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IMPACT OF HURRICANE FLOYD ON SEDIMENT DEPOSITION, EROSION, AND BENTHIC NUTRIENT FLUXES IN PAMLICO SOUND, NORTH CAROLINA

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ABSTRACT

Record flooding in eastern North Carolina during autumn 1999 caused large-scale sediment transport in the Albemarle-Pamlico estuarine system. This study was undertaken to quantify flood impacts on sediment redistribution and rates of sediment metabolism in Pamlico Sound. Acoustic surveys and textural, chemical, and isotopic analyses of short sediment cores were used to investigate sediment redistribution. Sediment-water exchanges during laboratory incubations and chemical gradients in porewater were used to quantify sediment metabolism.

Acoustic surveys revealed no large-scale sediment erosion or deposition in Pamlico Sound, and grain-size effects were limited to patchy, thin shell layers. Comparisons of sediment chronologies (^{137}Cs, ^{210}Pb) at locations sampled before and after flooding yielded clear evidence of net erosion or net deposition of ≤5 cm; deeper erosion, followed by rapid re-deposition, may have occurred at some locations. In cores collected near the mouths of the tributary estuaries (Neuse, Pamlico) $\delta^{13}C$ of particulate organic carbon (POC) showed anomalously light POC in core tops, consistent with transfer of POC from upstream sections of the estuaries. Pre-flood data on rates of sediment metabolism were lacking, but observed rates of oxygen utilization, denitrification, and POC oxidation were typical of similar environments elsewhere.

(estuaries, sediments, Pamlico Sound, floods, hurricanes, sediment chronology, ^{137}Cs, ^{210}Pb, stable carbon isotopes, benthic fluxes, denitrification, oxygen penetration)

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SUMMARY AND CONCLUSIONS

Rainfall from hurricanes Dennis, Floyd and Irene in September-October 1999 caused record flooding in eastern North Carolina. Massive transport of suspended sediment was evident from both ground-based and satellite observations; the latter show clear plumes of sediment-laden water entering Pamlico Sound from the estuaries of the Neuse and Pamlico rivers. This study was undertaken to quantify the extent and impacts of sediment redistribution in Pamlico Sound.

In view of the large size of Pamlico Sound, a hierarchical structure was adopted for this study. Acoustic surveys in the lower Neuse estuary and adjacent parts of Pamlico Sound were used to search for large-scale effects of flood discharges. Concurrently or subsequently, sediment cores were collected for detailed chemical, isotopic, or biogeochemical study. Any anomalies discovered from the acoustics would have been priority locations for coring; as none were found, emphasis was placed on reoccupation of sites which had been previously sampled, so that, where possible, post-flood data could be compared with pre-flood data. Net erosion/deposition, sediment provenance, and organic carbon (OC) delivery were investigated through measurements of depth profiles in sediment cores: radioactive chronometric tracers (^{137}Cs, ^{210}Pb), % OC, and δ^{13}C in OC. To assess sediment metabolism, short sediment cores were incubated in the laboratory for determination of benthic fluxes of oxygen, dissolved inorganic carbon (DIC), and nitrogen, and biogeochemically active ionic species (sulfate, ammonium, DIC) were determined in sediment porewaters.

Acoustic surveys revealed no bedforms indicative of large-scale erosion or deposition in Pamlico Sound and no tonal contrast due to deposition of new sand. Isolated bedforms were observed in the lower Neuse estuary. Among these, the only apparent flood deposits were discontinuous, thin (< 1 cm) shell deposits. The close similarity of porosity profiles in pre-flood and post-flood sediment cores confirms the absence of a distinctive flood lithology at the coring locations.

Pre-flood sediment cores from Pamlico Sound showed similar depth profiles of the chronometric tracers excess ^{210}Pb and ^{137}Cs. In consequence numeric modeling yielded quite uniform sediment-transport parameters: sediment-accumulation rates of 1-2 mm.yr^{-1}, sediment-mixing coefficients of 3-50 cm^{2}.yr^{-1}, and mixed-layer thicknesses of 4-10 cm. A core from the mouth of the Neuse estuary yielded both a higher accumulation rate (3.5 mm.yr^{-1}) and a thicker mixed layer (16 cm). Post-flood tracer profiles matched pre-flood profiles very well below the depth of apparent flood disturbance ($\leq$ ~24 cm). Careful comparison of pre-flood and post-flood profiles suggests that net erosion or net deposition was limited to $\leq$ ~5 cm. Greater depths of flood disturbance at some locations imply substantially greater erosion, followed by rapid sediment deposition.

At three of four coring locations post-flood concentrations of OC in sediments were very similar to pre-flood concentrations; at the fourth site, the post-flood OC was systematically higher in the top ~18 cm. In contrast post-flood $\delta^{13}C$-OC was systematically more negative in core tops (4 to ~20 cm) at all sites. More negative $\delta^{13}C$ implies seaward transport of upstream particulate organic carbon (POC), as might be expected during flood discharge; consistent with this interpretation, the disparity in isotopic compositions is most pronounced near the mouths of the Neuse and Pamlico estuaries. However, the offsets between pre-flood and post-flood $\delta^{13}C$-OC values extend to depths in the sediment column which exceed the depths of sediment disturbance, as deduced from ^{137}Cs and ^{210}Pb; particle-selective, non-local sediment mixing may explain this observation.

Sediment metabolism was found to be broadly consistent at four sites in muddy sediments. Benthic fluxes (O_2, DIC, NH_4^+, NO_3^-) and rates of denitrification were essentially uniform. Microelectrode profiles showed dissolved oxygen to be consumed within the top four mm of the sediment column. In contrast, porewater profiles of DIC, NH_4^+ and SO_4^{-2}, which average over much larger sediment volumes, showed efficient bioirrigation to depths of 15-20 cm. While the lack of pre-flood measures of sediment metabolism precludes a direct assessment of flood impacts, the present data are consistent with expectations for nearshore, organic-rich muds.

RECOMMENDATIONS

Sediments in North Carolina's sounds and estuaries contribute importantly to the health of coastal ecosystems and directly influence many of the economic and recreational uses of coastal waters. It is our strong recommendation, therefore, that we act to develop at least a first-order understanding of the operation and rates of the fundamental processes in these sedimentary environments. These processes include, for example:

- sediment transport and deposition;
- sediment resuspension and erosion;
- animal-sediment interactions;
- sediment-water exchanges of dissolved oxygen, nutrients, and potential toxins (trace elements, organic compounds, etc)
- burial and storage of nutrients and potential toxins.

As illustrated by this study, knowing baseline distributions and rates of critical processes prepares us to recognize change and to quantify its effects. This project was designed to assess the impacts of major flooding on sediments in Pamlico Sound. Research objectives included a subset of those listed above: mapping areas of major erosion or deposition; quantifying erosion and deposition in the areas most dramatically affected; quantifying effects of erosion or deposition, including the potential introduction of allochthonous (watershed) materials, on rates of exchange of dissolved oxygen and dissolved inorganic nitrogen. While this study was necessarily of limited scale, it is significant that the most secure conclusions applied to sites and parameters for which detailed pre-flood data existed.

In light of the foregoing we strongly recommend a systematic and ongoing effort to better characterize the estuarine and lagoonal sedimentary environments behind North Carolina's Outer Banks. Because of the size and complexity of the combined Albemarle-Pamlico system, the necessary research presents a substantial challenge. However, the same size and complexity increase both the attractiveness of the task to the research community and the urgency of task to managers.

INTRODUCTION

During September-October 1999 extremely heavy rainfall from hurricanes Dennis, Floyd and Irene brought record flooding to eastern North Carolina (Bales et al. 2000). Sustained flood discharges in the Neuse and Tar-Pamlico river basins supported massive fluxes of dissolved and particulate materials to Pamlico Sound. Some of these fluxes were monitored as they occurred (Bales et al. 2000; Bales 2003), and some ecological impacts of dissolved fluxes are being followed in ongoing research (Paerl et al. 2001; Peierls et al. 2003). While it is apparent from satellite imagery (see Paerl et al. 2001) that the floods transported massive quantities of suspended sediments, however, the extent and consequences of the redistribution of fine-grained sediments are largely unknown. This report addresses these issues for the western Pamlico Sound, which directly exchanges sediments with the Neuse and Pamlico estuaries (Figure 1).

Rainfall from hurricanes Dennis, Floyd, and Irene varied geographically in eastern North Carolina and contributed to flooding in different ways (Bales et al. 2000; Bales 2003). In general, the rainfall from Dennis (3-7 September) saturated soils, increasing runoff from Floyd rainfall (14-17 September); Irene (17-18 October) augmented and prolonged the continuing flooding from Dennis and Floyd. Most locations in the Coastal Plain received as much (or more) rainfall from Floyd as from Dennis and Irene combined, and peak river discharge occurred shortly after Floyd's passage (Bales et al. 2000). Accordingly, we adopt the convenient shorthand of attributing the flood discharges and their consequences to Floyd. However, the magnitude and duration of the hydrological event resulted from the closely spaced arrivals of the three large storms.

In many of the streams of the Neuse and Tar-Pamlico river basins, the peak post-Floyd discharges are the largest ever recorded; in these cases the recurrence intervals are estimated to range from 50 years to > 500 years (Bales et al. 2000; Bales 2003). The magnitudes of the peak discharges are important to transport of suspended sediment. Given an adequate sediment supply, the concentration of suspended sediment which a stream can carry commonly increases as the b^{th} power of the discharge (typically $1 < b < 2$; Knighton 1998), giving added weight to the highest discharges. So far as the floods of September-October 1999 are concerned, we should therefore expect that most sediment transport occurred during the 2-3 weeks following hurricane Floyd. In a number of the streams of the Neuse and Tar-Pamlico basins, however, the second highest discharges of record followed hurricane Fran in September 1996. Although the 1996 discharges were lower, they might have depleted stores of readily eroded sediment, thus reducing the post-Floyd sediment flux. Below we assess flood-induced sediment redistribution by comparing sediment cores collected before (1990, 1994, 1995) and after the major floods of 1996 and 1999. We believe that the impacts we report resulted largely from hurricane Floyd (1999) floods, but we cannot exclude contributions from hurricane Fran (1996).

Our research in western Pamlico Sound has two major objectives: to assess the extent of sediment redistribution following major floods in the tributary river/estuary systems; and to evaluate the impact of the sediment redistribution on exchanges of nutrients and oxygen between the sediments and the water column. We have investigated sediment redistribution

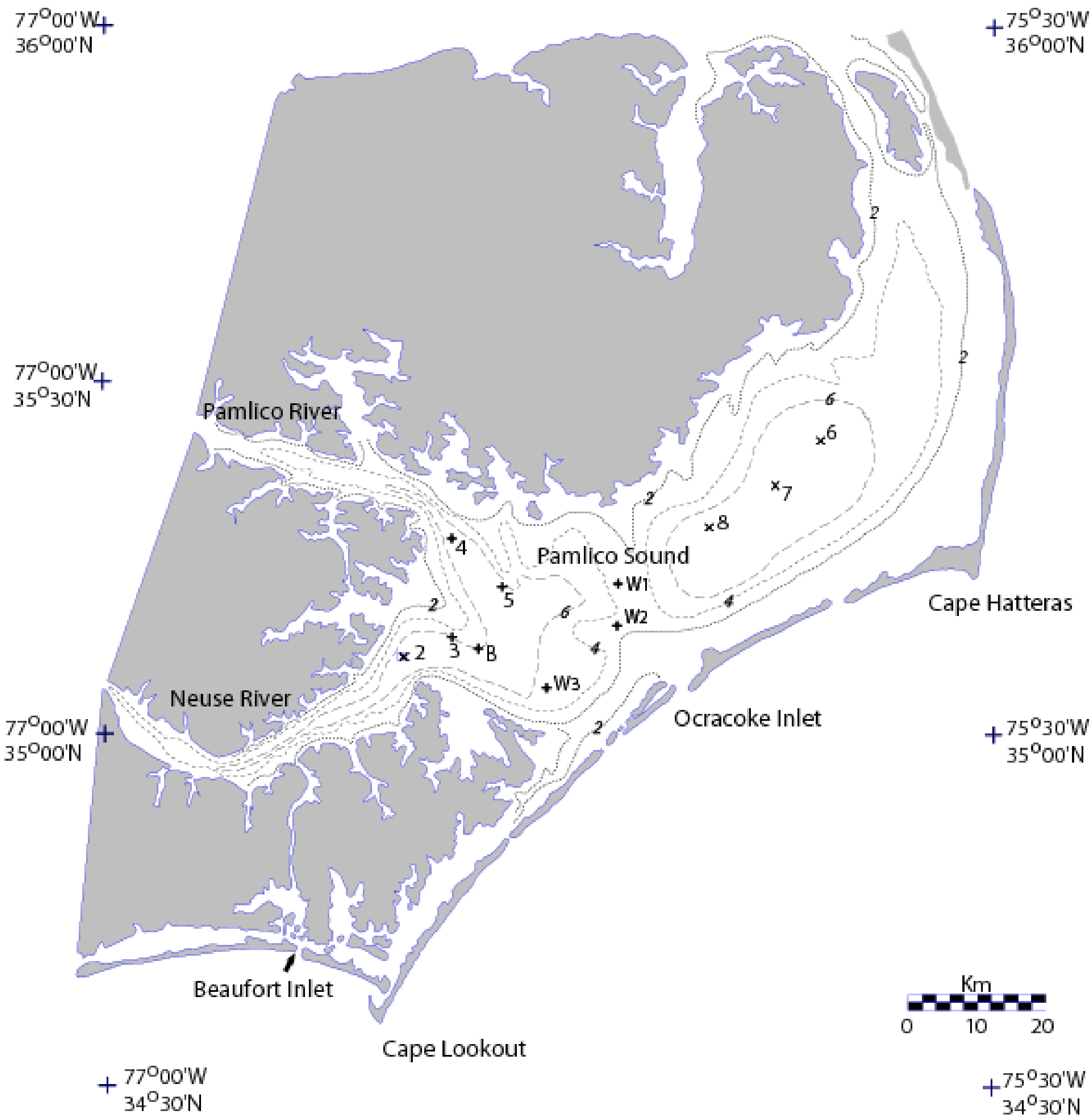

Figure 1. Western Pamlico Sound and its tributary Neuse and Pamlico estuaries. Sampling locations are indicated by x or +. Bathymetry contour interval 2 m.

through use of acoustic survey techniques and through various textural, chemical, and isotopic analyses of short (tens of cm) sediment cores. We have quantified sediment-water exchanges by incubating short sediment cores in the laboratory (determining benthic fluxes through sequential measurements of concentrations in overlying waters), and by measuring porewater concentration gradients at the sediment-water interface. To gain a long-term (millennial time scale) perspective on flood impacts we have also conducted preliminary examinations of longer (3.3-8.9 m) sediment cores.

METHODS

Acoustic Surveys. Prior to coring (Fall 2000 – Spring 2001), an Interferometric Seabed Inspection System (ISIS) was towed along sections of the Neuse River estuary, and seaward from the river mouth along the suspected corridor of sediment transport into southern Pamlico Sound. ISIS provides very accurate bathymetry and side-scan sonar imaging of overlapping track lines, each covering a swath that is approximately 80 m wide (40 m on each side of the survey vessel). This imaging system, a Submetrix 234 kHz unit, is designed specifically for shallow-water applications and obtains approximately 50 soundings per m^2 at swath widths 5-10 times the water depth. A Northstar differential GPS was used for navigation.

Seven areas were selected as survey sites, each 0.5-1.0 km^2, including several upstream locations where cores had previously been taken. The Neuse River was included in our survey work because, as a major tributary to Pamlico Sound, it was thought to contain important clues regarding flood-related sedimentation processes and patterns. Our intent was to use the information from the surveys to a) determine sediment texture and 3-dimensional seafloor relief, and b) screen for sites which showed evidence of recent erosion or deposition. Grab samples and observations from SCUBA divers provided ground truth information at survey sites where bottom targets were observed in the ISIS surveys.

Sediment Collection and Processing. Sediment cores were collected 13 July 2000 in the Neuse estuary and 3-4 October 2001 in western Pamlico Sound (Figure 1; Table 1). Coring stations were selected to span a range of distances from the source of flood waters, and whenever possible to coincide with sites that had been sampled before the major flooding events of the late 1990's. Station 2 is located near the seaward end of the Neuse estuary where satellite images taken during the 1999 flood show clear evidence of sediment-laden waters (Paerl et al. 2001). Stations 3 and 4 are located just outside the mouths of the Neuse and Pamlico estuaries. Stations B and 5—located 4 and 10 km southeast of stations 3 and 4, respectively—mark the region where Pamlico Sound approaches maximum depth. Stations W1, W2, and W3 are located > 20 km from tributary rivers and estuaries, adjacent to shoals that bound the western basin of Pamlico Sound. For comparison purposes, we also present data from cores collected in 1990 at stations 6, 7, and 8 located in the eastern basin of Pamlico Sound.

In Table 1 station numbers identify locations. 1990, 1994 and 1995 stations were located using LORAN-C, to a precision no better than about ±0.5 km. 2000 and 2001 stations were located more precisely (±0.1 km) using differential GPS, and station re-occupations were within ±0.3 km of their nominal locations in the 1990's.

Table 1. Sediment core samples discussed in this report.

Station	Water Depth, m	N Latitude	W Longitude	Date	Samples
2		35°06.6′	76°29.73′	9-13-90 7-13-00	P P,V
3	6.7	35° 08.122′	76° 24.840′	9-13-90 10-3-01	P P,V
B	7.3	35°07.456′	76° 21.854′	8-1-94 10-10-95 10-3-01	P P P,V
4	5.5	35° 16.373′	76° 24.709′	9-13-90 10-4-01	P P,V
5	6.4	35° 13.039′	76° 19.356′	9-13-90 10-3-01	P P,V
W1	6.4	35° 12.715′	76° 08.162′	10-3-01	P,V
W2	6.1	35° 09.551′	76° 13.715′	10-3-01	P,V
W3	6.7	35° 04.332′	76° 15.100′	10-4-01	P,V
6	5.9	35° 23.50′	75° 49.38′	9-14-90	P
7	6.1	35° 20.07′	75° 53.22′	9-14-90	P
8	6.4	35° 17.15′	75° 57.56′	9-14-90	P

P = diver-collected push core V=vibracore

Below we identify sediment cores by the notation uv-St, where u and v are the final two digits of the year of collection, and St identifies the station. For example, cores 90-3 and 01-3 were collected at station 3 in 1990 and 2001, respectively.

Two types of cores were collected: push cores and vibracores. Push cores for sediment chronology (^{210}Pb, ^{137}Cs, K, ^{226}Ra, and porosity), geochemical analyses (organic C, C:N ratio, C and N stable isotopes, and porewater constituents other than O_2), benthic flux measurements, O_2 microprofiles, and denitrification rates were collected by divers using SCUBA. Divers took care to collect an undisturbed sediment-water interface. For sediment chronology the CAB (cellulose acetate-butyrate) core tubes had 9.5 cm internal diameter (i.d.). Core length varied between 16 cm in sand (station W1) and 44-52 cm in muds (remaining stations). No core for chronology was collected at station W3. For remaining geochemical analyses, benthic flux measurements, O_2 microprofiles, and denitrification rates, 10.2 cm i.d. PVC core tubes were inserted by divers to a sediment depth of ~27 cm. Cores for geochemistry, benthic flux, O_2 microprofiles, and denitrification rates were not collected at stations 2, W2, and W3; O_2 microprofiles were not measured at station W1. Cores were stored vertically in racks on board ship and were refrigerated at the end of each day in the field. Push cores were returned to Chapel Hill and stored refrigerated (and uncapped for O_2-sensitive measurements) until subsampling.

Sediment cores for chronology were extruded (26 July 2000 or 9-13 October 2001) and subsampled in two-cm increments. Below the top four cm in each core, samples were trimmed to remove the two-four mm of sediment closest to the core tube. Each subsample was transferred to a pre-weighed polypropylene jar and stored frozen or refrigerated until it could be freeze-dried. For freeze drying, jar caps were removed and replaced with a rayon cleanroom wiper, secured with a rubber band. Sediment porosity was calculated from mass % water (wet-mass basis) (Berner 1971), assuming an average density of 2.5 $g.cm^{-3}$ for sediment particles.

Below we compare chronology and solid phase geochemistry results from 2001 cores with results from cores collected in 1990, 1994, and 1995. Procedures for sample collection and processing were similar in the earlier collections, except that sample depth increments varied and that the 1990 samples were oven-dried rather than freeze-dried. Solid phase geochemistry for 1990 cores was measured on the archived samples as part of this study.

