely varying rates of change, which may even preclude the identification of a change in the rate of RSL rise.

Zervas (2004) provided a summary of tide-gauge data for North Carolina. Eight instruments have been recording sea level for at least 20 yr. Unfortunately, many of these records have gaps or are considered unreliable for the purposes of this paper. The tide gauge at Wilmington, for example, provides the longest record (from 1935 onwards) but is located 40 km up-river from the open Atlantic Ocean and the area has been dredged by the US Army Corps of Engineers to deepen navigation channels (Zervas, 2004). It was also highlighted as an anomaly by Miller and Douglas (2006). Thus, we averaged the tide-gauge data from Duck, Oregon Inlet Marina, Beaufort and Southport to provide an instrumental record of historic sea level for North Carolina on an annual basis from 1973 to 2002 (Fig. 8). The three remaining tide gauges (Cape Hatteras, Atlantic Beach and Yaupon Beach) were not included because the data are unavailable. For the period since 1973, the averaged (five-year moving average) tide-gauge data show sea level to have risen at a rate of ~3.6 mm/yr \pm 0.4 mm (95% confidence interval 2.8 to 4.4 mm/yr).

The estimated rates of sea-level rise derived using a foraminifera-based transfer function are in close agreement with those recorded in averaged tide-gauge data in the study area (Fig. 8). This method can be considered effective in extending high resolution records of RSL change back into the late Holocene. Thus, the reconciliation of tide-gauge records with a historic RSL reconstruction from salt-marsh peat shows that foraminifera can be utilized as reliable sea-level indicators in coastal North Carolina.

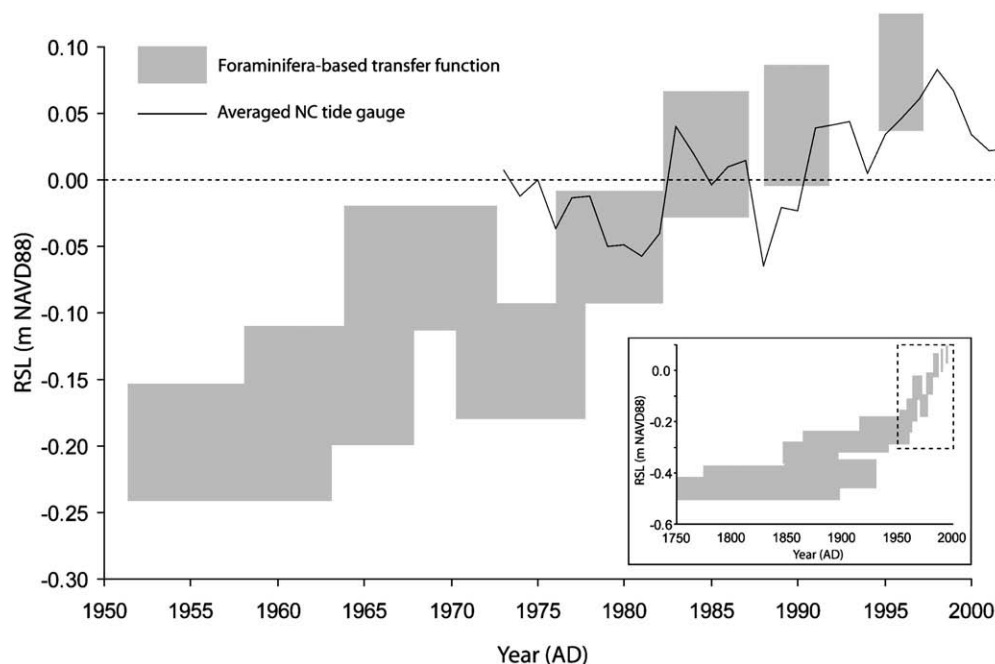


Figure 8. RSL reconstructed since AD 1950 from the Salvo core using the foraminifera-based transfer function. Since 1934 the rate of RSL rise is 4.6 mm/yr \pm 0.8 mm, compared to an averaged tide-gauge record (since 1973) for North Carolina that shows RSL rise of 3.9 mm/yr \pm 0.5 mm. Gray boxes represent age and altitude errors. *Inset:* Reconstructed RSL from the entire Salvo core (2.6 mm/yr \pm 0.1 mm).

Conclusions

We developed transfer functions using salt-marsh foraminifera, diatoms and a combination of both from three sites on the Outer Banks of North Carolina to investigate the relative utility of these microfossils in reconstructing late Holocene RSL at high resolution. All three transfer functions performed well (RMSEP < 0.05 m and $r^2_{\text{jack}} > 0.74$), initially suggesting that no particular microfossil has a clear advantage as a sea-level indicator although the multi-proxy model marginally out-performed the other two.

We applied the transfer functions to a short core of salt-marsh peat from Salvo, North Carolina. This is the first study to use 'paleo-performance' as a means to consider relative utility of microfossil groups. At 15 of the 18 sampled depths in the core there was no discernible difference in the PME's estimated by foraminifera, diatoms or the multi-proxy model when error bounds were included. However, matching analogue techniques suggest diatoms in the Salvo core lack modern analogues and reconstructions using them are considered to be unreliable. The lack of analogues is caused by site-specific distributions of modern diatoms and very high species diversity. The use of diatoms (or a multi-proxy approach) to reconstruct RSL at high resolution will require the development of a much expanded modern training set to encompass the variety of diatom assemblages between sites. In contrast, foraminifera had good modern analogues and are viewed as reliable. Modern salt-marsh foraminifera on the Outer Banks are generally cosmopolitan and occur in low-diversity assemblages.

We reconstructed RSL using foraminifera in the Salvo core with a chronology based upon ^{210}Pb and one radiocarbon date. The foraminifera-based transfer function is reconciled with the tide-gauge record in both absolute sea level and the rate of sea-level rise. Since 1973, the averaged tide gauges show sea-level rise of 3.6 mm/yr \pm 0.4 mm. The transfer-function estimates the rate of rise to be 4.6 mm/yr \pm 0.8 mm since 1934 and since 1963 to be 4.5 mm/yr \pm 1.5 mm. Thus, we have demonstrated that salt-marsh foraminifera on the Outer Banks can be utilized to develop reliable high-resolution records of late Holocene RSL in this region.

Acknowledgments

This research is part of NOAA Coastal Ocean Program grant and the North Carolina Coastal Geology Cooperative Program (NCCGC). We thank USGS cooperative agreement award 02ERAG0044 and National Science Foundation award EAR-0717364. This paper is a contribution to IGCP Project 495, "Quaternary Land-Ocean interactions: Driving Mechanisms and Coastal Responses". Permission to work on Pea Island National Wildlife Refuge, the Cape Hatteras National Seashore and the Pine Island Hunt Club is acknowledged. AK thanks the financial support of the University of Pennsylvania Summer Stipend in Paleontology and the 2007 Garry Jones Memorial Award (North American Micropaleontology Section, SEPM). Andrea Hawkes, Simon Engelhart, Matthew Wright and Candace Grand-Pre are thanked for their assistance in the field. We also thank R.T. Patterson and R.E. Martin for their review of this manuscript. Jesse Feyen (NOAA) is thanked for his assistance with the VDatum transformations.

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