Modern saltmarsh diatom distributions of the Outer Banks, North Carolina, and the development of a transfer function for high resolution reconstructions of sea level

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Abstract

We collected modern diatom samples from Currituck Barrier Island, Oregon Inlet and Pea Island marshes, Outer Banks, North Carolina, USA, which have different salinity regimes due to their varying distances from a major barrier island inlet. Multivariate analyses separate the saltmarsh diatom assemblages into distinct elevational zones, dominated by differing abundances of polyhalobous, mesohalobous and oligohalobous taxa, suggesting that the distribution of saltmarsh diatoms is a direct function of elevation, with the most important controlling factors being the duration and frequency of subaerial exposure.

We developed the first diatom-based transfer function for the east coast of North America to reconstruct former sea levels based upon the relationship between diatom assemblage and elevation. Results imply that this is possible to a precision of \( \pm 0.08 \) m, superior to most similar studies from temperate, mid-latitude environments. The transfer function is used to construct a relative sea-level curve from fossil assemblages from Salvo, North Carolina. These results suggest a sea-level rise of 0.7 m over the last c. 150 years, at an average of c. 3.7 mm year\(^{-1}\). This is consistent with existing sea-level data, and illustrates the utility of the transfer function approach.

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1. Introduction

Diatoms are unicellular algae with chrysophyte-like photosynthetic pigments. The cell wall is silicified to form a frustule, comprising two valves. Diatoms have been recorded and classified for over 200 years. In the late 1890s the systematic and taxonomic investigations of modern and fossil diatoms began to be supported by studies of distributional ecology (e.g. Cleve, 1894–1895). However, it was not until the 1920s that diatom analysis was recognized as a valuable tool in reconstructing ecological changes (e.g. Cleve-Euler, 1922; Hendey, 1964; Patrick and Reimer, 1966–1975; Cooper and Brush, 1991; Denys, 1991/1992; Vos and de Wolf, 1993; Hartley, 1996; Cooper, 1999).

The study of the ecology of contemporary diatom distributions has shown salinity to be the dominant control (Hendey, 1964). Accordingly many species have been classified based upon their salinity (halobian) preference (Hudstedt, 1953, 1957; van der Werff and Huls, 1958–1966). Polyhalobous species thrive in fully marine conditions, with a salinity
exceeding 30 practical salinity units (psu). Mesohalobous diatoms thrive in salt concentrations of between 0.2 psu and 30 psu. Oligohalobous diatoms generally occur in salt concentrations less than 0.2 psu. Vos and de Wolf (1993) and Juggins (1992) further divided the latter category into oligohalobous-halophilus, which have an optimum in weakly brackish waters, and oligohalobous-indifferent, which show a preference for fresh water, but are tolerant of slightly brackish conditions. Halophobous diatoms are highly intolerant of salt and are found exclusively in fresh water. Vos and de Wolf (1993) also coded diatoms based upon life form (planktic, benthic and epiphytic), substrate preference, pH, nutrient content and temperature. Many of these factors are directly related to elevation with respect to the tidal range.

In coastal sediments, diatoms are used to record environmental changes in salinity (e.g. Juggins, 1992) and subaerial exposure (e.g. Hemphill-Haley, 1995a). Round (1991) stated that diatoms preserved in sediments from continental margins will reveal a complex history of sea-level changes. However, the established reconstruction of coastal history based on diatom biostratigraphical techniques (e.g. Zong and Tooley, 1996) relies strongly on the simple classifications of taxa into freshwater, brackish or marine forms, and provide only qualitative estimates of ecological conditions. Given this general paucity of information, ecologists have recently adopted a quantitative approach to ecological reconstruction (e.g. Imbrie and Kipp, 1971; Nelson and Kashima, 1993; Hemphill-Haley, 1995a–c; Jones and Juggins, 1995; Wilson et al., 1995; Gasse et al., 1997; Sherrod, 1999; Zong et al., 2003; Sawai et al., 2004a,b). In coastal studies, the transfer function approach is producing a new generation of high-resolution sea-level reconstructions that is seeking to bridge the gap between short-term instrumental records and long-term, traditional geological reconstructions or geophysical predictions (e.g. Zong and Horton, 1998, 1999; Horton et al., 1999, 2000, 2003; Gehrels, 2000; Edwards and Horton, 2000, 2006; Gehrels et al., 2001, 2002; Edwards et al., 2004a,b; Horton and Edwards, 2005, 2006).

