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Salinity History of Coastal Marshes Reconstructed from Diatom Remains

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ABSTRACT: Sediment cores were collected from three Louisiana coastal marsh ponds, dated with radioisotopes, and analyzed for diatom remains to determine if long-term salinity changes were evident in the sediment record. A diatom-based salinity index formulated from a statistical comparison of available salinity data and changing diatom assemblages demonstrated that diatom remains appear to preserve salinity signals in coastal brackish and salt marsh environments. The salinity index was applied to sediment cores spanning the late 1600s to the 1990s and provided a more complete record of salinity than field data, which were temporally and spatially incomplete. The salinity reconstructions indicated that salinity has increased at two sites and decreased at a third since the early 1900s. The salinity changes are less than 1‰ per decade in all cases, and may be due to natural variability as depicted by the wide range of salinities observed between the late 1600s and 1900. Salinity regimes may be very localized (< 2 km from a hydrologic source), indicating single-site studies may not be applicable to regional inferences. This study demonstrates that diatoms can be used to reconstruct past salinity in coastal marsh environments and can provide a useful tool with which to study the changing hydrology of river-influenced ecosystems.

Introduction

Salinity changes resulting from hydrologic modification and habitat alteration in many coastal marshes around the world are of great concern. The modification of rivers (e.g., dams and levees; Meade and Parker 1984) and estuarine systems (e.g., dredging and impoundments; Swenson and Turner 1987; Turner 1987) have affected estuarine productivity (Glenn et al. 1996), coastal morphology (Wang 1996; Stanley and Goodfriend 1997), and freshwater resources (Baird and Heymans 1996; Wang 1996; Stanley and Goodfriend 1997). Much larger river modification projects are underway (e.g., the Three Gorges Dam System on the Changjiang River; Dudgeon 1995) or are planned

for the near future (e.g., dam construction on the Mekong River; Wolanski et al. 1996). The long-term effects of hydrologic changes are not known in most cases, although many researchers acknowledge that such studies are needed (e.g., Zedler et al. 1980). While various restoration and remediation projects are underway to counter the effects of hydrologic modifications, many of these projects cannot be adequately assessed yet (Thom 1997). Orson (1996) suggested paleoecological techniques should be applied more in the study and management of coastal marshes. The resulting data would aid in determining the degree to which the system has been modified and provide historic data from which future projections can be made.

Coastal Louisiana provides a good case study of how an ecosystem is affected by hydrologic modifications, of restoration projects underway to counter hydrologic effects, and how the lack of long-term data hinders formulation of appropriate res-

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toration efforts. Louisiana contains 41% (10,114,000 ha of the 25,000,000 ha) of the coastal marshes of the continental United States (Turner and Gosselink 1975), yet accounts for 80% of recent wetland loss (i.e., erosion; Alexander et al. 1986). The high rates of wetland loss ($0.86\% \text{ yr}^{-1}$ between 1955 and 1978; Baumann and Turner 1990), coupled with the subsequent economic losses (Costanza and Farber 1985), place wetland loss issues in the forefront of scientific and political debate in Louisiana. While there is consensus that wetland loss is a natural resource management problem, the causes are imperfectly understood, making it difficult to implement adequate preventative and remedial measures to counter wetland loss.

Coastwide increases in salinity have been hypothesized and debated as one of the major factors leading to wetland loss (Madden et al. 1988; Reed 1989; Gagliano 1994; Turner 1997). Salt water may stress and kill marsh plants, especially freshwater plants. This in turn can result in land loss due to the reduced ability of the marsh plants to hold organic matter in place (Good et al. 1982; McKee and Mendelssohn 1989). Plant presence or absence also is affected by many other, often related, factors (e.g., persistence and frequency of flooding; McKee and Mendelssohn 1989; Reed 1990; Cahoon and Reed 1995; Reed 1995). The main evidence supporting coastwide salinity increases as a factor in wetland losses is the northward movement of salt-tolerant marsh plants over the past several decades (Chabreck and Linscombe 1982; Fuller et al. 1995) and a northward extension of oyster leases in Barataria Bay (Van Sickle et al. 1976). Long-term salinity data (extending back to the mid 1950s in some cases) from 38 stations spread over coastal Louisiana demonstrate that salinities have increased at some stations (0.1‰ yr^{-1} to 2.2‰ yr^{-1}), but decreased (-0.1‰ yr^{-1} to -3.7‰ yr^{-1}) or remained unchanged at most (Wiseman et al. 1990; Swenson and Swarzenski 1995). These results indicate there is little evidence for a coastwide increase in salinity. The salinity increases appear to be localized events probably due to the dredging of navigation channels perpendicular to the coast (Wang 1988; Wiseman et al. 1990). Unfortunately, available salinity data are temporally and spatially sparse and are too recent to provide the baseline needed to test if, and to what extent, coastwide salinity in Louisiana has changed in this century.

