

# Salt Marsh Sedimentary Record of the Landfall of Hurricane Andrew on the Louisiana Coast: Diatoms and Other Paleoindicators

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## ABSTRACT

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Hurricane Andrew made landfall on the Louisiana coast on August 26, 1992, with the eye passing 40 km southwest of a salt marsh pond already under study. Storm surges ranging from 1-3 m in proximity to the pond resulted in the deposition of a mud layer, several centimeters thick, in many areas inundated by the storm surge. Analysis of pond sediment cores distinguished a hurricane mud layer characterized as a composite sediment, containing indicators of estuarine, brackish, and freshwater sources. The composite nature of the hurricane sediment is indicated by a higher diatom species diversity coupled with a more even species representation. Other distinguishing characteristics of the mud layer include lower marine diatom abundance, larger mean grain size, more poorly sorted sediment, and lower amounts of nitrogen in the sediment. Hurricane Andrew appears to have altered the geochemistry of the pond through the reduction of sulfide in the sediment allowing the proliferation of aquatic submerged flora (*Najas* sp.), resulting in a diatom assemblage shift towards epiphytic species. The submerged stand was still present two years after the hurricane landfall, and the diatom population has yet to revert to the pre-hurricane community.

**ADDITIONAL INDEX WORDS:** Terrebonne Bay, Gulf of Mexico, paleoecology.

## INTRODUCTION

High energy storms, including hurricanes, tropical storms, and winter cold front passages, affect sedimentary processes in many coastal regions (STUMPF, 1983), Louisiana notwithstanding (REED, 1989). While such storm events often result in the erosion of beaches and barrier islands (SNEDDEN *et al.*, 1988; STONE *et al.*, 1993), these same events can import large amounts of sediment into the coastal marsh interior (STUMPF, 1983; BAUMANN *et al.*, 1984; CAHOON and TURNER, 1987; REED, 1989). Generally, however, sediments imported to the coastal marshes of Louisiana are not derived from the eroded beaches and barrier islands, but instead appear to be reworked sediment from surrounding bays and other, nearby marsh regions (BAUMANN *et al.*, 1984; JACKSON *et al.*, 1995; NYMAN *et al.*, 1995). Sediment reworking often results in net sedimentation to the marsh surface (REJMANEK *et al.*, 1988; CONNER *et al.*, 1989). For example, BAUMANN *et al.* (1984) observed that 40% of the sedimentation on salt and brackish marshes of Barataria Bay between 1975 and 1979 was due to Hurricane Bob and Tropical Storm Claudette. The deposited sediments were thought to be reworked Barataria Bay bottom and marsh sediments. The two storm events contributed an average of 2.19 cm of sediment

on streamside marshes, and 1.46 cm on inland marshes (BAUMANN, 1980). In another study, JACKSON *et al.* (1993, 1995) documented the effects of Hurricane Andrew on several Louisiana marsh sites, and determined that a freshwater site was not affected, while an intermediate/brackish site lost 10-20 cm of sediment, resulting in its conversion to open water. Additionally, a saline marsh site received several new centimeters of sediment. These examples demonstrate the effects of storm-induced sediment reworking within the Louisiana coastal marsh system, which often results in sediment loss in some areas, coupled with net sediment gain in others.

While winter storms more frequently affect sedimentation processes in the Louisiana coastal marsh system (CAHOON and TURNER, 1987; REED, 1989; CAHOON *et al.*, 1995), hurricane events can result in larger impacts (NYMAN *et al.*, 1995). A hurricane affects coastal geomorphology most strongly at the point and time of landfall. HAYES (1978) presents a general overview of the history of a hurricane landfall. As the storm approaches land, tides rise, and wind velocities and wave heights increase, leading to the development of a storm surge. A long-shore current generally develops moving from right to left (relative to the movement of the storm). Upon landfall, water currents move with direct influence from wind direction (counter-clockwise). Water and sediment are pumped out of the bays on the left side of the storm, and into bays on the right side. When the storm begins to wane, winds blow either offshore, or left to right, coupled

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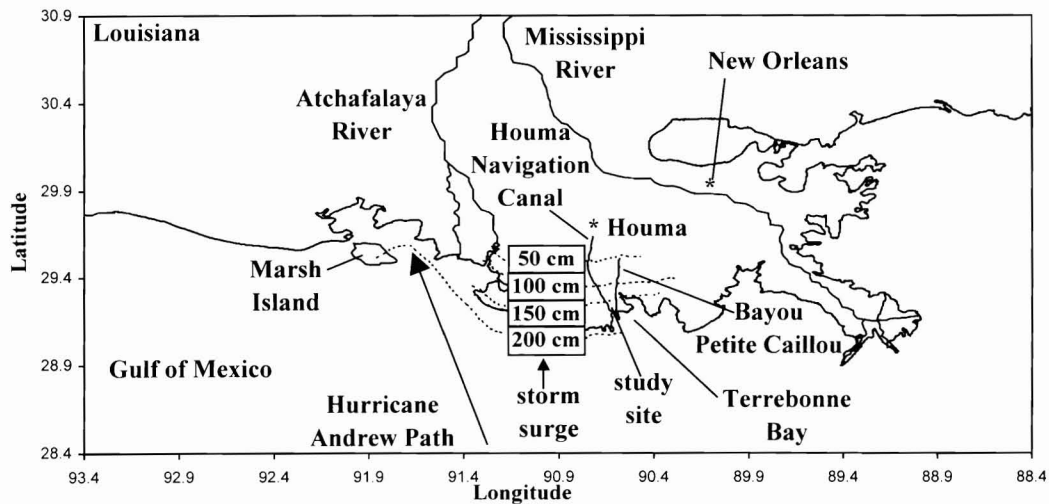


Figure 1. A map of coastal Louisiana indicating the path of Hurricane Andrew, contours of the accompanying storm surge (adapted from tide gauge data presented by Swenson (1994)), the location of the study site, and geographical points of interest.

with an offshore transport of sediment and water. Longshore currents reverse direction (left to right relative to the storm's path). After the storm has passed, mud settles out of suspension, and exposed fine-grained sediments are reworked.

Hurricane Andrew provided a good opportunity to study how such sediment reworking processes affect the sediment record. Hurricane Andrew made landfall on the south-central Louisiana coast at 0830Z (Greenwich Mean Time) on August 26, 1992, with the eye passing approximately 20 km northeast of Marsh Island and 30 km southwest of a site already under study (Figure 1). The ensuing economic damage was mainly due to flooding resulting from the accompanying storm surges of 1–3 m and heavy rainfall east of the storm path (JACKSON *et al.*, 1995; SWENSON, 1994). Water levels stayed above normal for approximately 103 hours south of Houma (STONE *et al.*, 1993). A mud layer several centimeters thick was deposited in many of the flooded areas. The deposited mud layer led to this project, which had three purposes: 1) to distinguish the hurricane sediment layer, 2) to determine the source of the sediment forming the mud layer, and 3) to determine if the deposited mud layer could interfere with paleoecological studies which were already underway. A sediment core had been taken at a salt marsh pond site eight days prior to the landfall of Hurricane Andrew on the Louisiana coast, providing good pre-hurricane sedimentological data (PARSONS, 1996).

