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Sedimentary evidence of hurricane strikes in western Long Island, New York

Elyse Scileppi
Department of Geological Sciences, Brown University, Providence, Rhode Island, USA (elyse_scileppi@brown.edu)

Jeffrey P. Donnelly
Geology and Geophysics Department, Woods Hole Oceanographic Institution, Mail Stop 22, Woods Hole, Massachusetts 02543, USA (jdonnelly@whoi.edu)

[1] Evidence of historical landfalling hurricanes and prehistoric storms has been recovered from backbarrier environments in the New York City area. Overwash deposits correlate with landfalls of the most intense documented hurricanes in the area, including the hurricanes of 1893, 1821, 1788, and 1693 A.D. There is little evidence of intense hurricane landfalls in the region for several hundred years prior to the late 17th century A.D. The apparent increase in intense hurricane landfalls around 300 years ago occurs during the latter half of the Little Ice Age, a time of lower tropical sea surface temperatures. Multiple washovers laid down between ~2200 and 900 cal yr B.P. suggest an interval of frequent intense hurricane landfalls in the region. Our results provide preliminary evidence that fluctuations in intense hurricane landfall in the northeastern United States were roughly synchronous with hurricane landfall fluctuations observed for the Caribbean and Gulf Coast, suggesting North Atlantic–wide changes in hurricane activity.

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1. Introduction

[2] Historical records show that New York City is at risk of being struck by a hurricane. Four documented strong hurricanes (Category 2 or higher on the Saffir-Simpson Scale) with high storm surges (~3 m) have made landfall in the New York City area since 1693 with the last occurring in 1893 [*Ludlum*, 1963]. Population growth during the 20th century has significantly increased the risk to lives and property should a strong hurricane recur today [*Pielke and Landsea*, 1998]. The frequency of hurricane landfalls is difficult to estimate from the instrumental and documentary records due to the relative rarity of these events and the short historical observation period. This study follows previous research in using sedimentary archives to reconstruct a history of past hurricanes [*Emery*, 1969; *Liu and Fearn*, 1993, 2000; *Donnelly et al.*, 2001a, 2001b, 2004a; *Donnelly*, 2005]. In this study, we refine and lengthen the hurricane record of the New York City area by first calibrating the

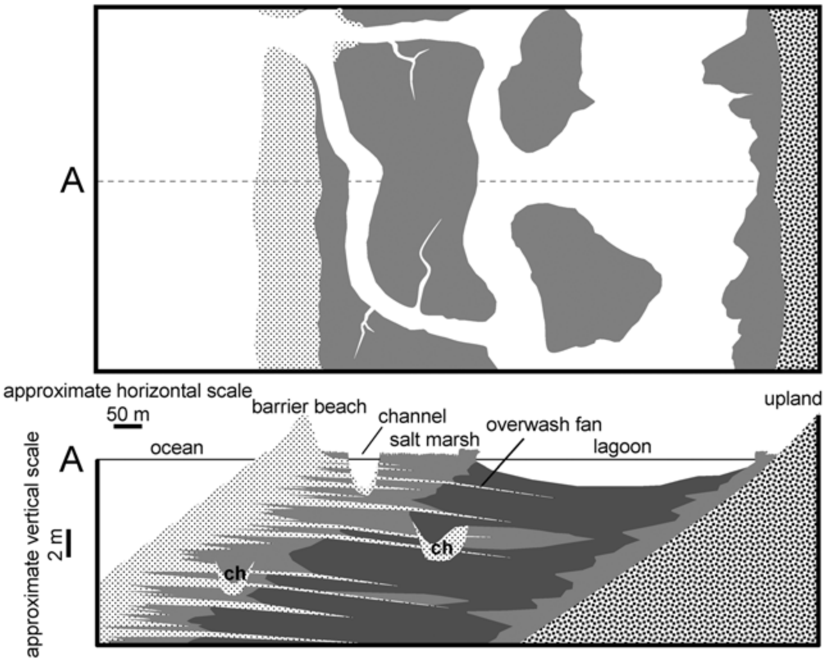

Figure 1. Map and cross section of conceptual model of a transgressional barrier system. Light gray shading indicates marsh peat accumulation and dark gray indicates lagoonal sediment. Fine stippled pattern indicates sandy barrier, washover, and channel deposits. Extreme storm surge overtops the barrier beach and transports sandy sediments into the backbarrier marshes, channels, and lagoons. As sea level rises, deposition occurs in the backbarrier environments, preserving the sandy overwash deposits within the sedimentary record. The presence of relic channels (ch) preserved in the backbarrier stratigraphy is noted.

sedimentary record to documented hurricanes and then extracting several thousand years of storm history from this sedimentary archive.

[3] When a hurricane makes landfall, waves and storm surge can overtop coastal barriers, depositing sandy overwash fans on backbarrier salt marshes and tidal flats [*Donnelly et al.*, 2001a, 2001b] or within coastal ponds [*Emery*, 1969; *Liu and Fearn*, 1993, 2000; *Donnelly*, 2005] (Figure 1). Long-term records are formed as organic-rich sediments accumulate over storm-induced deposits, preserving coarse overwash layers [*Orson et al.*, 1998; *Bricker-Urso et al.*, 1989; *McCaffrey and Thompson*, 1980; *Roman et al.*, 1997; *Redfield*, 1965, 1972]. Coring backbarrier areas provides a rich history of overwash deposition as discrete sand layers within organic and fine-grained backbarrier sediment. Such records of past storms can extend our knowledge of hurricanes into the prehistoric period.

[4] Previous studies extended the record of hurricane strikes beyond historical observation using the storm-induced deposits preserved in coastal environments [*Emery*, 1969; *Liu and Fearn*, 1993, 2000; *Liu*, 1999; *Donnelly et al.*, 2001a, 2001b]. A core collected from Oyster Pond in Falmouth, MA contains a 1000-year storm record with nine sand layers preserved within organic silt [*Emery*, 1969]. *Emery* [1969] interpreted these layers as material transported into the pond by hurricane waves. Overwash layers from at least four prehistoric storms are recorded in this core with the earliest dating to about 1000 cal yr B.P. (calibrated radiocarbon ages presented in years before 1950 A.D. (B.P.)) [*Emery*, 1969]. *Liu and Fearn* [1993, 2000] collected cores from coastal lakes along the northern Gulf Coast of Alabama and Florida that preserve 3500 and 5000 year records of hurricane landfall, respectively. The reconstructions of the northern Gulf Coast indicate that a period of more frequent hurricane landfall occurred between ~3650–930 cal yr B.P. (3400–1000 ^{14}C yr B.P.), with few hurricane landfalls observed during ~5000–3650 cal yr B.P. (4500–3400 ^{14}C yr B.P.) and the last ~930 years [*Liu*, 1999; *Elsner et al.*, 2000]. *Liu and Fearn* [2000] hypothesize that the active and inactive hurricane periods in the northern Gulf Coast are the result of shifting storm tracks between northeastern and southwestern

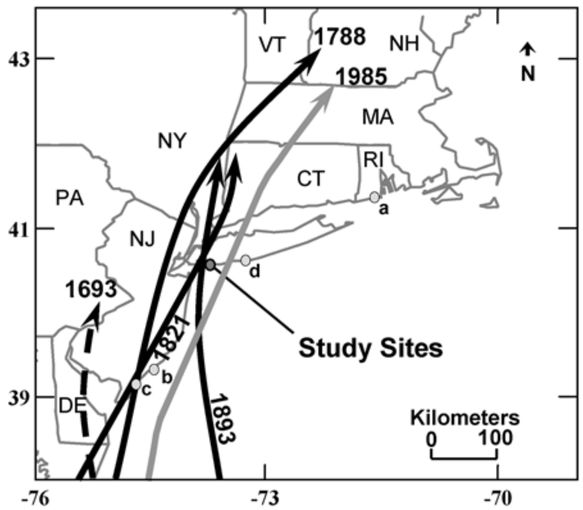

Figure 2. Tracks of hurricanes impacting the western Long Island region and study sites. Dashed track of 1693 indicates uncertainty with respect to the path of this hurricane. The gray track of 1985 (Gloria) indicates that this hurricane was a near-miss storm for the western Long Island study sites given that storm surge is typically highest on the right side of a hurricane. Previous paleohurricane reconstruction study sites labeled a, b, and c correspond to Succotash Marsh (RI), Brigantine Marsh (NJ), and Whale Beach Marsh (NJ), respectively. Site d is the location of the Great South Bay sea level data [*Rampino and Sanders*, 1980] discussed in the text.

locations. The authors propose that the phase of the North Atlantic Oscillation (NAO) and position of the Bermuda High determine hurricane paths, with a neutral NAO and southern Bermuda High steering storms into the Gulf Coast and a more positive NAO and northern position of the Bermuda High steering hurricanes north along the U.S. eastern seaboard [*Liu and Fearn*, 2000]. Thus changes in the millennial-scale mean position of the Bermuda High and phase of the NAO may result in a spatial see-saw pattern of hurricane activity between the northeastern United States and Gulf Coast.

[5] In order to lengthen the documented hurricane record of the northeastern United States, *Donnelly et al.* [2001a] cored Succotash Marsh in southern Rhode Island. *Donnelly et al.* [2001a] identified four historical and two prehistoric overwash events in a 700 year sediment record from Succotash Marsh. Cores from Whale Beach and Brigantine marshes in southern New Jersey were analyzed by *Donnelly et al.* [2001b, 2004a] and shown to contain overwash deposits from intense historical and prehistoric storms. Ages of thick, widespread storm deposits at Whale Beach are consistent with deposition by the 1821 hurricane and a prehistoric hurricane in 1278–1438 A.D. [*Donnelly et al.*, 2001b]. Thin and localized storm deposits at Brigantine Marsh correspond to two near-miss hurricanes in 1938 and 1944 as well as two northeasters in 1950 and 1962 A.D. Thicker and more extensive overwash layers, attributed to the 1821 hurricane and two prehistoric storms dating to 550–1400 A.D. and 500–600 A.D., are recorded at Brigantine Marsh [*Donnelly et al.*, 2004a]. Deposits left by intense hurricanes that made landfall were significantly thicker and more extensive than those deposited by historical northeasters and near-miss hurricanes [*Donnelly et al.*, 2001b, 2004a]. The studies by *Donnelly et al.* [2001a, 2001b, 2004a] demonstrate that past hurricane activity can successfully be reconstructed from backbarrier sediments of the northeastern U.S. coast. Additionally, these studies highlight the importance of multiple study sites which can provide a representative region-wide record and minimize the effects of changing local conditions [*Donnelly et al.*, 2004a; *Donnelly and Webb*, 2004].

[6] This study follows a similar approach to previous studies by *Donnelly et al.* [2001a, 2001b, 2004a] in order to determine the hurricane history for the New York City area. Cores were collected from three backbarrier salt marshes in western Long Island, NY (Hicks Beach, Lido Beach, and Alder Island marshes) (Figures 2 and 3) in order to test three hypotheses. (1) On the basis of historical hurricane tracks and accounts of high water levels and damage, sedimentological evidence of the 1893, 1821, and 1788 hurricanes is preserved in the backbarrier sedimentary record of western Long Island. (2) Prehistoric storm deposits are recorded in western Long Island and some of these overwash fans correlate with prehistoric storm deposits found in coastal New Jersey. (3) Periods of active and inactive hurricane activity in western Long Island are out of phase with the northern Gulf Coast on the basis of *Liu and Fearn*'s [2000] proposed hypothesis that atmospheric circulation creates a spatial see-saw pattern of hurricane tracks.