Push cores for geochemical analyses were processed on 8 October 2001. Overlying water was removed by siphon and the upper 2-cm of sediment was subsampled at half cm intervals. Near-surface sediment was extruded into a 0.5-cm segment of core liner, sliced using a stainless steel shim with beveled edges on two sides, and quickly poured or scraped into the open end of a cut-off 30-mL plastic syringe. Deeper sediment (2 to 25 cm) was subsampled at three cm intervals by extruding into a 3-cm segment of core liner predrilled with two side-by-side 2.4-cm ports. This sediment was transferred to cut-off 30-mL plastic syringes by “piston coring” horizontally through the ports. Cut-off syringes were then fitted with a plastic nozzle to facilitate sediment transfer. An aliquot of sediment for solid phase analyses was injected into a tared 20-mL plastic scintillation vial; the sample was frozen and freeze-dried. The remainder of the sediment was used to fill a 40-mL polypropylene centrifuge tube. Porewater was extracted by centrifugation at 7000 rpm for 15 min. Supernatant was pipetted using a 10-mL plastic syringe with large bore stainless steel needle, and passed through a 0.45 µm syringe filter. Processing and storage of the porewater varied between analyses and is described below.

Push cores for benthic flux measurements and O_2 microprofiles were stored uncapped in a cold room (5ºC) to maintain oxic overlying water and reduce metabolic activity prior to processing (19 October 2001 for Station W1; 26 October 2001 for Stations 3, B, 4, 5). Overlying water was drained by siphon and the upper 10-cm of core was carefully extruded into a 14.5-cm segment of core liner equipped with a flange at the upper rim to provide an o-ring seal with the inner wall of the benthic flux chamber. A rubber stopper and plastic Caplug® were used to seal the subcore bottom and align the sediment surface with the top of the flange. The subcore was then placed inside the barrel of the benthic chamber (12.7 cm i.d. × 25 cm long PVC) which was secured to the base plate by means of bungee cords. The benthic chamber was placed in a water bath at in situ temperature (19ºC), filled slowly with artificial seawater (Instant Ocean®) of in situ salinity (24 psu), and stirred continuously at ~60 rpm. Subcores were preincubated at in situ temperature in complete darkness with overlying water exposed to air for about one week prior to beginning benthic flux or O_2 microprofile measurements.

Push cores for denitrification rates were also stored uncapped in a cold room (5ºC) prior to processing (11 to 17 October 2001). Five subcores containing the undisturbed 0-3 cm depth interval were taken from each push core using specially designed incubators fashioned from cut-off 60 mL plastic syringes (Nie 2002).

Vibracores, which ranged from 3.32-8.65 m (10.9-28.4 ft), were taken in thin-walled aluminum conduit. The vibracoring technique involved attaching a vibrating head to the top of the core tube, which was then connected via flex cable to a gasoline-powered engine aboard ship. As the core tube vibrates, friction is reduced along the walls allowing the core tube to penetrate more easily into the bottom. Disturbance to the sediments is usually nil. Cores were taken until the core tubes were filled or to the point of refusal, which occurred when gravel, compact sand or significant shell deposits were encountered. Prior to coring, a core catcher was riveted into the bottom of each length of core tubing to help retain sediments during core extraction. An expandable stopper was inserted into the top of the core for the same purpose. Once on board ship, cores were cut into manageable lengths (~3 m), capped, and sealed for transport to the laboratory.

After returning to the laboratory, the vibracore tubing was cut lengthwise using a circular saw and template. Cores were then split into halves using thin wire to cut through the sediments. One of the core halves was visually described, photographed and subsampled (for further analysis) at 10-cm intervals. The other half was sealed for archive purposes. Prior to subsampling, acrylic trays (25 cm x 5 cm x 1 cm) were inserted into the working halves of the split cores to obtain thin slabs of material for X-radiography. X-ray analysis was performed at the Institute of Marine Sciences using a Picker Industrial X-ray Unit. Bulk samples from two of the cores (core 01-3, mouth of the Neuse River estuary; core 01-4, mouth of the Pamlico River estuary) were sent to a commercial dating facility for ^{14}C age determinations on organic carbon. Conventional 14C ages (in radiocarbon years) were converted to absolute (cal) ages through use of the publicly available Radiocarbon Calibration Program (Stuiver and Reimer 1993), revision 4.4.2, employing the bidecadal atmospheric calibration dataset.

Bottom Water Collection. Divers collected bottom water at each station by opening empty 125-mL polyethylene bottles approximately one meter above bottom. Samples were stored refrigerated prior to analysis.

Modern Sediment Chronology. Modern (last ~100 years) sediment chronologies are based upon the vertical distributions of radionuclide tracers in sediment cores (Goldberg and Bruland 1974; Robbins 1978; Appleby and Oldfield 1992; Nie et al. 2001). Here we use natural excess ^{210}Pb, a U-series nuclide of half-life 22.26 years, and ^{137}Cs, which is produced in nuclear fission and which was introduced into coastal environments of North Carolina as fallout from the atmospheric testing of nuclear weapons. Excess ^{210}Pb is defined as (total ^{210}Pb) – (^{226}Ra), corrected for radioactive decay between date of analysis and date of core collection. We determine total ^{210}Pb by alpha-spectrometric determination of the radioactive granddaughter ^{210}Po, while ^{137}Cs and ^{226}Ra are determined by gamma-spectrometry. Gamma spectrometry also provides determinations of Th-series nuclides (^{228}Ra, ^{228}Th) and ^{40}K; we do not report Th-series data here, but we do use K (from ^{40}K) as an indicator of bulk lithology.

For gamma-spectrometry dried sediment was packed into borosilicate Erlenmeyer flasks (10 mL, 25 mL, or 50 mL, depending upon the available mass of sediment) and stored at least ten days for ingrowth of ^{222}Rn on ^{226}Ra. Samples were then counted for one-three days on one of two intrinsic Ge detectors. Backgrounds (empty flasks) were counted for similar intervals after every six-eight samples. The detectors were standardized by counting appropriate standards in the same geometries (flask sizes) as the samples. For ^{226}Ra the standard was Reference Uranium Ore BL-4a (Canada Centre for Mineral and Energy Technology). For ^{137}Cs and ^{40}K a solution standard was prepared by diluting a commercial ^{137}Cs standard (Amersham International plc) in a laboratory solution of reagent grade KCl (130.3 mg K/g solution). Data reduction followed a common procedure for samples, backgrounds, and standards. Photopeak area was first corrected for baseline, as defined from regions above and below the peak area, and then for background. The background correction which was applied was the average of the two background determinations which bracketed the sample or standard count. Uncertainties in count rates, baselines, and backgrounds were all propagated and are reported as ± one standard deviation. ^{137}Cs was considered finite whenever the activity exceeded zero by at least two standard deviations.

Accuracy of gamma spectrometric determinations was assessed by counting NIST (National Institute of Standards and Technology) Standard Reference Materials (SRM) in 50 mL Erlenmeyer flasks. Rocky Flats Soil (SRM 4353) is certified for all of our analytes. Our results on this SRM were about 90%, 104%, and 105% of the certified values for ^{40}K, ^{137}Cs, and ^{226}Ra, respectively; except for ^{40}K, these deviations are within the quoted uncertainties of the certified values. River Sediment (SRM 4350B) is certified for ^{137}Cs and ^{226}Ra; our results were, respectively, about 105% (within quoted uncertainty) and 113% (slightly outside quoted uncertainty) of certified values. Our two Ge detectors yielded consistent results on the SRMs, so that our data are internally comparable, but there may be slight positive and negative biases in our results.

Microwave digestion was used to prepare samples for the determination of ^{210}Po. Precisely weighed aliquots (1.1–1.4 grams) of dried sediment were transferred to PFA (perfluoroalkoxy) digestion vessels and moistened with 8 N HNO_3. ^{209}Po yield tracer (NIST SRM 4236) was added, followed by 10 mL concentrated HNO_3 and 5 mL concentrated HF. The digestion vessels were then sealed and stored at least overnight before applying microwave heating (MDS-81D: CEM Corporation, Matthews, NC). Following microwave digestion, samples were transferred to PFA beakers containing 4 mL 50% H_2SO_4 and evaporated to fumes of SO_3. The residue was treated repeatedly by evaporating HNO_3 with minor added H_2O_2 to achieve a uniform, light color and to evolve fluorides remaining from the digestion process. The oxidized residue was then dissolved by heating in either 1 N HCl or ~0.8 N HNO_3. After cooling this solution was filtered to remove minor particulate matter. Filtered HCl solutions were ready for Po extraction by spontaneous deposition onto silver disks at about 80°C. In practice such solutions still contained sufficient fluoride to etch glass beakers. Filtered HNO_3 solutions were diluted precisely to 100 mL, and roughly 10 mL was withdrawn for future chemical analysis. The remaining ~90 mL was diluted to 300 mL, and pH was adjusted to 7.5 – 8 with NH_4OH to precipitate Fe,Mn,Al-hydroxides, which carry Po. This hydroxide precipitate was collected by centrifugation, washed, and dissolved in 1 N HCl for Po extraction as above.

Silver disks bearing tracer ^{209}Po and natural ^{210}Po were counted in vacuum under silicon surface-barrier or ion-implanted detectors. ^{210}Po was determined from the $^{210}Po/^{209}Po$ activity ratio and the known activity of tracer ^{209}Po. Assuming secular equilibrium, the total activity of ^{210}Pb is equal the activity of ^{210}Po. Uncertainty in total ^{210}Pb is determined by counting statistics for ^{210}Po. This uncertainty and the uncertainty in ^{226}Ra together determine the uncertainty in excess ^{210}Pb, and excess ^{210}Pb is regarded as finite so long as the activity exceeds zero by at least two standard deviations.

We employ a diffusion-advection-reaction model to estimate rates of sediment accumulation and sediment mixing from depth distributions of excess ^{210}Pb and ^{137}Cs (Nie et al. 2001; Nie, 2002). Excess ^{210}Pb appears to be immobile in organic-rich muds, so the single equation which describes its distribution in sediment cores contains terms for sediment compaction, transport by diffusion (sediment mixing) and advection (sediment accumulation), and radioactive decay. We specify the rate of sediment mixing (presumably largely biological) through a mixing coefficient, D_B ($cm^2.yr^{-1}$), which varies with depth according to the complementary error function (erfc; Nie et al. 2001); this yields a continuous approximation to simple two-layer models, with mixing confined to a surficial "mixed layer." D_{B0} is the magnitude of D_B at the sediment-water interface, and the thickness of the mixed layer, X_{ML}, is defined as the depth where $D_B = 0.1 \cdot (D_{B0})$. The input flux of excess ^{210}Pb is assumed to be constant, and the equation for excess ^{210}Pb is solved at steady state.

A satisfactory model for distributions of ^{137}Cs is necessarily more complicated. The input flux, resulting ultimately from atmospheric fallout from testing of nuclear weapons in the 1950's and 1960's, is time-dependent; we assume that the input flux to Pamlico Sound was proportional to atmospheric deposition of fission-product ^{90}Sr at New York City (HASL 1977; Larsen 1985). In addition, comparison of depth distributions of fallout Pu and ^{137}Cs in sediment cores from the Neuse River estuary implies that ^{137}Cs shows significant chemical mobility in saline pore waters. Thus the model for ^{137}Cs distributions in our sediment cores must include separate equations for the solid phase and the dissolved phase. We relate ^{137}Cs concentrations in the solid and dissolved phases through a simple proportionality:

$$[^{137}Cs_{solids}] = K_D \cdot [^{137}Cs_{dissolved}].$$

The concentrations of ^{137}Cs in solid and dissolved phases are in $dpm.g^{-1}$ and $dpm.mL^{-1}$, respectively, so that the distribution coefficient, K_D, has units of $mL.g^{-1}$. We choose this simple equilibrium model for adsorption-desorption of ^{137}Cs for its mathematical tractability, but we recognize that the actual behavior of ^{137}Cs is more complicated (e.g., Comans et al. 1991; Comans and Hockley 1992; Smith and Comans 1996). Because of the time-dependent input of ^{137}Cs, the model equations for ^{137}Cs must be solved at non-steady-state.

Solution of the model equations for excess ^{210}Pb and ^{137}Cs yields estimates of sediment accumulation rate (ω; $cm.yr^{-1}$), the mixing coefficient (D_{B0}; $cm^2.yr^{-1}$), and the thickness of the surficial, rapidly mixed layer (X_{ML}; cm). The optimal solution is the single set of these parameters which best fits *both* the distribution of excess ^{210}Pb and the characteristic subsurface maximum in the ^{137}Cs distribution. The distribution coefficient for ^{137}Cs (K_D; $cm^2.yr^{-1}$) is then adjusted to fit the peak broadening and the long tail in the ^{137}Cs distribution (Nie 2002). Choosing a single set of parameters which best-fits both excess ^{210}Pb and ^{137}Cs simultaneously deviates from common practice in the literature (Nie et al. 2001), but we believe that this procedure produces the most realistic constraints on sediment transport.

Biogeochemical Analyses. Post-Floyd flood waters may have transported significant quantities of organic-rich sediment to Pamlico Sound. The quantity of allochthonous organic matter in Sound sediments can be constrained by solid-phase geochemical tracers such as percent organic carbon (OC), organic carbon:nitrogen molar ratio (C/N), and stable isotope ratios of organic carbon and total nitrogen. Stable carbon isotope ratios, in particular, have been widely used to discriminate between terrestrial- and marine-derived organic matter (e.g., Hedges and Oades 1997).

For solid-phase analyses, freeze-dried sediment was ground to a fine powder with an agate mortar and pestle. OC and C/N were determined by a Carlo-Erba 1500 Elemental Analyzer after carbonate removal by vapor phase acidification (Hedges and Stern 1984). OC concentrations are reported as percent organic carbon in salt-free dry sediment. Stable isotope ratios of sediment organic carbon and total nitrogen were measured on CO_2 and N_2 in the effluent from the Elemental Analyzer using a Finnigan MAT 242 isotope ratio mass spectrometer equipped with a ConFlo II® interface. Isotope ratios are expressed in standard δ-notation (δ^{13}C-OC or δ^{15}N-TN) representing per mil differences between $^{13}C/^{12}C$ or $^{15}N/^{14}N$ ratio of a sample and standard (McKinney et al. 1950). All δ-values have been corrected for blank contributions, and are referenced to international isotope ratio scales using calibrated acetanilide as laboratory standard (Werner and Brand 2001). Analytical precision is estimated from repeated analysis (n = 9) of a homogenized sample of coastal sediment: OC = 3.03±0.03 %; C/N = 10.0±0.2; δ^{13}C-OC = -19.1±0.1 ‰; δ^{15}N-TN = 3.6±0.2 ‰ (uncertainties are expressed as standard deviations). Results from reanalysis of five sediment samples from core 95-B agree within analytical precision with values measured in 1995 (Ream 1997). This demonstrates that OC, C/N, δ^{13}C-OC, and δ^{15}N-TN in freeze-dried sediment do not change during long-term storage.

Flood-induced sediment redistribution in Pamlico Sound could have a long-term impact on benthic processes. Porewater concentration profiles are sensitive indicators of sediment biogeochemistry and may provide insight into the effect of the massive flood event on the benthic ecosystem. Bottom water and porewater samples were analyzed for ΣCO_2, nutrients (NH_4^+, NO_3^- + NO_2^-, and NO_2^-), and major anions (SO_4^{2-}, and Cl^-). Samples for ΣCO_2 were filtered directly into 1-mL tuberculin syringes (without bubble entrainment), sealed with plastic luer caps, and stored in the refrigerator prior to analysis. ΣCO_2 concentrations were measured by flow injection analysis (Hall and Aller 1992); the standard deviation for triplicate measurements is ≤ ±0.2 mM. Filtered water for nutrients was stored frozen in 10- or 15-mL vials. Samples were thawed just before analysis and acidified (10-µL concentrated HCl to ~5 mL sample) to dissolve iron precipitates. Nutrient concentrations were measured with a Lachet QuikChem automated ion analyzer employing standard colorimetric methods (Grasshoff et al. 1983). Bottom water and porewater samples from the upper two cm were analyzed without dilution; deeper porewater samples were diluted 1:14 with distilled water (NO_3^- and NO_2^- were not analyzed in diluted samples). The standard deviation for duplicate NH_4^+ analyses averaged ±1 µM; NO_3^- and NO_2^- were not detectable (< 2 µM) in any porewater samples. For SO_4^{2-} and Cl^- analyses, 1-mL of filtered sample was transferred to a 1.5-mL plastic vial and bubbled with CO_2 to lower pH and remove hydrogen sulfide. Samples were diluted 1:100 and anion concentrations were measured by ion chromatography (Dionex 2010i) with post-column chemical suppression; the coefficient of variation for both ions is typically ±3 %.

Benthic Flux Measurements. Deposition of flood-derived organic matter in Pamlico Sound might alter sediment-water exchange rates of O_2 and nutrients. Altered benthic fluxes could continue to impact water column processes long after the dissolved and suspended matter from the flood waters is flushed from the Sound. We measured benthic fluxes of O_2, ΣCO_2, NH_4^+, and NO_3^- by incubating intact cores in the dark at in situ temperature (19ºC) in PVC chambers capped with Plexiglas® [poly(methylmethacrylate)] lids (O-ring seal) equipped with inlet and outlet ports and a magnetic stir bar. A chamber barrel with a sealed PVC plate to mimic the sediment surface served as the control. Immediately prior to starting sediment incubations, overlying water was replaced with freshly prepared artificial seawater (Instant Ocean®, 19 psu). Four volumes of replacement water was allowed to gravity flow (~200 mL min^{-1}) through 1/8 inch flexible tubing (Tygon® R-3603); the end of the tube was placed just above the sediment surface and bent upward to prevent sediment disturbance by flowing water. The incubation began by capping the chamber with the Plexiglas lid, taking care to exclude air bubbles. The stirring rate in the benthic chamber was set to 60 rpm. Measured dissolution rates of alabaster plates (Santschi et al. 1983) indicate that this stirring speed results in an average diffusive boundary layer of 0.5 mm, a typical value for shallow marine sediments (Jørgensen and Revsbech 1985).

Samples of overlying water were collected at regular intervals by attaching a syringe to the chamber outlet port. A reservoir of artificial seawater was connected to the inlet port during sampling to maintain a constant volume of overlying water. Chamber water for O_2 measurement was collected in a mass-calibrated 10-mL plastic syringe and analyzed immediately by micro-Winkler titration (Grasshoff et al. 1983). Chamber water for ΣCO_2 and nutrients was collected in a 10-mL plastic syringe and dispensed, stored, and analyzed as described above except that nutrient samples were not filtered or diluted and were not analyzed for NO_2^- (we assume that $[NO_3^-] + [NO_2^-] \cong [NO_3^-]$). Typical precisions for chamber water analyses are ±1 μM (O_2), ±0.05 mM (ΣCO_2), and ±0.1 μM (NH_4^+ and NO_3^-). Benthic fluxes (F) for each chemical species are calculated as:

$$F = \frac{(m_s - m_c) A_c H}{A_s} ,$$

where m_s and m_c are least-square slopes for concentration (corrected for addition of replacement water) vs. time in sediment and control chambers, respectively; A_c is cross-sectional area of the benthic chamber; H is height of the water column inside the chamber (9.5 cm); and A_s is sediment surface area. Uncertainty in each reported flux value is based on error propagation of standard deviations of least-square slopes (m_s and m_c).

Salinity stratification in Pamlico Sound following the massive discharge of freshwater resulted in bottom water hypoxia that persisted for several weeks (Paerl et al. 2001). Benthic fluxes of NH_4^+ and NO_3^- are sensitive to bottom water O_2 concentrations (Höhener and Gächter 1996; Rysgaard et al. 1994) and may have been affected by the post-Floyd hypoxia. We allowed the incubations to continue for a period (~80 hr) sufficient to exhaust O_2 in the chamber water in order to examine how O_2 depletion may have impacted benthic fluxes. For NH_4^+ and NO_3^-, we calculate separate fluxes for oxic and hypoxic periods. Oxic fluxes (F^{ox}) are based on concentration changes during the period when $[O_2] > 63$ μM (2 mg L^{-1}); hypoxic fluxes (F^{hy}) are based on concentration changes when $[O_2] < 63$ μM. Here we adopt the operational definition of "hypoxia" (< 2 mg L^{-1}) given in Rabalais and Turner (2001).

Oxygen Microprofiles. High resolution oxygen profiles define the extent of the oxic layer and can be used to corroborate oxygen fluxes measured with benthic chambers. Oxygen microprofiles were measured following the procedure of Revsbech et al. 1980. Oxygen microsensors and micromanipulator were supplied by Unisense®.

Denitrification Rates. Microbial denitrification may be an important sink for nitrogen delivered to Pamlico Sound during the 1999 flood event (Paerl et al. 2001). Total sediment denitrification is equal to the benthic flux of N_2. However, this flux is difficult to measure directly owing to high background N_2 concentrations in air. Sensitivity can be greatly improved by using the isotope pairing technique (IPT) (Nielsen 1992) in which ambient nitrate is replaced with ^{15}N-labelled NO_3^- tracer. Details of the method are given in Nie (2002).