Several researchers studied the hurricane event and its resulting sedimentation, and easily distinguished the sediment layer, but the specific source(s) of the sediment were not determined (CAHOON *et al.*, 1995; JACKSON *et al.*, 1993, 1995; NYMAN *et al.*, 1995). Diatom analysis of the hurricane sediment, in conjunction with other paleoindicator methods, was a logical technique to employ to address this scientific problem. Apparently, diatom analysis has not been used previously to study hurricane storm deposits, although diatom assemblages have been useful tools in oceanographic studies for

distinguishing and studying water masses (LANGE *et al.*, 1987; VAN IPEREN *et al.*, 1987), and tidal and marsh sediment environments (McINTIRE and OVERTON, 1971; MOORE and McINTIRE, 1977; SULLIVAN, 1982; VOS and DE WOLF, 1993). The successful application of diatom analysis in these and other previous studies was the basis for the use of these methods for this study. Other paleoindicators, including sediment pigment, grain size, and organic data, were also employed in this study, as they have been useful in distinguishing hurricane layers in previous studies (BAUMANN *et al.*, 1984; REJMANEK *et al.*, 1988; CONNER *et al.*, 1989; CAHOON *et al.*, 1995).

There are several paleoindicators that have the potential to distinguish the sediment layer deposited after the passage of Hurricane Andrew. For example, it was hypothesized that a hurricane sediment layer could be distinguished by the increased abundance of diatom species previously determined to be rare at the study site (allochthonous species) in prior research (*i.e.*, the pre-hurricane sediment core). Furthermore, the species present in the hurricane layer could reveal some information about the source of the sediment (*e.g.*, the presence of marine species would be evidence for a nearshore origin of the sediment). Other indicators that could be useful for distinguishing a hurricane-deposited sediment layer include increased diatom valve preservation, estimated through the lack of valve fragmentation (a taphonomic indicator of the rapid burial of viable diatoms); elevated bulk density related to increased amounts of sand, which would also be a possible indicator of a nearshore source of sediment (CAHOON *et al.*, 1995; NYMAN *et al.*, 1995); and a decrease in organic matter due to the winnowing away of plant debris during a storm event (JACKSON *et al.*, 1995).

Hurricane Andrew also presented an opportunity to determine if a hurricane signal could interfere with a paleoecological study. It was possible that this, or other previous hurricane events, could have resulted in long-term changes (> 1

year) at the salt marsh pond (*e.g.*, hydrology), which could affect a paleoindicator study. Therefore, this study was designed to use diatom assemblages (and other ancillary sedimentary measurements) to distinguish the hurricane layer, determine the source(s) of the sediment forming the hurricane layer, and determine if the hurricane resulted in any residual (> 1 year) changes that could affect a paleoindicator study.

## MATERIALS AND METHODS

A sediment core was taken at a salt marsh pond located 5 km northwest of Terrebonne Bay, Louisiana (Figure 1) eight days prior to the landfall of Hurricane Andrew on the Louisiana coast (August 18, 1992), and will be referred to as the pre-hurricane core. A second core (referred to as the post-1 core) was taken at the same site approximately one year after the landfall of Hurricane Andrew (*i.e.*, September, 1993). This delay allowed the hurricane sediment layer to undergo natural processes of burial, diagenesis, and/or subsequent preservation, while allowing some time to determine if any post-hurricane effects were evident. A third, short sediment core (referred to as the post-2 core) and a fourth, long core (referred to as the post-2b core) were collected at the site in June, 1994, to determine if Hurricane Andrew had an effect on the surface diatom assemblage two years after landfall, and if the hurricane sediment layer was still visible in the sediment, respectively. The sediment cores were collected with 1 meter long, 3 inch diameter plastic tubes, except for the post-2 core, which was collected with a 20 cm, 3 inch diameter plastic tube. The first two cores were examined for visible structure in the laboratory, and then immediately sectioned into 1 cm (pre-hurricane core) and 0.5 cm (post-1 core) increments using a precision core extruder. Due to the nature of the core collection process (*i.e.*, using 1 m tubes to collect cores in a 1 m deep salt marsh pond), it was impossible to accurately measure core compaction during core collection. Measurements of core compaction were made during core extrusion, and these values were 3.0% and 5.5% for the first two cores respectively. The post-1 core was split into the smallest possible increments possible (0.5 cm). Smaller subsamples could not be accurately obtained due to the relatively large diameter of the core (*i.e.*, 3 inches). The pre-hurricane core was completely split into 69 samples, as it was used for a separate paleoecological study (PARSONS, 1996). The post-1 core was extruded down to a depth of 12 cm, at which point splitting was terminated due to the lack of changing sediment color and structure over the previous 4 cm. The 69 wet samples from the pre-hurricane core, and the 24 wet samples from the post-1 core were individually homogenized and divided into subsamples for various analyses (Figure 2), including sediment pigment, organic content, grain size, and diatom analyses, as outlined below. The top 0.5 cm of the post-2 sediment core was collected for diatom analysis. The post-2b core was frozen and split lengthwise to determine if a hurricane sediment layer was still evident two years after landfall.

Sediment pigment analysis was conducted by extracting each sediment sample in 90% acetone for 24 hours, filtering

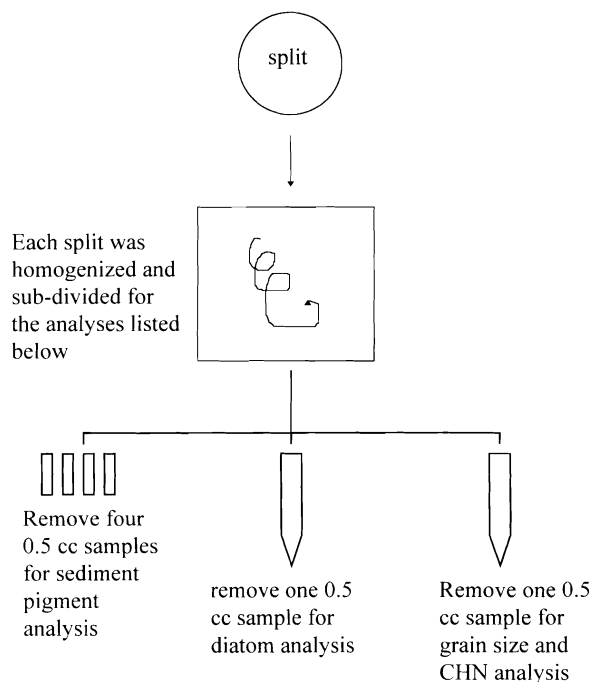


Figure 2. A flow chart of the core splitting procedure used to divide the sediment for the various analyses utilized to study the pre-hurricane and post-1 sediment cores collected at the study site.

the extract through a Whatman® GF/F glass fiber filter, and then reading the filtered extract for chlorophyll-*a* and phaeopigment fluorescence on a Turner® Type-10 fluorometer (TETT, 1982). The fluorometer readings were then converted to pigment concentrations according to equations presented in PARSONS *et al.* (1984). Sediment carbon, hydrogen and nitrogen (CHN) analysis was used to determine sediment organic content, and was measured with a Control Equipment Inc.® Elemental Analyzer Model 240-XA. Grain size analysis was performed on ashed samples with a Coulter® Multisizer, utilizing 50, 140, and 280  $\mu\text{m}$  aperture tubes (COULTER® ELECTRONICS LIMITED, 1988). Sediment grain sizes were reported as percent volume. Mean sediment grain size and sorting were determined via the method of moments (KRUMBEIN and PETTIJOHN, 1938). Each of the samples was prepared for diatom analysis through the addition of a 100  $\mu\text{l}$  aliquot containing a known concentration of glass microspheres (20  $\mu\text{m}$  diameter, Unisciences®, Ltd.) to obtain absolute abundances of the diatom species (BATTARBEE and KNEEN, 1982), followed by repeated sodium pyrophosphate washings to remove clay matter (BATES *et al.*, 1978), and a nitric acid digestion to remove organic matter and separate diatom valves. An aliquot of each cleaned sample (approximately 30  $\mu\text{l}$ ) was mounted on a microscope slide with Hyrax® mounting media. At least 250 valves were counted per sample at 750 $\times$  on a Zeiss® Universal microscope utilizing Nomarski® illumination. Upon identification, diatom species were classified and grouped according to the ecological and taxonomic definitions listed in Table 1. Generally, these classifications are broad,

Table 1. Definitions of the ecological and taxonomic classifications of diatom species, as used for this study. The general type of classification is given, followed by the reference from which the terms were adapted. Each term and its respective definition is listed in the last two columns.