2. Study Site

[7] The study site is composed of three backbarrier salt marshes (Hicks Beach, Lido Beach, and Alder Island marshes) which are located at (40.593°N, −073.695°W), (40.595°N, −073.601°W) and (40.597°N, −073.580°W), respectively. The

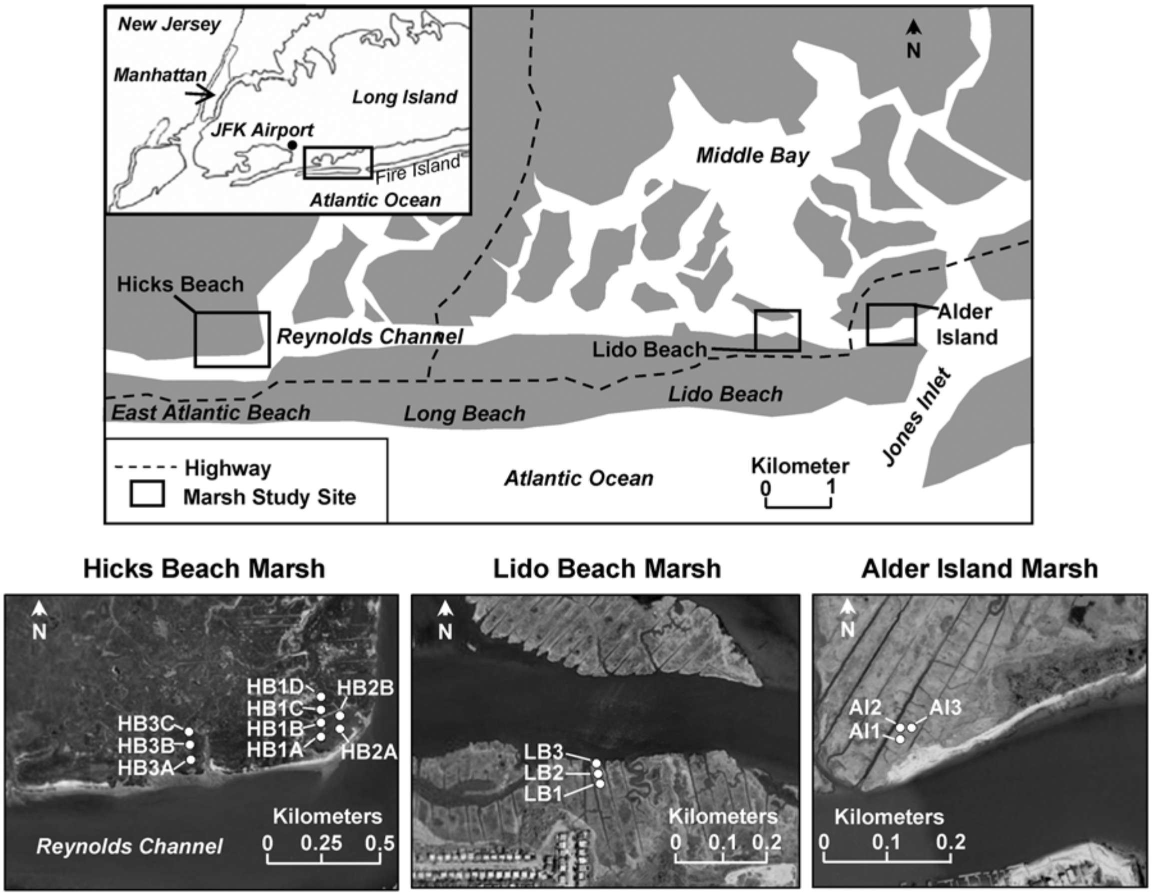

Figure 3. Map of the three study sites and the position of the study sites within the larger region of the New York Bight. At bottom, aerial photographs of each study site are provided with labeled core locations.

marshes are in Nassau County, east of Raritan Bay and north of Long Beach, NY (Figures 2 and 3). Hicks Beach Marsh, the westernmost study site, is around 9 km to the southeast of JFK Airport and 26 km to the southeast of Manhattan. Lido Beach and Alder Island marshes are located farther east and are 6 km and 9 km from Hicks Beach, respectively, providing a broad spatial sampling area.

[8] East Atlantic, Long, and Lido beaches are located to the south of the marshes and function as the area's barrier islands with a current height of 2.5–3.0 m (Figure 3). Historical topographic information for these islands is limited; however, the barrier heights appear to have been constant for at least the past 50, possibly the past 80, years. The height of the barrier islands acts as a filter to allow only intense storms with high surges to overtop the barrier and produce widespread overwash deposits in the backbarrier marshes. Hicks Beach and Alder Island marshes are currently separated from the barrier beach by Reynolds Channel, while Lido Beach Marsh is located on the northern side of the barrier island. The relatively large distance (over 1 km) between the Atlantic Ocean and the study sites further filters the overwash record, likely resulting in selective preservation of deposits at our study site from only the most intense storms. The source of coarse, sandy sediment at Hicks Beach, Lido Beach, and Alder Island marshes is primarily the barrier beach. The three study sites are located along southern-facing shoreline, minimizing possible effects of overwash due to winter storms (or northeasters) [*Terchunian and Merkert*, 1995] that typically have severe winds from the northeast. All three marshes are undisturbed and coring sites were selected to target relatively pristine sections of the marshes.

[9] Barrier islands are dynamic systems that evolve through migration and inlet development in response to changing sea level, sediment supply, and storms. Fire Island, located on the southern shore of Long Island, has remained stable and has

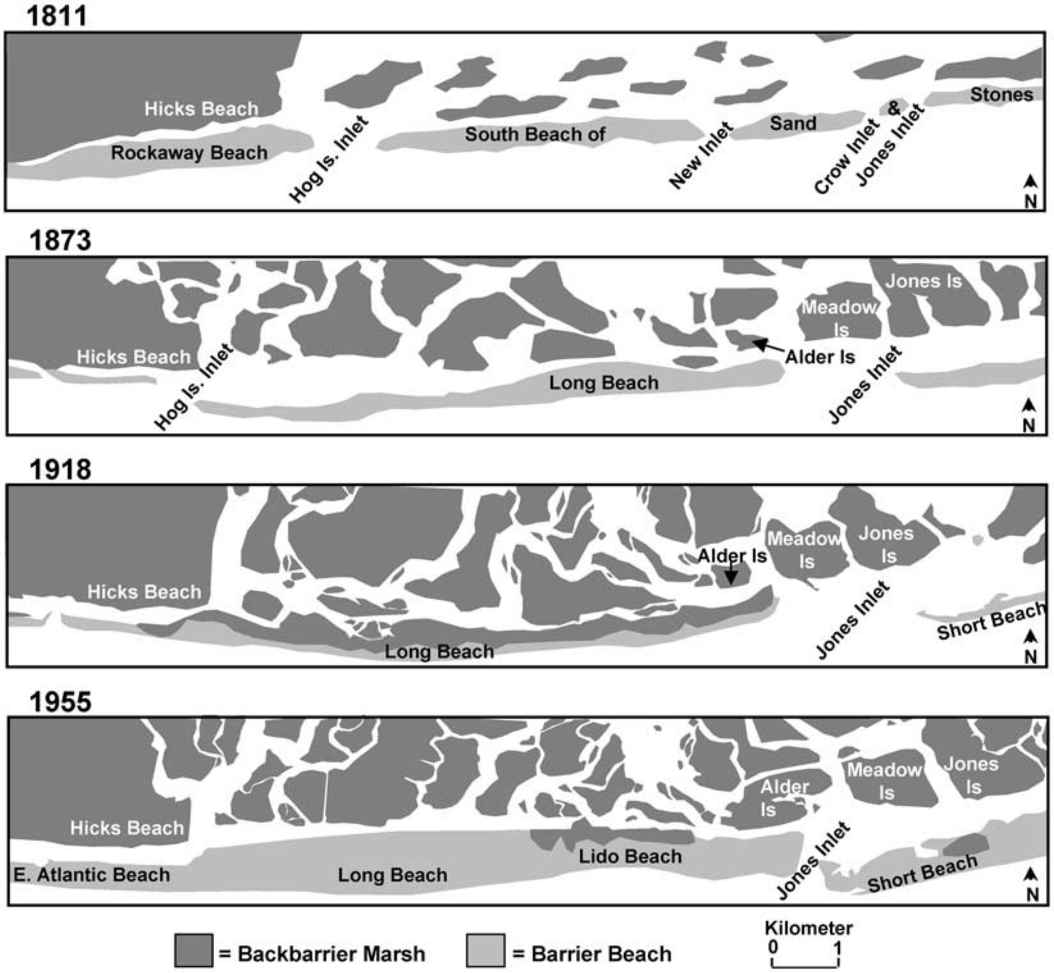

Figure 4. Changes in the location and position of coastal features within the study site area are shown for four years (1811, 1873, 1918, and 1955 A.D.). Information is collected from historical maps, and these records provide insight into relative position and number of inlets, although exact locations are less constrained in the earlier maps. (1811 Map of The Country Thirty Miles Round the City of New York by John H. Eddy; 1873 Map of Central Rail Road Extension Company of Long Island; 1918 map by the U.S. Geological Survey; 1955 map by the U.S. Geological Survey.)

not migrated a large distance over the last thousand years [*Leatherman*, 1983, 1985; *Panageotou and Leatherman*, 1986] especially west of Watch Hill where fewer inlet breaches have occurred [*Schwab et al.*, 2000]. During this time, the barrier island has been narrowing through erosion on both the bayside and oceanside [*Leatherman*, 1983]. Additional work shows that discontinuous barrier retreat has occurred along the southern shore of Long Island over the past 9000 years, with rapid sea level rise shifting the barrier 2 km landward over the last 7000 years [*Rampino and Sanders*, 1981; *Hennessy and Zarillo*, 1987]. Episodic inlet and tidal delta formation appear to be important in causing some degree of island migration [*Leatherman*, 1983, 1985] and vertical buildup [*Hennessy and Zarillo*, 1987] along the southern shore of Long Island. The barrier beaches in our study may have behaved in a similar manner given their shared sea level history and related sediment supply.

[10] Historical maps and charts document changes in inlet position and abundance along this coast from 1811 A.D. to the present. Hog Island Inlet was located adjacent to Hicks Beach Marsh in 1811 and persisted until the late 1800s (Figure 4). During the early 20th century, East Rockaway Inlet was formed nearby and the area of Atlantic Beach was augmented with dredged sediment [*Rather*, 2003], decreasing Hicks Beach's sensitivity to

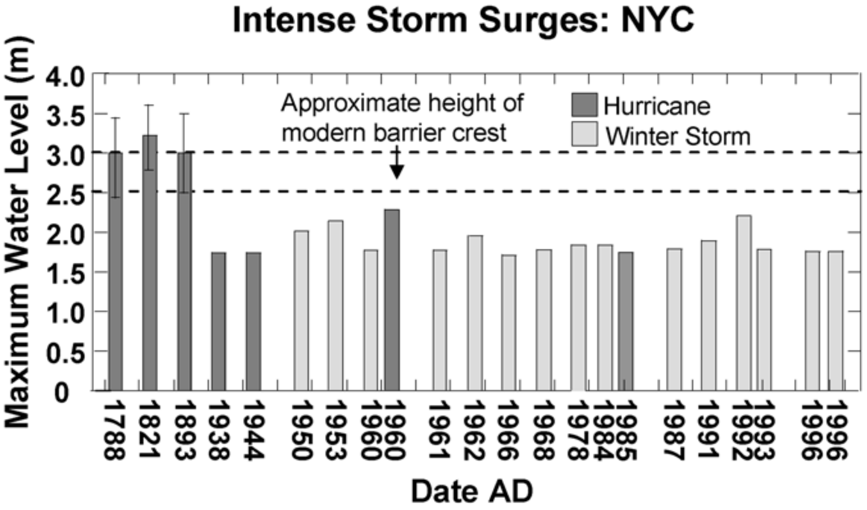

Figure 5. Storm surge heights relative to modern mean sea level which accompanied the 1788, 1821, and 1893 hurricanes inferred from historic archives and the most extreme flooding events of the 20th century recorded by the Battery Park (New York City) tide gauge from 1920 to present. The average height of the modern [2002] barrier crest (2.5–3.0 m) is indicated with dashed lines.

storm energy by increasing protection from the growing barrier beach. The early map from 1811 depicts additional inlets between Hog Island and Jones Inlets (Figure 4). Crow Inlet may have merged with Jones Inlet, located slightly to the east, through erosion of a small island separating the inlets. New Inlet may have closed through longshore sediment transport and deposition, merged with Jones Inlet, or been renamed Jones Inlet upon the original Jones Inlet closing. The name New Inlet suggests that this inlet formed post-settlement, possibly during the 1693 or 1788 hurricane. Ephemeral inlets can be created by hurricane activity and often do not result in long-lasting coastal features [*Leatherman*, 1985; *Terchunian and Merkert*, 1995]. Maps from the 17th and 18th centuries exist but lack the resolution, accuracy, and detail necessary in these coastal areas to determine changes in inlets during this time period.