Studies of diatoms and their relationship to relative sea level in coastal and estuarine environments from the east coast of North America, however, are sparse (e.g. Kapruan, 1980; Cooper and Brush, 1991, 1993; Laird and Edgar, 1992; Cooper, 1995). Thus in this paper we present diatom distribution data from three back-barrier study sites from the Outer Banks, North Carolina, USA (Currituck Barrier Island, Oregon Inlet and Pea Island). Furthermore, we develop the first diatom-based transfer function to reconstruct former sea-levels from passive coastal margins in North America. The transfer function is applied to fossil assemblages from Salvo, North Carolina to derive quantitative estimates of former sea-levels.

2. Study sites

We have selected three study sites, Currituck Barrier Island, Oregon Inlet and Pea Island marshes, Outer Banks, North Carolina, USA (Fig. 1). These sites have different salinity regimes due to their varying distances from a major barrier island inlet. The tidal conditions of the Outer Banks are unique; the astronomical tidal range is small (e.g. diurnal range of 0.36 m at Oregon Inlet) but with significant, very variable and rapidly changing wind tides from less than 30 cm to more than 3 m (during hurricanes) in amplitude (Riggs, 2002).

Currituck Barrier Island is the most northerly back-barrier site, with the greatest distance (56 km) from Oregon Inlet, a major inlet which has existed since 1846 AD. The salinity of open water at Currituck Sound is low (c. 5 psu) at the time of sample collection (August 2002). The marsh at this site is approximately 200 m in width and displays a succession from narrow tidal flat through Juncus roemerianus low marsh to a mixed J. roemerianus and Spartina cynusoroides high marsh. The porewater salinity values increase from the Sound (5 psu) to the marsh fringe to a maximum within the S. cynusoroides marsh community (12 psu). Salinity, subsequently, decreases to 6 psu at the landward end of the transect (Culver and Horton, 2005; Horton and Culver, in press). The pH values also show an increase from Currituck Sound (3.4) to the S. cynusoroides marsh community (6.2). The sediments coarsen landward, with a maximum clay fraction of 23% within Currituck Sound and a minimum of 6% at the landward edge of transect. The loss on ignition (LOI) values and proportion of vegetation cover increases from the sound to the S. cynusoroides marsh community, with 100% vegetation cover reached 16 m along the transect.

The back-barrier marsh site at Oregon Inlet is less than 1 km from the waterway, which links Pamlico Sound to the Atlantic Ocean. The site thus displays similar salinities (c. 31 psu at time of sampling) to a normal marine environment. The marsh is approximately 200 m wide and covers a broad range of environments including, a narrow tidal flat and Spartina alterniflora and Juncus roemerianus marshes, with freshwater shrubs found at the landward edge of the transect. Porewater salinity values generally decrease from Pamlico Sound to the landward edge of the transect (Culver and Horton, 2005; Horton and Culver, in press). Maximum salinity values are found within the marsh fringe (23 psu) with an decrease to 8 psu, 112 m along the transect. The pH values show a gradual decline along the transect with high values within the tidal flat and marsh fringe, decreasing to a minimum of 5.1 at the landward edge of the transect. The percent clay fraction fluctuates along the transect with relatively high values within the marsh fringe and the landward edge of the transect (maximum of 29%). Similar to salinity, LOI has relatively high values within the marsh fringe. Vegetation cover shows the expected increase inland along the transect, attaining 100%, 32 m along the transect.