Type	Reference Adapted From	Term	Definition
Trophic	McCORMICK and CAIRNS, 1994	eutrophic	species common in bodies of water where nutrients are not limiting
		mesotrophic	species common in bodies of water where nutrients are sometimes limiting
		oligotrophic	species common in bodies of water where nutrients are often limiting
Salinity	ROUND, 1981	marine	species common in water bodies with a salinity range of 20–40 ppt
		estuarine freshwater	species common in water bodies with a salinity range of 5–20 ppt species common in water bodies with a salinity range of 0–5 ppt
Niche	ADMIRAAL, 1984	planktonic	species (partially) dependent of the water column for their life cycle
		benthic-mobile	mobile species associated with the sediment surface and/or solid substrate
Valve Form	ROUND <i>et al.</i> , 1990	benthic-immobile	immobile species associated with the sediment surface and/or solid substrate
		centric	generally a round valve, where siliceous ribs radiate outward from the valve center
		araphid	a simple pennate valve, generally bipolar and elongate in shape, with siliceous ribs extending from both sides of a longitudinal sternum
		monoraphid	a raphid pennate valve, generally bipolar and elongate in shape, with siliceous ribs extending from both sides of a longitudinal sternum. One of the two valves contains raphe slits within the sternum
		biraphid	a raphid pennate valve, generally bipolar and elongate in shape, with siliceous ribs extending from both sides of a longitudinal sternum. Both of the valves contain raphe slits within the sternum

which is necessary due to the dynamic environment typical of the Louisiana coastal marshes. Major species identified (> 1.5% relative abundance) are listed in Table 2, along with their respective classifications and authorities. The references used in identification and classification are listed in the heading of Table 2.

Data are generally referred to as one of three types throughout this manuscript. Individual species data refer to the relative abundance data of a particular diatom species. Composite data refer to diatom groupings that were formulated according to the classifications defined in Table 1 by summing the relative abundances all species falling within a particular category (*e.g.*, marine species). Additional composite diatom groupings included absolute valve abundances and species evenness, which is a measure of dominance. Evenness is derived from the Shannon-Weiner diversity index ( $H'$ ), and is calculated by dividing  $H'$  by the number of species present, where  $H' = -\sum (p_i)\ln(p_i)$ , and  $p_i$  is the relative abundance of each species present in the sample. Ancillary data refer to the other sediment measurements taken, including pigment, organic matter, and grain size measurements.

The 69 samples from the pre-hurricane sediment core were initially analyzed for a separate project, and will be discussed after the statistical procedures are presented that were used for the samples from the post-1 core. The 24 samples collected from the post-1 sediment core were analyzed utilizing both univariate and multivariate statistical techniques available in the SAS® statistical program (SAS®, 1988). The statistical techniques were initially used to determine if a hurricane sediment layer could be distinguished in the post-1 sediment

core, and subsequently to determine the characteristics of the hurricane sediment layer, thereby providing information on the source of the sediment. A complete linkage cluster analysis was used to statistically determine if the samples could be separated into distinctive groups (zones) based on the individual species data, thereby indicating the presence of a distinct hurricane sediment layer. Based on these cluster analysis results, canonical discriminant analysis was employed on the ancillary and composite data to determine paleoindicator variations between the zones, thereby providing the best means of separating one zone from another according to the most influential paleoindicators. The individual species data were excluded because of constraints on degrees of freedom. The species data were analyzed separately by computing the zone-average for each species, which were then used to compute the standard deviation between the zones. These standard deviation values were used as a proxy indicator for species response. When the standard deviation was high, it indicated that the zone-averaged relative abundance of a given species was changing across the zones. If the standard deviation was low, it meant that the zone-averaged relative abundance of a given species did not change appreciably across the zones.

A second cluster analysis was conducted on the individual species data (> 1.5% relative abundance) from the 69 samples from the pre-hurricane core and the 24 samples from the post-1 core to ensure there was no evidence of significant erosion in the pond due to the hurricane landfall. Evidence of erosion would prevent any attempts to match up the top of the pre-hurricane core with the bottom of the post-1 core,

Table 2. A list of all diatom species counted that are  $\geq 1.5\%$  relative abundance in any of the samples the first three sediment cores studied. The authority for each species and their respective ecological classifications are also listed. The symbols for each classification are as follows: SALINITY: m = marine, e = estuarine, f = freshwater; NICHE: bi = benthic-immobile, bm = benthic-mobile, p = planktonic; TROPHIC: et = eutrophic, mt = mesotrophic, ot = oligotrophic; VALVE FORM: a = araphid, b = biraphid, c = centric, m = monoraphid. References for the ecological classifications are indicated by the superscript above each classification, with the superscripts referring to the following works: 1—KRAMMER and LANGE-BERTALOT, 1991; 2—VOS and DE WOLF, 1993; 3—CALJON, 1983; 4—HENDEY, 1973; 5—PATRICK and PALAVAGE, 1994; 6—HUSTEDT, 1955; 7—SLADECEK, 1973; 8—PATRICK and REIMER, 1966; 9—GERMAIN, 1981; 10—ROUND et al., 1990; 11—CLEVE-EULER, 1968; 12—NÁVARRO, 1982; 13—FOGED, 1975; 14—PRASAD et al., 1990; 15—FOGED, 1986a,b; 16—ARCHIBALD, 1983; 17—FOGED, 1987; 18—HADI et al., 1984; 19—MANN, 1994; 20—HUSTEDT, 1939.