[11] The presence of a nearby inlet or a locally reduced barrier height may increase the sensitivity of a particular area to storm-induced deposition. High storm surges associated with major hurricanes that overtop the entire barrier often result in extensive sheet overwash deposits [*Donnelly and Webb*, 2004], whereas lesser storms with lower storm surge can breach low-elevation sections of the barrier forming localized overwash lobes. Likewise, the presence of a nearby inlet allows for storm energy to more easily penetrate into the backbarrier area, letting a lesser hurricane with lower storm surge transport coarse sediment into the backbarrier. In order to control for localized sensitivity changes, this study employed a multiple-site approach, as strong hurricanes making landfall in the New York City area would likely result in storm surge and waves of sufficient height to overtop the barrier across wide stretches of coast and not merely at localized areas.

3. Historical Records of Regional Hurricanes

[12] Four historically documented hurricanes that caused approximately 3 m of storm surge made landfall in the New York City area in 1893, 1821, 1788, and likely 1693 (Figures 2 and 5). For the purposes of this study, we define storm surge as the maximum water level attained during an event as measured in height above mean sea level (MSL) and is highest on the right side of a hurricane [*Donnelly and Webb*, 2004]. When tropical cyclones enter middle-latitudes they often undergo an extratropical transition that can either dissipate the storm or intensify the winds and accelerate the storm's forward motion, with the latter resulting in an increased storm surge [*Brand and Guard*, 1978; *Bosart and Lackmann*, 1995; *Hart and Evans*, 2001]. Severe winter storms, minimal hurricanes, and near-miss hurricanes (including Gloria in 1985) impacting the region in the 20th century caused coastal inundation levels to rise a maximum of ~1.5–2.0 m above MSL (Figure 5).

[13] The category 2 hurricane that made landfall in the New York City area on 24 August 1893 [*Neumann et al.*, 1993] resulted in a high storm surge and serious damage (Figure 2). Many accounts record high water levels accompanying the storm as well as large boats being driven a hundred feet inland [*New York Times*, 1893]. The hurricane caused dramatic changes to the Long Island coastline and destroyed Hog Island, which was located to the south of Rockaway Beach [*Coch*, 1997, 1998]. The *New York Times* reported that half a mile of "the Boulevard" was submerged in the Astoria District [*New York Times*, 1893]. We interpret "the Boulevard" to be Vernon Boulevard which runs along the water in the Astoria District. The lowest elevation along Vernon Boulevard is around 3 m above MSL and is about half a mile in length. The storm surge accompanying the 1893 hurricane therefore was likely close to 3 m in height (Figure 5).

[14] The hurricane of 3 September 1821 was an intense hurricane with a storm surge at least 3.2 m above MSL that caused extensive damage to the New York City area [*Ludlum*, 1963; *Redfield*, 1831; *Boose et al.*, 2001] (Figures 2 and 5). *Redfield* [1831] notes that the hurricane struck at low tide and water levels at New York City rose thirteen feet in an hour. Given that this storm surge estimate is from downtown Manhattan where some degree of storm surge funneling may have occurred, 3.2 m may be a slight overestimate for the water levels along the Long Island barrier beach. Nevertheless, historical accounts of the 1821 hurricane describe damage and storm intensity that likely correspond to a category 3 hurricane on the Saffir-Simpson scale [*Donnelly et al.*, 2001b; *Boose et al.*, 2001; *Ludlum*, 1963] with approximately 3 m of storm surge along the southern coast of Long Island. After tracking along the New Jersey coastline, the 1821 hurricane made landfall near Hicks Beach marsh (Figure 2) [*Ludlum*, 1963]. Accounts from Long Island report extensive damage to the area, with descriptions of ships "driven high and dry on the sandy stretches of Long Beach and Rockaway Beach" [*Ludlum*, 1963]. The 1821 hurricane is described as one of the most damaging to the New York City area in its history [*Ludlum*, 1963].

[15] The hurricane of 19 August 1788 was a powerful storm of unusually short duration [*Ludlum*, 1963]. Powerful onshore winds accompanying the storm lasted less than half an hour [*Ludlum*, 1963]. *Ludlum* [1963] suggests that a combination of small size and fast movement may explain the unusual behavior of this storm. *Boose et al.* [2001] estimate that the 1788 hurricane was a category 3 hurricane on the Saffir-Simpson scale. Historical accounts state that the cellars on Front and Water Streets in Manhattan were flooded with water [*Ludlum*, 1963]. On the basis of the elevation of this intersection, we estimate that the 1788 storm surge was also close to 3 m (Figure 5), which would require a severe hurricane. As in the case of the 1821 storm, three meters may be a slight overestimate for the storm surge along the Long Island barrier given that storm surge funneling in the New York Bight may have amplified the water level height in downtown Manhattan. The short duration of the storm likely limited the amount of overwash at the study sites, with less time for winds to accumulate water along the shoreline and for waves to impact the barrier.

[16] Historical accounts written by early European settlers note an additional hurricane for the New York City area in 1693. Accounts of the October 1693 hurricane reveal considerable modifications to the Long Island shoreline, including reports that the hurricane broke through Fire Island Cut [*Ludlum*, 1963]. The 1693 storm may have had a significant effect on the New York City area, including the study sites, but little historical documentation is available.

4. Methods

4.1. Field and Core Description Methods

[17] We used a multiple-site approach in this study in order to assess the spatial consistency of overwash deposits [see *Donnelly and Webb*, 2004]. A total of 15 vibracores were taken from the marsh sites and analyzed in this study: nine from Hicks Beach (HB), three from Alder Island (AI), and three from Lido Beach (LB) marshes (Figure 3). Cores were taken along transects with three transects at Hicks Beach and a single transect at Lido Beach (Figure 3). All cores were described for sediment type, color (Munsell soil chart), grain size, macrofossils, and abruptness of contact between distinct sedimentary units. Cores were refrigerated at 4°C to prevent desiccation and mold.

[18] Coarse, inorganic units were identified primarily through detailed core descriptions. In several cases (HB1A, HB1B, HB1D, HB2A, HB3A, HB3B, LB1, and LB2), we performed loss-on-ignition (LOI) to determine the percent organic

composition of the sediments [*Dean*, 1974]. Contiguous 1 cm^3 samples were extracted for the entire length of each core with the exception of HB1D, LB1, and LB2 where only the top 1.0 to 1.5 m was sampled. Samples were weighed, heated at 105°C for 14 hours, and baked at 550°C for 4 hours. Following each heating phase, samples were placed in a desiccator to cool and weighed. LOI allowed for the characterization of inorganic layers preserved within the organic-rich matrix. Grain-size analysis was performed for the upper 1.0 to 1.5 m of cores LB1 and LB2 at 1 cm intervals using a Beckman-Coulter LS 13320 laser particle-size analyzer. Grain size was measured on the LOI ash and these data provide an additional quantitative description of the sediments preserved in the core.

[19] We identified overwash layers on the basis of their sedimentary characteristics which fit a set of criteria. Typical backbarrier sedimentation is characterized by fine-grained, organic-rich mud and peat while barrier beach sediment in western Long Island consists of well-sorted and rounded sand. Sand units punctuating the backbarrier sediments are interpreted as overwash deposits given that barrier beaches are the most likely sediment source and the relatively coarse grain size must result from higher transport energy. Overwash deposits commonly have sharp lower contacts which indicate a sudden onset of high transport energy and, in some cases, the erosion of substrate during the event [*Donnelly et al.*, 2001b; *Donnelly and Webb*, 2004]. Dark, parallel laminations of heavy minerals are common features of overwash deposits [*Schwartz*, 1975; *Hennessy and Zarillo*, 1987] and similarity between the buried sand and modern beach sand point to the barrier beach as the major sediment source.

4.2. Chronostratigraphic Methods

[20] Cores were dated using a combination of heavy-metal (lead and copper) concentrations, pollen stratigraphy, and radiocarbon dating. In addition, estimates for local rates of sea level rise were used to further constrain the ages of sediments. We focused on core HB1A to develop our initial chronostratigraphy and determine if inorganic layers correspond with documented intense hurricanes. Additional dating was performed on the other cores in order to correlate among cores, to test the continuity of overwash deposits at the study sites, and to extend the record of overwash events into the prehistoric.

[21] Established pollen horizons based on historically documented changes in vegetation provide useful dating tools. Flora assemblages in the region experienced dramatic shifts during the historical period, including an early shift from arboreal to disturbance/agricultural species (circa 1700 A.D.) and a more recent decline in *Castanea* (Chestnut) abundance (circa 1915 A.D.) [*Anderson*, 1974; *Brugam*, 1978; *Clark and Patterson*, 1984, 1985; *Donnelly et al.*, 2001a; *McAndrews et al.*, 1973]. Fossil pollen was counted to provide age constraints on coarse-grained, inorganic sedimentary units. Due to the time-consuming nature of this technique, we chose to focus pollen analyses on a single core, HB1A. Sixteen samples were taken from HB1A and processed using the standard pollen processing techniques of *Faegri and Iverson* [1989]. Samples were selected with an even distribution from all non-overwash units in the upper 2 m of the core. Four tablets of *Lycopodium* grains were added to each sample, providing an estimate of natural pollen concentration. Eight samples (11 cm, 27 cm, 30.5 cm, 50.5 cm, 95.5 cm, 159.5 cm, 169.5 cm, and 180 cm) were subjected to an additional hydrofluoric acid treatment to dissolve remaining silica grains. Samples obtained from 11 cm and 27 cm depth were in poor condition and therefore were excluded from the pollen count. A minimum of 100 regional pollen grains were counted per interval to obtain representative pollen percentages.

[22] We estimated ages for the observed shifts in pollen percentages for western Long Island on the basis of historical documents and previous pollen studies. While the rise in *Ambrosia*, *Rumex*, and *Plantago*-undifferentiated (weed) pollen has been shown to correspond to European-style land clearance, the timing of settlement, and therefore the pollen shift, varies spatially [*Anderson*, 1974; *Brugam*, 1978; *Clark and Patterson*, 1984, 1985; *Donnelly et al.*, 2001a; *McAndrews et al.*, 1973]. On the basis of historical accounts for North Branford, CT, *Brugam* [1978] applies a date of 1700 A.D. to the initial increase in *Ambrosia* and *Rumex* pollen. *Clark and Patterson* [1985] used early historical records to date the agricultural pollen rise on the north shore of eastern Long Island and a documented settlement date of 1680–1700 A.D. was applied to the disturbance species rise at that site. Additionally, the increase in agricultural indicator species in a pollen record from Fairfield, CT was radiocarbon dated to 1666–1788 A.D. [*Lederer et al.*, 2000]. *Donnelly et al.* [2001a, 2001b] assigned a date of

~1700 A.D. to the *Ambrosia* and *Rumex* rise at Whale Beach Marsh in southern New Jersey and to the *Rumex* rise at Succotash Marsh in southern Rhode Island. In this study, we also estimate the date of ~1700 A.D. (±25) for the rise in agricultural indicators on the basis of prior age estimates for nearby areas as well as historical documents recording initial European settlement for Nassau County in 1644 A.D. [*Thompson*, 1843]. By estimating 1700 A.D. (±25), we are assuming a lag of about 50 years after initial settlement for larger-scale land clearance to alter the regional pollen signal. The first appearance of *Plantago lanceolata* pollen, introduced from Europe, is assigned a date of the early 1800s [*McAndrews et al.*, 1973; *Donnelly et al.*, 2004b].

[23] *Castanea* (Chestnut) trees suffered a dramatic decline in population when *Endothia parasitica*, an infectious fungus, was introduced to New York City in 1904 A.D., destroying most of the mature chestnut trees there by 1910 [*Anderson*, 1974]. By 1915 A.D. most of the mature *Castanea* trees in southern Connecticut, southeastern New York, and northeastern New Jersey had been killed, with severe effects on Long Island by 1910–1920 A.D. [*Anderson*, 1974]. *Clark and Patterson* [1985] applied the date 1920 A.D. to the disappearance of *Castanea* pollen from records at Fresh Pond marsh and Deep Pond Lake in northeastern Long Island. *Donnelly et al.* [2001b] assigned a date of 1920 A.D. for the *Castanea* decline observed at Whale Beach Marsh in southern New Jersey. Given the close proximity of our study sites to New York City, the sudden decline of *Castanea* pollen in core HB1A likely dates to around 1915 A.D. (±5).