RESULTS

Physical properties of sediments

Acoustic Surveys. Examination of the ISIS images revealed a rather homogeneous sediment textural pattern (little or no tonal contrast) with isolated bedforms and oyster reefs in the lower Neuse River estuary, and small shell patches in southern Pamlico Sound. Bathymetry was very uniform and there was no evidence of subaqueous delta formation. Bedforms did not occur along estuarine transport corridors and there was virtually no indication of deposition of new sand in Pamlico Sound. In fact, insofar as ISIS could discriminate sediment texture, the bottom appeared to be composed of silt and clay, and almost completely devoid of sand except where associated with isolated bedforms. Field notes taken by divers at two months and four months after the hurricane indicated that a flocculent mud layer covered vast areas of the bottom.

Nearly all of the targets that were identified in the surveys, and subsequently sampled by divers, were in the lower Neuse River estuary. Oyster reefs were the most prominent and well-defined features. Considerable work has been done on oyster reefs in this system and, except for possible questions regarding biological recruitment or mortality, they have no direct connection to flood sedimentation. However, the isolated parabolic-shaped bedforms are especially interesting and potentially important because they were composed primarily by shells from *Macoma* sp, a common estuarine clam. The shell deposits, which had crests from three-six m long, were less than one cm thick and resembled “starved” ripples. They appeared to be very recent unconsolidated deposits, and divers verified that the shell had been deposited over a fine-grained substrate.

Vibracore Descriptions. Visual descriptions and X-radiographs reveal that cores from stations 3, B, 5, W3 and 4, located seaward of the tributary rivers, contain thick sections of organic-rich muds that range from slightly bioturbated to intensely bioturbated and that cores from stations W1 and W2, located farther east in the vicinity of Bluff Shoal, contain significant amounts of sand and shell. The most intensively bioturbated sediments occur in the upper ~1 m of every core except that from station W1.

Cores from stations 3 and 4, which are counterpart cores taken just seaward of the mouths of the Neuse and Pamlico Rivers, respectively, are characterized by homogeneous, well-sorted gray mud with sections of faint laminations of silt/fine sand and isolated patches of shell and woody organic material. These cores appear to be recording, insofar as can be determined by core stratigraphy, the same depositional and erosional processes at both river mouths. Many of their deeper sedimentary units appear to be bounded by sharp contacts, but primary sedimentary structures indicative of deposition under conditions of high sediment loads are virtually absent. A thick basal peat (~80 cm thick) was present at the bottom of the station 3 core, probably marking the subaerial marsh surface at the base of the Holocene. Commercial ^{14}C dates in this peat layer indicate ages of 7,920 ± 600 radiocarbon yr (8830 ± 660 cal BP) at 7.95 m and 8,560 ±240 radiocarbon yr (9650 ± 260 cal BP) at 8.65 m; the cited uncertainties correspond to two standard deviations.

Farther into Pamlico Sound, cores from stations W1 and W2 showed a wider range of lithologic features. Station W1 sediment, taken in a geographic position closest to Bluff Shoal, was comprised primarily of green, rust and white-colored sand. This was the only core that contained an apparent grain size trend, a fining-upward sequence at the top of the core, that could be attributed to diminishing energy conditions or long-term variation in size of source sediment. Station W2 sediment, taken in a geographic position closest to Ocracoke Inlet, was comprised primarily of clam and oyster shells within a matrix of mud. This was the only core that contained any indication of primary sedimentary structures (cross laminations) associated with abundant sediment supply and high energy conditions.

Sediment Porosity. Figure 2 shows the porosity data from the push cores which were used in establishing modern sediment chronology. As noted above, porosity was calculated from mass % water, assuming that sediment solids have average density 2.5 $g.cm^{-3}$; at the high porosities (>0.75) typical of fine-grained sediments, however, the calculated porosity is insensitive to solids density, within plausible limits. The porosities of surface samples (0-2 cm intervals) are subject to systematic errors. In cores of muddy sediments (01-3, 01-4, 01-5, 01-B, 01-W2) the overlying water cannot be cleanly separated from surface sediment, and porosity of the 0-2 cm interval is likely to be overestimated. In the sandy core (01-W1) water was observed to drain from the 0-2 cm interval during subsampling, causing porosity to be underestimated.

In recently deposited sediments, porosity is affected primarily by sediment grain size and bioturbation/bioirrigation (Berner, 1971; Berner 1980). Fine-grained sediments have the highest porosities because electrostatic charges on grain surfaces limit grain-to-grain contacts. Sands, being coarser and commonly lacking significant surface charge, pack more closely. Bioturbation, which mixes sediment grains and water, and bioirrigation, which forces water into the sediment column in open burrows, both act to increase porosity. Counteracting the effects of bioturbation and bioirrigation, continuing sediment deposition drives a slow upward advection pore waters, compacting the sediment column and reducing porosity. If lithology (grain size,

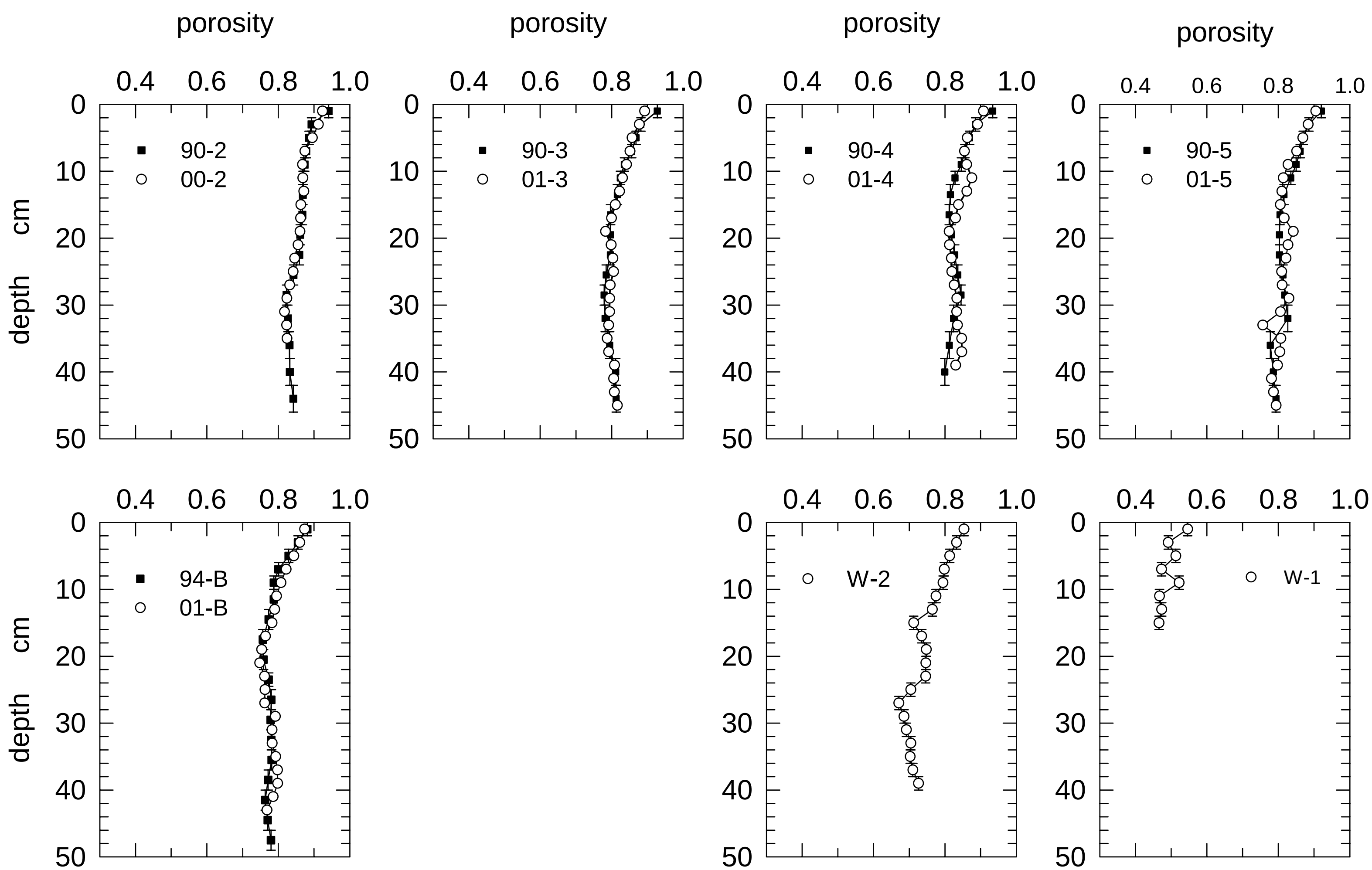

Figure 2. Sediment porosities, mouth of Neuse estuary (station 2) and Pamlico Sound. Open circles: 2001 data. Closed squares: previous data from the same stations.

bulk composition) remains constant, compaction should reduce sediment porosity relatively rapidly in the top 10-20 cm of the sediment column and more slowly at greater depth. In short sediment cores (meters or less) the decrease in porosity with depth at steady state is commonly quasi-exponential.

Average porosities in cores from stations 3, 4, 5, and B are higher than in cores from stations W1 and W2 (Figure 2), consistent with higher sand content at the last two stations. Station W1 is extreme in this regard, and the shortness of the core (16 cm total length) is due to the difficulty of manually forcing a core tube into sandy sediment.

Non-steady processes can cause deviations from trends of smoothly decreasing porosity with increasing depth in the sediment. Abrupt negative excursions (e.g., core 01-W2, 14-16 cm and 24-28 cm; core 01-5, 32-34 cm) suggest deposition of coarser material; based upon visual examination of the samples in question, shell fragments account for part or all of the coarse grains in question. Abrupt positive excursions in porosity (e.g., core 01-4, 10-14 cm; 01-5, 18-20 cm; 01-W1, 4-6 cm and 8-10 cm) might result from increased fine-grained sediment. In the muddy cores (01-4, 01-5) at least, however, such excursions might also result from an episode of rapid deposition, burying the sediment-water interface, or from non-local mixing; in either case we would expect the porosity anomalies to disappear gradually through compaction.

Where stations were reoccupied in 2000-2001 sampling (Figure 2, stations 2, 3, 4, 5, B) we find only minor differences in sediment porosity between samplings. While some of these differences are reflected in the chronometric tracer data, in general the reproducibility of porosity profiles provides further evidence that flood deposition did not appreciably change sediment lithology at these stations.

Modern sediment chronology

Chronometric Tracers in Pre-flood (1990, 1994) Sediment Cores. Significant flood-induced erosion or deposition might be detectable in depth profiles of our chronometric tracers, ^{137}Cs or excess ^{210}Pb. For example, low concentrations or inventories (integrated activities per cm^2) of either radionuclide would suggest recent erosion. High inventories, or surface layers showing anomalous characteristics might imply unusual recent deposition. Because such features might differ only subtly from those to be expected in the absence of major flooding, a stronger argument for flood effects might be made by comparing profiles of the radionuclide tracers in cores collected before and after the flooding. This is the strategy which we employ below. However, any comparisons of this type must immediately raise the question whether temporal differences can be detected against the background of spatial variability. Thus it is appropriate to consider pre-flood (1990, 1994) tracer distributions in some detail.

Figure 3 shows the ^{137}Cs depth profiles in sediment cores collected during 13-14 September 1990 (stations 2-8) or 1 August 1994 (station B). In all cases data have been decay-corrected to the dates of core collection. Station 2 (core 90-2) is from the mouth of the Neuse estuary, while the remaining stations are in the open waters of Pamlico Sound (Figure 1). ^{137}Cs profiles from the Pamlico Sound stations share a number of common features. A ^{137}Cs maximum, more or less well-defined, occurs at shallow depth (6-12 cm). Maximum activities (as of date of collection)

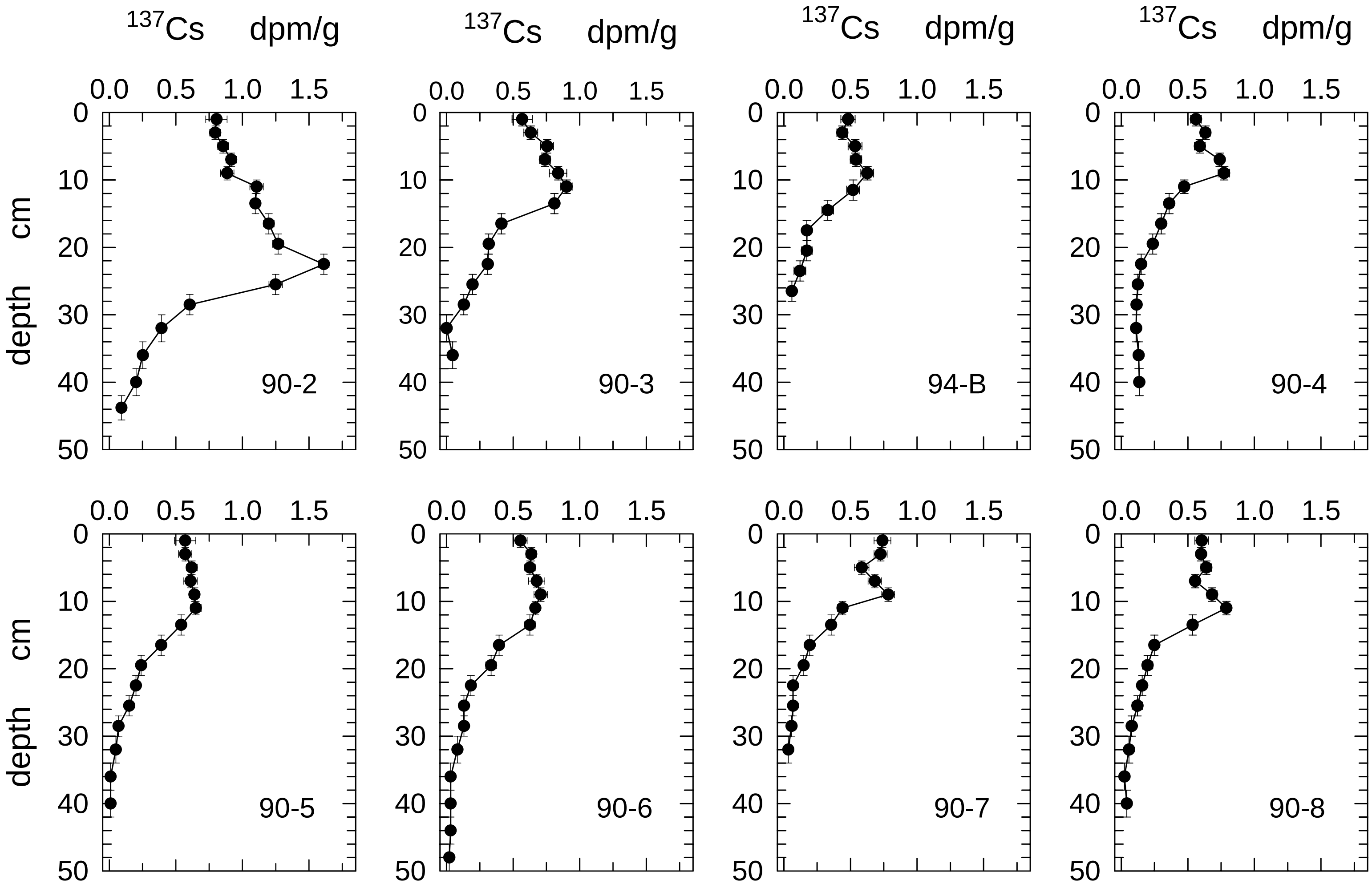

Figure 3. ^{137}Cs profiles, Pamlico Sound sediment cores of 1990 and 1994. dpm = disintegrations per minute

in these cores range 0.65-0.90 $dpm.g^{-1}$ (average 0.75). In all cases ^{137}Cs decreases slowly with depth below the maximum and remains finite to at least 25 cm.

Figure 4 shows excess ^{210}Pb in the same cores, except that no data are available for core 90-7. Core 90-2, from the mouth of the Neuse estuary, is again extreme, while all of the cores from Pamlico Sound yield similar profiles. Maximum activities of excess ^{210}Pb (8.2 – 11.4 $dpm.g^{-1}$) occur at or near the sediment-water interface. In most cases the excess ^{210}Pb has disappeared by a depth of about 30 cm; indeed, the maximum depth of penetration of excess ^{210}Pb is similar to that of ^{137}Cs, and in some cases ^{137}Cs is finite to greater depth. Surface layers of quasi-constant excess ^{210}Pb are apparent in Pamlico cores 90-4, 90-5, and 90-8, implying that bioturbation was more intense at stations 4, 5 and 8 than at stations 3, B, and 6. Below the surface, rapidly mixed layers the slopes of excess ^{210}Pb vs depth are similar among all the cores from Pamlico Sound. This implies similar rates of sediment accumulation, as we demonstrate below.

In general, then, cores collected in 1990 and 1994 over a wide area in Pamlico Sound yield very similar distributions of the chronometric tracers, ^{137}Cs and excess ^{210}Pb. This suggests that spatial variability in the muddy sediments of Pamlico Sound may have been minimal in the years preceding hurricane-induced flooding.

Clearly core 90-2, from the mouth of the Neuse River estuary shows the influence of a larger sediment supply. The maximum in ^{137}Cs is deeper, and both ^{137}Cs and excess ^{210}Pb penetrate to at least 40 cm. These features imply a higher rate of steady-state sediment accumulation at station 2 than in the open Pamlico Sound. Exposure to alkali elements (K, Rb, Cs) in seawater can cause desorption of ^{137}Cs from sediment particles (e.g., Zucker et al. 1984); thus the higher maximum activity of ^{137}Cs in core 90-2 likely reflects less desorption at station 2 than in Pamlico Sound. As in the cores from Pamlico Sound, however, ^{137}Cs penetrates at least as deeply in 90-2 as does excess ^{210}Pb. We argue below that deep penetration of ^{137}Cs is satisfactorily explained by desorption and chemical mobility of ^{137}Cs in porewater; thus this process is likely important at station 2, also.

<u>Model Results on Pre-Hurricane Sediment Cores</u>. Figure 5 illustrates results of modeling excess ^{210}Pb and ^{137}Cs distributions in two pre-hurricane cores from Pamlico Sound, 90-4 and 90-6 (see Figure 1 for station locations). These cores are chosen to indicate the range in quality of fit for ^{137}Cs and to illustrate the effects of different parameters on the shapes of the model curves. ^{137}Cs is generally less satisfactorily fit than excess ^{210}Pb. Core 90-4 yields the lower accumulation rate because excess ^{210}Pb decreases more rapidly below the base of the mixed layer. On the other hand, the nearly homogeneous excess ^{210}Pb in the mixed layer of 90-4 requires a substantially higher D_{B0} than does the gradually decreasing excess ^{210}Pb in the mixed layer of 90-6. The lower K_D in 90-4 reflects the persistence of finite ^{137}Cs to the deepest sample in this core. It is clear, however, from the poor fit to ^{137}Cs in 90-4 that processes not included in the model have affected the ^{137}Cs distribution in this core.

Table 2 summarizes the modeling results for all the pre-hurricane sediment cores for which data on both excess ^{210}Pb and ^{137}Cs are available. Of greatest importance here are the sediment accumulation rates, ω, which range between 0.11 and 0.22 $cm.yr^{-1}$ in the open Pamlico Sound; station 2, in the mouth of the Neuse estuary, yields a higher accumulation rate (0.35 $cm.yr^{-1}$).