Species	Authority	Salinity	Niche	Trophic	Valve Form
<i>Achnanthes brevipes</i> var. <i>intermedia</i>	(Kützing) Cleve	m <sup>1</sup>	bi <sup>1</sup>	et <sup>2</sup>	m <sup>1</sup>
<i>Achnanthes delicatula</i>	(Kützing) Grunow	e <sup>1</sup>	bi <sup>1</sup>	mt <sup>3</sup>	m <sup>1</sup>
<i>Actinopterychus senarius</i>	Ehrenberg	m <sup>4</sup>	bm <sup>4</sup>		c <sup>4</sup>
<i>Amphora acutiusscula</i>	Kützing	e <sup>1,6</sup>	bm <sup>1,6</sup>	mt <sup>5,6</sup>	b <sup>1,6</sup>
<i>Amphora angusta</i> var. <i>ventricosa</i>	(Gregory) Cleve	m <sup>1</sup>	bm <sup>1</sup>		b <sup>1</sup>
<i>Amphora copulata</i>	Giffen	e <sup>1</sup>	bm <sup>1</sup>	ot <sup>4,7</sup>	b <sup>1</sup>
<i>Amphora tenuissima</i>	Hustedt	m <sup>6</sup>	bi <sup>6</sup>	et <sup>5</sup>	b <sup>6</sup>
<i>Bacillaria paradoxa</i>	Gmelin	e <sup>1,6</sup>	bm <sup>1,3</sup>	mt <sup>3,5,7</sup>	b <sup>1</sup>
<i>Biremis ambigua</i>	(Cleve) Mann	m <sup>4,6</sup>	bm <sup>4,6</sup>		b <sup>4,6</sup>
<i>Caloneis westii</i>	(W. Smith) Hendey	e <sup>1</sup>	bi <sup>1</sup>	mt <sup>4,7</sup>	b <sup>1</sup>
<i>Chaetoceros</i> #1			p <sup>10</sup>		c <sup>10</sup>
<i>Cocconeis disculoides</i>	Hustedt	m <sup>6,12</sup>	bi <sup>2,12</sup>		m <sup>12</sup>
<i>Cocconeis placentula</i> var. <i>euglypta</i>	Ehrenberg	e <sup>8</sup>	bi <sup>1</sup>	et <sup>2,3,5</sup>	m <sup>1</sup>
<i>Coscinodiscus centralis</i>	Ehrenberg	m <sup>4</sup>	p <sup>4</sup>		c <sup>4</sup>
<i>Coscinodiscus gigas</i>	Ehrenberg	m <sup>13</sup>	p <sup>13</sup>		c <sup>13</sup>
<i>Craticula cuspidata</i>	(Kützing) Mann	e <sup>1,8</sup>	bm <sup>1</sup>	et <sup>3,5</sup>	b <sup>1</sup>
<i>Cyclotella choctawhatcheeana</i>	Prasad	e <sup>14</sup>	bm <sup>14</sup>	et <sup>14</sup>	c <sup>14</sup>
<i>Cyclotella litoralis</i>	Lange & Syvertsen	m <sup>6</sup>	p <sup>6</sup>		c <sup>6</sup>
<i>Cyclotella meneghiniana</i>	Kützing	e <sup>1</sup>	bm <sup>1</sup>	et <sup>2,5</sup>	c <sup>1</sup>
<i>Cyclotella</i> cf. <i>striata</i>	Grunow	m <sup>1,11</sup>	p <sup>1,11</sup>	ot <sup>5</sup>	c <sup>1,11</sup>
<i>Cyclotella</i> #3			p <sup>10</sup>		c <sup>10</sup>
<i>Dickieia ulvacea</i>	Berkeley ex. Kützing	e <sup>19</sup>	bm <sup>19</sup>		b <sup>19</sup>
<i>Diploneis didyma</i>	(Ehrenberg) Ehr.	m <sup>1,4,13</sup>	bm <sup>1,13</sup>	et <sup>2,3</sup>	b <sup>1</sup>
<i>Diploneis finnica</i>	(Ehrenberg) Cleve	e <sup>1,8</sup>	bi <sup>1</sup>	ot <sup>1</sup>	b <sup>1</sup>
<i>Diploneis puella</i>	(Schumann) Cleve	e <sup>8</sup>	bi <sup>1</sup>	ot <sup>1</sup>	b <sup>1</sup>
<i>Ditylum brightwellii</i>	(West) Grunow	m <sup>10</sup>	p <sup>10</sup>		c <sup>10</sup>
<i>Epithemia turgida</i>	(Ehrenberg) Kützing	e <sup>1</sup>	bm <sup>1,2</sup>	mt <sup>2,3</sup>	b <sup>1</sup>
<i>Eunotia</i> #1			f <sup>0</sup>	ot <sup>10</sup>	b <sup>10</sup>
<i>Fallacia pygmaea</i>	(Kützing) Stickle & Mann	e <sup>1,8,13</sup>	bm <sup>1,3,6</sup>	et <sup>1,2,3,5</sup>	b <sup>1</sup>
<i>Fragilaria brevistriata</i>	Grunow	e <sup>1,8</sup>	bi <sup>1,2,3,9</sup>	mt <sup>1,2,3</sup>	a <sup>1</sup>
<i>Fragilaria pinnata</i>	Ehrenberg	m <sup>1,4</sup>	bm <sup>1,2,3</sup>	et <sup>1,2,3</sup>	a <sup>1</sup>
<i>Gomphonema subclavatum</i>	Grunow	f <sup>8</sup>	bm <sup>1</sup>	ot <sup>1,5</sup>	b <sup>1</sup>
<i>Gyrosigma peisonis</i>	(Grunow) Hustedt	e <sup>3,6,12</sup>	bm <sup>3,6,12</sup>	mt <sup>3</sup>	b <sup>3</sup>
<i>Melosira moniliformis</i>	(O. F. Muller) Agardh	e <sup>1,4</sup>	bi <sup>1,2,4</sup>		c <sup>1</sup>
<i>Melosira nummuloides</i>	(Dillwyn) Agardh	e <sup>1,4,6</sup>	bi <sup>1,4,6</sup>	mt <sup>3</sup>	c <sup>1</sup>
<i>Navicula abunda</i>	Hustedt	m <sup>6,15</sup>	bm <sup>6,15</sup>	et <sup>15</sup>	b <sup>6</sup>
<i>Navicula circumtexas</i>	Meister	e <sup>8</sup>	bm <sup>8</sup>	et <sup>5</sup>	b <sup>8</sup>
<i>Navicula consentanea</i>	Hustedt	e <sup>20</sup>	bm <sup>20</sup>	et <sup>20</sup>	b <sup>20</sup>
<i>Navicula gregaria</i>	Donkin	e <sup>1</sup>	bm <sup>1</sup>	et <sup>1,5,7</sup>	b <sup>1</sup>
<i>Navicula phyllepta</i>	Kützing	e <sup>1,4</sup>	bm <sup>1</sup>	et <sup>1</sup>	b <sup>1</sup>
<i>Navicula pusilla</i>	W. Smith	e <sup>1</sup>	bm <sup>1</sup>		b <sup>1</sup>
<i>Navicula salinarum</i> var. <i>minima</i>	(Grunow) Colby	e <sup>1,6</sup>	bm <sup>1,6</sup>	mt <sup>3</sup>	b <sup>1</sup>
<i>Navicula yarrensis</i>	Grunow	m <sup>6,12,13</sup>	bm <sup>6,12</sup>		b <sup>6</sup>
<i>Nitzschia brevissima</i>	Grunow	e <sup>1</sup>	bm <sup>1</sup>	ot <sup>5</sup>	b <sup>1</sup>
<i>Nitzschia compressa</i>	(Bailey) Boyer	m <sup>1,3</sup>	bm <sup>1</sup>	mt <sup>3,5</sup>	b <sup>1</sup>
<i>Nitzschia filiformis</i>	(W. Smith) Van Heurck	e <sup>1</sup>	bi <sup>1</sup>	et <sup>1</sup>	b <sup>1</sup>
<i>Nitzschia lanceola</i>	Grunow	m <sup>1,13</sup>	bm <sup>1,17</sup>		b <sup>1</sup>
<i>Nitzschia proxima</i>	Hustedt	m <sup>1</sup>	bm <sup>1</sup>		b <sup>1</sup>
<i>Nitzschia pubens</i>	Cholnoky	e <sup>1,16</sup>	bm <sup>1,16</sup>		b <sup>1</sup>
<i>Nitzschia scalaris</i>	(Ehrenberg) W. Smith	e <sup>1,3,6</sup>	bm <sup>1,6</sup>	et <sup>2,3</sup>	b <sup>1</sup>
<i>Nitzschia sigma</i>	(Kützing) W. Smith	m <sup>1,4,6</sup>	bm <sup>1,3,6</sup>	m <sup>3</sup>	b <sup>10</sup>
<i>Nitzschia tryblionella</i>	Hantzsch in Rabenhorst	e <sup>1,2,3</sup>	bm <sup>1,6,17</sup>	m <sup>3</sup>	b <sup>1</sup>
<i>Odontella rhombus</i>	(Ehrenberg) W. Smith	m <sup>3,4,6</sup>	p <sup>2,3</sup>		c <sup>6</sup>
<i>Petroneis marina</i>	(Ralfs in Pritchard) Mann	m <sup>3,4,10</sup>	bm <sup>3,4,10</sup>		b <sup>10</sup>
<i>Pleurosigma angulatum</i>	(Quekett) W. Smith	m <sup>1,4</sup>	bm <sup>1,4</sup>		b <sup>1</sup>
<i>Rhizosolenia</i> #1		m <sup>10</sup>	p <sup>10</sup>		c <sup>10</sup>
<i>Rhopalodia acuminata</i>	Krammer	e <sup>1</sup>	bi <sup>2</sup>		b <sup>1</sup>
<i>Stauroneis producta</i>	Grunow	e <sup>1</sup>	bm <sup>1</sup>	ot <sup>5</sup>	b <sup>1</sup>
<i>Tabularia tabulata</i>	(Agardh) Snoeijis	e <sup>3</sup>	bi <sup>2,12</sup>	et <sup>2,3,7</sup>	a <sup>10</sup>
<i>Thalassiosira eccentrica</i>	(Ehrenberg) Cleve	m <sup>3,12</sup>	p <sup>2,3</sup>	mt <sup>3</sup>	c <sup>3</sup>
<i>Thalassiosira linneata</i>	Ehrenberg	m <sup>15</sup>	p <sup>15</sup>		c <sup>15</sup>
<i>Thalassiosira oestrupii</i> var. <i>venrickii</i>	G. Fryxell & Hasle	m <sup>15</sup>	p <sup>15</sup>		c <sup>15</sup>
<i>Tryblionella granulata</i> var. <i>granulata</i>	(Grunow) Mann	m <sup>1,6</sup>	bm <sup>1,6</sup>	et <sup>5,18</sup>	b <sup>1,10</sup>
<i>Tryblionella granulata</i> var. <i>hyalina</i>	Amosse	m <sup>1,12</sup>	bm <sup>1,12</sup>	et <sup>5,18</sup>	b <sup>1,10</sup>
<i>Tryblionella hungarica</i>	(Grunow) Mann	e <sup>1,3</sup>	bm <sup>1,17</sup>	et <sup>1,3,7</sup>	b <sup>1,10</sup>