One approach that can rectify this lack of data is the study of the sediment record through the analysis of diatom valves in a dated sediment core (i.e., a paleoenvironmental reconstruction). Diatoms are useful indicators of past environmental conditions because their morphology is species-

specific, species have specific water quality-chemistry preferences, and the valves preserve well in sediments (Battarbee 1986). Identification and enumeration of diatom valves coupled with information on optimal water conditions for growth can be used to reconstruct salinity at the time the diatoms were living. Much work has been conducted to classify diatoms according to their salinity preferences and this work has intensified in recent years (reviewed by Juggins 1992) in response to the increased application of paleoenvironmental reconstruction studies. Sediment core dating has become much more refined in the past two decades, allowing higher resolution studies of past environmental conditions using dated sediment cores (Schelske 1991). This refinement coupled with the recent scientific and managerial desire for long-term data has resulted in the present interest in paleoenvironmental reconstructions.

Paleoenvironmental reconstructions have been used to study salinity changes in closed systems such as lakes and reservoirs. Progressive freshening of uplifted lakes and impounded estuaries in Scandinavia has been demonstrated using diatom assemblages in cores (Cleve 1899; Räsänen and Tolonen 1983; Räsänen 1986). Studies of saline lakes in the northern Great Plains region of North America have been conducted to develop and calibrate diatom-based paleosalinity models. These models have been used to determine diatom responses to various ions (Cumming and Smol 1993; Wilson et al. 1994, 1996) and to study paleoclimate changes (Cumming and Smol 1993; Fritz et al. 1993), including precipitation (Fritz 1990) and droughts (Laird et al. 1996a,b, 1998).

In coastal and estuarine environments the use of diatom remains to study salinity changes has been more qualitative. Changing diatom assemblages have been associated with coastal transgression and regression events (Cleve 1899; Denys and Verbruggen 1989; Vos and de Wolf 1993; Espinosa 1994) and increased freshwater inputs to estuaries (Cooper 1995). Diatoms as quantitative indicators of changing salinity in recent sediments of estuarine-marsh systems have had limited use, unlike the case in lakes and reservoirs. One of the few examples of such a study is that by Juggins (1992), who developed a salinity transfer function along a salinity gradient in the Thames estuary and used this model to reconstruct salinities at sites around London, England.

Estuarine (and coastal marsh) salinity reconstructions have not been utilized extensively, possibly due to the dynamic changes typical of these environments. Spatial studies conducted on the living diatom assemblages found in estuarine and coastal marsh environments have demonstrated

Fig. 1. A map of central coastal Louisiana showing the locations of the three study sites: the Fourleague Bay brackish marsh pond (FLB), the Terrebonne Bay salt marsh pond (TSMP), and Airplane Lake (APL). Important geographical features are labeled. Salinity monitoring stations were located either at the same site (e.g., APL) or within 2 km (FLB and TSMP) of the coring sites, and are therefore not marked.

that diatom assemblages show patterns of zonation regardless of the highly variable nature of these systems. Several studies have been conducted to determine how diatom assemblages change along a salinity gradient in estuaries and salt marshes (McIntire and Overton 1971; Moore and McIntire 1977; Amspoker and McIntire 1978; Admiraal and Peletier 1980; Cook and Whipple 1982; Wildermann 1987; Juggins 1992; Underwood et al. 1998). These studies demonstrated that diatom assemblages shifted dramatically from a freshwater population to an estuarine population at a salinity threshold from as low as 1‰ (McIntire and Overton 1971) to as high as 7‰ (Admiraal and Peletier 1980). Because many diatom species have specific salinity preferences at higher salinities (e.g., Juggins 1992; Underwood et al. 1998) they should be useful as a proxy for past salinity changes in coastal environments.

While diatoms have been used successfully to document historical salinity changes in closed systems such as lakes and reservoirs, they have been used less frequently in estuarine systems, possibly due to the highly variable nature of this environment. The living diatom flora of estuarine environments exhibit quantifiable changes along salinity gradients, and many estuarine systems altered by hydrologic modifications may have these effects quantified and therefore better understood through salinity reconstruction studies. The goals of this study were to determine if diatom remains preserved a salinity signal in the coastal marsh sediments of Louisiana, and, if so, to use diatom remains to reconstruct salinity changes in the past.

Materials and Methods

CORE COLLECTION

We sampled three marsh water bodies in the south-central region of coastal Louisiana (Fig. 1): east of Fourleague Bay (FLB), northwest of Terrebonne Bay (TSMP), and west of Barataria Bay (Air-

plane Lake-APL). Two sediment cores were collected manually at each of the three sites in August 1992 (TSMP), August 1993 (APL), and October 1994 (FLB). All cores were collected in a plastic tube (3 inch diam, 1.3 m long). Using ~1 m tubes to collect cores underwater in a ~1 m deep salt marsh pond made accurate measurement of compaction during core collection impossible, so we measured compaction during extrusion in the laboratory. Cores were stored at 4°C. The longest core was split the day after collection on a custom-made threaded extruder, allowing precise measurements for slicing. Visual observations and core length were recorded prior to and during extrusion. Each of the cores was split into 1-cm increments, which were then homogenized and subsampled.