[24] The initial increase in lead and copper concentrations in core sediments corresponding to the industrial revolution can be used as an additional stratigraphic marker [*Donnelly et al.*, 2001a]. The industrial revolution elevated the production of pollution and caused unnaturally high levels of heavy metals in the environment. These pollutants were deposited from the water and atmosphere, settling onto and being preserved within anoxic environments, such as salt marshes [*McCaffrey and Thompson*, 1980; *Bricker-Urso et al.*, 1989; *Donnelly et al.*, 2001a]. Lead and copper concentrations were measured in cores HB1A, HB1B, HB1D, HB3A, HB3B, and HB3C using X-ray fluorescence spectrometry (XRF). Samples were taken at 2 cm intervals for the length of each core, freeze-dried for 48 hours, ground to a uniform powder, weighed to 5 g, and pressed into pellets under 10 tons of pressure. Elemental concentrations of the total mass were determined using UniQuant 5.0 software and corrections were made on the basis of LOI percent organic results for each sample. We further corrected lead and copper concentrations on the basis of XRF results from ten certified sediment standards. A duplicate sample was analyzed to confirm reproducibility of XRF results. Additionally, lead concentration for core AI1 was measured at 3 mm resolution and ten second exposure time using a scanning ITRAX XRF with a molybdenum tube at Woods Hole Oceanographic Institution.

[25] We estimated the age of the initial increase in lead and copper concentrations from western Long Island in order to use the metals data as a dating tool. The increase in lead and copper concentrations above background levels in the northeastern United States was estimated by *Donnelly et al.* [2001b] to date to the mid 1800s. *McCaffrey and Thompson* [1980] date the initial rise in heavy metals to the early 1860s. *Bricker-Urso et al.* [1989] provides a date range of 1865–1885 for the initial rise in lead and copper concentrations for a site in southern Rhode Island. A ^{210}Pb chronology confirms age estimates of the initial rise with a date of 1870 A.D. (±19) [*Bricker-Urso et al.*, 1989]. In this study, we assign a date of ~1860 (±20) to the initial increase in lead and copper concentrations on the basis of previous studies and our site's proximity to the industrial area of New York City.

[26] Eight radiocarbon dates were obtained from organic, fine-grained sections of the marsh cores (Table 1). Plant macrofossil samples (leaf fragments of *Spartina alterniflora*) were taken at the base of the lowermost sand layers in cores HB1A, HB1B, and HB3B, as well as just below sand layers in AI1 and LB1. Radiocarbon samples taken from leaf material directly below the sand layers provide maximum ages for overlying overwash deposits. When overwash is deposited on a marsh or tidal flat surface, some erosion of the surface can occur leading to older radiocarbon ages. This geologic uncertainty is inherent in the radiocarbon samples for this study but allows for event-layer ages to be approximately dated. A *S. alterniflora* root was selected for radiocarbon analysis from a depth of 147–148 cm in AI1 due to a lack of leaf fragment material. Because the root was penetrating from above, the radiocarbon age of the root sample provides a minimum age estimate for that interval and the overwash deposits below it. Inor-

Table 1. Radiocarbon Dates and Calibrated Calendar Age Ranges

Index Number	Laboratory Number	Core	^{14}C Age	Calibrated Calendar Age at 2 Sigma (Probability)	$\delta^{13}C$, ‰	Sample Depth, cm	Material Sampled
1	OS-33646	HB1A	200 ± 35	1644 – 1694 A.D. (0.273) 1727 – 1813 A.D. (0.538) 1838 – 1842 A.D. (0.002) 1853 – 1859 A.D. (0.004) 1861 – 1867 A.D. (0.004) 1875 – 1875 A.D. (0.001) 1918 – 1952 A.D. (0.177)	−11.58	139 – 140	*S. alterniflora* leaf fragment
2	OS-33647	HB1B	910 ± 30	1034 – 1190 A.D. (0.972) 1197 – 1207 A.D. (0.028)	−12.7	170.5 – 171.5	*S. alterniflora* leaf fragment
3	OS-33645	HB3B	330 ± 30	1477 – 1642 A.D. (1.000)	−12.78	89.5 – 91	*S. alterniflora* leaf fragment
4	OS-54303	AI1	610 ± 30	654 – 547 BP (1.000)	−12.19	147 – 148	in situ *S. alterniflora* root
5	OS-50391	AI1	2690 ± 40	2861 – 2747 BP (1.00)	−15.27	358 – 360	*S. alterniflora* leaf fragment
6	OS-46568	LB1	700 ± 35	1257 – 1316 A.D. (0.758) 1354 – 1389 A.D. (0.242)	−12.27	116 – 117	*S. alterniflora* leaf fragment
7[a]	OS-53006	AI1	3140 ± 40	3448 – 3317 BP (0.88) 3308 – 3263 BP (0.12)	−17.11	311 – 312	*S. alterniflora* leaf fragment
8[a]	OS-52843	AI1	3940 ± 50	4522 – 4239 BP (1.000)	−19.02	357 – 358	*S. alterniflora* leaf fragment

[a] Rejected on the basis of comparison with regional sea level data.

ganic material was removed using a >1 mm sieve and sonicated in deionized water for several minutes. Selected macrofossils were removed from the remaining plant material, dried overnight at 105°C, weighed, and sent to the National Ocean Sciences Accelerator Mass Spectrometry (NOSAMS) Facility at Woods Hole Oceanographic Institution for analysis. Ages were converted to calendar year using the Calib5 program [*Reimer et al.*, 2004] and all calibrated age ranges at 2 sigma are reported. In the case of multiple age calibrations, independent pollen and heavy metals dates within a core were used to narrow the possible age range.

[27] Measured rates of local sea level rise were used to further constrain the ages of the sediments and provide insight into inaccurate radiocarbon ages. As sea level rises gradually, marshes in the northeastern United States typically accrete sediments vertically at matching rates through deposition of vegetation and tidally derived mud [*Donnelly et al.*, 2004b; *Orson et al.*, 1998; *McCaffrey and Thompson*, 1980; *Redfield*, 1965, 1972]. The continually rising, long-term (decadal scale or greater) marsh surface provides a timeline for our marsh cores. Sea level data from nearby locations in Great South Bay, NY and Brigantine, NJ provided the local sea level estimate for the past 6000 years [*Stuiver and Daddario*, 1963; *Rampino and Sanders*, 1980]. Salt-marsh accumulation rates have been roughly 1 mm/year over the last millennium at Great South Bay [*Rampino and Sanders*, 1980], similar to other regional reconstructions [*Donnelly et al.*, 2004b]. The New York City tide gauge provided evidence of an average sea level rise rate of 2.8 mm/yr for the years 1857–2001 A.D. [*Donnelly et al.*, 2004b]. A high-resolution sea level reconstruction from eastern Connecticut revealed that the three-fold increase in the rate of sea level rise occurred in the late 19th century [*Donnelly et al.*, 2004b].

[28] These sea level rise measurements provide constraints for assessing radiocarbon dates and for estimating ages in peat units. In situ radiocarbon-dated salt-marsh remains should fall among local sea level data on an age/depth plot given that salt marshes occur in the intertidal zone and accrete vertically to keep pace with sea level rise. Sampling root material can lead to a radiocarbon date that is slightly younger than the surrounding sed-

iment given that the plant material is penetrating into sediment below. When older organic material has been reworked and deposited in the sediment, the resulting radiocarbon age can be far older than and unrepresentative of the surrounding sediment. Therefore radiocarbon-dated salt-marsh remains that plot above local sea level data are likely contaminated with older carbon and were excluded from further analysis.

[29] At Lido Beach Marsh, accretion-rate estimates based on sea level measurements from the New York City tide gauge for the 20th century and combined sea level data from Great South Bay, NY [*Rampino and Sanders*, 1980], Brigantine, NJ [*Stuiver and Daddario*, 1963], and Barn Island, CT [*Donnelly et al.*, 2004b] allowed us to estimate ages of overwash layers preserved in the salt marsh peat in the upper portion of the cores. An estimated accretion-rate range of 2.5–3.0 mm/yr was applied to the most recent 150 years [*Donnelly et al.*, 2004b] and a rate of 1 mm/yr was applied to the preceding ~700 years of the uppermost peat deposit [*Rampino and Sanders*, 1980; *Donnelly et al.*, 2004b].

[30] We estimated ages for Alder Island Marsh on the basis of radiocarbon ages and heavy metals concentrations measured in core AI1. Radiocarbon age validity was tested by plotting the age and depth with accepted local sea level measurements [*Stuiver and Daddario*, 1963; *Donnelly et al.*, 2004b] allowing us to eliminate erroneous dates from age assessments of overwash layers. Regional sea level data [*Stuiver and Daddario*, 1963; *Donnelly et al.*, 2004b] were also used to approximate ages within the peat units as marshes are tied to tidal range.

5. Results

5.1. Stratigraphic Description of Cores

[31] Cores in this study contain similar stratigraphies and are dominantly composed of mud and peat units with *Spartina alterniflora* plant fragments. Four classes of sediment occur in the cores: sand, peat, muddy peat with sand, and mud. Sand layers are composed mainly of well-rounded, well-sorted quartz grains and are found punctuating otherwise fine-grained, organic-rich sediment in all cores. LOI results from cores HB1A, HB1B, HB1D, HB2A, HB3A, HB3B, LB1, and LB2 indicate that all inorganic layers present were noted as sand units during visual description (Figure 6). Sediments composed of less than 10% organic material based on LOI data match intervals described as sand through visual core description. Thin sand units identified in visual description tend to have slightly higher percent organic material (~20%) likely due to sampling resolution which may be measuring sand with some amount of adjacent peat units. In addition, some degree of root penetration through the thin sand layer may have increased the measured organic content. Mud units range from 5–20% organic material and peat units are highly organic, ranging from 20% to 60% organic material. High-resolution grain-size analysis for LB1 and LB2 indicates several thin, coarse-grained layers preserved within peat and mud sediments which were not detected by visual inspection.

5.2. Interpretation of Sedimentary Units

[32] Numerous sedimentary units meet our criteria for identifying overwash deposits. Sand layers punctuate the fine-grained, organic-rich sediment that typifies backbarrier environments in all cores. Sand layers vary in thickness and all visible coarse layers show abrupt lower and gradational upper contacts with surrounding peat and mud. The grain size of sandy units generally ranges from 0.1 to 0.5 mm, corresponding to medium and fine sand. Sparse coarser grains with sizes ranging from 1.5 to 2.0 mm and shell fragments were present in some sand units. Rounded, well-sorted quartz grains typify beach sand and confirm the barrier beach as the likely sediment source. Dark laminations of heavy minerals, including magnetite and garnet, within sand units were observed for Hicks Beach and Alder Island cores. The sand layers preserved in the cores are interpreted as overwash layers given their sedimentary characteristics.