which would be an indication of hurricane sedimentation in the pond. Upon satisfactory results indicating no significant erosion, an additional cluster analysis was then performed on a data set containing the individual species data  $> 1.5\%$  relative abundance in any sample from the top 10 cm of the pre-hurricane, the 24 samples of post-1, or the top 0.5 cm from the post-2 cores. This analysis was used to determine if the bottom of the post-1 core matched up with the top of the pre-hurricane core, which could confirm the presence of a deposited sediment layer on top of the sediment surface from the pre-hurricane core after the passage of Hurricane Andrew. Conversely, erosion of the sediment surface layer from the pre-hurricane core in response to the hurricane could be confirmed by the absence of grouping among the top samples from the pre-hurricane core with the bottom samples of the post-1 core. Additionally, this analysis was used to determine if the surface diatom assemblage from the post-2 core was distinctive from the assemblages of the other two cores.

Where necessary, data were adjusted to values ranging between 0 and ( $\pm$ )1, by multiplying or dividing respective units of measure by factors of 10. This was performed on most of the ancillary data for the multivariate analyses to prevent the large-valued variables from dominating the results (JOHNSON and WICHERN, 1992). All data are numerically displayed according to the significant figures rules of SOKAL and ROHLF (1969).

## RESULTS

### Core Observations

Inspection during core splitting revealed the presence of a distinctive sediment layer in the post-1 sediment core, distinguished primarily by differences in color and sulfide odor. However, these observations were not adequately documented with photographs or via standard color chips, preventing further evaluation. No distinctive sediment layer was evident in the post-2b sediment core taken at the study site two years after landfall.

### Diatom Analysis

A total of 24,681 valves were counted in the first three sediment cores representing 107 species from 45 genera. The 64 species identified that were  $> 1.5\%$  relative abundance in any sample from the first three sediment cores are listed in Table 2, along with their respective authorities and ecological preferences.

### Cluster Analysis

Cluster analysis results indicated that there was a distinctive sediment layer (4.75–7.75 cm) present in the post-1 sediment core, hereafter referred to as Zone 2, based on differences in the diatom assemblage. Additionally, the samples above (Zone 1) and below (Zone 2) this layer were similar (Figure 3). Results of the second cluster analysis (not shown) conducted on the 69 samples from the pre-hurricane core and the 24 samples from the post-1 core did not reveal any evidence of erosion. Subsequently, cluster analysis of samples from the pre-hurricane, post-1, and post-2 sediment cores

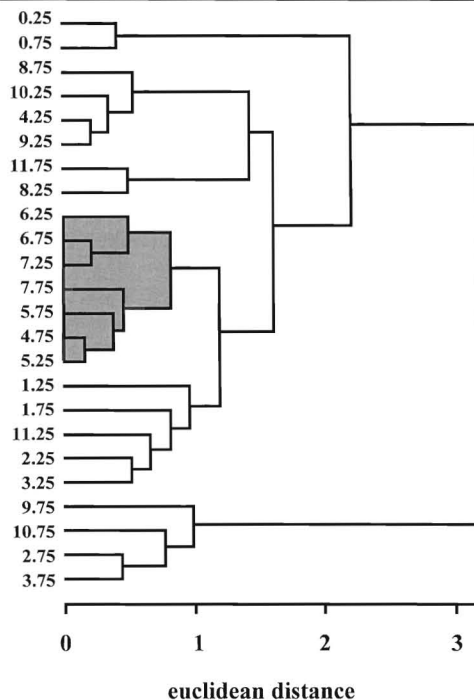


Figure 3. A dendrogram of the complete-linkage cluster analysis results of the diatom assemblage  $> 1.5\%$  relative abundance from the second sediment core. Each value represents one of the 24 sample depths (cm) in the post-1 sediment core. The shaded area distinguishes the sample grouping that forms Zone 2.

demonstrated that there is some overlap between the bottom samples from the post-1 core and the top samples of the pre-hurricane core (Figure 4). The overlap is graphically illustrated through the grouping of three bottom samples from the second core (9.75 post-1, 10.25 post-1, and 10.75 post-1) with nine out of the ten samples from the top of the pre-hurricane core (1.50 pre–9.50 pre), and through the grouping of the top sample from the pre-hurricane core (1.50 pre) with the remainder of the samples from the post-1 core. Additionally, the dendrogram reveals that the surface layer of the post-2 core is distinctive from the other two cores (Figure 4).