The Pea Island site is in a nature reserve located 14 km south of Oregon Inlet. Pamlico Sound adjacent to the study site had a salinity at the time of sample collection of c. 29 psu (somewhat higher than normal; Williams et al., 1973). The marsh is approximately 400 m wide and exhibits a narrow tidal flat, Spartina alterniflora, Juncus roemerianus and Spartina patens marsh environments. Porewater salinity increases from 23 psu, within the tidal flat stations of Pamlico Sound, to an exceptionally high
value of 56 psu, 193 m along the transect, at the transition between the *J. roemerianus* and *S. patens* marshes near a desiccated salt pond (Culver and Horton, 2005; Horton and Culver, in press). Salinity subsequently decreases to 12 psu at the landward edge of the transect. The pH values exhibit a gradual gradient along the transect from 5.5 to 7.2. The clay fraction oscillates along the transect. LOI remains relatively low (<8%) within the tidal flat and *S. alterniflora* marsh, with a sharp increase to 27% at the transition between the *J. roemerianus* and *S. patens* marshes. Vegetation cover increases along the transect with two thresholds crossed at the transition between tidal flat and *S. alterniflora* marsh and between the *J. roemerianus* and *S. patens* marshes.

The core to which the transfer function was applied (SAL02S1P1) was taken at the southern margin of Clark’s Bay at Salvo, 14.5 km south of the Pea Island site. The back-barrier marsh at Salvo is about 400 m in width. A narrow, fringing *Spartina alterniflora* zone is succeeded landward by a broad *Juncus roemerianus* marsh. At the time of collection (August 2002), sea-grass wrack, driven onto the marsh by storms, had killed the *Juncus* grass and *Salicornia bigelovii* and *Borrichia frutescens* had colonized linear, coast-parallel zones of the marsh. The core was taken in one of these zones, 10 m from a creek where the salinity was 30 psu.

### 3. Materials and methods

#### 3.1. Modern samples

We collected samples of surface sediment from a series of stations along transects from narrow tidal flat and vegetated marshes of the Currituck Barrier Island, Oregon Inlet and Pea Island sites to above Highest Astronomical Tide (HAT). We leveled all stations to benchmarks and elevations are expressed relative to mean sea level (MSL). At each station, we collected two samples of approximately 5 cm$^3$ (5 cm$^2$ surface sample by 1 cm thick) and 30 cm$^3$ (30 cm$^2$ surface sample by 1 cm thick) volume for diatom and environmental analyses, respectively. Sampling intervals were determined according to changes in elevation and vegetation zones.

We mixed the 1 cm thick sediment samples for diatom analysis to average seasonal effects. In these intermittently high energy environments, the surface diatom assemblage at any sampling point is likely to be a mixture of locally produced taxa and transported taxa. Such a mixture of allochthonous and autochthonous diatom valves would also occur in sediments that accumulated in the past (Zong, 1997). Therefore, we do not attempt to separate the allochthonous component from the diatom assemblages. We prepared all diatom samples for investigation using light microscopy following...
3.2. Core collection

We retrieved a 100 mm diameter push corer for laboratory. We instrumentally leveled the Salvo core to a benchmark and the elevation is expressed relative to MSL. In the laboratory, we cut centimeter slices of sediment from the core at specific sampling intervals for diatom and/or chronological analyses. The chronological framework for Salvo core SAL02S1P1 is provided by \(^{210}\text{Pb}\) and \(^{14}\text{C}\) dating. We picked plant macrofossils as points in a multi-dimensional space. Similar samples are located together and dissimilar samples apart. Birks and Hulme (1977) stressed the complementarity of the cluster analysis (DCA). Unconstrained cluster analysis based on un-weighted Euclidean distance, using no transformation or standardization of the percentage data, is used to classify modern samples into more-or-less homogeneous faunal zones (clusters). DCA is an ordination technique and is used to represent samples into more-or-less homogeneous faunal zones (clusters).

Samples analyzed by direct gamma counting were initially dried homogenized and packed into standardized vessels before counting for at least 24 h. Detectors were calibrated using a natural matrix standard (IAEA-300) at each energy of interest and verified for at least 24 h. Detectors were calibrated using the keys of Hartley (1996); van der Werff and Huls (1958–1966) and Patrick and Reimer (1966–1975).