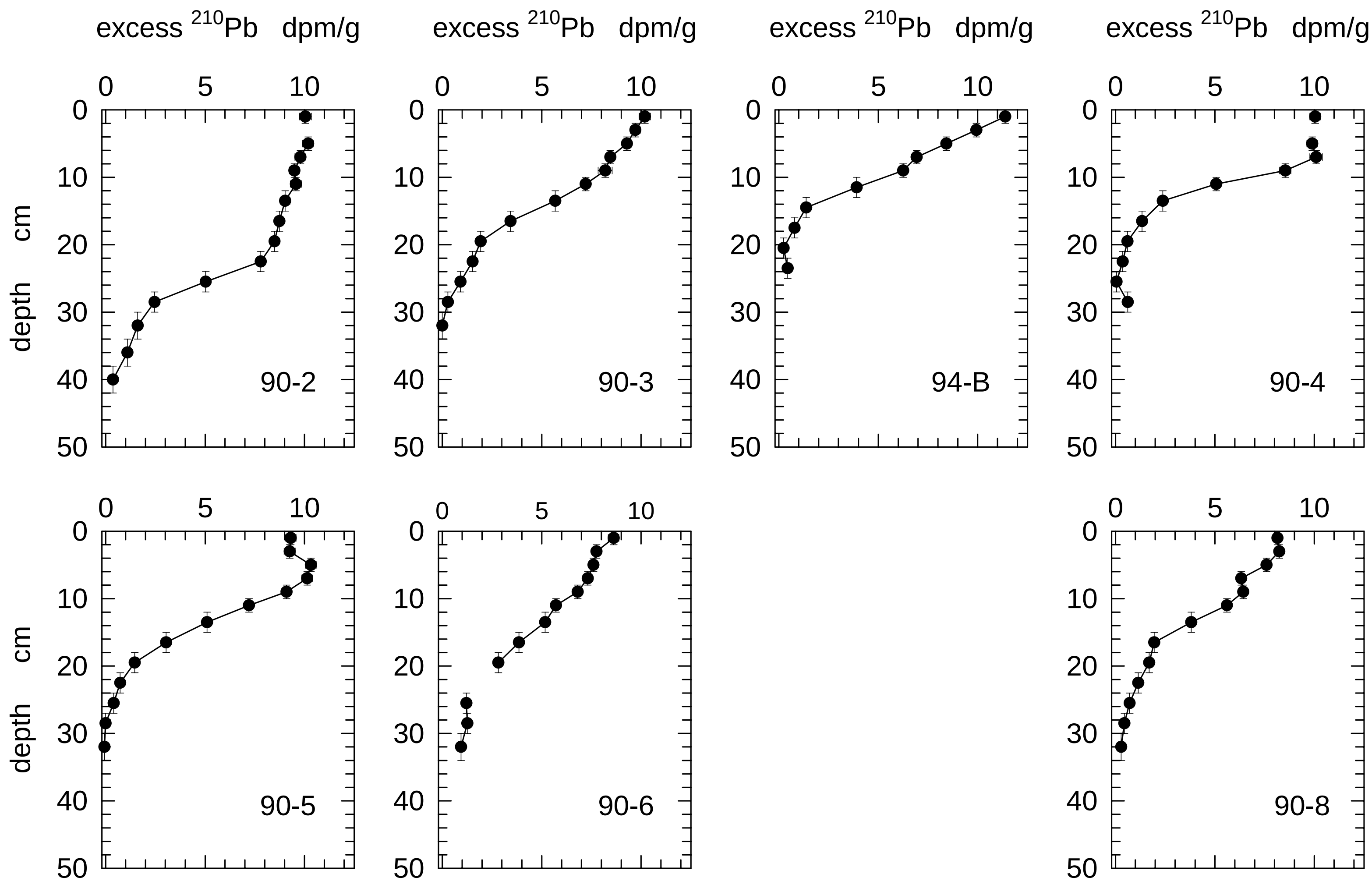

Figure 4. Excess ^{210}Pb profiles, Pamlico Sound sediment cores of 1990 and 1994. dpm = disintegrations per minute.

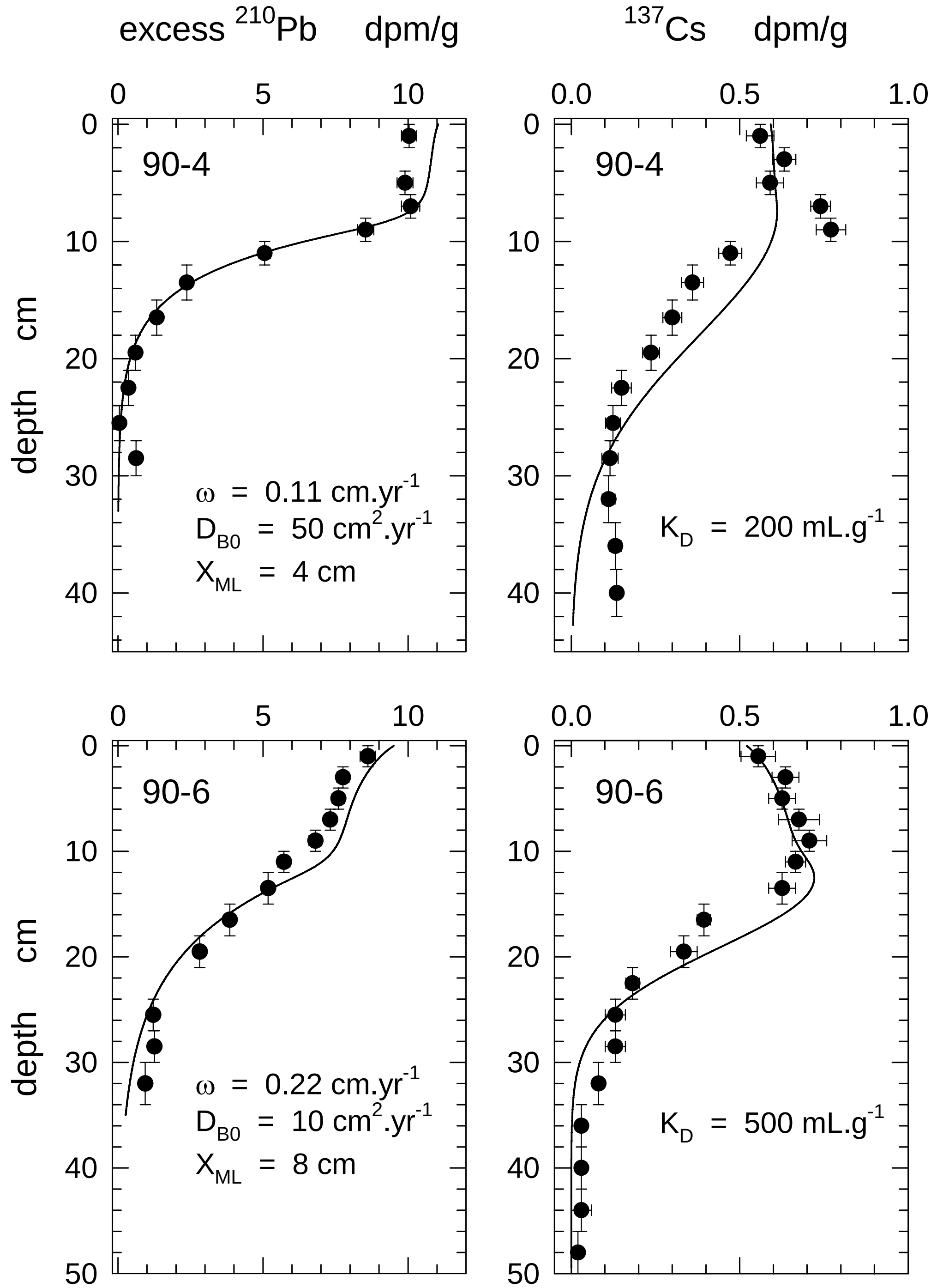

Figure 5. Illustrations of model fits to excess ^{210}Pb and ^{137}Cs data

Table 2. Modeling results, pre-flood (1990, 1994) sediment cores

Core	ω $cm.yr^{-1}$	D_{B0} $cm^2.yr^{-1}$	X_{ML} cm
90-2	0.35	8	16
90-3	0.18	6	8
90-4	0.11	50	4
90-5	0.15	10	6
90-6	0.22	10	8
90-8	0.22	15	5
94-B	0.13	3	10

The mixing parameters, D_{B0} and X_{ML}, are in the range to be expected in muddy coastal sediments (Boudreau 1994) and comparable to those we have recently inferred for three sites in Chesapeake Bay (Nie et al. 2001). Distribution coefficients for ^{137}Cs (K_D's; not shown in Table 2) are in the range of 10^2-10^3 at all stations, comparable to values reported for the lower Neuse estuary (Nie 2002).

Chronometric Tracers in Post-flood Sediment Cores. Figure 6 shows post-flood (2000-2001) ^{137}Cs profiles, superimposed on pre-flood profiles, where those are available. The post-flood data have been decay-corrected to the dates of core collection. Absent flood-induced changes or other non-steady-state disturbances, ^{137}Cs profiles in 2000-2001 cores should differ from those of the 1990's due to radioactive decay (half-life 30.0 years) and to steady-state transport processes (sediment accumulation, sediment mixing, porewater diffusion). The effects of radioactive decay are easily computed, and to facilitate comparisons, the 1990 (stations 2, 3, 4, 5) or 1994 (station B) data in Figure 6 have been decay-corrected to the date of collection of the 2001 cores (3-4 October 2001). Between samplings at a station, sediment mixing and porewater diffusion of ^{137}Cs might have broadened the subsurface maximum in ^{137}Cs, but these processes should not have affected the depth in the sediment column at which the maximum occurs. Thus any significant change in the depth of the ^{137}Cs maximum may be interpreted as having resulted from net deposition or erosion.

Stations W2 and W1 were first sampled in 2001, so there are no pre-flood data with which to compare the 2001 profiles. Note that station W1, in sand (cf porosity, Figure 2), has much lower ^{137}Cs than the remaining, muddier stations. Considering the variation observed among pre-flood ^{137}Cs profiles in Pamlico Sound (Figure 3), the 2001 profiles from W2 and W1 show no conspicuous evidence of flood-induced disturbance.

Comparing pre-flood and post-flood ^{137}Cs profiles from stations 2, 3, B, 4, and 5 yields greater insight into possible effects of flooding. The best indicators available from ^{137}Cs data are anomalous changes in ^{137}Cs concentrations or in the depth of the ^{137}Cs maximum, as described above. Concentration anomalies are identified as differences from the decay-corrected data of 1990 or 1994. Any change in the depth of the maximum should be considered relative to the expectation of 1-2 cm burial due to steady-state sediment accumulation between the pre-flood

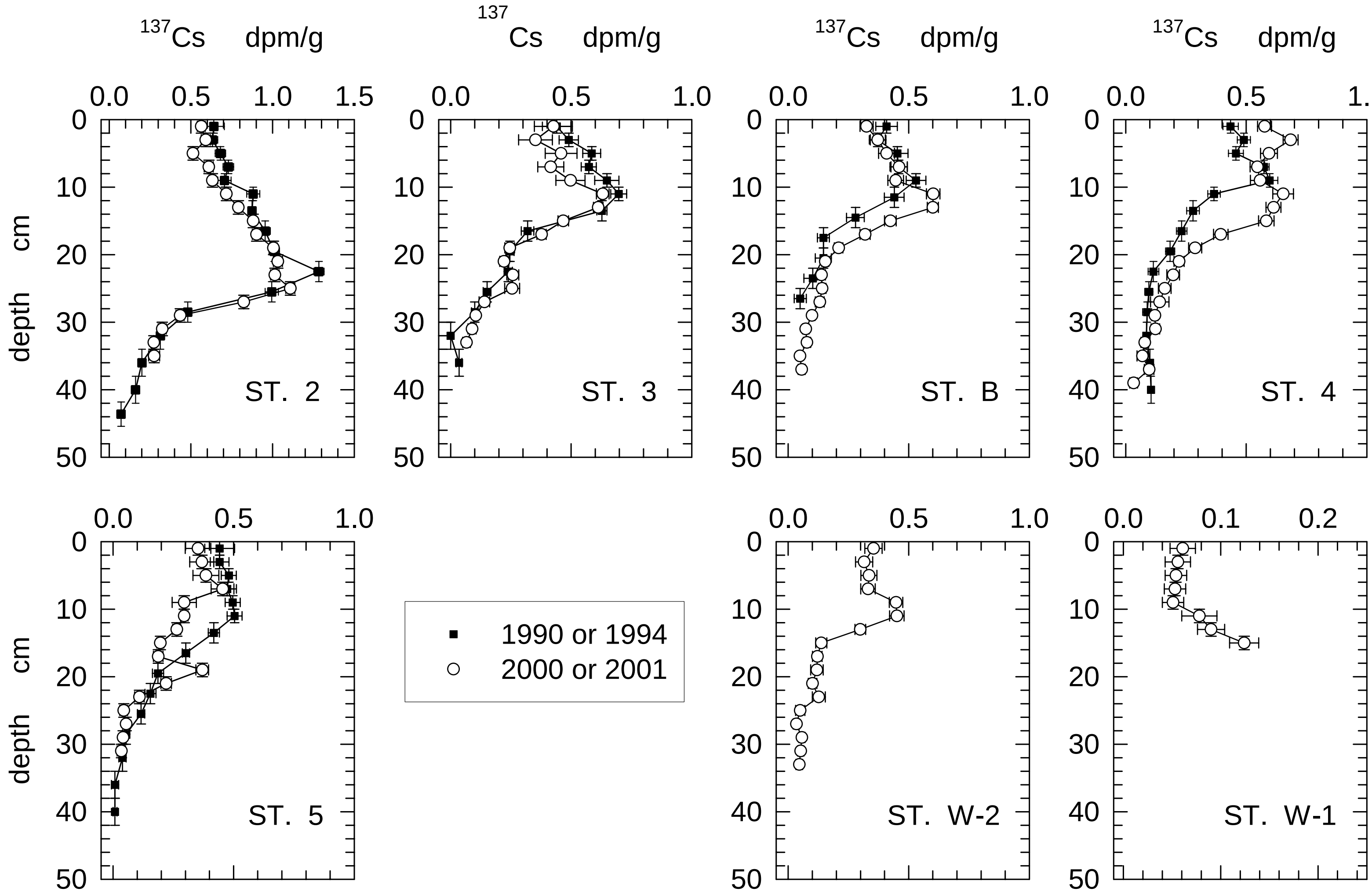

Figure 6. Pre-flood (1990 or 1994) and post-flood (2000 or 2001) ^{137}Cs profiles in Pamlico Sound sediment cores. For ease of comparison pre-flood data have been decay-corrected to 3 October 2001. Note the different ^{137}Cs scales for stations 2 and W-1.

and post-flood samplings. At station 2 (mouth of Neuse estuary), the only substantial anomaly in the 2001 profile is a low ^{137}Cs concentration at the maximum. By itself this anomaly does not require a major flood impact. The 1990 and 2001 profiles at station 3 are also very similar, though the apparent coincidence of the 1990 and 2001 maxima might imply net erosion of the ~2 cm of steady-state sediment accumulation which should have occurred in the interim. At station B the depth of the 2001 maximum is not sharply defined, but it might be 1-2 cm deeper than expected from the 1994 data; in addition the ^{137}Cs concentration at the maximum is slightly elevated in the 2001 core, but so small an effect could be due to spatial heterogeneity, rather than to flooding. Stations 4 and 5 suggest potentially larger flood impacts. The 2001 profile at station 4 has roughly uniform ^{137}Cs in the top 16 cm. Allowing for 1-2 cm steady-state sediment accumulation between 1990 and 2001 (Table 2), the 2001 concentrations at 6-12 cm depth are in reasonable agreement with those expected from the 1990 profile, but there remain substantial positive concentration anomalies in the intervals 0-6 cm and 12-18 cm. These features suggest significant net flood deposition at station 4. 2001 data from station 5 show negative concentration anomalies from 8-18 cm and a positive anomaly at 18-20 cm. The latter might be explained by roughly 2 cm net deposition during 1990-2001, close to that expected at steady state (Table 2). However, this small correction would leave unexplained the large negative concentration anomalies at shallower depths. As at station 4 it appears likely that flooding caused substantial disturbance of the sediment column at station 5.

In summary, only the ^{137}Cs data from station reoccupations provide perspective on flood-induced sediment redistribution, and comparison of pre-flood and post-flood profiles suggests that erosion and deposition were patchy in Pamlico Sound. At 3 of 5 stations (2, 3, B) the flood effect appears limited to 0-2 cm net erosion or deposition. ^{137}Cs data from stations 4 and 5 suggest larger impacts, but they do not clearly define the magnitudes of those impacts.

The addition of data for excess ^{210}Pb (Figure 7; stations 2, 3, B, 4, 5 only) clarifies the picture and suggests that, in one case at least, minor *net* change may represent the combined effects of substantial erosion and deposition. Steady-state expectations for excess ^{210}Pb differ from those for ^{137}Cs. Except as altered by extreme events, the input flux of excess ^{210}Pb may plausibly be taken as constant, and ^{210}Pb in brackish-marine sediments exhibits no significant mobility in pore waters. Then, if particle-transport processes (sediment accumulation, sediment mixing) operate at constant rates, sediment profiles of excess ^{210}Pb should not change. That is, at steady-state in the sedimentary environment, repeated sampling at a station over time should yield substantially the same sediment profile of excess ^{210}Pb. This condition appears to be met by station 3 (Figure 7), confirming the minimal change which was inferred from ^{137}Cs (Figure 6). Pre-flood and post-flood profiles of excess ^{210}Pb at station B are likewise very similar, except that post-flood concentrations are sharply reduced in the 0-4 cm interval; as suggested from ^{137}Cs, any disturbance at station B may have been limited to a shallow surface layer.

To completely erase pre-flood profiles of excess ^{210}Pb, flood-induced erosion would have had to reach to depths >20 cm in Pamlico Sound and >30 cm at the mouth of the Neuse estuary (station 2). Failing that, we should expect that the unaffected, deeper sections of the post-flood profiles should coincide with pre-flood profiles, after vertical translation to account for net erosion or deposition. This is well illustrated in Figure 7 by station 2, where essentially no adjustment is required to bring pre-flood and post-flood profiles into coincidence for depths $\geq$ 24 cm; this is

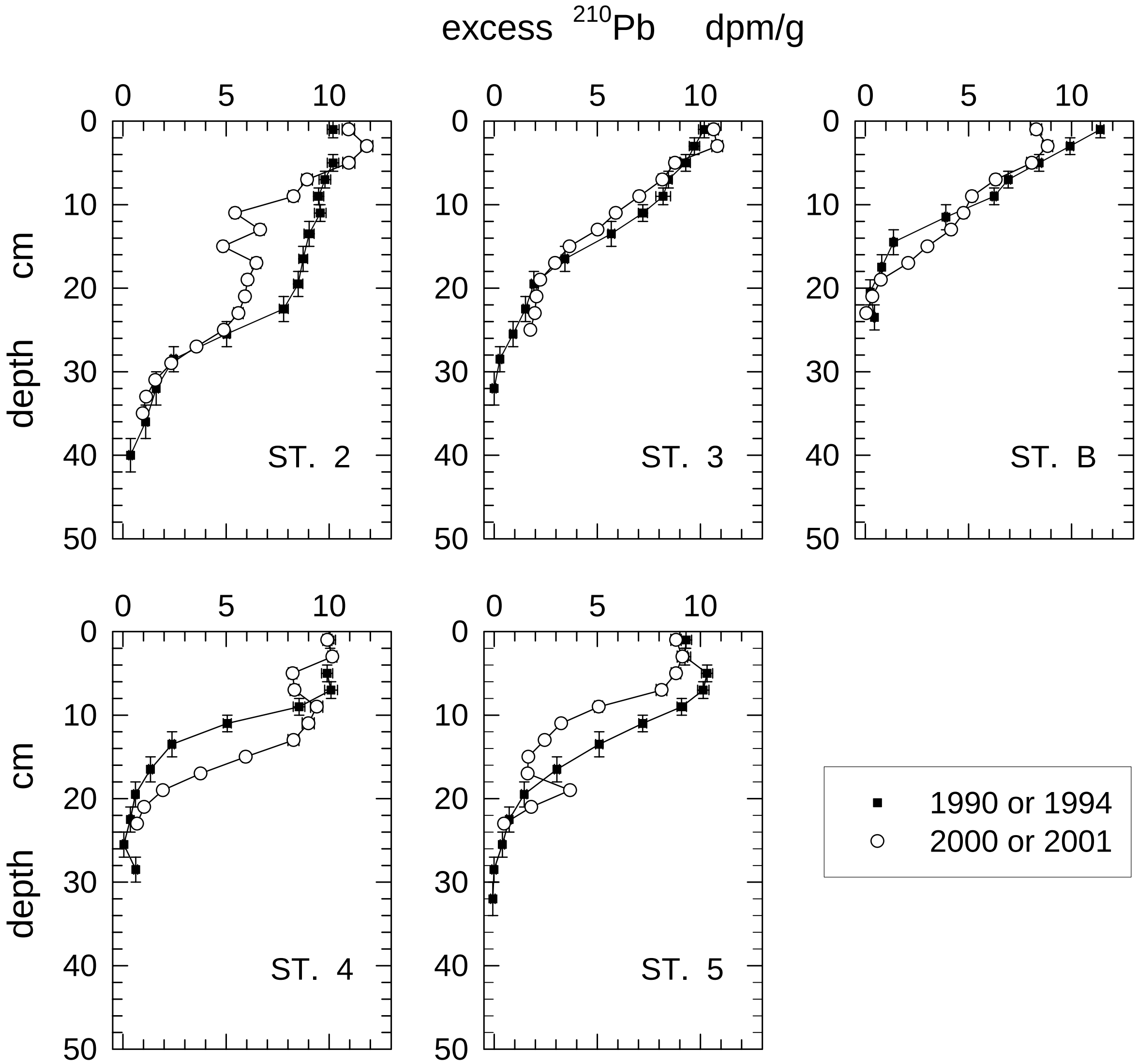

Figure 7. Pre-flood (1990 or 1994) and post-flood (2000 or 2001) excess ^{210}Pb profiles in Pamlico Sound sediment cores.

consistent with the conclusion from ^{137}Cs, that station 2 had seen little net erosion or deposition. For depths < 24 cm, however, the post-flood profile of excess ^{210}Pb diverges strongly from the pre-flood one. Thus erosion and deposition may have reset the top 24 cm of this sediment column. Working similarly with station 4, about 5 cm net deposition is required to bring pre-flood and post-flood excess ^{210}Pb profiles into register for depths >12 cm, but at least the top 8 cm of the sediment column appears to have been replaced during flooding. At station 5, the local maximum observed in ^{137}Cs at 18-20 cm is present also in excess ^{210}Pb. Subtracting about 2 cm of net flood deposition removes these deep concentration anomalies, but this would require that as much as 18 cm of the sediment column was eroded and re-deposited at station 5 during flooding. Alternatively, if the deep (16-22 cm) concentration anomalies in the 2001 data from station 5 are attributed to non-local sediment mixing (e.g., burrow infilling), then substantial net erosion may have occurred at this station; we return to this point below.