### Canonical Discriminant Analysis

The canonical discriminant analysis (CDA) indicated that the three zones in the post-1 core could be successfully distinguished, and were statistically different from one another ( $p \leq 0.0001$ ) according to the multivariate  $T^2$  test. Table 3 indicates which variables were most important in the formulation of each canonical eigen vector (can1 and can2), and how each vector weighed the three zones. The five best parameters separating the three zones were species representation (evenness), sediment nitrogen content, mean grain size, marine diatom abundance, and sediment sorting. The separation of the three zones is evident in the plot of the two canonical variables (Figure 5). Can1 accounts for 71.18% of the between-zone variance, and can2 accounts for the remaining 28.82% of the between-zone variance. The profiles of

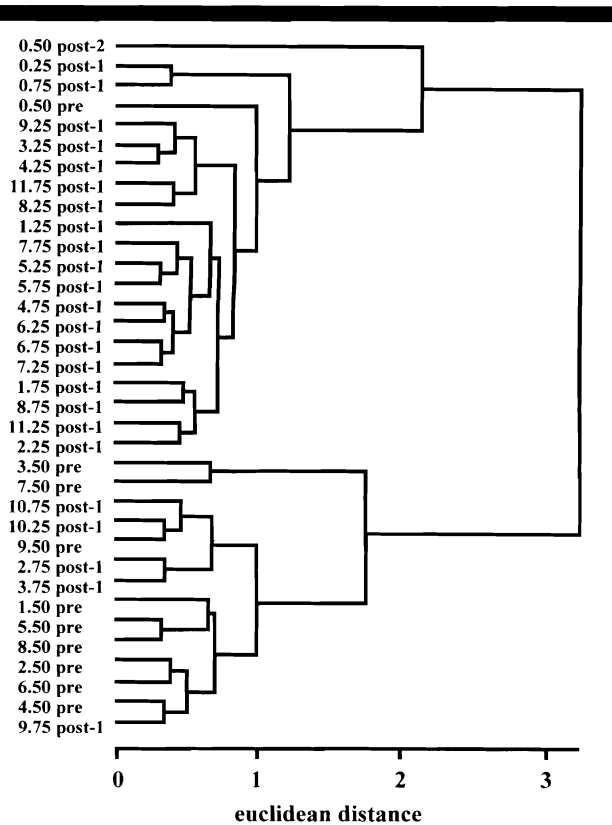


Figure 4. A dendrogram of the complete-linkage cluster analysis results of the diatom assemblage > 1.5% relative abundance from the pre-hurricane (pre), post-1, and post-2 sediment cores. Each value represents the depth (cm) of each sample from the three cores.

the five best parameters separating the three zones are given in Figure 6.

### Univariate Analysis

The ten diatom species that have the highest standard deviations across the three zones in the post-1 core are given in Table 4, with each respective zone-averaged relative abundance. The relative abundance profiles for these ten species are displayed in Figure 7. Note how the majority of these species peak in Zone 2 (*Amphora acutiuscula*, *Navicula abunda*, *Navicula gregaria*, *Navicula salinarum* var. *minima*, *Nitzschia filiformis*, *Craticula cuspidata*, *Stauroneis producta*,

and *Diploneis puella*), whereas the remaining two species have their lowest abundance in Zone 2 (*Cocconeis placentula* var. *euglypta* and *Thalassiosira oestrupii* var. *venrickii*). The majority of these species are classified as estuarine forms, while two, *Navicula abunda* and *Thalassiosira oestrupii* var. *venrickii*, are classified as marine forms. Six of the species, *Amphora acutiuscula*, *Navicula abunda*, *Navicula gregaria*, *Navicula salinarum* var. *minima*, *Craticula cuspidata*, and *Stauroneis producta*, are classified as benthic-mobile forms, while three are classified as benthic-immobile forms (*Cocconeis placentula* var. *euglypta*, *Diploneis puella*, and *Nitzschia filiformis*). One species is a planktonic form (*Thalassiosira oestrupii* var. *venrickii*).

Table 5 displays the diatom species that have a relative abundance  $\geq 5\%$  in the surface sediment from the pre-hurricane, post-1, and post-2 cores taken at the study site over a two-year period. Notice how the dominant species present in the pre-hurricane core (taken in August, 1992) are less than 5% abundant nearly two years later in the post-2 core (taken in June, 1994), indicating how the diatom assemblage has substantially changed in the two years after landfall.

### DISCUSSION

The cluster analysis and CDA results demonstrate that Zone 2 is a distinct layer within the post-1 core, according to both the diatom assemblages and the ancillary data. The similarity of Zone 1 to Zone 3, coupled to the distinctiveness of Zone 2, suggests that Zone 2 represents a sediment layer, approximately 3 cm thick, that was deposited by Hurricane Andrew. There does not appear to be evidence of significant erosion of the pond sediments according to the cluster analysis results. Additionally, there appears to be some overlap between the bottom samples of the second core with the top of the first core that may indicate net sedimentation in the pond, a scenario which is discussed in more detail below.

The canonical discriminant analysis results indicate that five of the composite or ancillary paleoindicator measurements in particular best distinguish the hurricane sediment layer: marine diatom abundance, diatom species evenness, sediment nitrogen content, mean sediment grain size, and sediment sorting. These five variables exhibit the following characteristics distinguishing Zone 2. Marine diatom abundance is lowest in Zone 2; diatom species evenness is highest in Zone 2; nitrogen content is lowest in Zone 2; mean grain size is largest in Zone 2; and the sediment is most poorly sorted in Zone 2.

Table 3. Results of the canonical discriminant analysis indicating the variability, zone weights, and variable weights for each eigenvector.

Eigenvector	Can1	Can2
Between-zone variance explained	71.18%	28.82%
Weight towards Zone 1	-	+
Weight towards Zone 2	+	-
Weight towards Zone 3	-	-
#1 variable	species evenness (+)	species evenness (+)
#2 variable	mean grain size (+)	marine diatom abundance (+)
#3 variable	sediment nitrogen content (-)	species diversity (+)
#4 variable	sediment sorting (+)	biraphid diatom abundance (-)
#5 variable	benthic-mobile diatom abundance (+)	sediment nitrogen content (-)

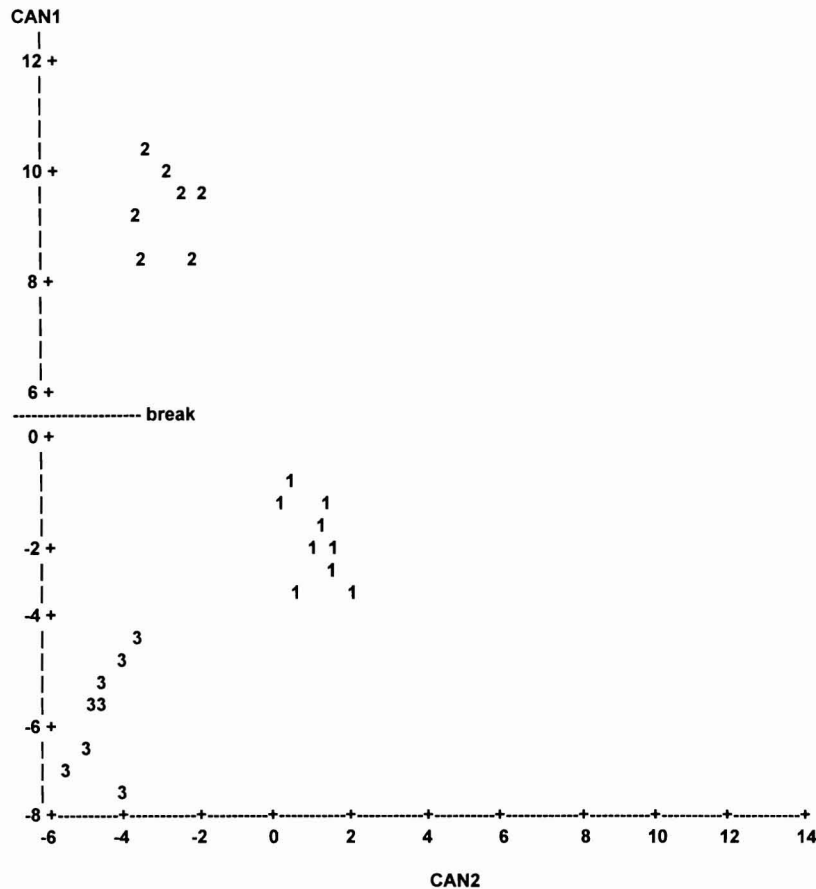


Figure 5. A graphical representation of the canonical discriminant scores obtained for each of the 24 samples from the post-1 sediment core. The two axes are the scores from each eigen vector, while the plotted numbers represent each of the three zones present in the post-1 core.