4. Diatom distributions

We employed two multivariate methods to detect, describe and classify the elevation distribution of diatoms at each site: unconstrained cluster analysis; and detrended correspondence analysis (DCA). Unconstrained cluster analysis based on un-weighted Euclidean distance, using no transformation or standardization of the percentage data, is used to classify modern samples into more-or-less homogeneous faunal zones (clusters). DCA is an ordination technique and is used to represent samples as points in a multi-dimensional space.

Table 1

<table>
<thead>
<tr>
<th>Method</th>
<th>Elevation (m MSL)</th>
<th>(^{14}\text{C}/^{210}\text{Pb}) (years BP)</th>
<th>Calibrated age range (AD/BC)</th>
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<tr>
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<td></td>
<td></td>
<td>Max</td>
</tr>
<tr>
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<td>Mixed/modern</td>
<td></td>
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<td>0.12</td>
<td>Mixed/modern</td>
<td></td>
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<td>Mixed/modern</td>
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<td>1989</td>
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<td>1790</td>
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analysis and ordination techniques. Cluster analysis is effective in classifying the samples according to their diatom assemblage but DCA gives further information about the pattern of variation within and between groups. This is important as the precise boundaries between clusters can be arbitrary. Using this combination of techniques we delimit diatom zones on the basis of sample clusters that are mutually exclusive in ordination space. The elevation of each station within the reliable clusters determines the vertical zonation of each saltmarsh environment.

4.1. Currituck Barrier Island Marsh

The Currituck marsh has the lowest species diversity of the three study sites; we identified 56 species of diatoms (>2% relative abundance) from the 14 surface samples. The diatom assemblages are dominated by oligohalobous-indifferent species (e.g. Navicula tripunctata, Nitzschia palea and Cocconeis placentula), with significant influences from oligohalobous-halophilus (e.g. Cyclotella meneghiniana and Navicula arvensis) and mesohalobous species (e.g. Nitzschia obtuse). Cocconeis placentula, C. meneghiniana and N. arvensis dominate the tidal flat and marsh fringe section of the transect (0–14 m along the transect) with maximum percentages (19%, 11% and 10%, respectively) within the Sound (Fig. 2). The transition within the marsh fringe and Spartina cynosoroides marsh community corresponds to a rapid increase in the relative abundance of N. tripunctata and N. palea, which reach their maximum abundance (25% and 14%, respectively) 106 m along the transect.

Cluster analysis of diatom assemblages at each station detects two cluster zones (Fig. 3). Zone C-I is dominated by species associated with vegetation including the brackish/freshwater epiphyte (live attached to a living plant) Cocconeis placentula with other frequencies of the freshwater epiphyte Nitzschia palea, the brackish/freshwater planktonic species Cyclotella meneghiniana and Navicula arvensis. The elevational range is from −0.17 m to 0.51 m above MSL (a vertical range of 0.68 m). Zone C-II is dominated by oligohalobous species, notably the oligohalobous-indifferent species Navicula pelliculosa and Navicula lateropunctata which can resist periods of desiccation and the freshwater epiphyte N. palea. The zone spans an elevation range of 0.07 m (0.51 m to 0.58 m above MSL).

4.2. Oregon Inlet Marsh

We identified 64 diatom species (>2% relative abundance) from the 15 surface samples. The assemblage is dominated by the polyhalobous species, such as Paralia sulcata, Opephora marina and Dimeregramma minor, representing 39% of the total assemblage (Fig. 4). Oligohalobous-indifferent (e.g. Navicula pelliculosa and Navicula lateropunctata) and mesohalobous (e.g. Navicula pygmaea) are also significant contributors to the total assemblage. Opephora marina, D. minor and N. pelliculosa occupy the tidal flat (0–2 m along the transect) reaching relative abundances of 10%, 13% and 9%, respectively. These species and other polyhalobous taxa are replaced by oligohalobous species, such as N. lateropunctata within the marsh fringe (4–22 m along the transect). The assemblages within the Juncus roemerianus marsh are a combination of polyhalobous, oligohalobous-indifferent and mesohalobous species, with a notable increase in certain polyhalobous species (P. sulcata and Cocconeis scutellum) at the landward edge of the transect.