5.3. Overwash Deposits at Hicks Beach

[33] Three overwash layers are evident in core HB1A. This core was dated using a combination of heavy-metal concentrations, pollen biostratigraphy, radiocarbon, and local sea level data. *Ambrosia* (Ragweed) and *Rumex* pollen percentages increase directly above the lowermost sand unit at 95.5 cm from ~1.5% to 8.5% and ~0% to 2.8%, respectively (Figure 7). An abrupt increase in *Poaceae* (Grass) and *Plantago*-undifferentiated pollen coincides with the rise in abundance of *Ambrosia* and *Rumex* pollen around 95.5 cm. Arboreal pollen percentages (i.e., *Pinus*, *Quercus,* and “All Trees and Shrubs”) generally decrease

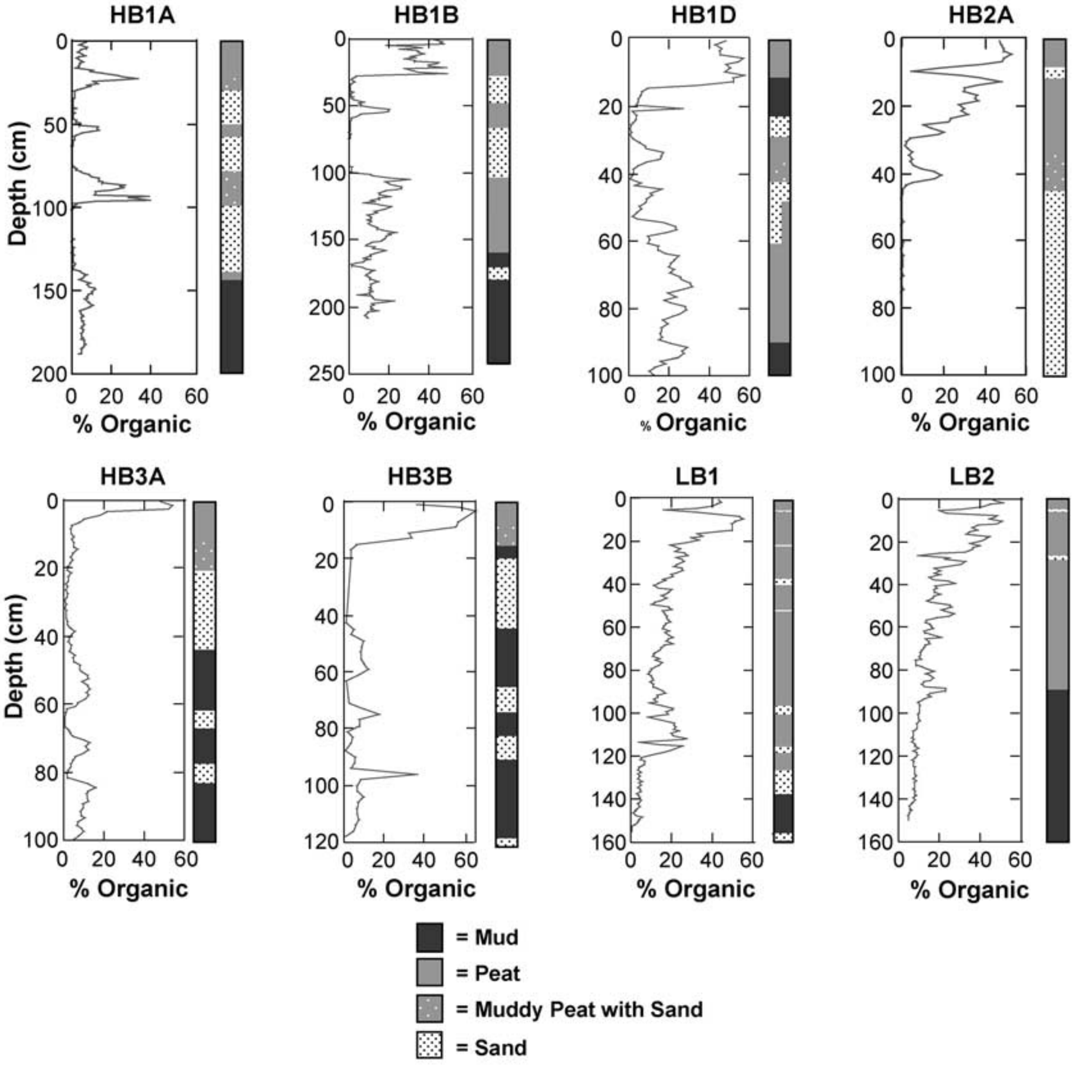

Figure 6. Loss on ignition (LOI) and core descriptions for eight backbarrier cores. Sand layers identified visually typically fall below 10% organic material. Thin sand units identified visually tend to have slightly higher percent organic material (~20%) likely due to sampling resolution which incorporates adjacent organic sediment.

throughout the pollen sequence with an accelerated decline beginning at 95.5 cm. A date of 1700 A.D. (±25) was therefore assigned to 95.5 cm. *Plantago lanceolata* pollen was rare in core HB1A and appears only at 56.5 cm (1.8%) and 83 cm (0.6%) depth, straddling the core's middle overwash deposit and providing a date of the early 19th century at 83 cm (Figure 7). Above the uppermost overwash layer, *Castanea* (Chestnut) pollen declines from 3.3% to nearly zero above 30.5 cm depth and justifies assigning a date of 1915 A.D. (±5) to 30.5 cm. (Figure 7).

[34] The heavy metal concentrations in core HB1A increase at about 58 cm, allowing us to assign an age of 1860 A.D. (±20) to this depth (Figure 8). Lead and copper concentrations in core HB1A remain low between 186 cm and 58 cm depth with lead concentrations between 10 to 30 ppm and copper concentrations around 2 ppm (Figure 8). Lead concentrations begin to rise below the uppermost sand layer at 58 cm with a concentration of 71 ppm and peak at 24 cm at 235 ppm. Copper concentration shows a similar rise beginning at 58 cm with a concentration of 8 ppm and a peak of 85 ppm at 24 cm. Although lead and copper

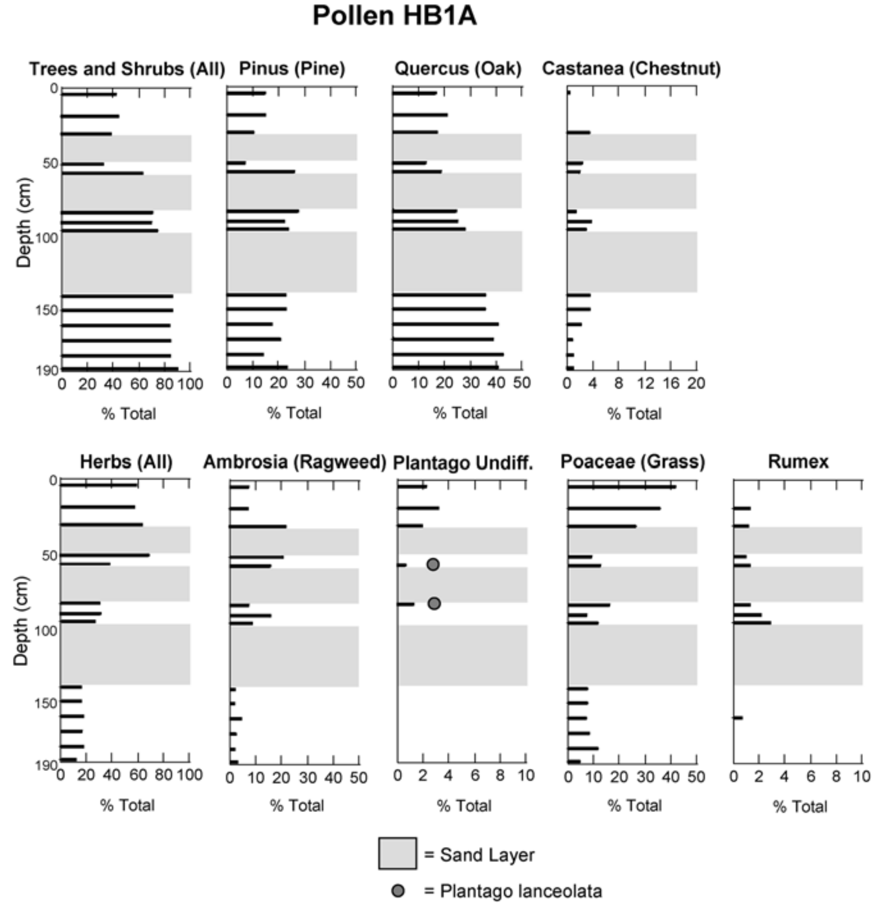

Figure 7. Results of pollen analysis on Hicks Beach core HB1A show an increase in agricultural indicators (~1700 A.D. ± 25), the first appearance of the introduced species *Plantago lanceolata* in the early 1800s, and a decline in *Castanea* (Chestnut) pollen associated with the Chestnut Decline in the early 20th century. Sand layers are indicated with gray shading.

concentrations decrease in the uppermost part of HB1A, the concentrations remain elevated over early historical and prehistoric levels (Figure 8).

[35] The radiocarbon age obtained from the plant remains at the base of the lowermost sand layer (139–140 cm) of core HB1A is 200 ± 35 years (index number 1, Table 1). Calibrating this radiocarbon date at 2 sigma results in seven calendar date ranges: 1644–1694, 1727–1813, 1838–1842, 1853–1859, 1861–1867, 1875–1875, and 1918–1952 A.D. Only the 1644–1694 date range is consistent with pollen and heavy metals results for HB1A and therefore this age range is assigned to the base of the lowermost sand layer (Figure 9).

[36] Core HB1A's three overwash deposits are consistent with the documented 1893, 1821, and 1693 hurricanes on the basis of pollen stratigraphy, heavy metals concentrations, and radiocarbon dating (Figure 9). Historical accounts indicate that these three storms were the most likely to overtop the barrier beaches in western Long Island, with winter storms and less-intense hurricanes resulting in less damage and lower water levels. With the decline in *Castanea* pollen percentages (1915 A.D. ± 5) above the uppermost sand layer and the rise in heavy metals below (1860 A.D. ± 20), the sand unit likely corresponds to the 1893 hurricane (Figure 9). The middle sand layer is bracketed by a rise in heavy metals above (1860 A.D. ± 20) and the appearance of invasive *Plantago lanceolata* below (~1800 A.D.), and likely corresponds to the 1821 hurricane overwash deposit (Figure 9). The lowermost sand layer is bracketed by the rise in agricultural pollen indicators above (1700 A.D. ± 25) and a radiocarbon date of 1644–1694 A.D. below. The age constraints on the lowermost sand layer are consistent with the 1693 hurricane (Figure 9). With no observed layer between the

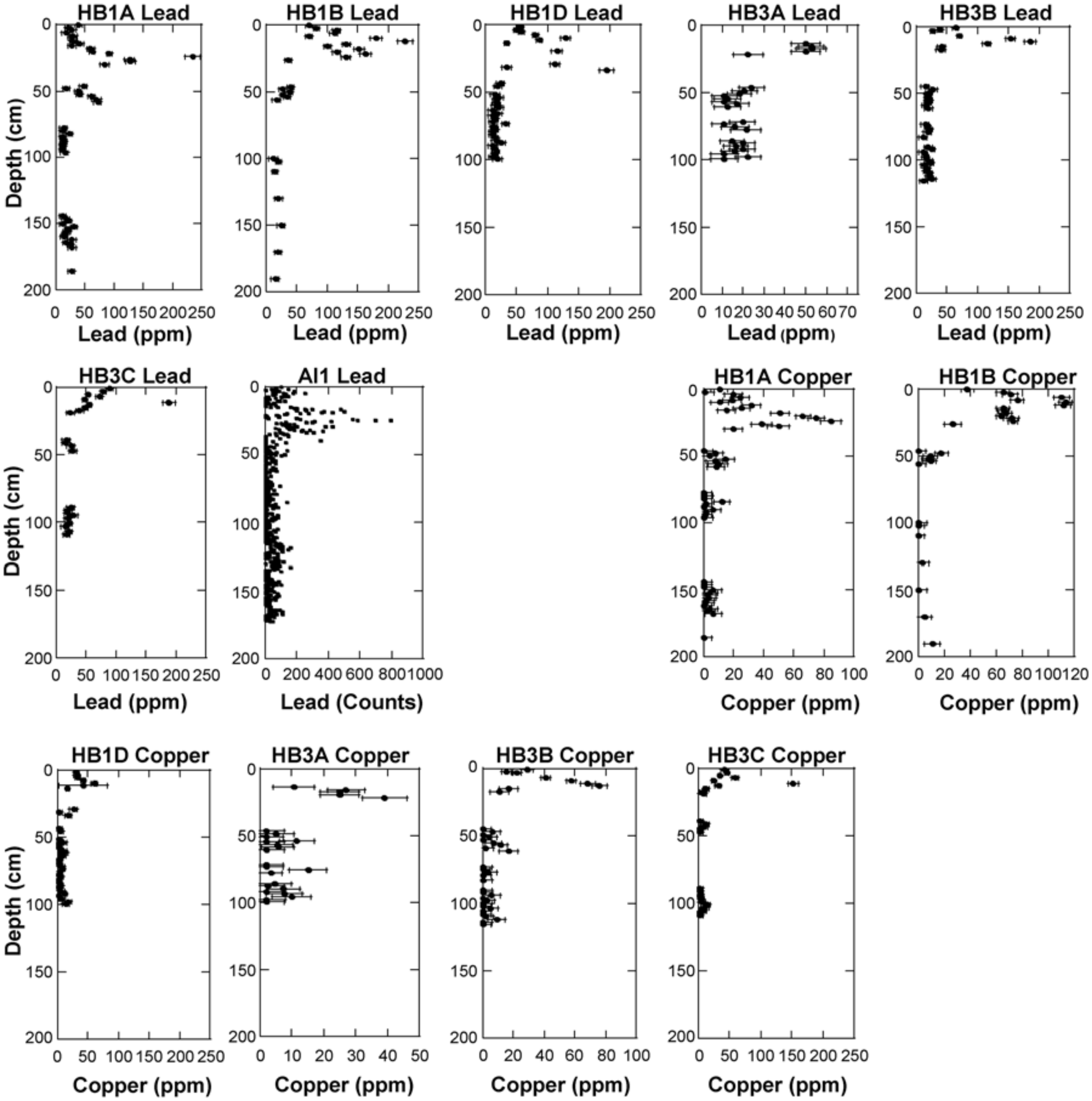

Figure 8. Heavy-metal (lead and copper) concentrations for seven cores. The initial increase in heavy-metal concentrations corresponds to the industrial revolution and dates to 1860 A.D. ± 20.