CORE DATING

Selected samples were dated by ^{137}Cs (Milan et al. 1995) and ^{210}Pb (Cutshall et al. 1983) using a Princeton Gamma-Tech 60 mm diam intrinsic germanium "N" type coaxial detector (40% efficiency) interfaced to an EG&G Ortec 92X spectrum master integrated gamma-spectroscopy system. Samples for ^{210}Pb were held for 2 wk before analysis to allow for equilibrium between atmospheric ^{222}Rn and ^{210}Pb . Samples for ^{137}Cs were counted for at least 4 h in order to yield a counting error of 10% in the vicinity of 1963–1964, the year of peak ^{137}Cs fallout for the southeastern U.S. (Pennington et al. 1973). Samples for ^{210}Pb were briefly counted with a source of ^{210}Pb to measure the sample self-absorption potential. The samples were then recounted for 24 h in order to obtain a significant amount of net counts above background. To determine supported ^{210}Pb , additional counts were conducted for ^{214}Pb activity. Supported ^{210}Pb was subtracted from the total to obtain excess ^{210}Pb , from which sedimentation rates were determined. Results for ^{137}Cs and ^{210}Pb are reported as pCi g^{-1} (dry wt sediment).

The ^{137}Cs -based sedimentation rates were determined as follows: the difference between the date each core was collected and 1963–1964 was divided by the depth where the peak in ^{137}Cs activity occurred. Sedimentation rates were determined from the excess ^{210}Pb using the constant rate of supply (CRS) model. The assumption was made that there is negligible migration of ^{210}Pb in the sediment and that the supply of excess ^{210}Pb is constant over time. Sedimentation rates were determined through the inverse of the slope of the least-squares regression line that was fitted to each ^{210}Pb profile. The ^{137}Cs and ^{210}Pb estimated sedimentation rates were averaged to give an overall sedimentation rate that would apply for the whole length of each sediment core.

DIATOM ANALYSIS

Separate portions of selected homogenized samples were prepared and analyzed for diatoms according to Parsons (1998). Glass microspheres (20- μ m diam, Unisciences[®], Ltd.) were added to the sample (to estimate absolute abundance of diatoms; Battarbee and Kneen 1982) in a 15-ml graduated polypropylene centrifuge tube; clay particles were removed by rinsing several times with 2% sodium pyrophosphate (Bates et al. 1978). Samples were cleaned in boiling nitric acid and rinsed six times with distilled-deionized water via centrifugation. Cleaned samples were dried on a 25 mm $\times$ 25 mm #1 coverslip and mounted on a slide with Hyrax[®]. Slides were examined using a Zeiss[®] universal microscope at a magnification of 625 $\times$. At least 250 diatom valves were counted per slide, which provides a good estimate of the diatom species $\geq 1.5\%$ of the population (Parsons 1996).

The top sample and every tenth sample thereafter were counted from each core. If obvious differences were noted between adjacent samples, every fifth sample was counted. If obvious differences were noted between these adjacent samples, every sample in the interval was counted.

DIATOM DATA ANALYSIS

A diatom-based salinity index (SI) was formulated using a multiple-variable regression technique comparing diatom species-salinity groupings with the available salinity data. A similar approach was taken by Flower (1986) in his study of pH changes in lakes. When compared with maximum likelihood and weighted average techniques employed in other studies (see Juggins 1992), this technique is not as complex and probably lacks some needed detail. We believe our simplified approach is adequate to determine if the diatom assemblage reflects salinity changes in the coastal marsh environment.

Salinity classifications were determined from the literature for as many as possible of the counted diatom species $\geq 1.5\%$ of the population. Many diatom taxonomic texts were used to identify and classify the diatom species encountered in this study (Hustedt 1939, 1955; Voigt 1960; Hendey 1964; Patrick and Reimer 1966, 1975; Cleve-Euler 1968; Foged 1975, 1980, 1986a,b, 1987; Germain 1981; Navarro 1982; Archibald 1983; Caljon 1983; Gasse 1986; Krammer and Lange-Bertalot 1986, 1988, 1991a,b; Prasad et al. 1990; Round et al. 1990; Vos and de Wolf 1993; Mann 1994). Broad salinity classifications were used to standardize the disparate salinity groupings devised by these references, and to acknowledge the dynamic environment typical of the Louisiana coastal marshes. The

TABLE 1. Characteristics of the salinity data used in this study. The sampling stations are listed according to the agency that collected the data (Louisiana Department of Wildlife and Fisheries: LDWF; Department of Health and Hospitals: DHH) and corresponding coring sites (Airplane Lake, APL; Terrebonne marsh site, TSMP; or Fourleague Bay marsh site, FLB). Samples were collected weekly or monthly, although not on a consistent basis (% missing). Salinity ranges and means are also listed.