Three zones are identified by cluster analysis (Fig. 5). Zone OI-I extends from −0.83 m to 0.10 m above MSL with an elevational range of 0.93 m, and is dominated by the marine/brackish episammonic (live attached to sand grains) species Opephora marina and Dimeregramma minor. Zone OI-II is dominated by the marine planktonic species Paralia sulcata and Navicula lateropunctata, and ranges from 0.23 m to 0.38 m above MSL. Zone OI-III extends from 0.40 m to 0.42 m above MSL and is composed of P. sulcata and the marine/brackish episammonic species Cocconeis scutellum.
4.3. Pea Island Marsh

Pea Island Marsh has the highest species diversity of the three study sites; we identified 70 diatom species (>2% relative abundance) from the 17 surface samples (0–1 cm). All salinity classifications are found in high abundances. However, polyhalobous (*Opephora marina* and *Diploneis smithii*) and oligohalobous-halophilus (*Amphora veneta*, *Nitzschia inconspicua* and *Navicula cincta*) taxa dominate the assemblages (Fig. 6). The tidal flat sampling stations have a mixed assemblage, dominated by polyhalobous *Opephora marina*, mesohalobous, *Mastogloia lanceolata* and oligohalobous-halophilus *Fragilaria pinnata*. The latter two species are replaced within the *Spartina alterniflora* floral environments by *A. veneta*, *N. inconspicua*, *N. cincta* and *D. smithii*.

Cluster analysis detects two cluster zones (Fig. 7): Zone PI-I is dominated by the marine epissamnic species *Opephora marina* and species including *Mastogloia lanceolata* and the brackish/freshwater tychoplanktonic (live in plankton, but are derived primarily from other habitats) species *Fragilaria pinnata* with an elevational range of −0.05 m to 0.36 m above MSL; and Zone PI-II is dominated by *Amphora veneta* a benthic species tolerant of periodic wet subaerial environments (Hudstedt, 1953, 1957), *Nitzschia inconspicua*, and the marine/brackish epipelon taxa *Navicula cincta* and *Diploneis smithii* with an elevational range of 0.33–0.52 m above MSL.

5. Discussion

A prerequisite of employing microfossils to determine former sea levels is that their controlling environmental variables are established (Thomas and Varekamp, 1991). The diatom assemblages of Currituck Barrier Island, Oregon Inlet and Pea Island marshes show vertical zonations suggesting that distribution of diatoms in saltmarsh environments are a function of elevation (e.g. Zong and Horton, 1998). Thus, we combined the data from the three study sites to produce a regional training set and have employed partial canonical correspondence analysis (CCA) to further study the relationship between diatoms and elevation (Table 2). Partial CCAs of the diatom and environmental data from the three study sites support the hypothesis that diatom assemblages are related to elevation and hence

![Figure 3](image-url)

Fig. 3. (A) Unconstrained cluster analysis based on unweighted Euclidean distance (species >5% are shown), (B) detrended correspondence analysis and (C) vertical zonation of diatom assemblages (%) from Currituck Barrier Island marsh.
submergence. The six environmental variables (elevation, salinity, pH, LOI, clay fraction and vegetation cover) account for 31% of the explained variance in the diatom data. However, 69% total variation of the diatom data remains unexplained. Whether this is due to some overlooked factor (e.g. between-site variation in diatom composition) or to a large amount of stochastic variation remains unclear. Nevertheless, the explained percentage is considerably greater than those found in many other similar biological datasets, which have a large number of samples with many zero values, and have been used to develop transfer functions (Jones and Juggins, 1995; Gasse et al., 1997; Zong and Horton, 1999; Sawai et al., 2004a,b) and foraminiferal (Horton et al., 1999, 2003; Horton and Edwards, 2005, 2006; Horton and Culver, in press) datasets.