Potassium

In pre-flood sediment cores, potassium concentrations increase systematically down the Neuse estuary, from < 10 mg/g in the upper estuary to an average of about 15 mg/g at the estuary mouth (Benninger and Wells 1993). In pre-flood sediment cores from Pamlico Sound, K concentrations are generally ≥ 15 mg/g. Thus, had flooding transferred significant sediment from the upper Neuse estuary into Pamlico Sound, this transfer might have been reflected in reduced K concentrations in post-flood Pamlico Sound core tops. The precision and accuracy of our K analyses by gamma spectrometry preclude a sensitive test of this possibility. However, we observed no consistent differences in K concentrations (data not shown) between pre-flood and post-flood cores, and we conclude that inorganic sediment from the upper Neuse estuary was not discharged in quantity to Pamlico Sound.

Biogeochemical analyses

Sediment Organic Carbon Concentrations and Stable Isotope Ratios. Figure 8 shows organic carbon (OC) depth distributions before and after the passage of Hurricane Floyd. For Stations 3, B, and 5, the before and after profiles are remarkably similar. For Station 4, OC concentrations are consistently higher in the core collected after the hurricane. Organic carbon concentrations are not particularly sensitive to episodic deposition because near-surface concentrations are comparable over broad areas of the estuary (Alperin et al. 2000). Furthermore, gradients in the upper few cm are modest, making it difficult to discern erosion events.

In contrast to the OC profiles, δ^{13}C-OC depth distributions are systematically shifted to more negative values in the upper 5-20 cm (Figure 9). This shift cannot be explained by a diagenetic isotope effect, and suggests that sediment OC from a distinct source was deposited after the 1990, 1994 cores were collected.

Porewater Concentration Profiles. Concentration profiles of ΣCO_2, NH_4^+, SO_4^{2-}, and Cl^- for Stations 3, B, 4, 5, and W1 are summarized in figures 10-14. These data provide evidence that these sediments are bioirrigated to depths of 15-20 cm. The magnitude of the concentration gradients below 20 cm (Station B > 4 > 3 > 5 > W1) provides a qualitative indicator of the ranking of the quantity and reactivity of the organic matter at each station.

Benthic fluxes

Benthic flux data are summarized in Figure 15. Benthic fluxes were measured twice: values reported as #1 were measured approximately 1 month before those reported as #2. For nitrate and ammonium, "oxic" fluxes represent the initial period after benthic chamber closure when the oxygen concentration in the overlying water > 2 mg L^{-1}; "hypoxic" fluxes represent the time interval when oxygen concentrations were < 2 mg L^{-1}.

Benthic fluxes at all five stations are relatively consistent. Benthic fluxes of oxygen and ΣCO_2 were stable during the 1 month interval between analysis #1 and #2, whereas fluxes involving nitrogen species were consistently lower during the second sampling interval.

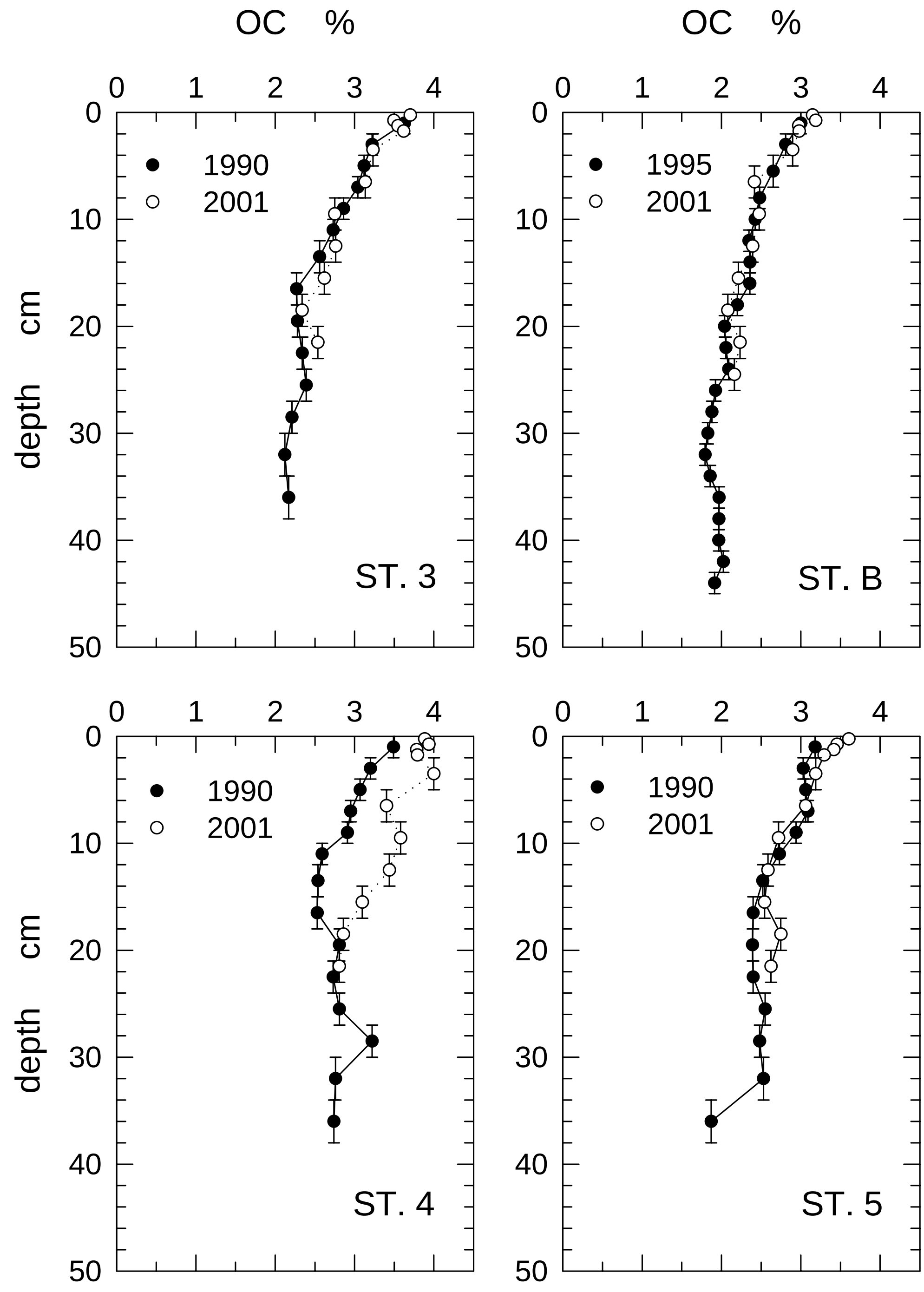

Figure 8. Pre-flood (1990 or 1995) and post-flood (2001) organic carbon (OC) concentrations in Pamlico Sound sediment cores.

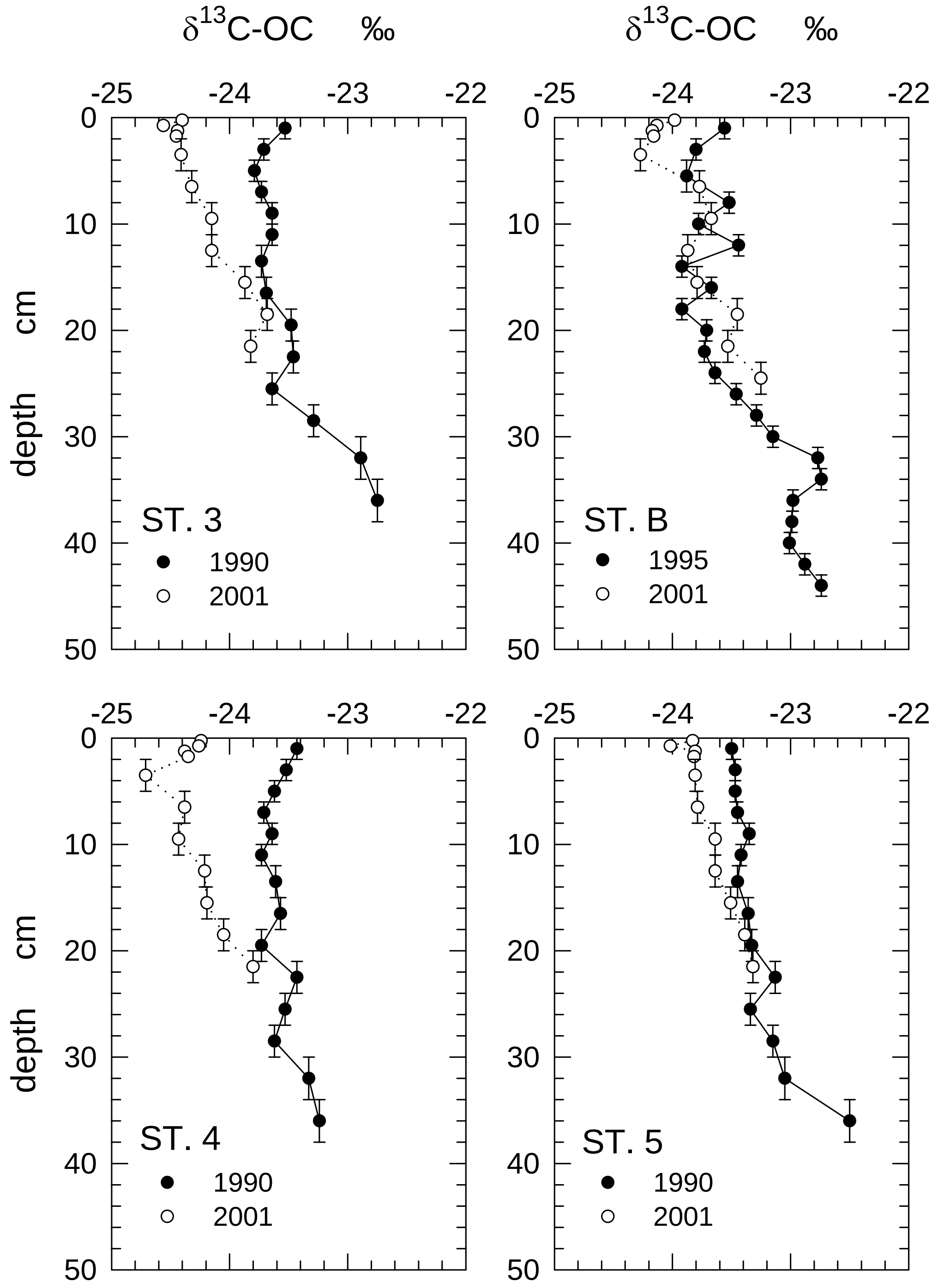

Figure 9. Pre-flood (1990 or 1995) or post-flood (2001) δ^{13}C-OC values in Pamlico Sound sediment cores

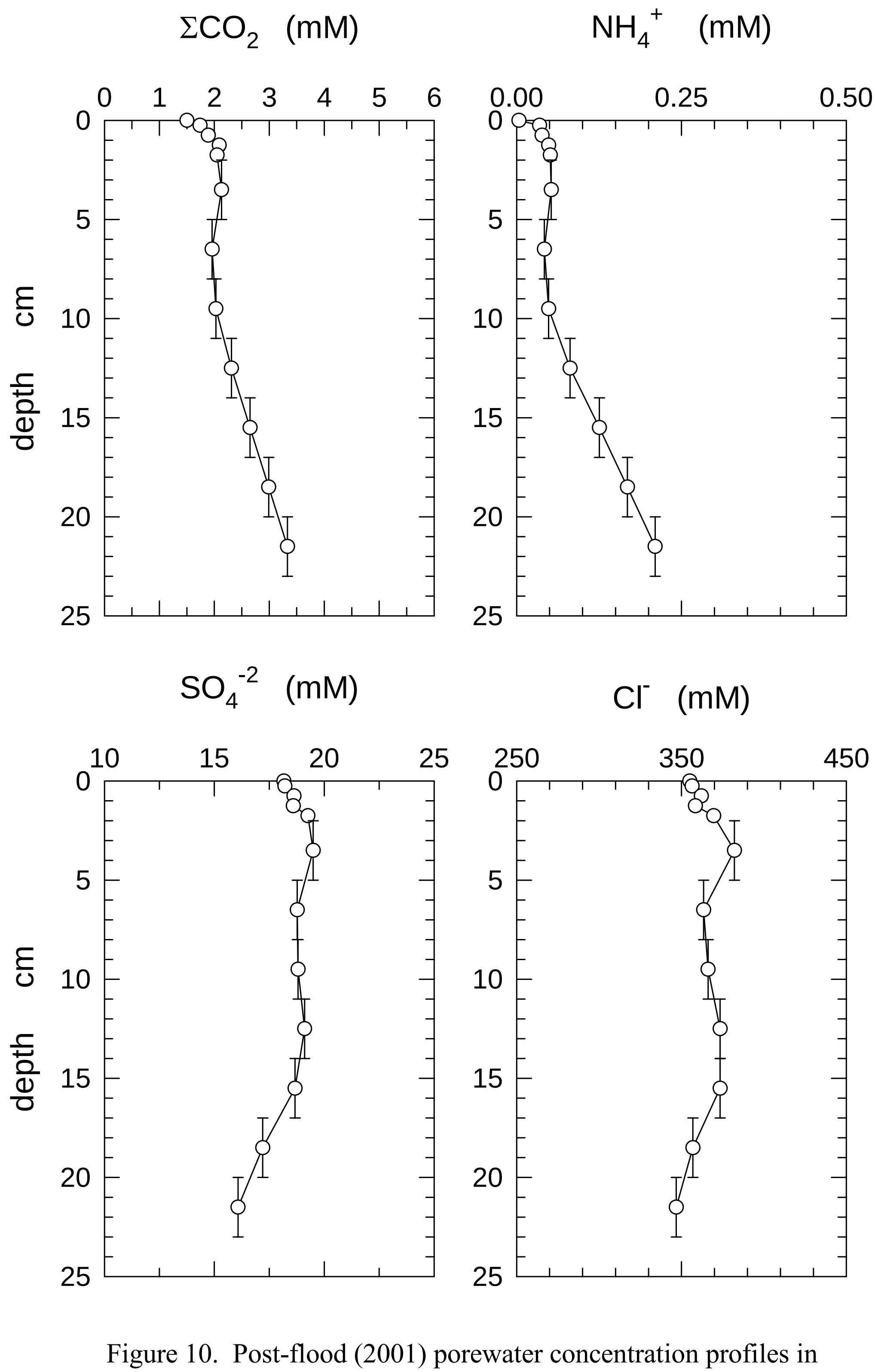

Figure 10. Post-flood (2001) porewater concentration profiles in a sediment core from Pamlico Sound station 3.

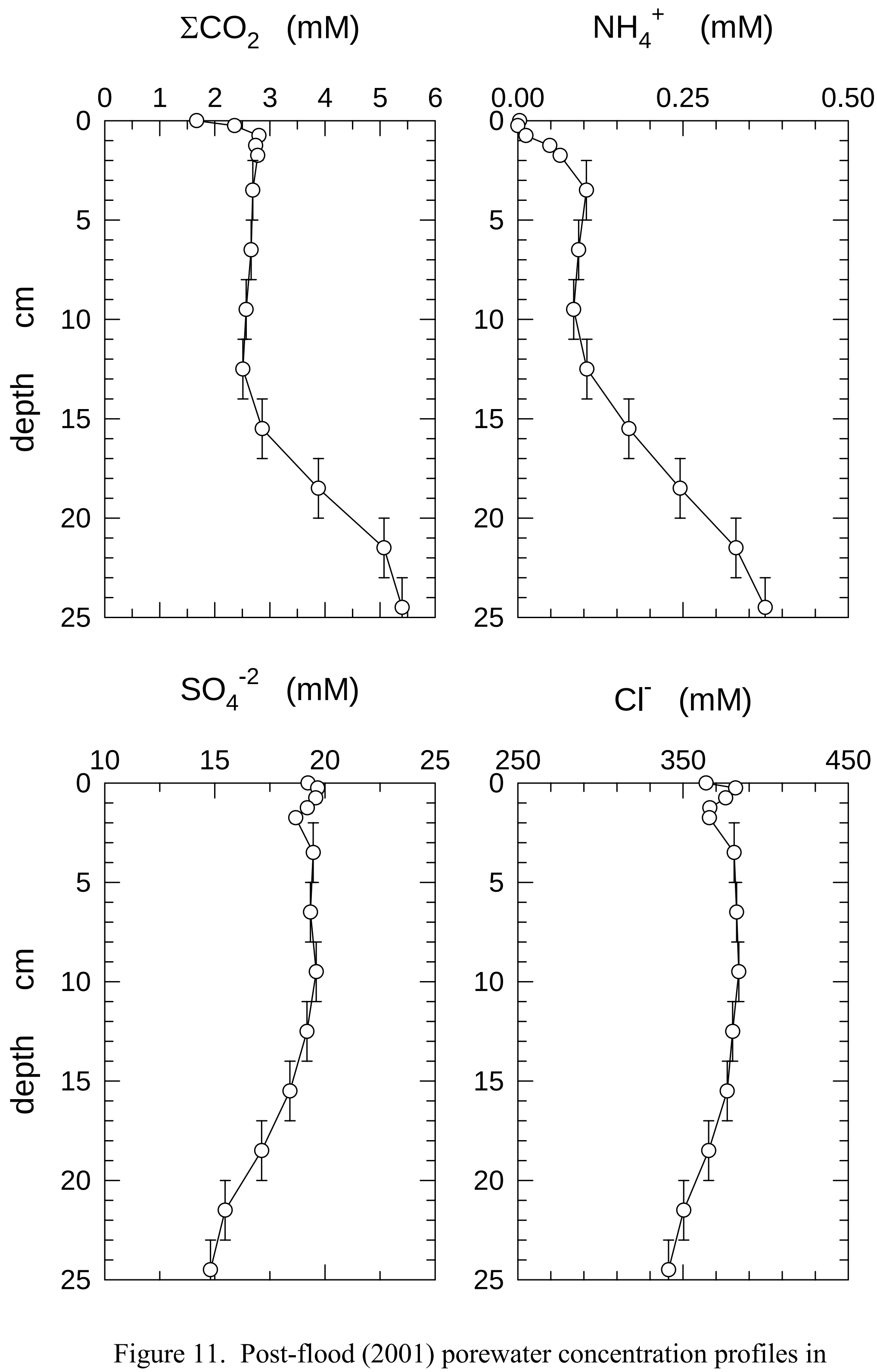

Figure 11. Post-flood (2001) porewater concentration profiles in a sediment core from Pamlico Sound station B.