1693 and 1821 units, the small and fast moving 1788 hurricane [*Thompson*, 1843] is not likely recorded in this core (Figure 9). The consistency of HB1A's sand layers with the documented hurricanes for this area confirms that the marshes are recording only the most intense storms. (Figure 9)

[37] Heavy-metal concentrations and radiocarbon dates provide ages for additional Hicks Beach Transect 1 cores and allow for correlation. Lead and copper begin to increase above background concentrations in core HB1B at 49 cm and lead concentrations increase around 35 cm in core HB1D (Figure 8). Heavy metals (1860 A.D. ± 20) in these Transect 1 cores increase directly below the uppermost sand layer and above a deeper sand layer and provide evidence for the 1893 and 1821 hurricane overwash deposits (Figure 9). The core stratigraphies in Transect 1 are similar to HB1A, allowing for confident correlation of the 1693 hurricane overwash layer across cores, with no evidence of the 1788 hurricane (Figure 9). A radiocarbon date of 910 ± 30 was observed for the base of core HB1B's lowermost sand layer at 170.5–171.5 cm (index number 2 in Table 1; Figure 9). The calibrated age range for this date

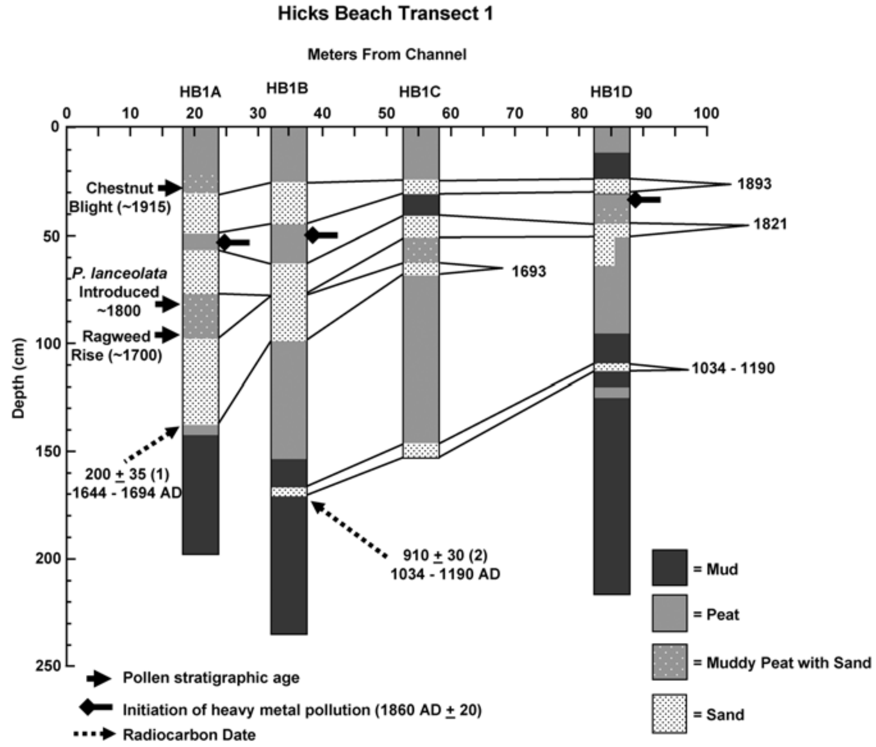

Figure 9. Core stratigraphies for Hicks Beach Transect 1 are shown with chronostratigraphic results of pollen shifts, heavy metals, and radiocarbon dates. Correlations of sand layers based on available age constraints and visual inspection are shown.

is 1034–1190 A.D. at 2 sigma (97% confidence) and matches layers in cores HB1C and HB1D on the basis of visual correlation (Table 1 and Figure 9). This sand layer corresponds to a prehistoric storm, likely a hurricane, at Hicks Beach occurring between 1034 and 1190 A.D.

[38] In Hicks Beach Transect 3, heavy-metal concentrations in cores HB3A, HB3B, and HB3C increase initially above the uppermost sand layers at 20 cm, 17 cm, and 15 cm depth, respectively (Figures 8 and 10). The heavy metals results indicate that the uppermost sand layer for Transect 3 is likely the 1821 overwash deposit (Figure 10). With no overwash layers above the lead pollution horizon in Transect 3 cores, the overwash for the 1893 hurricane may not have reached this section of the marsh (Figure 10). On the other hand, a layer of "muddy peat with sand" is visible above the heavy metals rise in Transect 3 and may represent a less substantial overwash layer that was deposited by the 1893 hurricane in this area (Figure 10). The radiocarbon sample taken from the base of the lowermost overwash deposits in core HB3B has an uncalibrated age of 330 ± 30 and a calibrated range of 1477–1642 A.D. at 2 sigma (index number 3 in Table 1, and Figure 10). This early overwash layer is likely present in HB3A as well on the basis of visual correlation (Figure 10) and provides evidence either of the 1693 hurricane or a prehistoric storm affecting Hicks Beach around the 16th century A.D. (Figure 10). If the layer in question corresponds to the 1693 hurricane, then the layer above may correspond to the 1788 hurricane. More dating is necessary to sort out the chronology in Transect 3. Age constraints were not obtained for Transect 2; however, the stratigraphic similarities between this transect and Transects 1 and 3 indicate that overwash deposits likely match historical storms and possibly a prehistoric storm.

5.4. Overwash Deposits at Alder Island

[39] At Alder Island, overwash deposits constrained in age by lead concentrations and radiocarbon dates are consistent with historical storms and reveal a longer history of prehistoric storms. Lead (relative counts) measured for Alder Island core AI1 increases initially at 33 cm depth, directly above the uppermost sand layer (Figure 8). Although no pollen data are available to constrain the

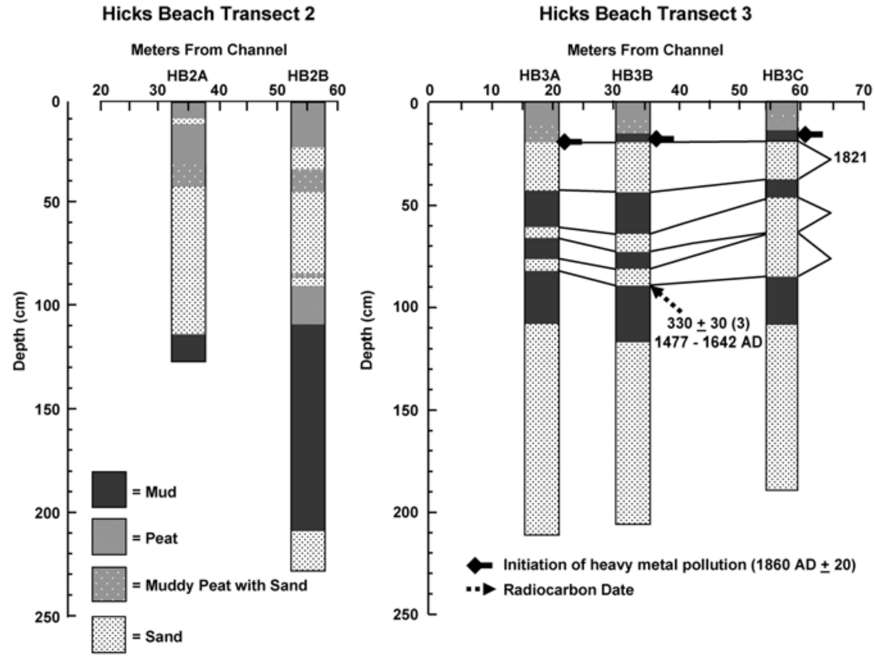

Figure 10. Core stratigraphies for Hicks Beach Transects 2 and 3 are shown with chronostratigraphic results of heavy metals and radiocarbon dates. Correlations of sand layers based on available age constraints and visual descriptions are shown.

layer from below, the increase in lead and copper directly above is consistent with this layer being deposited by the 1821 hurricane which occurred just prior to the industrial revolution (1860 A.D. ± 20). The 1893 overwash deposit is not recorded at core AI1; however, age estimates based on regional sea level data [*Stuiver and Daddario*, 1963; *Donnelly et al.*, 2004b] suggest that core AI3 may record the 1893 hurricane (Figure 11). Additionally, accretion-rate estimates based on local and regional sea level data [*Stuiver and Daddario*, 1963; *Donnelly et al.*, 2004b] indicate that sand layers beneath the 1821 overwash roughly correspond to the late 18th and 17th centuries and were likely deposited by the 1788 and 1693 hurricanes (Figure 11).

[40] Seventeen sand layers present deeper in core AI1 provide evidence of two intervals of frequent overwash deposition that occur at 170–300 cm (9 layers) and 385–430 cm (8 layers) surrounded by long intervals of uninterrupted backbarrier sediments (Figure 11). Four radiocarbon samples were selected from core AI1 to bracket the intervals with numerous sand layers. Samples taken at 147–148, 311–312, 357–358, and 358–360 cm depth are dated in radiocarbon years to 610 ± 30, 3140 ± 40, 3940 ± 50, and 2690 ± 40, respectively (Table 1). Calibrating these dates provides calendar ages of 654–547, 3448–3317 (88% confidence), 4522–4239, and 2861–2747 cal yr B.P. (index numbers 4, 7, 8, and 5, respectively, in Table 1). Organic material dated from 311–312 and 357–358 cm depth (index numbers 7 and 8) was likely contaminated with older terrestrial material given that the ages are significantly older than sea level indicators from a similar depth [*Rampino and Sanders*, 1980; *Stuiver and Daddario*, 1963] and have more-negative delta 13C values (Figure 12 and index numbers 7 and 8 in Table 1). These delta 13C values, −17.11 and −19.02 for index points 7 and 8, respectively, indicate that the samples likely contain a mixture of C3 and C4 (e.g., *S. alterniflora*) plant remains. Thus the samples were likely contaminated with older C3 plant remains. The two outlier dates (index numbers 7 and 8 in Table 1) were excluded from age assessments in AI1 (Figure 12).