5.1. Transfer function development

Given that the distribution of saltmarsh diatoms is strongly influenced by surface elevation, we can use diatoms as ‘proxies’ for elevation, providing a suitable means of converting faunal data into environmental (e.g. elevation) data can be found. A transfer function quantifies this relationship between the environmental variable of interest and the environmental proxy so that the former may be expressed as a function of the latter. Birks (1995) outlined the general application of transfer functions to paleoenvironmental reconstruction, and here we concentrate on their use as it relates to diatoms and sea-level reconstruction (e.g. Hemphill-Haley, 1995b,c; Zong and Horton, 1999; Sherrod, 1999; Gehrels et al., 2001; Zong et al., 2003; Sawai et al., 2004a,b). For the purpose of this paper, it is sufficient to note that the transfer function is a means of quantifying the ecological optimum and tolerance of each species based on their modern response to environmental conditions.

We developed a diatom-based transfer function using a unimodal-based technique known as weighted averaging partial least squares (WA-PLS). The performance of each transfer function was assessed in terms of the root-mean square of the error of prediction (RMSEP) and the squared correlation ($r^2$) of observed versus predicted values. The RMSEP indicates the systematic differences in prediction errors, whereas the $r^2$ measures the strength of the relationship of observed versus predicted values. These statistics were calculated as ‘apparent’ measures in which the whole training set was used to generate the transfer function and assess the predictive ability. The data were also jack-knifed (also known as ‘leave-one-out’ measures). Jack-knifing is a measure of the overall predictive abilities of the dataset.

A regional transfer function was developed for elevation based on 117 species and 46 samples from Currituck Barrier Island, Oregon Inlet and Pea Island marshes. The transfer function produces results for six components. The choice of component depends upon the prediction statistics (RMSEP and $r^2$) and the principle of parsimony, i.e. choosing the lowest component that gives an acceptable model. Therefore, we have chosen component two because it performs significantly better than component one when jack-knifed errors are considered: prediction errors are lower and squared correlations are higher (Table 3). Using component two, the relationship between observed and diatom-predicted elevation is very strong (Fig. 8),
which illustrates the powerful performance of the WA-PLS transfer functions ($r^2_{jack} = 0.81$). Indeed, these results indicate that very precise reconstructions of former sea levels are possible. The transfer function provides an error estimate for sample-specific former sea-level reconstructions (RMSEP$_{jack} = 0.08$ m), which is less than or equal to other regional transfer functions from temperate marshes and tropical mangroves (e.g., Horton et al., 1999, 2003; Zong and Horton, 1999; Gehrels, 2000; Gehrels et al., 2001; Edwards et al., 2004a,b; Sawai et al., 2004a,b; Horton and Edwards, 2005, 2006).

Caution should, however, be exercised when applying such transfer functions since several characteristics within the contemporary and fossil data may affect the accuracy of sea level reconstructions. The accuracy of the transfer function is hindered by spatial and temporal diatom variations. WA-PLS transfer functions also calibrate the diatom data to one environmental variable (elevation). This may unrealistically force the influence of all environmental factors onto a single parameter and give misleading results (Le, 1992; Huntley, 1993). A potentially more serious problem is post-depositional changes of diatom assemblages (e.g., frustule transport and taphonomy). Thus, samples may violate one of the basic assumptions of quantitative paleoenvironmental reconstructions (Birks, 1995): the taxa in the training or calibration set and their ecological responses to the environmental variable(s) of interest have not changed significantly over the time span represented by the fossil assemblage.

Fig. 5. (A) Unconstrained cluster analysis based on unweighted Euclidean distance (species >5% are shown), (B) detrended correspondence analysis and (C) vertical zonation of diatom assemblages (%) from Oregon Inlet marsh. OH, oligohalobous-halophilus; H, halophobous.
5.2. Transfer function application

The transfer function is used to calibrate the fossil diatom assemblages collected from Salvo core SAL02S1P1. The calibration process assigns a paleo-marsh-surface elevation to each fossil sample together with sample-specific standard errors of prediction for individual fossil samples (bootstrapped standard error of prediction).