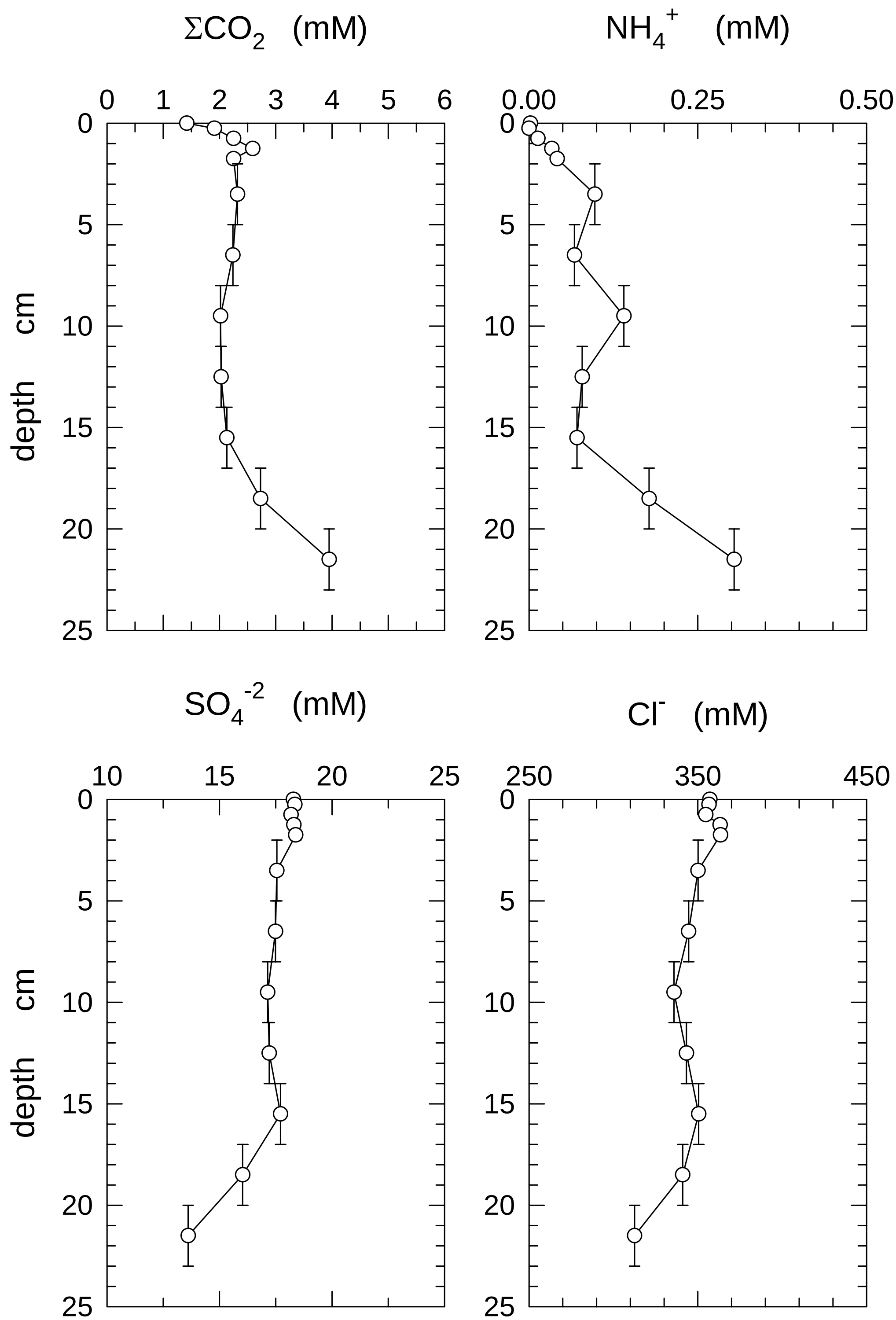

Figure 12. Post-flood (2001) porewater concentration profiles in a sediment core from Pamlico Sound station 4.

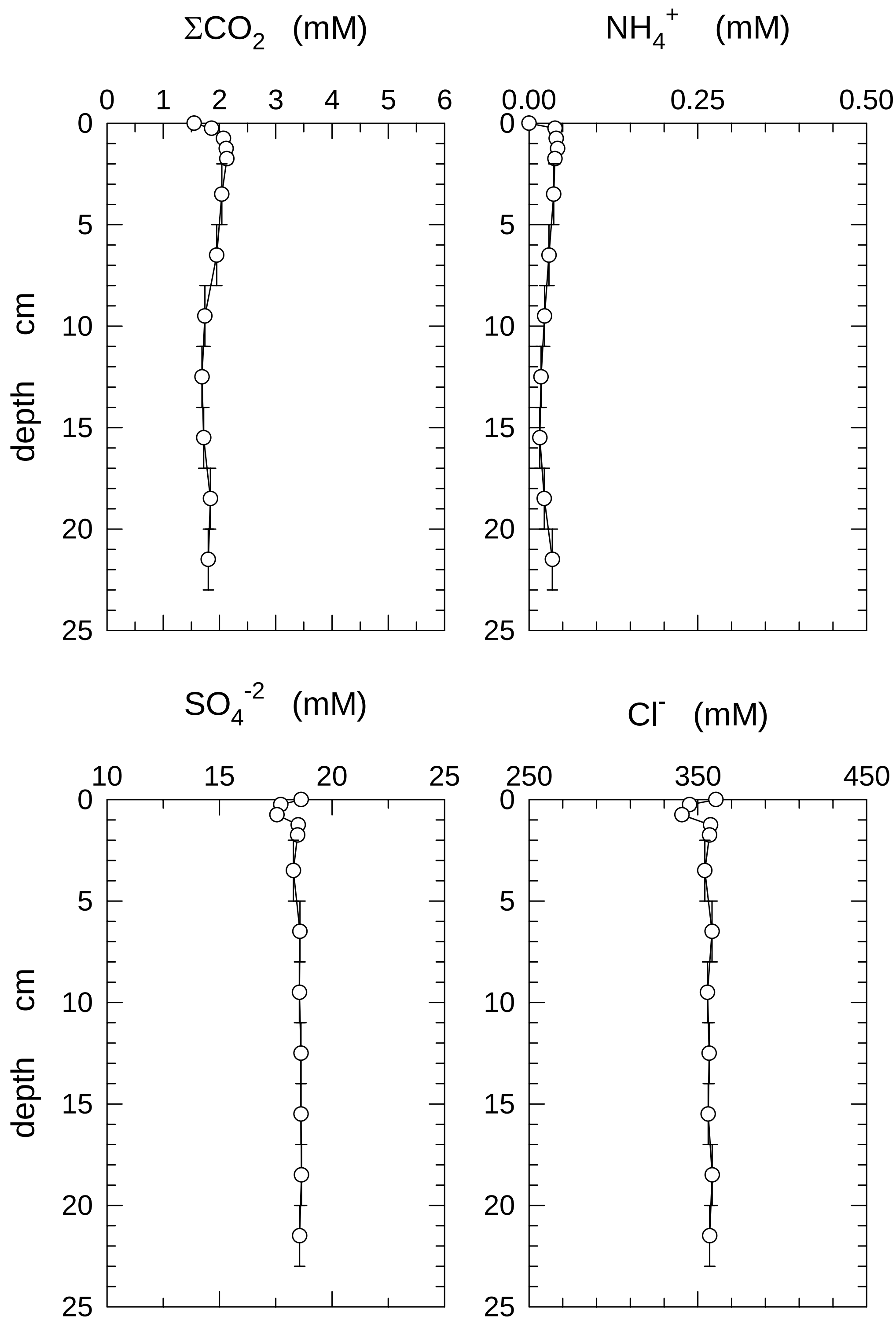

Figure 13. Post-flood (2001) porewater concentration profiles in a sediment core from Pamlico Sound station 5.

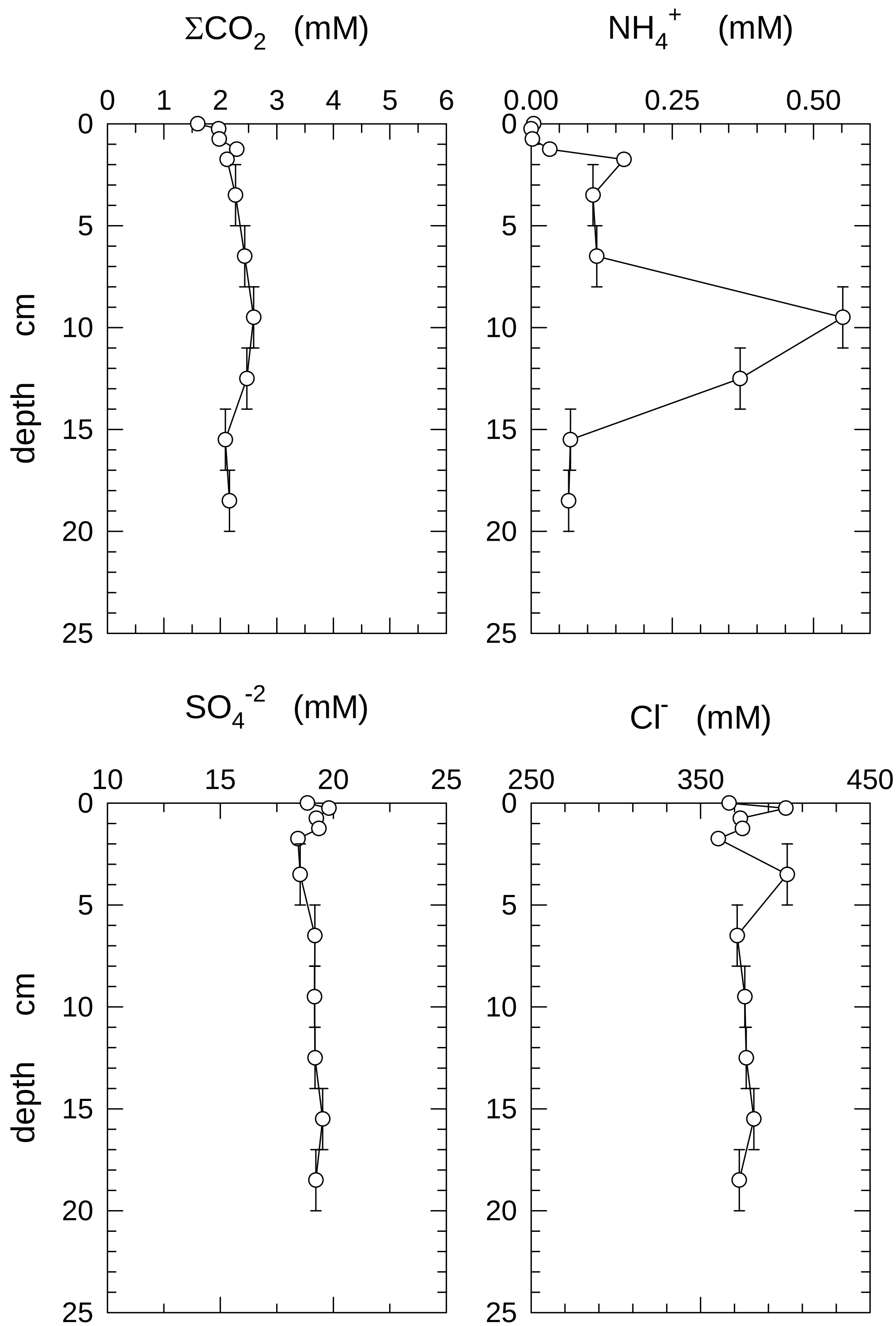

Figure 14. Post-flood (2001) porewater concentration profiles in a sediment core from Pamlico Sound station W-1.

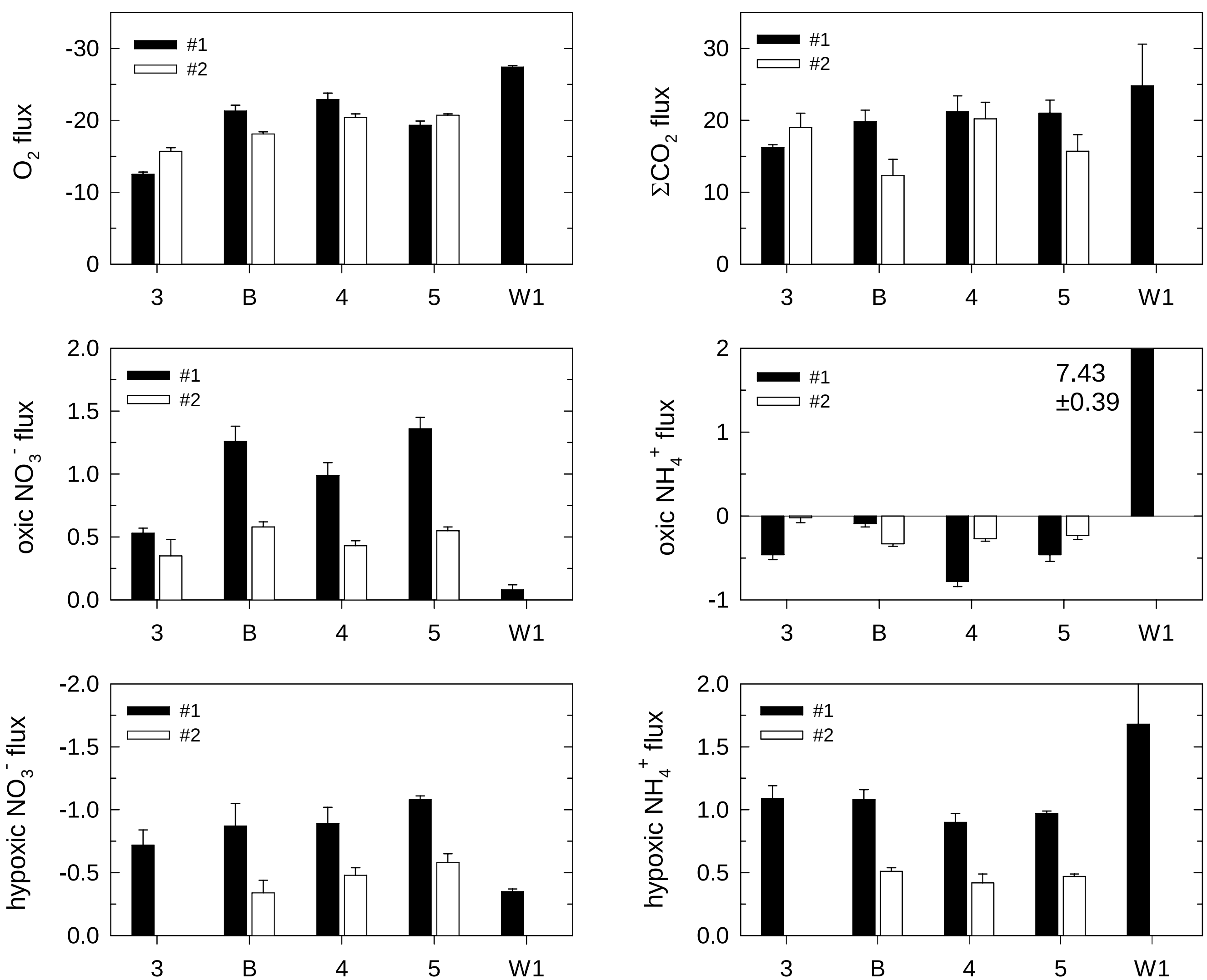

Figure 15. Results of benthic flux measurements in Pamlico Sound sediment cores. All fluxes are in mmol.m^{-2}.d^{-1}.

Oxygen microprofiles

Figure 16 shows oxygen concentration profiles near the sediment-water interface. Note that the depth scale is in mm rather than cm. At all four sites, porewater oxygen is fully depleted by a depth of four mm. This indicates rapid rates of OC remineralization and/or oxidation of reduced inorganic compounds such as sulfide.

Denitrification rates

Denitrification rates measured by the IPT and during the hypoxic period in the benthic chambers are summarized in Figure 17. The denitrification rates estimated by the two methods are in excellent agreement and suggest an average rate of 0.85 mmol N m^{-2} d^{-1} for stations 3, B, 4, and 5. The denitrification rate at station W1 is considerably lower.

DISCUSSION

Flood impacts in the sediments of Pamlico Sound

Bathymetry and Sediment Lithology. In clastic sediments, events of major flooding may be expressed as erosional scour, anomalous deposition, or storm layers of coarser sediment. In the Neuse-Pamlico system, significant net erosion would likely be confined to the estuaries, where flood discharges are channelized. Bay-head deltas might form in Pamlico Sound, where the confined flows leave the estuarine channels. In the flooding which followed hurricane Floyd, however, neither net erosion nor net deposition occurred on a scale which we could detect as bathymetric change through acoustic surveys in the Neuse estuary and the adjacent areas of Pamlico Sound. Nor did flood discharges leave a continuous layer of coarser sediment; rather, we found coarser sediment (fine sand and shell) only in isolated bedforms.

The absence of detectable bathymetric change and the lack of a continuous sand layer do not imply that the floods which followed hurricane Floyd moved only minor quantities of sediment. Indeed, because the concentration of suspended sediment commonly increases non-linearly with water discharge, floods dominate sediment transport, and major floods can deliver a sediment load equivalent to many decades of normal sediment transport; the impact of tropical storm Agnes (1972) on sediment discharge to Chesapeake Bay provides a well-documented example (Zabawa and Schubel 1974; Gross et al. 1978; Hirschberg and Schubel 1979). Probably several factors explain the limited bathymetric and lithologic expressions of a major flood event in the sediments of Pamlico Sound. Newly delivered sediments would have accumulated over a wide area of a large receiving basin. This contrasts with the confined area of the upper Chesapeake Bay within which major deposition from tropical storm Agnes was recorded (Zabawa and Schubel 1974). In addition, initial storm deposits in Pamlico Sound may well have been redistributed as normal circulation, including estuarine exchange with the Neuse and Pamlico rivers, was reestablished. Divers reported a widespread, flocculent mud layer at the bottom as long as 4 months after passage of hurricane Floyd, demonstrating that the surface sediments were not yet cohesive enough to resist transport. The low abundance of sand in the flood deposits can be attributed to limited sources of fine sand in the tributary estuaries.

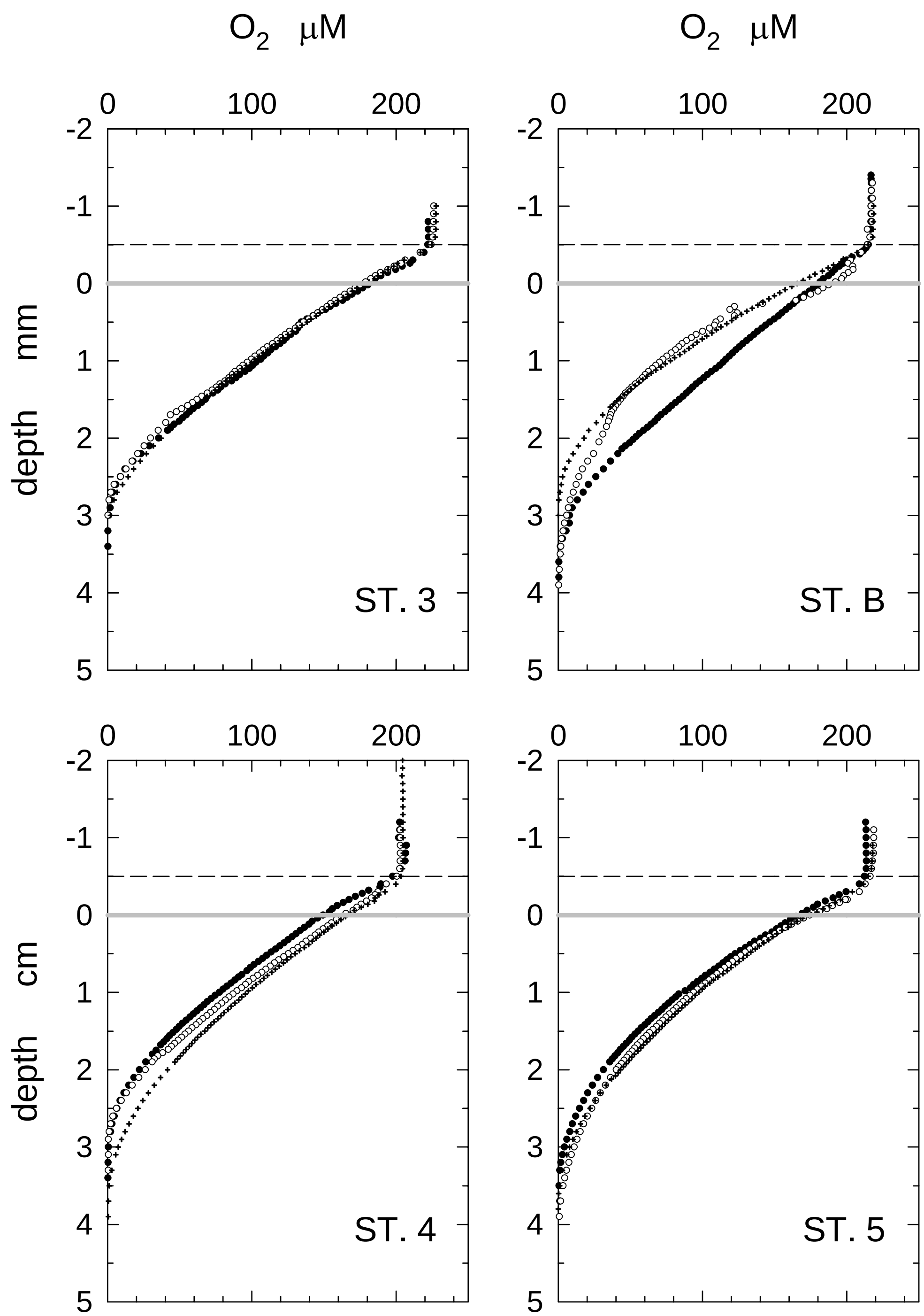

Figure 16. Porewater oxygen microprofiles in Pamlico Sound sediment cores. The grey line represents the sediment-water interface; the dashed line denotes the top of the diffusive boundary layer.