[41] Radiocarbon sample number 4 provides a minimum age for the end of the active interval (170–300 cm) with an age of around 600 cal yr B.P. (Figure 11). Because this sample was composed of in situ root material and was collected from around 20 cm above the active interval, this radiocarbon age is likely a few hundred years

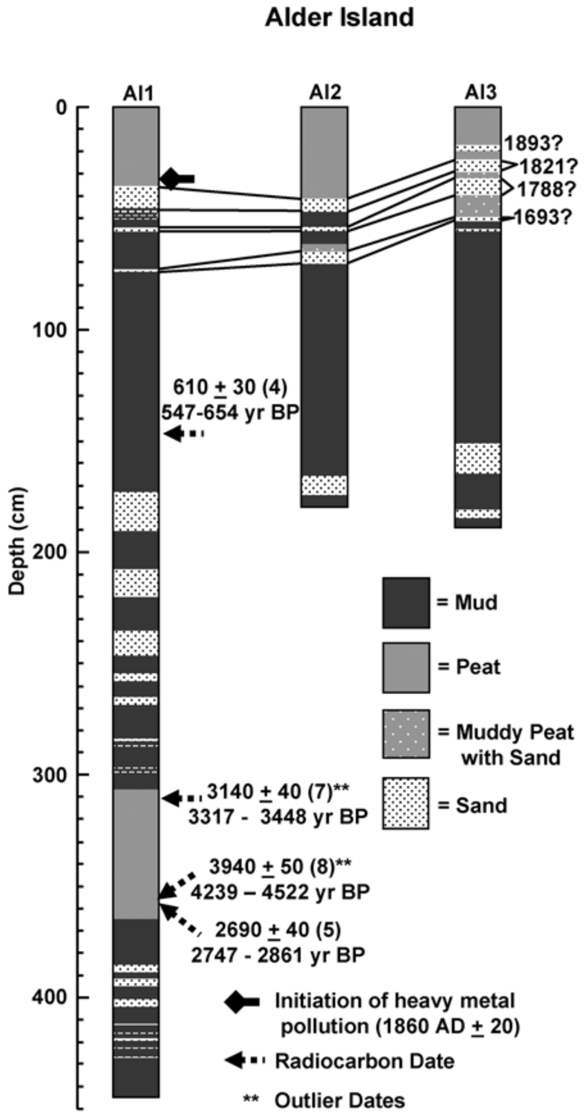

Figure 11. Core stratigraphies for Alder Island are shown with chronostratigraphic results of heavy metals pollution and radiocarbon dates. Correlations of sand layers based on available age constraints and visual descriptions are shown (see Figure 12).

younger than the actual end of the active period. According to these approximations, the termination of the proposed active period likely dates to around 900 cal yr B.P. The lower radiocarbon sample number 5, with an age of around 2800 cal yr B.P., helps to constrain the onset of the proposed active period (Figure 11). Given that this age is within a high marsh peat unit (accreting in near equilibrium with sea level rise), regional sea level data [*Stuiver and Daddario*, 1963; *Donnelly et al.*, 2004b] can be used to extrapolate an age closer to the period's onset. As roughly 50 cm of peat accumulated after about 2800 cal yr B.P. at a rate of approximately 1 mm/year (in order to keep pace with sea level), the upper part of the peat unit likely dates to around 2300 cal yr B.P. Thus the age of the period of frequent washover deposition in AI1 is likely about at 2200 to 900 cal yr B.P. (Figure 11). The deeper interval of overwash may be evidence of a similar interval of more frequent hurricane-induced deposition, which occurred prior to 2800 cal yr B.P. (Figure 11). The results from AI1 are tentative given that few radiocarbon constraints exist and the observed pattern in hurricane activity needs to be verified in additional long cores from the study area.

5.5. Overwash Deposits at Lido Beach

[42] The cores from Lido Beach are similar to those from Alder Island and Hicks Beach. Accretion-rate estimates at Lido Beach (2.5–3 mm/yr for the last 150 years and 1 mm/yr for the preceding ~700 years in the uppermost peat unit) provide insight into the ages of sand layers in the uppermost peat unit. The thin, uppermost sand layer

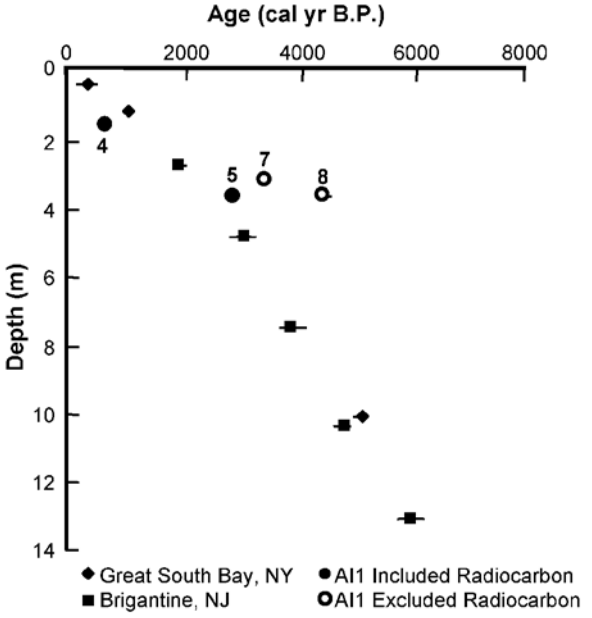

Figure 12. Alder Island radiocarbon dates are plotted with sea level data from Great South Bay, NY (d in Figure 2) [*Rampino and Sanders*, 1980], and Brigantine, NJ (b in Figure 2) [*Stuiver and Daddario*, 1963]. Two Alder Island radiocarbon dates (open circles, index points 7 and 8) fall above the local sea level data, indicating that samples contain older, reworked organic material. We excluded these samples from our age model.

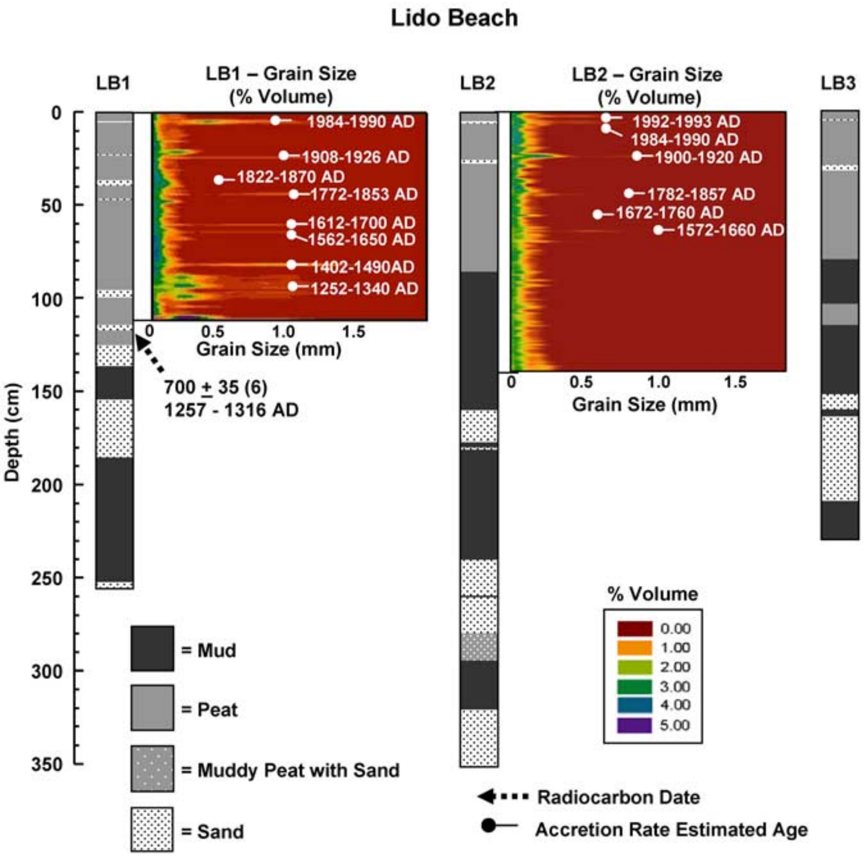

Figure 13. Core stratigraphies for Lido Beach are shown with a radiocarbon date and high-resolution grain-size results. These contour plots of grain size show changes in percent volume of each grain size with depth. Red represents zero percent volume, and purple represents five percent volume. Ages of coarse layers estimated from the age model are shown in white on the grain size plots.

observed at Lido Beach at 4 cm is most likely related to either Hurricane Gloria in 1985 or the northeaster which occurred in March of 1984 with storm surges of 1.7 m and 1.8 m, respectively, based on sea level accretion-rate estimates and water-level data (Figure 5 and Figure 13). Accretion rates also indicate that sand layers preserved in Lido Beach cores at around 24–25 cm may correspond to the 1893 hurricane, considering age uncertainty (Figure 13). In addition, two sand layers found in LB1 at 39–40 cm and 45–46 cm in core LB1 likely correspond to the 1821 and 1788 hurricanes, respectively, on the basis of accretion rates (Figure 13). A deeper sand layer in LB1 at 95cm dates to 1252–1340 A.D. on the basis of accretion rates, providing evidence of a prehistoric storm at Lido Beach. A radiocarbon age of 700 ± 35 years was obtained from the base of a sand layer at 116–117 cm in core LB1 and calibrates to 1257–1316 A.D. at 2 sigma (index number 6 in Table 1, and Figure 13). This overwash layer in core LB1 provides evidence of an additional prehistoric storm, and at least two sand layers below this date indicate that additional prehistoric storms are recorded.

[43] The high-resolution grain-size analysis of the LOI ash revealed several additional coarse layers in upper portions of LB1 and LB2. Percent volume of grain-size classes are shown on a color scale with red corresponding to 0% volume and purple corresponding to 5% volume (Figure 13). Estimated accretion rates based on regional sea level reconstructions (2.5–3 mm/yr for the last 150 years and 1 mm/yr for the preceding ~700 years in the uppermost peat unit) indicate that ages of coarse layers are consistent with known hurricanes including the 1693 hurricane at 60–61 cm in core LB1 and 54–55 cm in core LB2 as well as the 1821 (possibly 1788) hurricane at 43–45 cm in core LB2. Several coarse layers are observed

deeper in the core and may correspond to prehistoric storms. In addition, a coarse layer observed at 2 cm in core LB2 may be related to the northeaster of 1992 (December) given accretion-rate age estimates and water-level data which indicate a 2.2 m storm surge (Figures 5 and 13). Layers which appear only in high-resolution grain-size analysis may be the result of less-intense or near-miss storms given that the layers are more subtle and cannot be observed through visual assessment. Moderate storm surge through inlets and tidal creeks and high winds accompanying storms have the potential to transport a small amount of sediment into the backbarrier without overtopping the barrier. Such alternative means of sediment transport may explain these subtle coarse layers observed in Lido Beach cores.

5.6. Overwash Deposit Summary

[44] In sum, Hurricane Gloria (1985) is likely recorded in the Lido Beach cores but is not observed at Alder Island or Hicks Beach. Hurricane Gloria struck at low tide, passed directly to the east of the study sites, and produced a moderate storm surge of 1.7 m on the western side of the storm. Lido Beach Marsh's proximity to the ocean and possibly lower dune heights may have allowed this storm to overtop the barrier locally; however, the lack of overwash at Hicks Beach and Alder Island indicates that Hurricane Gloria did not result in widespread overtopping of western Long Island's barrier beaches. Deposits likely related to the 1893 hurricane are not observed in all cores, but are preserved at several cores from Hicks Beach, Lido Beach, and possibly core AI3 at Alder Island (Figure 14). Deposits attributable to the 1821 hurricane are present in nearly all cores from the three study sites indicating that the hurricane had widespread effects on the western Long Island coast (Figure 14). Evidence of the 1788 hurricane is somewhat limited in cores analyzed in this study, and only Lido Beach and Alder Island likely record this event (Figure 14). On the basis of the extent of the preserved overwash deposits, the 1693 hurricane deposit may have had a somewhat wider and more consistent impact on western Long Island than the 1788 hurricane; however, our study's relatively limited spatial sampling requires caution in this interpretation. According to historical accounts [*Ludlum*, 1963], the 1788 hurricane was a small and fast moving storm with an extremely brief period of high winds. The short-lived winds may not have provided the energy necessary to build a storm surge high enough to overtop all sections of the barrier beach in western Long Island.

[45] Deeper sand deposits indicate that a number of prehistoric overwash layers are preserved at the study sites. Some of these prehistoric overwash layers are not consistent across the three marsh locations, suggesting that these storms may have been near-miss or less-intense storms that overtopped the barrier in localized areas, producing overwash lobes as opposed to sheet overwash. Other prehistoric overwash layers may appear across sites, such as the layers at Hicks Beach and Alder Island that date to roughly the 11th century A.D. Further dating is necessary to determine whether prehistoric overwash layers are extensive deposits resulting from intense storms or more localized overwash fans. Alder Island core AI1 records numerous prehistoric overwash deposits including two intervals of relatively frequent overwash, one tentatively dated to 2200 – 900 cal yr B.P. and the second dated to prior 2800 cal yr B.P. (Figure 11). The cores from Hicks Beach, Lido Beach, and Alder Island marshes record little overwash activity between around 900 and 250 cal yr B.P. which is consistent among the study sites, suggesting that this region experienced fewer major storms during this time.