Station	APL (LDWF)	DHH 107 (TSMP)	DHH 190 (FLB)
Length of record	1972-1998	1972-1996	1971-1996
Frequency of sampling	weekly	monthly	monthly
% missing	58%	63%	63%
Salinity range (‰)	2-34	0-25	0-26
Mean salinity (‰)	20.2	9.4	4.1

salinity groups used in this study, based on Kolbe (1927) and Round (1981), refer to salinity ranges within which a particular species thrives best, or most commonly occurs: freshwater (0-5‰), estuarine (5-20‰), and marine (> 20‰). The percentage of the diatom population classified in each group was summed for each sample.

In several cases a salinity classification could not be assigned to a diatom species because either the species could not be identified or no salinity information was found in the literature. This problem was corrected by dividing the percentage of the diatom population within each salinity group by the percentage that could be classified, thereby standardizing the classifications to one and allowing direct comparisons among the samples. The three salinity classifications could not be used concurrently in the multiple-variable regression due to singularity difficulties caused by the standardization procedure. The SI, therefore, was based on two ratios: the fresh water to estuarine component (FE) and the estuarine to marine component (EM).

SALINITY DATA ANALYSIS

Salinity data were obtained from the Louisiana departments of Wildlife and Fisheries (LDWF) and Health and Hospitals (DHH) at Airplane Lake and two other sites within 1 km of the other two coring sites (FLB and TSMP; Fig. 1). Some characteristics of the salinity data are given in Table 1. We applied a seasonal correction to the data in an attempt to circumvent potential problems due to the highly variable nature of the data and sporadic sampling. The seasonal correction was computed as follows: monthly means for each salinity data set were calculated and then these values were subtracted from the specific measurements taken during the respective month.

An overall mean salinity was computed by averaging the monthly means. This value was added to the difference between the monthly mean and

TABLE 2. Description and core dating results of the three study sites; the Terrebonne salt marsh pond (TSMP), Airplane Lake (APL), and the Fourleague Bay brackish marsh pond (FLB). The areas were estimated from scaled aerial maps; salinity ranges are from Table 1. Water depths were recorded from field observations; major plant communities were identified in the field. Postextrusion core lengths and % compaction values are given. See text and refer to Figure 2 for core dating results and discussion.

Study site	TSMP	APL	FLB
Surface water area (hectares)	1	25	2
Salinity (‰)	0–25	2–34	0–26
Water depth (m)	0.5–1	1–2	0–0.5
Major plant community	<i>Spartina alterniflora</i>	<i>Spartina alterniflora</i>	<i>Spartina patens</i>
Confirmed stability (via maps)	since 1932	since 1955	since 1955
Date cores were collected	August 18, 1992	August 26, 1993	October 17, 1994
Postextrusion core length (cm)	68.7	105.7	74.3
% compaction	3.0	4.3	8.3
¹³⁷ Cs peak (cm)	35.5	9.5	36.5
¹³⁷ Cs sedimentation rate (cm yr ⁻¹)	1.24	0.33	1.19
²¹⁰ Pb sedimentation rate (cm yr ⁻¹)	0.8	0.31	0.8
Average sedimentation rate (cm yr ⁻¹)	1.0	0.32	1.0
Time frame represented by each core	1924–1992	1664–1993	1920–1994

each specific measurement to return the data to the same range of values as in the raw data. This step was needed to compare the SI with the salinity data directly. Three-year running averages of the seasonally corrected salinity data were used to simulate surface sediment mixing processes.

STATISTICAL ANALYSIS

Sedimentation rate estimates acquired through core dating allowed us to assign an approximate date to each sample analyzed for diatoms. The years in which salinity data and diatom data matched were used for statistical analysis relying on the assumption that sedimentation rate-derived dates of the diatom data corresponded to the actual dates of the salinity data. A regression analysis (PROC REG procedure of SAS® 1988) was conducted between the diatom (FE and EM) and salinity data to determine if there was a significant and positive linear relationship between the two datasets. A significant relationship would provide evidence that the diatoms preserved in the sediment preserved a record of past salinity in Louisiana's coastal marshes. The regression model was then applied to the diatom data to formulate a SI for all of the samples analyzed from the three sediment cores; the assumption was that the SI would reflect actual salinity trends. Trends in the data were examined using a model II regression analysis of the SI versus the core dates since both terms have errors associated with their estimates (Sokal and Rohlf 1969). Significant regression results would indicate annual trends in the SI, and therefore, salinity. The SI and 3-yr running averaged salinity data were plotted together versus time (date) for each site to inspect visually how well the SI reflected actual salinity and if date mismatches were evident between the actual dates of the salinity data

versus the radioisotope-derived dates of the SI data.

Results

CORE DATING AND SITE DESCRIPTIONS

Table 2 presents general site descriptions, field measurements made during the core collection trips, and core dating results. Two of the sites (TSMP and APL) are surrounded by salt marsh dominated by *Spartina alterniflora*, while the brackish marsh site (FLB) was a homogeneous marsh of *Spartina patens*. The three sites ranged in size from a small pond (TSMP) to a larger lake (APL), and also differed in water depth, ranging from very shallow (0.5 m, FLB) to rather deep for a marsh water body (1–2 m, APL). Postextrusion sediment core lengths ranged from 68.7 cm to 105.7 cm, with associated levels of compaction of 3% to 8.3%.