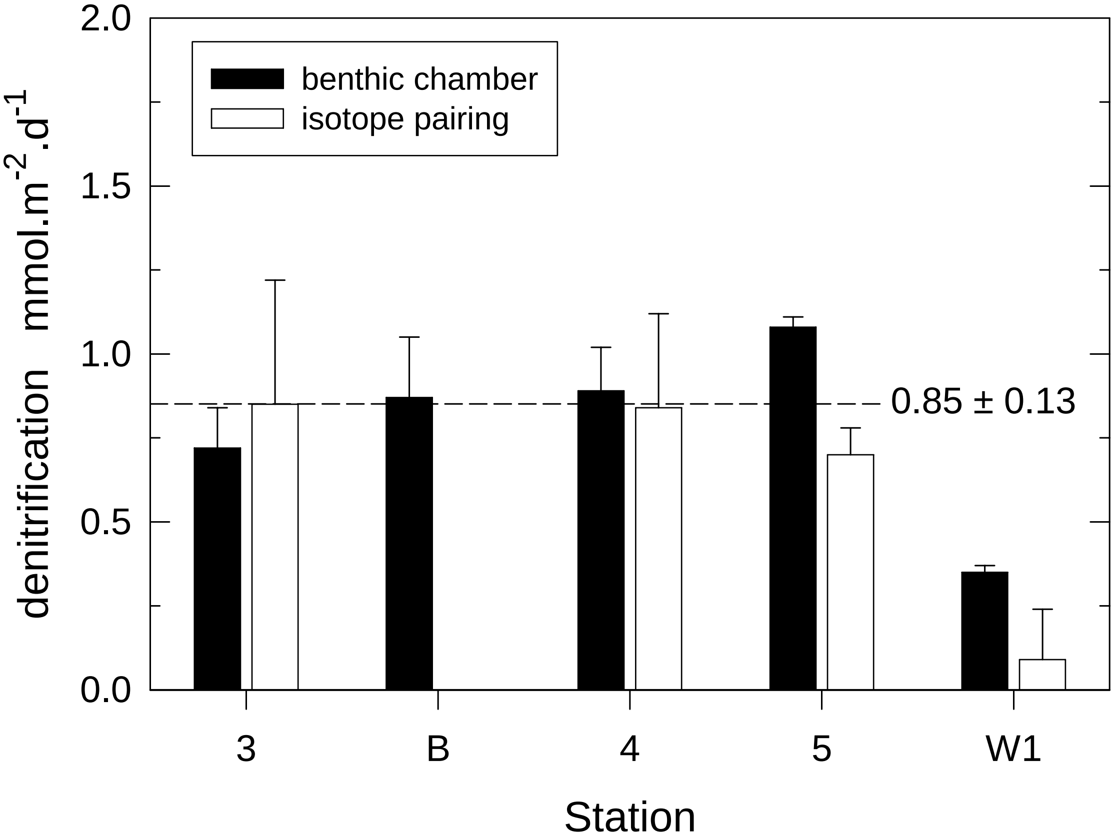

Figure 17. Denitrification rates in Pamlico Sound sediment cores measured by two methods.

As noted above, floods are major agents of sediment delivery to estuaries or the coastal ocean. Pamlico Sound has likely received a large share of its fine-grained sediments during floods, many of them hurricane-induced. Historic records indicate that approximately 60 hurricanes have significantly impacted Pamlico Sound since 1750, and by extrapolation probably more than 1000 since southern Pamlico Sound came into existence in the mid-Holocene. Would these flooding events be recognizable in the sedimentary record? Our results suggest that lithologic clues to former floods may be subtle, limited to patchy deposits of shells or fine sand. As an added complication, the low average rates of sediment accumulation imply that many such features will be erased by bioturbation before they can be preserved. In long cores, however, we have observed isolated shell-rich layers and sections of faintly laminated fine sand. Our working hypothesis is that such layers can yield at least a partial record of previous major floods in the Pamlico Sound drainage basin.

Chronometric Tracers and $\delta^{13}C$. Absent lithologic indicators of flood deposition or erosion, evidence of flood impacts may be sought through chemical or isotopic properties of the sediments. In principle flood deposition might be recognized by the presence of a chemical or isotopic anomaly in surface sediments. A suitable elemental, molecular, or isotopic tracer must vary in a predictable way over geography, so that its presence can be taken as evidence of new input. For example, we might seek, in surface sediments from Pamlico Sound, compositions known to be unique to the drainage basins of the Neuse or Tar-Pamlico river basins, or to the landward ends of the corresponding estuaries; positive results would indicate new inputs to Pamlico Sound. In practice it is difficult to identify chemical or isotopic species which reflect sources unambiguously. One problem, of course, is that the drainage basins of the tributary estuaries are the ultimate sources of much of the mud in Pamlico Sound; any new input from the drainage basins is likely to share many characteristics with the sediment which is already there. A second problem is that terrestrial inputs may change their compositions in transit, responding, for example, to increasing salinity or to microbial processes. To some extent we can overcome these problems by measuring potential tracers in sediment depth profiles, contrasting surface sediments with those at greater depth.

To recognize erosion we must choose tracers which vary predictably with time, so that their absence from surface sediment at a site implies loss of sediment from that site. Again, because the factors which control spatial variability in deposition are poorly understood, measurements must be distributed vertically (over depth in the sediment column), as well as laterally.

We have chosen the sedimentary chronometric tracers (excess ^{210}Pb and ^{137}Cs) and the carbon-isotopic composition of the organic fraction of the sediments to assess flood erosion and deposition in Pamlico Sound. The input history (^{137}Cs) or decay half-life (excess ^{210}Pb) of the chronometric tracers make them most sensitive to processes which occur on time scales of decades to ca 100 years, longer than would be preferred for this application. However, the processes which distribute these tracers within surface sediments produce depth gradients which flood-induced erosion or deposition might disturb; our task, then, is to recognize the disturbances. The δ^{13}C of particulate organic C makes a useful tracer because of the strong gradient in this property in the sediments and seston of the Neuse and Pamlico estuaries, typically from $\delta^{13}C \leq -27‰$ (PDB) at the landward ends of the estuaries to $\delta^{13}C \approx -22$ ‰ (PDB) at the mouths (Matson and Brinson 1990; Alperin et al. 2000). Lighter C in POC of surface sediments from Pamlico Sound would indicate anomalous discharge of POC from upper reaches of the estuaries. Since peak flooding following hurricane Floyd almost totally displaced saline waters from the Neuse and Pamlico estuaries (Paerl et al. 2001), such discharges of light POC to Pamlico Sound were very likely. For both the chronometric tracers and δ^{13}C we rely upon detailed depth profiles from sediment cores, and the clearest interpretations result from comparisons between cores collected at the same locations before and after flooding.

If we find systematic differences in depth profiles from sediment cores collected before and after major floods, these differences might reflect simple spatial variability rather than flood-induced, temporal change. The preferred way to address this concern is through replicate analyses at each station which is sampled, but resource limitations usually preclude this approach. Here we rely upon internal consistency within our data set. We noted above the similarity among pre-flood profiles of ^{137}Cs (Figure 3) and of excess ^{210}Pb (Figure 4) from muddy sediments over a wide area of Pamlico Sound. Reflecting this similarity, our modeling yields narrow ranges in the critical sediment-transport parameters (ω, X_{ML}; Table 2). The remarkable similarities in the porosities in sediment cores collected before and after flooding (Figure 2) likewise suggest lateral uniformity of lithology in the muddy sediments and rapid recovery of the pre-flood regime of bioturbation. Among properties which do differ in cores collected before and after flooding, the differences are restricted to core tops (Figures 6, 7, 8, 9); deeper sections of the profiles are surprisingly similar between 1990 (or 1994, 1995) and 2001 (or 2000) cores. For all these reasons we think it plausible to interpret our post-flood/pre-flood differences in surface sediments as resulting from flood impacts on sediment delivery, sediment erosion, and sediment deposition.

We have argued above that vertical offsets in the congruent portions of post-flood vs pre-flood profiles of excess ^{210}Pb provide an estimate of *net* erosion or deposition due to flooding. Determined in this way, net flood-induced deposition or erosion in Pamlico Sound and the mouth of the Neuse estuary fell in the range 0-5 cm. At two stations (2, 4) minor net deposition may have resulted from deep erosion (to > 20 cm at station 2), followed by deposition which restored, or more than restored, the pre-flood sediment column. In Figures 18-21 we re-examine these conclusions, adding the data on δ^{13}C (POC) (particulate organic carbon), which may also indicate the presence of newly-deposited sediment. Each of Figures 18-21 comprises sets of three panels of pre-flood and post-flood data: excess ^{210}Pb, ^{137}Cs, and δ^{13}C. The presentation of the chronometric tracer data is altered (from Figures 6 and 7) by offsetting the depth scale for the 1990's data to achieve a reasonable fit to the deeper sections of the profiles of excess ^{210}Pb and ^{137}Cs. In all cases the 1990's ^{137}Cs data have been decay-corrected to 3 October 2001.

Figure 18 shows data from station 3. As previously argued (Figures 6, 7) these data are well

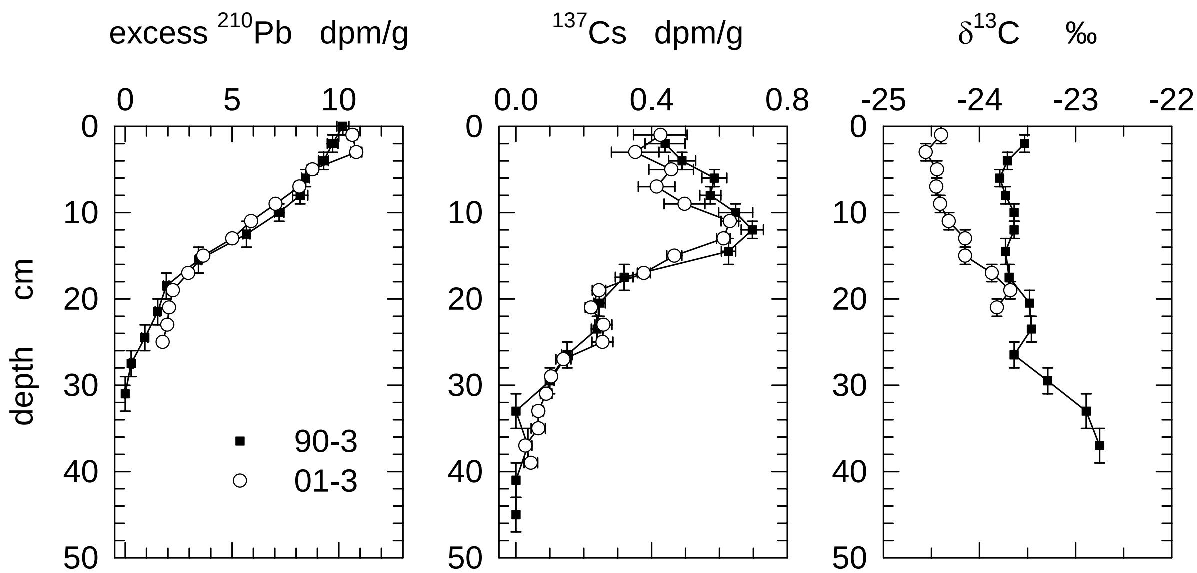

Figure 18. 1990 and 2001 data compared for station 3. All ^{137}Cs data are decay-corrected to 3 October 2001. For ^{210}Pb 1.0 cm has been subtracted from 1990 depths, reflecting 1 cm flood erosion. 1990 depths for ^{137}Cs and δ^{13}C are increased by 1.0 cm, the net of 2.0 cm accumulation during 1990-2001 and 1.0 cm flood erosion.

explained by very minor net flood erosion or deposition: pre- and post-flood profiles of excess ^{210}Pb are nearly identical. In Figure 18 we show the effect of one cm net erosion, which also fits ^{210}Pb well and which offsets the 1990 and 2001 ^{137}Cs maxima, allowing for steady-state sediment accumulation at this station between 1990 and 2001. The $\delta^{13}C$ data imply that new POC penetrated to at least 16 cm. This appears to require that gross erosion considerably exceeded one cm. Based upon the chronometric tracers, erosion to 16 cm appears improbable. However, given a pre-flood mixed-layer thickness (X_{ML}, Table 2) of eight cm, we might not detect flood-induced erosion of eight-ten cm, followed by seven-nine cm deposition and mixing, in the profiles of excess ^{210}Pb and ^{137}Cs. To explain the $\delta^{13}C$, we might then appeal to non-local mixing below 10 cm. For this to work, such deep mixing would have to impact $\delta^{13}C$(POC) while producing no substantial effects in excess ^{210}Pb and ^{137}Cs. We lack the information to rigorously evaluate this possibility.

In Figure 19 (station B) 1994 and 1995 data are re-plotted to illustrate the effect of 2 cm net flood deposition. As compared to Figures 6 and 7, this adjustment improves the fit of the pre- and post-flood excess ^{210}Pb, while still allowing for minor steady-state burial (ca 1 cm) of the ^{137}Cs maximum between 1994 and 2001. In this case the $\delta^{13}C$ data suggest that deposition of allochthonous organic C was limited to the top 4-5 cm. Low values of excess ^{210}Pb over this interval are consistent with this interpretation.

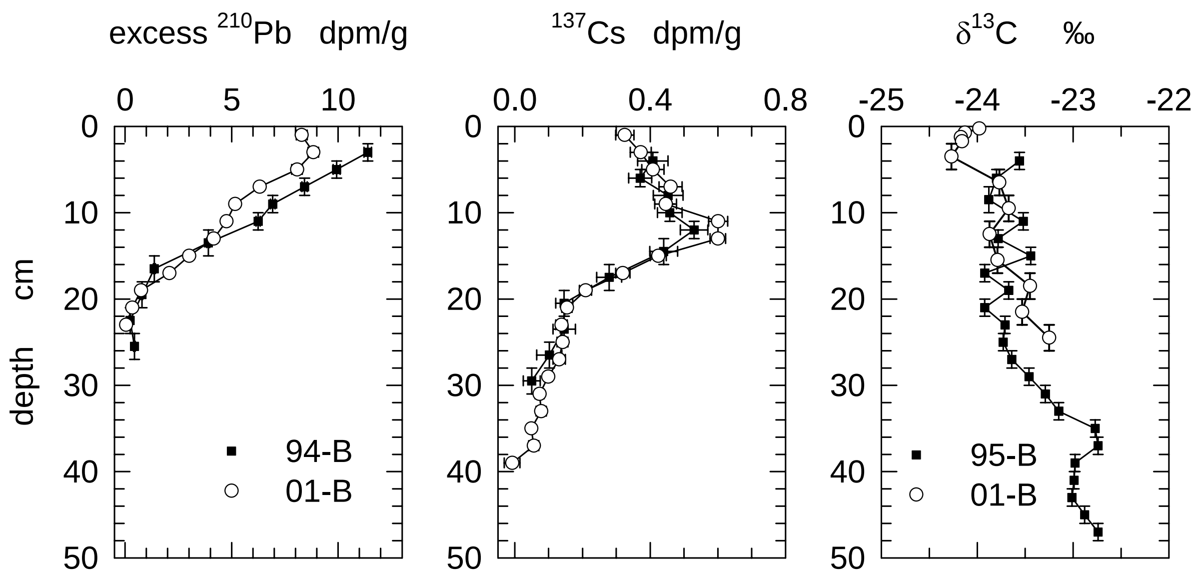

Figure 19. 1994 (^{210}Pb, ^{137}Cs) and 1995 ($\delta^{13}C$) data compared with 2001 data for station B ^{137}Cs data are decay-corrected to 3 October 2001. 1994-1995 depths are increased by 2 cm for ^{210}Pb, reflecting flood deposition, and by 3 cm for ^{137}Cs and $\delta^{13}C$, reflecting flood deposition plus steady-state accumulation during 1994/95 to 2001.

Figure 20 shows the data for station 4, with 1990 profiles offset to account for 4.5 cm net flood deposition. The 2001 profile of excess ^{210}Pb is well fit below about 12 cm by this adjustment, as is the lower section of the 2001 ^{137}Cs profile. ^{137}Cs lacks a clearly defined maximum in the 2001 data; concentrations above 12 cm are erratic and higher than anticipated. Thus we might argue for erosion to about 12 cm, but, in view of the excess ^{210}Pb, not much deeper. As at station 3, the δ^{13}C data suggest substantially greater penetration of light POC (to 20 cm or more). Again, we can only appeal to non-local mixing to introduce light POC below 12 cm.

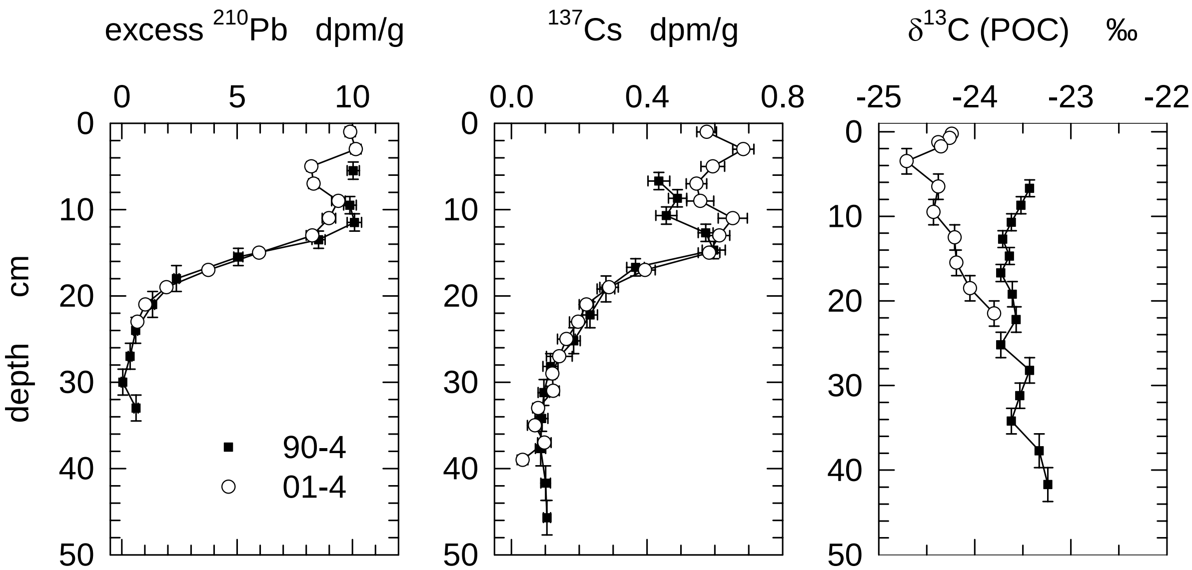

Figure 20. 1990 and 2001 data compared for station 4. 1990 ^{137}Cs data are decay-corrected to 3 October 2001. 1990 depths are increased by 4.5 cm for ^{210}Pb, reflecting flood deposition, and by 5.7 cm for ^{137}Cs and δ^{13}C, reflecting flood deposition plus steady-state accumulation during 1990-2001.

At station 5 (Figure 21) the 2001 profiles of excess ^{210}Pb and ^{137}Cs both show a local maximum at 18-20 cm, which might suggest net deposition. From Figures 6 and 7, however, it is clear that eliminating these maxima by adding 3 cm net deposition only increases discrepancies elsewhere in the 1990 and 2001 profiles of excess ^{210}Pb and ^{137}Cs. The chronometric tracers are better fit by net erosion of 4-5 cm (Figure 21). This would require that the maxima at 18-20 cm (2001 core) resulted from non-local mixing, probably infilling of a large polychaete or shrimp burrow (Katuna and Ingram 1974). The chronometric tracers are permissive of an additional 6-8 cm of erosion which was replaced by subsequent deposition. As at stations 3 and 4 this is not adequate to explain the penetration of light POC without additional transport.