The Salvo core comprises 4 cm of grey sand, which is overlain by 51 cm of brown peat (Fig. 9a). The modern surface of the core rests at 0.14 m above MSL. We identified a total of 53 diatom species from 18 samples. The core is dominated by polyhalobous and mesohalobous taxa such as the tychoplanktonic benthic species *Actinocyclus octonarius*, *Diploneis bombus* (marine brackish epipelon, that is, it lives on or in substrate), *Diploneis smithii*, *Opephora marina*, *Paralia sulcata*, and the marine/brackish epipelon taxa (*Navicula digitoradiata* and *Nitzschia scalaris*). The reconstructed paleo-marsh-surface elevations derived from the transfer function reflect the changes in diatom assemblages and are summarized in Fig. 9a. The highest (0.51 ± 0.21 m) and lowest (0.22 ± 0.05 m) reconstructed elevations occur within the peat, and are associated with relatively high and low abundances of the polyhalobous species *D. smithii*, respectively. The high elevation reconstruction is also derived from a sample with unusually high relative abundances of *N. scalaris* (>20%) when compared with the maximum abundance recorded in the modern dataset (8%). As a result this sample has a large associated error term and its reconstructed elevation should therefore be treated with caution.

To illustrate fully the potential application of the transfer function technique, we place the diatom-based reconstructions from the Salvo core into a temporal framework established from the associated chronological data presented in Table 1. Sample ages were derived by linear interpolation between dated horizons. Alternative interpolation methods (e.g. a single best-fit polynomial curve) do not significantly alter the inferred age-depth relationship or the resulting pattern of relative sea-level change. The resulting curve is presented in Fig. 9b and suggests an overall rise of around 0.7 m during the last c. 150 years, at a long-term average rate of 3.7 mm year\(^{-1}\). This value is slightly higher than other studies examining relative sea-level changes over the last few centuries in neighboring areas, and may reflect the influence of local processes such as sediment consolidation or greater crustal subsidence due to postglacial fore-bulge collapse. For example, to the north of the study area, in Chesapeake Bay, Froomer (1980) identified a 2.74 mm year\(^{-1}\) rise during the last three centuries and Stevenson et al. (2002) suggested a rate of more than 3.2 mm year\(^{-1}\) during the 20th century. Further along the coast in Connecticut, Varekamp et al. (1992), Nydick et al. (1995) estimated that relative sea-levels have risen between 0.3 and 0.6 m since c. 1800, whilst van de Plassche et al. (1998) preferred a value of little over 1 mm year\(^{-1}\). In New England, Donnelly et al. (2004) documented a linear rate of sea-level rise of 1.0 mm year\(^{-1}\) from the 14th to the mid-19th century, with an acceleration to 2.8 mm year\(^{-1}\) from 1856 to 2001.

Over shorter periods of time, instrumental data from tide gauges are available for comparison with the transfer function data. Tide gauge data for the area cover the last 70–80 years and record relative sea-level rises of 2.22 ± 0.25 mm year\(^{-1}\) at Wilmington, North Carolina (1935–1999) and 4.42 ± 0.16 mm year\(^{-1}\) at Sewells Point, Virginia (1927–1999). Over a similar time interval, the Salvo core data suggests an average rate of relative sea-level rise of c. 4.5 mm year\(^{-1}\), which is toward the upper end of the instrumental record.

Whilst the reconstructions from the Salvo core are of relatively low temporal resolution (1 sample every c. 20 years), these data suggest small amplitude oscillations of around 10–20 cm are superimposed on the long-term rise in relative sea-level. Additional cores with smaller sampling intervals will be necessary to determine the significance of these oscillations. Nevertheless, these data demonstrate that the transfer
function approach can provide an accurate and precise assessment of relative sea-level change within a study area. The collection of this type of sequential data has the potential to produce high-resolution records of sea-level change that are necessary to further research into sub-millennial sea level variability (Horton and Edwards, 2005).