The peaks in ¹³⁷Cs activity represent the year(s) 1963–1964 (Milan et al. 1995) and occur at a core depth of 9.5 cm (APL), 35.5 cm (TSMP), and 36.5 cm (FLB) (Fig. 2). Note that several data were excluded within the TSMP core for the determination of the ²¹⁰Pb regression line (indicated by the x's; Fig. 2). These data were from the surface mixed layer (the top three samples; Benninger et al. 1979), bioturbation events (35 cm and 60 cm; Heijnis et al. 1987), or a peat layer (69 cm) that contained a large amount of plant material (Parsons 1996), which can enrich surrounding sediments with ²¹⁰Pb (Koide et al. 1972; Olsen et al. 1985). Sedimentation rates ranged from 0.32 cm yr⁻¹ (APL) to 1.0 cm yr⁻¹ (FLB and TSMP) as determined by averaging the sedimentation rates estimated by the ¹³⁷Cs and ²¹⁰Pb techniques. The cores contained a record of 68 yr (TSMP) to a potential of 330 yr (APL). The 330-yr record of the APL core is questionable as this value is based on

Fig. 2. ^{137}Cs activity and regression of $\ln(^{210}\text{Pb})$ activity versus core depth at Airplane Lake (APL—triangles), the Fourleague Bay brackish marsh site (FLB—squares), and the Terrebonne Bay salt marsh pond site (TSMP—black circles). The $\ln(^{210}\text{Pb})$ activity regression line equations and r^2 values are FLB (solid line) $\ln(y) = -0.0333x + 1.4684$ ($r^2 = 0.58$); TSMP (large-dashed line) $\ln(y) = -0.0303x + 0.8444$ ($r^2 = 0.82$); and APL (small-dashed line) $\ln(y) = -0.0997x + 1.8456$ ($r^2 = 0.97$).

the assumption that the whole core has an average sedimentation rate of 0.32 cm yr^{-1} . The lack of ^{137}Cs activity in the upper 3.5 cm and 6.5 cm of the APL and FLB cores, respectively, and the constant ^{210}Pb activity in the upper 3.5 cm of the TSMP core demonstrate that sediment mixing appeared to be limited to the upper 4 cm of sediment in the three cores.

DIATOM ANALYSIS

A total of 33,726 diatom valves representing 205 species from 60 genera were identified and enumerated in 101 samples analyzed from the three sites. Of these 205 species, 125 could be assigned a salinity classification. The 43 most common species ($\geq 5\%$ abundance in any sample) are given in Table 3. The proportion of valves counted that could be classified ranged from 90% from FLB-68 cm to 100% from several samples in the APL and TSMP cores. A total of 37 samples were counted from FLB (1–20, 25, 30, 35, 40, 45, 50, 55, 60, 65–71, 74, and 75), 37 from TSMP (1–10, 15, 20, 25–35, 39–43, 45, 50, 55, 60, 65–69), and 27 from APL (1–10, 13, 17, 20–22, 24, 26, 28, 30, 40, 50, 60, 70,

TABLE 3. All diatom species $\geq 5\%$ relative abundance in at least one sample that could be assigned a salinity classification. The references used to obtain these classifications are indicated by the superscript following each species, which refer to the following works: 1—Foged 1980; 2—Foged 1987; 3—Marshall and Alden 1993; 4—Prasad et al. 1990; 5—Caljon 1983; 6—Vos and deWolf 1993; 7—Foged 1986a; 8—Hustedt 1955; 9—Patrick and Reimer 1966; 10—Hendey 1964; 11—Carpelan 1978; 12—Krammer and Lange-Bertalot 1986, 1988, 1991a,b; 13—Round et al. 1990; 14—Mann 1994; and 15—Hustedt 1939. The maximum relative abundance is given for each species (rounded to the nearest percentage), including the core site (A = Airplane Lake; F = Fourleague Bay; and T = Terrebonne Bay) and depth in which the maximum abundance occurred.