The mean grain size profile shown in Figure 6a does not indicate the presence of graded sediment within the hurricane layer. This observation is possibly due to the size of each sample split (0.5 cm) which may have been too large to properly document sediment grading if it were present. A second explanation for the absence of graded sediment is that the sediments deposited in this environment through storm activity are generally reworked from the surrounding marsh, and the reworking mechanisms may not have resulted in the formation of a graded sediment. The sediment is more poorly sorted in Zone 2, however, which is typical of high energy sediment deposition.

The sediment deposited by Hurricane Andrew in Zone 2 contains nearshore, salt marsh, and freshwater signals. The most likely nearshore source would be Terrebonne Bay, which MCKEE *et al.* (1995) proposed serves as a sediment sink on decadal time scales. During infrequent storm events such as hurricanes, MCKEE *et al.* (1995) hypothesized that the sediment is transported from the upper portion of Terrebonne Bay to the marshes to the north. The decreased levels of nitrogen in the hurricane layer (Figure 6b) also suggest that Terrebonne Bay is the sediment source. Carbon also displayed decreased levels in the hurricane layer, but the values

fluctuated through the core enough to prevent carbon from being a good, distinguishing indicator of Zone 2. Lowered concentrations of organic matter are typical of a more saline sediment source like Terrebonne Bay, when compared with less saline areas, such as salt and brackish marshlands, as plant detritus and freshwater inputs are diluted moving down through the upper estuary (MCKEE *et al.*, 1995). It is also possible that the organic matter was winnowed out of the sediment via reworking processes related to the hurricane event (JACKSON *et al.*, 1995). Therefore, sediments imported from Terrebonne Bay could be responsible for the lower nitrogen content of the sediment located in Zone 2. Additionally, the presence of one diatom species, *Navicula abunda*, could indicate a Terrebonne Bay sediment source. The peak in the abundance of *Navicula abunda* in the hurricane layer is interesting in that this particular diatom is classified as a marine, benthic-mobile form (Table 2), has only been found in significant numbers in Terrebonne Bay sediments (*personal observation*), and was rare in all sediment samples from the pre-hurricane core.

While these results may be indicative of a nearshore source (Terrebonne Bay), several diatom indicators point to a less saline sediment source, signified by the lower abundance of



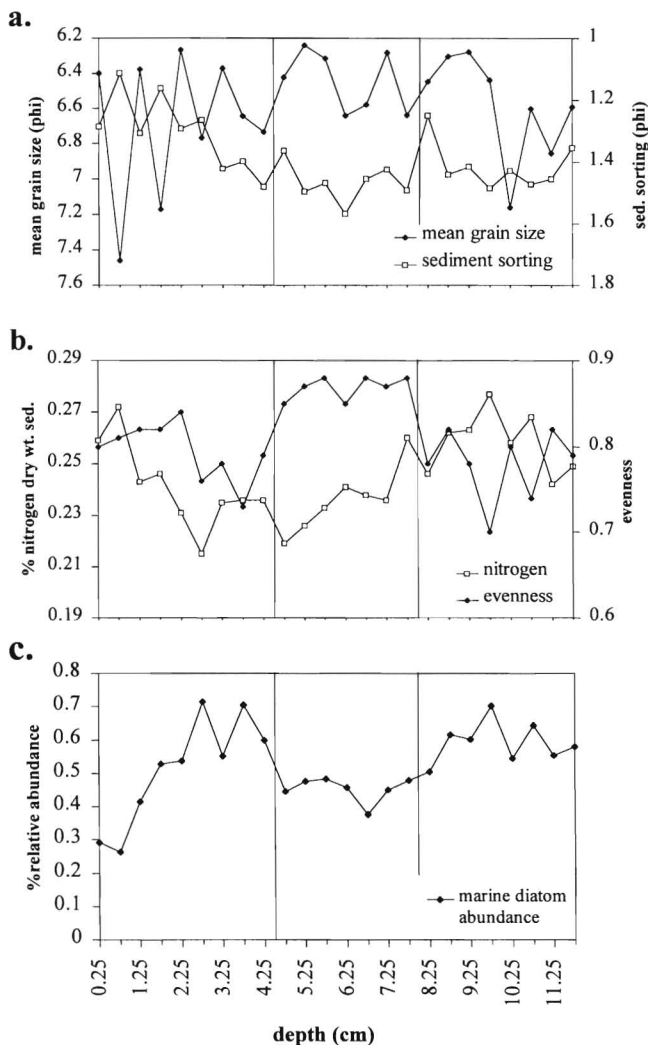


Figure 6. Depth profiles of the five variables that best distinguish the hurricane layer (the middle zone) according to the canonical discriminant analysis. The three zones of the post-1 sediment core are distinguished by the two vertical lines present on each graph.

marine diatoms in Zone 2 (Figure 6c). One possible interpretation of this observation is that a portion of the sediment was transported from an area in the marsh which was less saline. Wind directional shifts were observed during Hurricane Andrew, with the wind shifting from the east, to the northeast, and then to the southeast before dying down (STONE *et al.*, 1993), possibly causing water movements to move obliquely and to the right of the wind direction, which in the case of Hurricane Andrew would have resulted in east-west movements of water as the winds shifted, in a scenario similar to that presented by HAYES (1978). Such water movements could have imported brackish and freshwater sediment from marsh areas to the west near the Atchafalaya River Basin, or from the fresher marshes to the north. Both sources are feasible, because large areas of coastal marsh, including freshwater regions, were inundated by storm flood

Table 4. The ten diatom species displaying the most variation between zones. The accompanying numbers are the overall coefficients of variation (c.v.) for each species across the zones, and the zone-averaged relative abundance values within each zone.