6. Concluding remarks

We collected modern diatom samples from Currituck Barrier Island, Oregon Inlet and Pea Island marshes, Outer Banks, North Carolina, USA to elucidate the relationship of the diatom assemblages with elevation and environment. Multivariate analyses separate the saltmarsh diatom assemblages into distinct elevational zones, dominated by differing abundances of polyhalobous, mesohalobous and oligohalobous taxa:

- Currituck Barrier Island marsh is the greatest distance from a major barrier island inlet and has low open water salinity. As a result, the assemblages consist of oligohalobous-indifferent species (e.g. Navicula tripunctata,

<table>
<thead>
<tr>
<th>Component</th>
<th>RMSE</th>
<th>( r^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated (apparent) errors</td>
<td>0.09</td>
<td>0.79</td>
</tr>
<tr>
<td>2</td>
<td>0.04</td>
<td>0.95</td>
</tr>
<tr>
<td>3</td>
<td>0.03</td>
<td>0.97</td>
</tr>
<tr>
<td>4</td>
<td>0.02</td>
<td>0.99</td>
</tr>
<tr>
<td>5</td>
<td>0.02</td>
<td>0.99</td>
</tr>
<tr>
<td>Prediction (jack-knife) errors</td>
<td>0.12</td>
<td>0.60</td>
</tr>
<tr>
<td>2</td>
<td>0.08</td>
<td>0.81</td>
</tr>
<tr>
<td>3</td>
<td>0.08</td>
<td>0.82</td>
</tr>
<tr>
<td>4</td>
<td>0.08</td>
<td>0.81</td>
</tr>
<tr>
<td>5</td>
<td>0.09</td>
<td>0.79</td>
</tr>
</tbody>
</table>

Table 3
Statistics summary of the performance of weighted averaging partial least squares (WA-PLS) from diatom assemblages of Currituck Barrier Island, Oregon Inlet and Pea Island marshes
Fig. 8. (A) Scatter plots and (B) residuals showing the relationship of the regression of observed elevations versus diatom-predicted elevations using WA-PLS from Currituck Barrier Island, Oregon Inlet and Pea Island marshes.

Fig. 9. (A) Salvo Core SAL02S1P1 diatom diagram. Diatom abundance is calculated as a percentage of total diatom valves (species >5% are shown). Lithology, marsh elevations predicted using WA-PLS with associated error ranges are shown. OH, oligohalobous-halophilus; OI, oligohalobous-indifferent. Surface elevation of the core is 0.14 m above MSL. (B) Reconstruction of Holocene mean sea-level curve for Salvo Core SAL02S1P1 using the diatom-based transfer function.
Nitzschia palea and Cocconeis placentula), with significant influences from oligohalobous-halophilus (e.g. Cyclo-
tella meneghiniana and Navicula arvensis) and mesohalobous species (e.g. Nitzschia obtusa);

- Oregon Inlet marsh is nearest the inlet and displays similar open water salinities to a normal marine environment. Thus the diatom assemblages are dominated by polyhalo-
bose species indicative of this environment such as the marine planktonic species Paralia sulcata and the ma-
rine/brackish episammic taxa Opephora marina and Di-
meregramma minor;

- Pea Island marsh has the highest species diversity of the three study sites, with taxa from the complete salinity spectrum, although it is dominated by polyhalobous (Ope-
phora marina and Diploneis smithii) and oligohalobous-
halophilus (Amphora veneta, Nitzschia inconspicua and Navicula cincta) taxa.

The strong relationship between elevation and the diatom assemblages at each site is supported by partial canonical corre-
respondence analysis on the combined dataset from the three study sites, suggesting the distribution of saltmarsh diatoms is a direct function of elevation, with the most important con-
trolling factors being the duration and frequency of subaerial exposure.

We developed the first diatom-based transfer function for the east coast of North America to reconstruct former sea levels with a precision of ±0.08 m. We applied the transfer function to construct a relative sea-level curve from fossil as-
semblages from Salvo, North Carolina. These results suggest

- that the input data are adjusted for regional faunal influences from oligohalobous-halophilus (e.g. Peltier et al., 2002;


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