Marine Species		
<i>Achnanthes brevipes</i> var. <i>intermedia</i> (Kützing) Cleve ¹	7%	(F66)
<i>Actinopteryx senarius</i> Ehrenberg ^{2,6,7}	10%	(T65)
<i>Amphora tenuissima</i> Hustedt ⁸	6%	(T41)
<i>Diploneis didyma</i> (Ehrenberg) Ehr. ^{2,12}	11%	(T65)
<i>Diploneis smithii</i> (Brebisson) Cleve ^{8,12}	5%	(F70)
<i>Ditylum brightwellii</i> (West) Grunow ¹³	7%	(A10)
<i>Melosira moniliformis</i> (O.F. Muller) Agardh ⁶	8%	(F75)
<i>Navicula jarrensis</i> Grunow ^{2,8}	27%	(T68)
<i>Nitzschia compressa</i> (Bailey) Boyer ^{5,12}	19%	(T2)
<i>Nitzschia lanceola</i> Grunow ^{2,12}	6%	(A5)
<i>Nitzschia panduriformis</i> Gregory ^{2,8}	10%	(A2)
<i>Petronella marina</i> (Ralfs in Pritchard) Mann ^{5,13}	24%	(A20)
<i>Thalassiosira eccentrica</i> Ehrenberg ⁵	10%	(A1)
<i>Tryblionella granulata</i> var. <i>granulata</i> (Grun.) Mann ⁵	59%	(T8)
Estuarine Species		
<i>Achnanthes submarina</i> Hustedt ¹²	44%	(F15)
<i>Amphora copulata</i> Giffen ¹²	36%	(T55)
<i>Bacillaria paradoxa</i> Grunow ^{2,7,8}	8%	(F2)
<i>Biremis ambigua</i> (Cleve) Mann ^{8,10}	8%	(T69)
<i>Caloneis westii</i> (W. Smith) Hendey ¹²	11%	(A24)
<i>Cyclotella caspia</i> Grunow ³	5%	(A1)
<i>Cyclotella choctawhatcheeana</i> Prasad ⁴	5%	(F1)
<i>Cyclotella meneghiniana</i> Kützing ¹¹	10%	(T69)
<i>Cymbella lanceolata</i> (Ehrenberg) Kirchner ¹²	8%	(F68)
<i>Dickicia ulvacea</i> Berkeley ex. Kützing ¹⁴	8%	(F19)
<i>Diploneis finnica</i> (Ehrenberg) Cleve ^{8,12}	21%	(F71)
<i>Diploneis puella</i> (Schumann) Cleve ⁹	14%	(F5)
<i>Fallacia tenera</i> (Hustedt) Mann ¹²	9%	(A2)
<i>Fragilaria brevistriata</i> Grunow ^{2,12}	56%	(T41)
<i>Gyrosigma peisonis</i> (Grunow) Hustedt ^{5,8}	5%	(T41)
<i>Luticola mutica</i> (Kützing) Mann ⁶	5%	(F70)
<i>Melosira nummuloides</i> (Dillwyn) Agardh ^{1,8,10}	9%	(F75)
<i>Navicula circumtexta</i> Meister ⁹	8%	(T1)
<i>Navicula consentanea</i> Hustedt ¹⁵	8%	(T1)
<i>Navicula salinarum</i> var. <i>minima</i> (Grunow) Colby ^{2,8,12}	10%	(F7)
<i>Nitzschia filiformis</i> (W. Smith) Van Heurck ^{1,2}	13%	(F3)
<i>Rhopalodia acuminata</i> Krammer ^{6,12}	10%	(T40)
<i>Tabularia tabulata</i> (Agardh) Snoeijs ^{1,2,6}	6%	(T39)
Freshwater Species		
<i>Anomoeoneis sphaerophora</i> (Kützing) Pfister ^{1,7,9}	7%	(F66)
<i>Aulacoseira granulata</i> (Ehrenberg) Simonsen ^{1,6}	12%	(F74)
<i>Cocconeis placentula</i> var. <i>euglypta</i> Ehrenberg ^{1,6,7}	5%	(T69)
<i>Fragilaria pinnata</i> Ehrenberg ^{1,6,12}	17%	(A7)

Fig. 3. Regression of the diatom-based salinity index (SI) versus measured salinity from salinity and core data collected at or in the vicinity of Airplane Lake (APL), the Fourleague Bay brackish marsh site (FLB), and the Terrebonne Bay salt marsh pond site (TSMP). The SI was computed as follows, where FE refers to the fresh water to estuarine ratio and EM refers to the estuarine to marine ratio: $SI = 36.88(FE) - 0.61(EM) + 9.03$; $r^2 = 0.86$; $p < 0.0001$.

80, 90, 100, and 106). Fewer than 250 diatom valves were found in APL core samples below 30 cm so the statistical analyses were limited to the upper 30 cm of the core, which represented the time frame 1901 to 1993.

STATISTICAL ANALYSES

A statistically significant linear regression model ($p < 0.0001$) was formulated using two diatom-salinity components, FE and EM, that predicted the actual salinity values ($r^2 = 0.86$), where one unit of SI equaled 0.86 units of salinity (‰) (Fig. 3). SI values for samples below 30 cm in the APL core indicate that salinities may have fluctuated over a range of approximately 5–30‰ during the past 300 yr (Fig. 4a). This is based on the assumption that the SI reflected an adequately preserved diatom population regardless of the low counts in these samples. In the past century, the salinity index demonstrated that there was an overall significant increase in salinity of 0.10 SI (0.09‰) yr^{-1} in the upper 30 cm of the APL core ($p = 0.0008$; Fig. 4b). The FLB SI displays a significant decrease of 0.11 (0.09‰) yr^{-1} ($p < 0.0001$; Fig. 4c). There is an overall significant increase of 0.015 SI (0.01‰) yr^{-1} in the TSMP core ($p = 0.009$; Fig. 4d). The bottom sample of the TSMP core was not included in the SI reconstruction because analyses indicated a possible allochthonous origin of this peat layer (Parsons 1996).