Species	c.v.	Zone 1	Zone 2	Zone 3
<i>Amphora acutiuscula</i>	0.010	0.004	0.020	0.004
<i>Navicula abunda</i>	0.017	0.008	0.037	0.016
<i>Navicula gregaria</i>	0.010	0.009	0.019	0.004
<i>Navicula salinarum</i> var. <i>minima</i>	0.009	0.010	0.014	0.002
<i>Cocconeis placentula</i> var. <i>euglypta</i>	0.021	0.033	0.008	0.013
<i>Thalassiosira oestrupii</i> var. <i>venrickii</i>	0.009	0.015	0.004	0.013
<i>Nitzschia filiformis</i>	0.012	0.019	0.023	0.008
<i>Craticula cuspidata</i>	0.006	0.006	0.013	0.007
<i>Stauroneis producta</i>	0.008	0.010	0.023	0.014
<i>Diploneis puella</i>	0.021	0.037	0.063	0.033

waters (Figure 1; JACKSON *et al.*, 1995). The flood waters were retained in the marsh for over four days in many cases, due to the nature of the drainage of the marsh systems (STONE *et al.*, 1993). As the flood waters receded to the south,

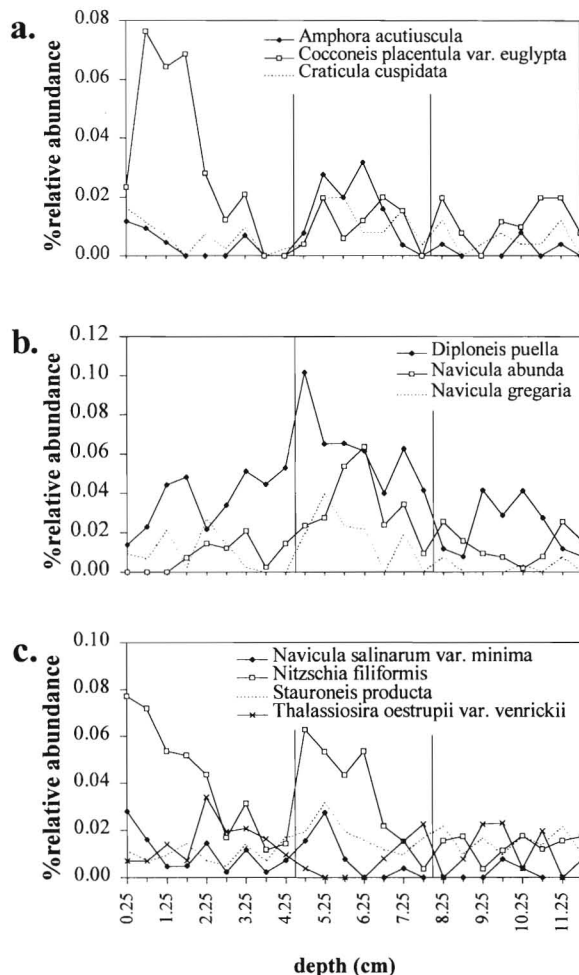


Figure 7. Depth profiles of the ten diatom species that display the most variability across the three zones of the post-1 sediment core.

Table 5. Comparison of diatom relative abundances in the upper 0.5 cm of the TSMP site over a two year period (> 5% abundance, b = benthic-mobile forms, e = epiphytic forms). While *Cyclotella meneghiniana* and *Bacillaria paradoxa* are generally considered to be cosmopolitan diatoms, being present in the water column and on the sediment surface respectively, both were epiphytic on plant samples taken in June, 1994 along with the third and fourth sediment cores.

Species	Niche	August 1992	Species	Niche	August 1993	Species	Niche	June 1994
<i>Tryblionella granulata</i>	b	0.162	<i>Fragilaria brevistriata</i>	e	0.207	<i>Nitzschia filiformis</i>	e	0.454
<i>Amphora copulata</i>	b	0.135	<i>Tryblionella hungarica</i>	b	0.076	<i>Cyclotella meneghiniana</i>	e	0.083
<i>Nitzschia compressa</i>	b	0.085	<i>Amphora copulata</i>	b	0.073	<i>Cocconeis placentula</i> var. <i>euglypta</i>	e	0.082
<i>Navicula salinarum</i> var. <i>minima</i>	b	0.083	<i>Nitzschia compressa</i>	b	0.059	<i>Bacillaria paradoxa</i>	e	0.052
<i>Navicula circumtexta</i>	b	0.082	<i>Tryblionella granulata</i>	b	0.058			
<i>Navicula consentanea</i>	b	0.081						

sediments may have been imported to the study site from the brackish and freshwater areas to the north and west, resulting primarily in the deposition of brackish water species (included in the estuarine classification). A peak in freshwater diatoms also occurs in the hurricane layer, although the result is not statistically significant ( $p \leq 0.512$ ).

The hurricane layer appears to contain sediment from a variety of sources, and therefore has a composite nature. The higher species evenness (Figure 6b) can be explained by allochthonous inputs of freshwater, estuarine, and marine diatom species atypical of the study site. Diatoms were imported and mixed together from a variety of sources during the storm, resulting in a collage of species where none dominate. This scenario is also indicated through the species profiles displayed in Figure 7. Seven of these ten species are estuarine forms that peak in abundance in Zone 2, indicating that these species may have been imported to the site from other estuarine/brackish areas nearby, where they were more abundant (*i.e.*, reworking).

The similarity of Zones 1 and 3 in all of the analyses indicates that Hurricane Andrew did not have an effect on the sediment composition one year after landfall, except for the hurricane layer found at 4.75–7.75 cm. This observation demonstrates that sediment deposition processes returned to pre-hurricane characteristics. However, an important effect that Hurricane Andrew had on the salt marsh pond two years after landfall was the proliferation of submerged aquatic plants (*Najas* sp.) in the pond, which were not present prior to the hurricane. There appears to be several impacts of this new contributor to the pond productivity, including possible baffling of tide and wind-induced water currents by the plants' stems and whorls, which may have increased sedimentation in the pond. Post-hurricane sedimentation appears to be approximately 4 cm/yr, based on the thickness of Zone 1 (post-hurricane layer), which is four times greater than the average pre-hurricane pond sedimentation rate of 1 cm/yr (PARSONS, 1996). Other researchers have reported an increase in sedimentation rates by a factor of one to three for other study sites (CAHOON *et al.*, 1995). A second consequence of the aquatic plants is the increased presence of epiphytic diatom species, which is demonstrated in the species assemblage shift displayed in Table 5. This species shift is apparently related to the proliferation of the aquatic plants. The development of this aquatic stand of plants may be due to a decrease in sediment and pore water sulfide levels, related to

geochemical changes caused by sediment mixing and redeposition processes of Hurricane Andrew (JACKSON *et al.*, 1995). Decreased levels of sulfides allows submerged plants to flourish. JACKSON *et al.* (1995) found that sulfide levels in sediment and pore water samples from a core taken 30 km from the study site were lower after the passage of Hurricane Andrew than before the event, strengthening the argument for lowered sulfide levels at the study site. Therefore, the emergence of aquatic plants and subsequent diatom species shift could be a result of lowered sediment sulfide levels, as observed by JACKSON *et al.* (1995). If Hurricane Andrew altered the geochemistry of the pond sediments, subsequently causing a diatom species shift, then it is possible that hurricane events preserved in the sediment could be distinguished by the diatom species shift towards epiphytic forms.

## CONCLUSIONS

This study set out to determine if a hurricane layer could be distinguished, and it was successfully identified. A second purpose was to determine the source of the sediment imported by Hurricane Andrew. Results indicated that the sediment has characteristics of many environments, and was probably imported and reworked from a variety of locations. The results of this study concur with other published hurricane studies, especially with the conclusions that hurricanes are a major source of sediment for the marshes of coastal Louisiana, and that hurricanes tend to rework sediments in marsh and estuarine environments.

While the hurricane layer was no longer readily obvious in the sediments two years after landfall, possibly indicating chemical diagenetic processes, the distinctive diatom assemblage would not have been affected and should still be a good indicator of this storm event in future studies. Additionally, Hurricane Andrew appears to have caused a diatom species shift towards epiphytic species, related to the proliferation of aquatic plants. This shift has been evident for two years, indicating that a hurricane event can affect diatom stratigraphy. If hurricanes often result in a shift to an epiphytic diatom community, this observation may provide a signal with which to distinguish hurricane sediment layers in paleoecological studies.

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