In summary, comparison of the chronometric tracers in sediment cores collected before and after hurricane-induced flooding suggests that net erosion and deposition were limited to 0-5 cm at our stations 2, 3, B, 4, and 5. These results, if representative of the sector of Pamlico Sound between the mouths of the Neuse and Pamlico estuaries and Ocracoke Inlet, explain our failure to detect bathymetric change through acoustic surveys. At all stations, it appears that erosion reached more deeply into the sediment column, perhaps as deeply as 24 cm (station 2). Presumably deep erosion would have occurred either during passage of the hurricanes or during the peak flooding which followed. Subsequent deposition restored the sediment column to within 5 cm of the pre-flood condition. In present data our only tracer of allochthonous inputs to Pamlico Sound is δ^{13}C(POC). We interpret light POC in 2001 core tops, relative to pre-flood cores, as evidence of

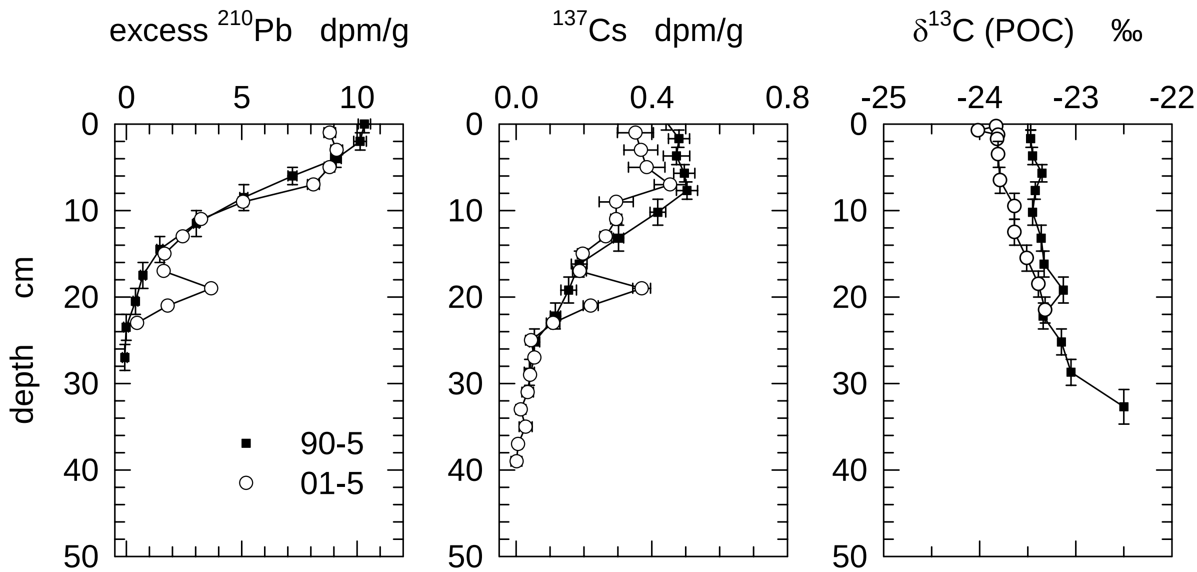

Figure 21. 1990 and 2001 data compared for station 5. All ^{137}Cs data are decay-corrected to 3 October 2001. For ^{210}Pb 5.0 cm has been subtracted from 1990 depths, to show the impact of 5 cm net flood erosion. 1990 depths for ^{137}Cs and δ^{13}C are decreased by 3.3 cm, the net of 1.7 cm accumulation during 1990-2001 and 5 cm flood erosion.

anomalous terrigenous or estuarine inputs. Consistent with this interpretation, the anomalies in core-top δ^{13}C(POC) are largest near the mouths of the estuaries and decrease rapidly with distance into Pamlico Sound. In four of five cases, the depth distributions of δ^{13}C(POC) suggest deeper disturbance of the sediment column than we have inferred from depth profiles of the chronometric tracers; present data are insufficient to resolve these discrepancies.

A broader spectrum of chemical or isotopic tracers would be desirable, both to test interpretations derived from present data and to permit recognition of flood impacts in sediments too old to contain excess ^{210}Pb and fallout nuclides. Organic chemical (e.g., Bianchi et al. 2002) and fossil biotic (e.g., Cooper 2000; Cronin et al. 2000) indicators might also be considered. Any sediment tracer has promise if substantial gradients in concentration are likely within the estuaries and Pamlico Sound. As applied to older sediments, however, all tracers face a common problem, that of distinguishing events of sediment redistribution from more gradual changes in the environment of deposition.

Isotope Mass-balance Calculations. The systematic shift in δ^{13}C-OC in cores collected after the flood (Figure 9) can be used to estimate the fraction of flood-derived organic carbon:

$$f_H = \frac{\delta_A - \delta_B}{\delta_H - \delta_B},$$

where f_H is the fraction of OC derived from flood detritus, δ_A is δ^{13}C-OC after the flood, δ_B is δ^{13}C-OC before the flood, and δ_H is δ^{13}C of organic detritus deposited during the flood. The value for δ_B is estimated from the average δ^{13}C-OC of pre-flood cores (-23.6 ± 0.2 ‰), while the value for δ_H is based on the average δ^{13}C of seston at 11 sites in the Neuse River estuary during the flood period (Clesceri 2003).

Results of the isotope mass-balance calculation (Figure 22) suggest that up to 25% of the organic carbon in the surface sediments was deposited during the flood; over depth ranges where f_H is finite the mass-weighted averages of OC from flood deposition are 12%, 12%, 19% and 3% at stations 3, B, 4, and 5, respectively . Thus, while we cannot know the total masses of OC delivered to these sites during flood discharge, significant flood-derived OC remained in October 2001. The inventory of flood-derived OC is calculated as the depth-integrated product of f_H and OC concentration. The pattern in inventories indicates that deposition of flood detritus was most pronounced near the mouths of the estuaries (compare Figures 1 and 23).

Benthic Fluxes and Denitrification Rates as Indices of Sediment Metabolism. Benthic fluxes (Figure 15) and denitrification rates (Figure 17) provide a partial index of rates of sediment metabolic processes and serve to place our Pamlico Sound stations in a broader geographic context. Four of the five stations (3, B, 4, 5) for which we report these data were in muds, having comparable and high porosities ($0.76 < \varphi < 0.93$; Figure 2) and OC (2 < % OC < 4; Figure 8). Station W1 was in a muddy sand, reflected in low porosity ($0.39 < \varphi < 0.62$) and low OC (0.07 < % OC < 0.77). Relatively few biogeochemical studies have included sandy sediments, which are commonly thought to play a small role in the remineralization of organic matter (e.g., Schulz et al. 2000). Our data suggest that sand-rich sediments at station W1 made low contributions to denitrification (Figure 17) and nitrate-exchange generally (Figure 15), but supported fluxes of O_2, ΣCO_2, and NH_4^+ that were equivalent to those observed at muddy sites.

O_2 fluxes were directed into the sediment in all cases (Figure 15: the negative sign implies flux from water to sediment). The magnitudes of the fluxes (-12.5 to -27.4 $mmol.m^{-2}.d^{-1}$) are similar to those reported for pre-flood cores from the Neuse estuary (Fisher et al. 1982; Rizzo and Christian 1996; Alperin et al. 2000) and at the low end of the range of warm-season O_2 fluxes reported for coastal sediments at other locations (e.g., Nixon 1981; Jørgensen 1983; Jørgensen and Sørensen 1985; Miller-Way et al. 1994; Warnken et al. 2000). Thus, while pre-flood O_2-flux data are not available for our Pamlico Sound sampling sites, any potential increase in sediment O_2 demand due to flood deposition probably did not persist to October 2001.

Sediment O_2 fluxes are opposite in sign, but of comparable magnitude, to ΣCO_2 fluxes (Figure 15); the average flux ratio, $\Sigma CO_2:O_2$, is -0.98 ± 0.20. Clearly this result is consistent with an overall stoichiometry whereby one mole of O_2 is consumed per mole of OC oxidized to DIC. However, no simple mechanism is implied. Sediments consume O_2 in the oxic metabolism of OC, but also in the oxidation of other reduced species (sulfide, Fe^{+2}, Mn^{+2}, etc; Jørgensen 1983; Yoon and Benner 1992), which are themselves largely produced in the oxidation of OC. For the O_2 flux to accurately represent the total oxidation of OC, all these reduced products must be re-oxidized.

As noted above, rates of nitrification and denitrification are sensitive to water-column O_2 concentrations, so fluxes of NH_4^+ and NO_3^- are reported separately for oxic ($O_2 > \sim 63$ μM ≈ 2 $mg.L^{-1}$) and hypoxic ($O_2 < 63$ μM) conditions in Figure 15. Under oxic conditions, NH_4^+ fluxes from muddy sediments (stations 3, B, 4, 5) were of low magnitude and negative sign (directed into the sediment). Porewater gradients (Figures 10-13) drove a positive flux of NH_4^+ into the top 1-2 cm of the sediment column, so the absence of a flux to the water column must have been due to intense nitrification in the top ~1 cm of the sediments. This is consistent with the expected zonation of nitrifying bacteria (e.g., Deming and Baross 1993). However, while some suppression of the NH_4^+ flux due to nitrification is anticipated, complete suppression appears to be unusual. NH_4^+ fluxes under (presumably) oxic conditions from coastal sediments are typically positive (e.g., Aller 1980; Nixon 1981; Yoon and Benner 1992; Miller-Way et al. 1994; Warnken et al. 2000); while this is generally true also of NH_4^+ fluxes in the Neuse estuary (Fisher et al. 1982; Rizzo and Christian 1996; Alperin et al. 2000), Rizzo and Christian (1996) observed two instances of negative NH_4^+ flux in the Neuse. Hypoxic NH_4^+ fluxes were positive from sediments at stations 3, B, 4, 5 (Figure 15), and the magnitude of these fluxes ($\leq$ ~1 $mmol.m^{-2}.d^{-1}$) were typical of the low end of the range of NH_4^+ fluxes reported from other coastal settings, including the Neuse estuary. Hypoxic conditions would decrease the rate of nitrification, allowing NH_4^+ to escape to the water column (Rysgaard et al. 1994).

NO_3^- (strictly $NO_3^- + NO_2^-$) fluxes also changed sign between oxic and hypoxic conditions (Figure 15), but in the opposite sense from NH_4^+: NO_3^- fluxes were positive under oxic conditions, negative under hypoxic conditions. Over the range of O_2 concentrations in the flux experiments (0 - 238 μM), increasing O_2 stimulates nitrification (Rysgaard et al. 1994), augmenting the NO_3^- flux and diminishing the NH_4^+ flux. Others have reported variations in the sign of NO_3^- fluxes in oxic flux measurements (e.g., Nowicki and Nixon 1985; Rizzo and Christian 1996; Alperin et al. 2000). In most flux experiments the NH_4^+ flux has been observed to be of substantially larger magnitude than the NO_3^- flux, but Rizzo and Christian (1996) report instances in which the two N fluxes were of comparable magnitude.

Overall, our benthic fluxes from the muddy sediments of Pamlico Sound are broadly consistent with results from previous studies in similar environments. Possible points of difference include: relatively low magnitudes of O_2 and NH_4^+ fluxes; consistently zero or negative NH_4^+ fluxes under oxic conditions; possibly elevated NO_3^- fluxes. For at least two reasons these differences cannot be confidently attributed to effects of flood deposition or erosion. First, methods for flux measurements are not standardized, and differing fluxes may be due, or partly due, to differences in techniques. Second, and more importantly, while temporal variability can be estimated from a number of seasonal studies, there has been little systematic evaluation of spatial variability. Callender and Hammond (1982) deployed duplicate chambers of two different designs in the Potomac River estuary; even though both types of chamber were relatively large (0.16 m^2 and 0.30m^2), these replicated measurements of benthic fluxes showed high variability. This is probably a general phenomenon. Several studies have demonstrated that directly measured benthic fluxes from estuarine sediments exceed calculated diffusive fluxes by a large margin (1.3X – 10X; Warnken et al. 2000, and references therein). Flux enhancement, relative to the diffusive flux, is attributed to bioirrigation by benthic macrofauna, and the patchy distribution of macrobenthos can cause spatial variability in flux.

Denitrification rates at the four muddy stations (3, B, 4, 5) averaged 0.85 ± 0.13 $mmol.m^{-2}.d^{-1}$ (Figure 17). These rates were measured under oxic conditions (Nie 2002) and at 19 °C, a reasonable approximation of the annual average temperature for Pamlico Sound waters (Garrett 1994). The average rate is within the range reported for coastal marine sediments: 0 - 26 $mmol.m^{-2}.d^{-1}$, with most values falling between 1.2 and 6.0 $mmol.m^{-2}.d^{-1}$ (Seitzinger 1988). As with the benthic fluxes, therefore, post-flood denitrification rates in the muds of Pamlico Sound present no obvious anomaly. Comparing denitrification rates with N fluxes (NO_3^- and NH_4^+; Figure 15), we see that denitrification is a major process in N cycling in Pamlico Sound, at least when bottom waters are oxic. Under hypoxic bottom water denitrification at our average rate would be of less relative importance in the N cycle (NH_4^+ fluxes > 0), but hypoxia (< 2 mg $O_2.L^{-1}$ by our definition) appears to be rare in Pamlico Sound (Peierls et al. 2003). Under oxic conditions, when NO_3^- fluxes were positive (into the water column), denitrification was clearly supported by NO_3^- produced within the sediment by nitrification; in contrast, denitrification was a sink for water-column NO_3^- under hypoxic conditions, presumably due to suppression of nitrification in the sediments. Finally, the denitrification rate is small relative to the ΣCO_2 flux (average 18.2 ± 3.1 $mmol.m^{-2}.d^{-1}$ for stations 3, B, 4, 5; Figure 15). This implies that denitrification is a small contributor to remineralization of OC in Pamlico Sound muds; a minor role for denitrification is typical of coastal sediments, where the predominant oxidants for OC are O_2 and SO_4^{-2}.

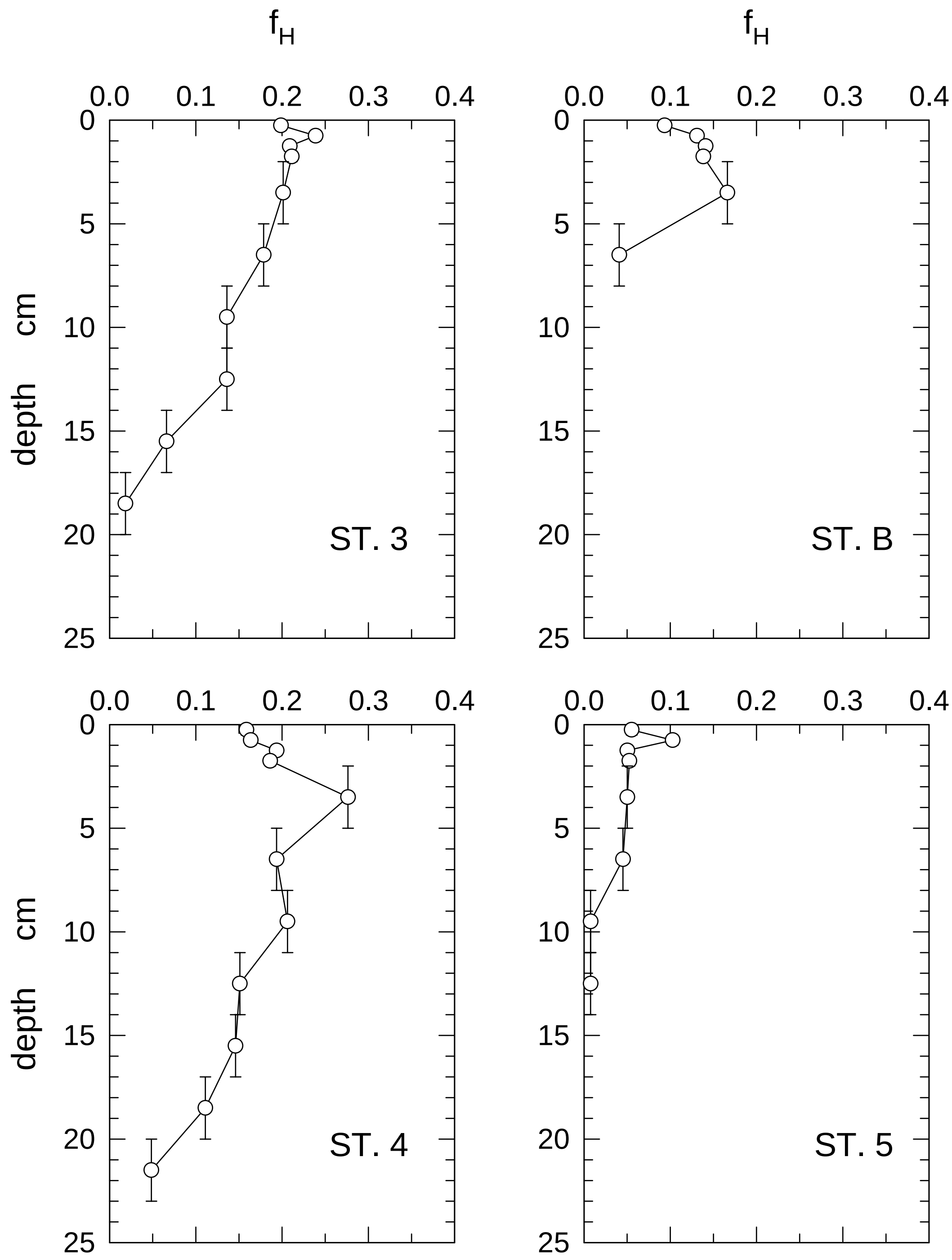

Figure 22. Fraction of sediment organic carbon derived from flood detritus in post-flood Pamlico Sound sediment cores

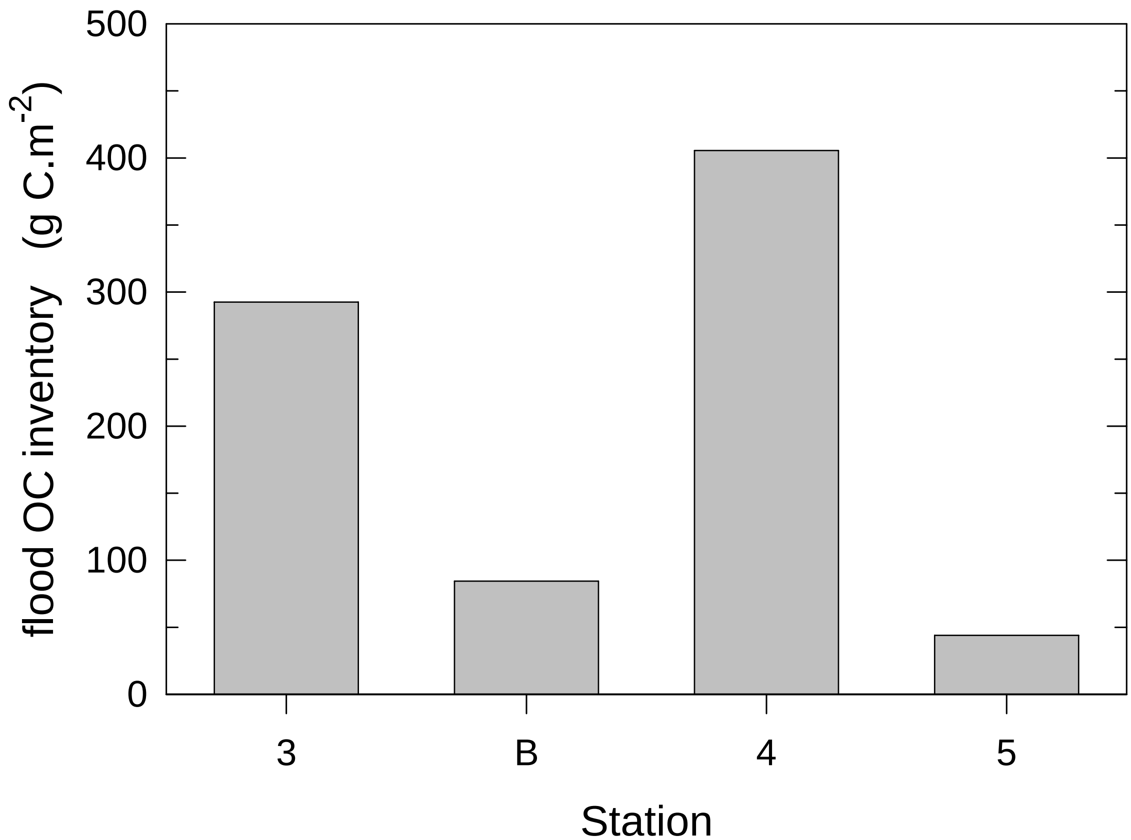

Figure 23. Inventory of sediment organic carbon derived from flood detritus in post-flood Pamlico Sound sediment cores

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ABBREVIATIONS

Abbreviation	Definition or Explanation
cal	absolute years; refers to ^{14}C age which has been calibrated to take account of variable $^{14}C/^{12}C$ in the carbon reservoir
cm	centimeter
D_B	bioturbation coefficient for diffusive sediment mixing ($cm^2.yr^{-1}$)
DIC	dissolved inorganic carbon
DIN	dissolved inorganic nitrogen
erfc	error function complement
ft	foot or feet
g	gram
hr	hour
i.d.	inner diameter
IPT	isotope pairing technique (to determine denitrification rate)
ISIS	interoferometric seabed inspection system (for acoustic survey)
kHz	kilohertz = thousands of cycles per second
km	kilometer
L	liter
m	meter or milli- (10^{-3})
mL	milliliter
mM	millimolar = millimoles per liter
mol	mole
NIST	National Institute of Standards and Technology
OC	organic carbon
PDB	PeeDee belemnite (standard for C-isotope analysis)
PFA	perfluoroalkoxy; a fluorinated hydrocarbon polymer
POC	particulate organic carbon
psu	practical salinity units
PVC	polyvinyl chloride, a chlorinated hydrocarbon polymer

rpm	revolutions per minute
SCUBA	self-contained underwater breathing apparatus
SRM	Standard Reference Material (NIST)
X_{ML}	mixed layer thickness in sediment modeling (cm)
yr	year
ω	sediment accumulation rate ($cm.yr^{-1}$)
°C	degrees Celsius
$\delta^{13}C$	$1000*[(^{13}C/^{12}C)sample-(^{13}C/^{12}C)std]/[(^{13}C/^{12}C)std]$, per mil (‰)
μm	micrometer
ΣCO_2	total dissolved inorganic carbon = $H_2CO_3 + HCO_3^- + CO_3^{-2}$, mol/kg
φ	porosity