COMPARISON OF THE SI AND SALINITY DATA

The SI data display the same range of salinities as the actual salinity data from the three study sites (Fig. 5), but date mismatches are evident (exam-

Fig. 4. The diatom-based salinity index (SI) determined salinity profile for the Airplane Lake (A and B), Fourleague Bay (C), and Terrebonne Bay (D) sediment cores. Statistically-significant overall model II trends in the SI are illustrated for Airplane Lake from 1901 to 1993 ($SI = 0.103(\text{year}) - 185.1$; $r^2 = 0.49$; $p = 0.0009$); Fourleague Bay ($SI = -0.105(\text{year}) + 214.1$; $r^2 = 0.58$; $p < 0.0001$) and Terrebonne Bay ($SI = 0.012(\text{year}) - 14.22$; $r^2 = 0.18$; $p = 0.009$).

Fig. 5. Direct comparison of the salinity index (black diamonds and dotted lines) and 3-yr running average salinity data (open squares and solid lines) for Fourleague Bay (A), Airplane Lake (B), and Terrebonne Bay (C). The asterisks indicate possible date mismatches between the two datasets.

ples indicated by the asterisks in Fig. 5). The FLB SI appears to be mismatched with the salinity data, possibly due to dating errors (Fig. 5a). The FLB SI shows more variability than the 3-yr averaged salinity data, suggesting that the salinity data may have been smoothed too much. A decreasing trend in the APL SI is evident (Fig. 5b) but is not corroborated by the actual salinity data collected at Airplane Lake. The TSMP SI matches the salinity data well except for 1986–1992 (Fig. 5c).

Discussion

THE SALINITY INDICES

Diatom remains appear to preserve a record of past salinity in the sediment of the coastal marshes of Louisiana (Fig. 3). The SI reconstructions do not support the hypothesis of significant coastwide salinity increases, but indicate that salinity trends

vary regionally and temporally (Fig. 4), confirming earlier salinity studies (Wiseman et al. 1990; Swenson and Swarzenski 1995). The large fluctuations in the SI between the late 1600s and 1900 indicate that salinities may exhibit wide fluctuations on century time scales (Fig. 4a). The SI increase at APL between 1901 and 1993 ($\sim 1\text{‰}$ per decade; Fig. 4b) may be another example of such fluctuations. This increase appears to be driven by a group of high SI values in the 1960s during a period of low Mississippi River discharge in the 1950s and 1960s (Bratkovich et al. 1994). Century-scale fluctuations in salinity may be driven by climatic variation, as evidenced in fluctuating river discharge (Bratkovich et al. 1994) and possibly precipitation (Laird et al. 1996a,b). There is an apparent decrease in the SI from 1978 to 1993, but this trend is not supported by the accompanying salinity data (Fig. 5b), which demonstrates that the SI model has flaws (see below). The decreasing salinity indicated in the FLB SI ($\sim 1\text{‰}$ per decade; Fig. 4c) may be due to the increased discharge of the Atchafalaya River as it began to capture the flow of the Mississippi River (Bratkovich et al. 1994). This hypothesis is confirmed by a statistically significant relationship between the FLB SI and Atchafalaya River discharge ($r^2 = 0.365$, $p < 0.0001$, data not shown). While the TSMP SI demonstrates that salinity has increased, the increase is minute (0.01‰ yr^{-1} ; Fig. 4d). The lack of a large change could reflect robustness of the SI model at TSMP, or indicate that the salinity regime has changed little at the TSMP site. The latter possibility is interesting in that the Houma Navigational Canal (HNC) is less than 2 km away from TSMP, and Wang (1988) demonstrated that the HNC may serve as a conduit of higher salinity Gulf waters into the area. The TSMP results may indicate that the areas affected by higher salinities might be very localized (< 2 km distance).

ROBUSTNESS OF THE SI MODEL

While sediment-preserved diatoms can be used to reconstruct salinity profiles in the coastal marshes of Louisiana, the SI reconstruction model can and should be improved. The r^2 of the regression model (0.86) upon which the SI is based indicates that it does not explain 14% of the variability. Figure 3 reveals that the SI did not perform well at the high salinity end of the model ($\sim 20\text{‰}$), and that many data points near the low end were poorly estimated as well. Figure 5 demonstrates that the SI and salinity data did not match up well in some cases. Much of this error could be due to the sporadic nature of the available salinity data, improper salinity classification of some of the diatom species, or errors associated with core dating.

CRITIQUE OF SALINITY DATA

The salinity data used in this study were discrete data, and the sporadic nature of the data collection (Table 1) may have resulted in a poor representation of the salinity regime. This is best exemplified by the observation that the data were collected less than 50% of the time, and were often collected during the spring (e.g., Airplane Lake; March through May between 1992 and 1998). The data were also collected weekly or monthly, which is typical for Louisiana salinity data (Swenson and Swarzenski 1995). The hydrology of Louisiana's coastal marshes is very dynamic and cyclic salinity variability is influenced by diurnal tides (on daily scales), river flow, and precipitation (seasonal to annual scales; Swenson and Swarzenski 1995). An analysis of salinity measurements should account for these cyclic variations, but this is generally not the case.

CRITIQUE OF DIATOM DATA

The responses of diatoms to salinity can vary widely among species and within a species. There is evidence that a diatom species can display different salinity optima in different water bodies, although tolerance ranges generally overlap (Cumming and Smol 1993; Fritz et al. 1993; Wilson et al. 1994, 1996). Some diatom species may have very large tolerances (i.e., euryhaline) and therefore will not be useful to reconstruct estuarine salinity (Juggins 1992). Wilderman (1987) believed this was especially true at salinities of 8–16‰, for which no reliable indicators may exist. The potential robustness seen in the TSMP SI at a salinity of ~10‰ may reflect such tolerances. Many species exhibit salinity optima. Because these responses are not linear, linear models (as was used for this study) might not be the best analytical approach (Juggins 1992). A particular diatom species response to salinity changes may differ based on the duration, frequency, and magnitude of change (Carpelan 1978; Admiraal and Peletier 1980). It is important, therefore, to know how salinity changes (frequency, etc.) and how a species will react to these salinity changes.

CRITIQUE OF CORE DATING RESULTS

The core dating techniques employed in this study result in average estimates of sedimentation rates. The ^{137}Cs estimates are an average rate for the period between 1963–1964 and the time the core was collected, while the ^{210}Pb estimates are an average based on the slope of a regression for the sediment core samples analyzed. As sedimentation rates vary year to year (especially during hurricane events, Parsons 1998), the use of an overall average sedimentation rate can cause a poor estimation of

core-derived dates. There were differences between estimates of sedimentation rate as determined by ^{137}Cs and ^{210}Pb for FLB (33% difference; 1.19 versus 0.8 cm yr⁻¹; Table 2) and TSMP (35%; 1.24 versus 0.8 cm yr⁻¹; Table 2). The differences in the two estimates indicate changing sedimentation rates (greater since 1963–1964), compaction, or oxidation (Turner unpublished data).

The possible errors and flaws in the core dating estimates may have caused date mismatches between some core samples and the salinity data. Date mismatches (e.g., FLB, Fig. 5a) could increase variability in the SI regression, resulting in decreased r^2 . The high r^2 (0.86; Fig. 3), however, demonstrates the core dates and actual salinity dates matched up reasonably well, considering the errors that can be expected.

COMPARISON WITH OTHER DIATOM-BASED SALINITY INDICES

The SI model developed in this study performed similarly to salinity indices applied in other sediment core studies. Fritz (1990) developed a diatom-based salinity index to reconstruct a salinity history of Devils Lake, North Dakota, U.S., and compared the model to available salinity records. While their model estimated salinities fairly well below 10‰, it did not consistently differentiate salinities between 10‰ and 25‰. Laird et al. (1996a) demonstrated that diatom-inferred salinity changes in a sediment core from Moon Lake, North Dakota, matched up well with available climatological data (precipitation minus evapotranspiration) after the 1940s, but mismatches were apparent in the mid 1970s. Wilson et al. (1996) reported their recent refinement of a salinity inference model for a region in British Columbia, Canada, in which the r^2 was improved to 0.87. We believe, therefore, that our salinity model is an adequate attempt at reconstructing salinity in coastal marsh environments.

Conclusions

The SI holds great potential as a tool to further study salinity changes in Louisiana and other coastal marshes impacted by hydrologic modifications. This study has demonstrated that there is no evidence for a coastwide increase in salinity. Fluctuations in salinity may be related to increased riverine discharge (FLB) and may vary widely over centuries (APL). This demonstrates the importance of riverine freshwater inputs as a controlling factor of salinity, and that long-term studies are needed to determine natural variability. While the SI has revealed much about historical salinity regimes in coastal Louisiana, some of the results are questionable, and may reflect flaws in this study and the

model design. An apparent decrease in the SI of the APL core was not corroborated by salinity data. The TSMP SI had less variability than the salinity data, indicating that the model may be too robust at a salinity of $\sim 10\text{‰}$. The next logical step is to address these flaws and refine the SI. Field data on the salinity ranges and optima for the diatoms living in the marshes of coastal Louisiana should be collected so that the SI can more accurately predict actual salinity values (i.e., improve the r^2 and slope so that both approach one). Application of the refined SI to more sites with longer sediment records would provide a wealth of information on salinity changes. It also potentially would provide improved baseline data from which anthropogenic impacts and marsh deterioration can be assessed, and proper remedial measures taken.

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