6. Discussion

6.1. Site Sensitivity Through Time

[46] The study sites appear to be sensitive to only the most severe hurricanes in western Long Island. The strong agreement between the sedimentary record and historically documented hurricanes show that the barrier system has acted as a filter, overtopped extensively only by exceptionally high storm surges. If we assume that the low sensitivity of the marsh sites was constant through time, the cores presented here provide a ~3500 year record of western Long Island's most severe hurricanes.

[47] Barrier coasts are dynamic systems and differences in backbarrier sensitivities can result from several factors including sea level, sediment-supply, inlet, and barrier-elevation changes [*Donnelly and Webb*, 2004; *Rampino and Sanders*, 1981; *Hennessy and Zarillo*, 1987]. Sea level rise can increase the sensitivity of backbarrier study sites by moving the shoreline farther inland and narrowing the barrier beach though time. While sea level has been rising during the study period, nearby Fire Island, and possibly the barriers fronting our study site, have largely remained stationary

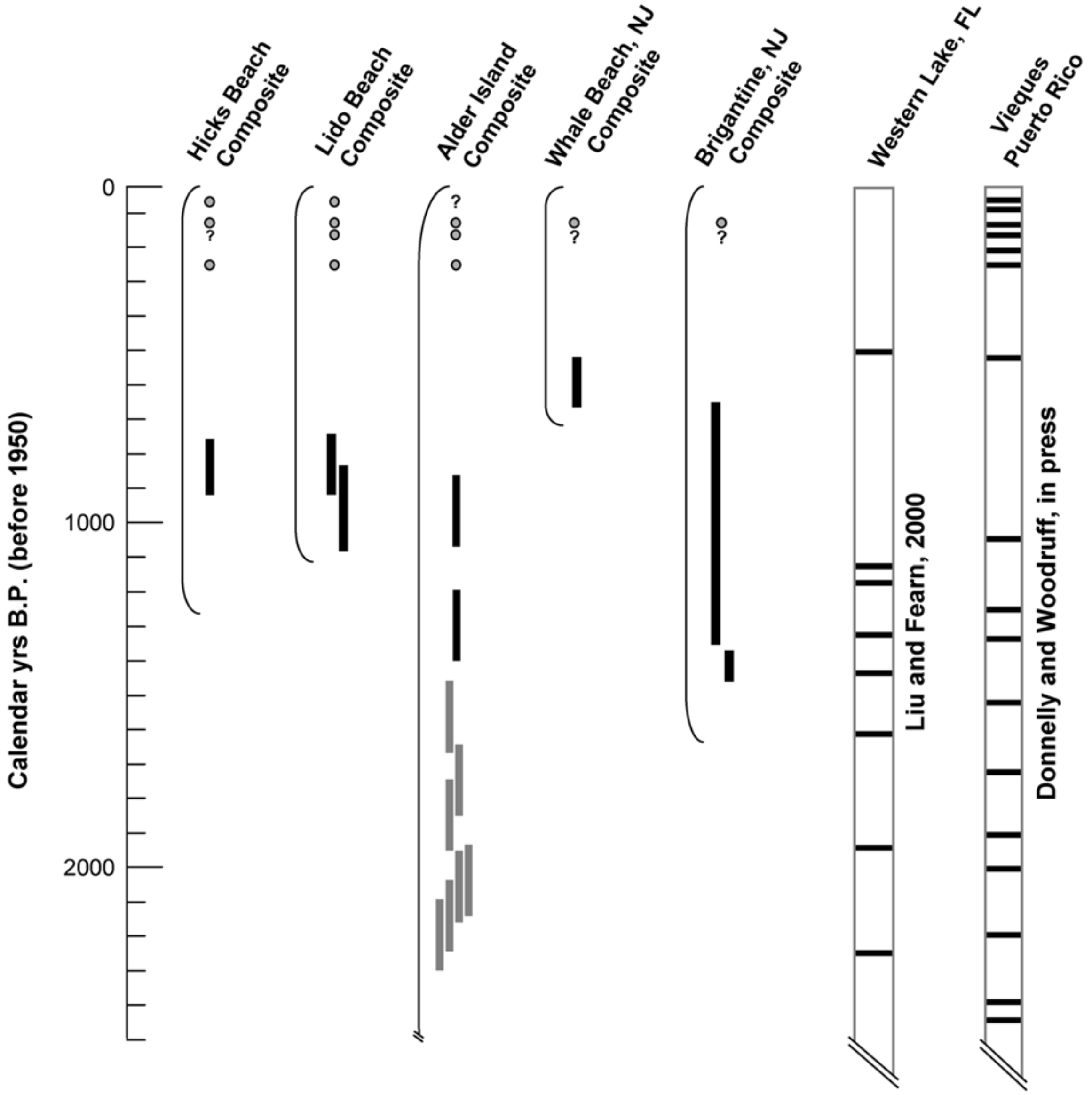

Figure 14. Records of overwash among the three sites in western Long Island (Hicks Beach, Lido Beach, and Alder Island marshes) and two southern New Jersey sites (Brigantine (b in Figure 2) and Whale Beach (c in Figure 2)). Gray dots represent deposits attributed to severe historical hurricanes. Black bars represent likely age range of prehistoric deposits replicated in multiple cores. Gray bars are the likely age range of prehistoric deposits recovered in only AI1. The bracket represents the approximate length of each record. Question marks indicate that a sediment record related to a historical severe hurricane was recovered in only one core or could not be distinguished from another historical severe-hurricane deposit. On the right, the timing of washover deposits attributed to intense hurricane landfalls from the N. Gulf Coast and Vieques, Puerto Rico, are depicted. The ages of these layers are derived from linear interpolation of the multiple calibrated radiocarbon ages from each core. All events are plotted on a scale of years B.P. (Before Present), with "Present" corresponding to 1950 A.D.

over the last thousand years [*Leatherman*, 1983]. However, drowned backbarrier estuarine deposits recovered off the New Jersey [*Stahl et al.*, 1974] and Long Island [*Rampino and Sanders*, 1980, 1981] coasts indicate that the barrier complexes of New Jersey and New York existed in the early Holocene many kilometers seaward of their current position. Given the age and location of these deposits 2 km seaward of the current barrier [*Rampino and Sanders*, 1980, 1981], the barrier systems of western Long Island have transgressed landward over the last 7000 years at an average rate of 0.28 m per year. Analyses of aerial photographs and charts from Whale Beach, NJ revealed barrier transgression rates of about 2 m per year over the last 150 years [*Donnelly et al.*, 2001b]. Thus it is likely that the barriers fronting the backbarrier study sites have translated landward over the last several thousand years potentially increasing the sensitivity of the sites to washover deposition (Figure 1).

[48] Opening and closing inlets have the potential to change the backbarrier's sensitivity to storm-induced deposition, with nearby active inlets exposing the backbarrier to higher energy during storms [*Donnelly et al.*, 2001a; *Warren and Niering*, 1993]. The more numerous nearby tidal inlets depicted by historical maps from the 19th century show that the backbarrier areas of Hicks Beach and Alder Island may have had a higher sensitivity to storm energy during that time than in the 20th century. On the other hand, the presence of an inlet adjacent to Alder Island since at least 1811 indicates that site may have experienced a constant sensitivity to storm surge and waves over this time period. Lido Beach was protected by a barrier beach over the last two centuries and, as a result, overtopping of the barrier by storm surge and waves was necessary to deposit overwash layers on the backbarrier marsh. While the presence of numerous tidal inlets can increase the backbarrier's sensitivity to overwash, the number of these inlets may be tied to changes in storm activity. Storms often form new tidal inlets and the greater number of inlets in western Long Island during the 19th century may have been the result of increased storminess.

[49] Spatial and temporal variability in barrier beach height can further complicate the sedimentary record of storms, varying the sensitivity of backbarrier locations [*Donnelly and Webb*, 2004]. For example, a lower elevation for the barrier beach would increase sensitivity of the backbarrier to storm energy by allowing lower storm surges to overtop the barrier. Additionally, when a major hurricane overtops the barrier, its elevation is typically lowered and may require time to rebuild. If subsequent storms occur before barrier beach recovery, weaker storms can overtop the lowered barrier more easily.

[50] Furthermore, the distance of a marsh from the barrier likely affects its sensitivity to storm surge, with marshes located farther from the barrier receiving overwash sediment during only the most intense events. In this study, two of the marsh study sites (Hicks Beach and Alder Island marshes) are separated from the barrier island by a channel which may sequester overwashed sediment. Lido Beach Marsh, on the other hand, is located on the back side of the barrier island, closer to the shoreface than Hicks Beach and Alder Island. This geographic distinction has been present since at least 1811 (Figure 4) and may indicate that Lido Beach has had a higher sensitivity than Hicks Beach and Alder Island marshes. Similarity in overwash records among the three study sites supports the notion that major storms with high surges do transport coarse sediment to all backbarrier areas. The preservation of thin overwash laminae at Lido Beach Marsh that are related to lesser storms may be due to a higher sensitivity given its proximal location to the shoreface.

[51] The record of past storm occurrences can be complicated by coastal dynamics; however, the mud and peat sediment types appearing throughout the record show that these areas were experiencing quiescent sedimentation during at least the past $\sim$3500 years, indicating that the study sites were likely protected behind the barrier system over that time. Finally, the close agreement between documented intense hurricanes and the recent sedimentary record in western Long Island indicates these backbarrier marshes have been sensitive to overwash deposition associated with the strongest landfalling hurricanes impacting the area.

[52] Another confounding factor arises when two storms deposit coarse sediment in a relatively short time period, such as within the same decade [*Donnelly and Webb*, 2004]. Individual events can be identified only when separated by a layer of backbarrier sediment. If marsh re-growth and mud deposition has not resumed or if erosion of backbarrier sediment occurs, two overwash deposits can appear as a single sand unit. Two such interpretations are made for cores HB3C (Figure 10) and HB1B (Figure 9) where two storms may be represented by a single sand unit.

6.2. Region-Wide Comparison

[53] Several hurricanes recorded in the coastal sediments of western Long Island likely had region-wide effects. A core collected from Fresh Pond Marsh on the north shore of Suffolk County, Long Island contains a sand layer that is consistent with the 1821 hurricane on the basis of pollen stratigraphy and ^{210}Pb chronology which constrains the layer to between 1800 and 1880 A.D. [*Clark and Patterson*, 1985]. The records at Whale Beach and Brigantine marshes in southern New

Jersey contain overwash deposits that are consistent with the 1821 hurricane (Figure 14); however, dating uncertainty at Brigantine and Whale Beach marshes cannot eliminate the 1788 hurricane as the cause of the deposit [*Donnelly et al.*, 2004a]. Whale Beach preserves a prehistoric storm deposit dated to 1278–1438 A.D. which may correspond to the overwash in western Long Island of similar age (possibly corresponding to prehistoric layers in the 13th and 14th centuries A.D. at Lido Beach) (Figure 14). Brigantine Marsh records evidence of two prehistoric storms with overwash deposits above and below a date of ~600 A.D. These overwash deposits at Brigantine Marsh may correlate with deeper layers at Lido Beach and Alder Island (Figure 14). Deposits associated with the hurricanes of 1893 and 1693 are not observed in sites studied in southern New Jersey (Figure 14). The 1821 hurricane likely had region-wide effects on the basis of the spatial consistency and extent of the overwash deposits (Figure 14). Further dating is needed to determine if individual prehistoric storm events can be correlated among sites. In general, the cores from Hicks Beach, Lido Beach, Alder Island, and Brigantine marshes show little overwash activity between around 900 and 250 cal yr B.P. suggesting that this region experienced few major storms during this time (Figure 14).

6.3. Hurricane Activity During the Little Ice Age

[54] Hurricanes derive much of their energy from warm ocean waters and only form where sea surface temperature (SST) is above 26°C. Recent work analyzing data from the past 30–35 years shows that an increase in global and regional SSTs correlate with an increase in the number and proportion of storms reaching Category 4 and 5 strength [*Webster et al.*, 2005; *Emanuel*, 2005]. The relationship between hurricanes and SST indicates that cooler climate conditions in the past may have resulted in fewer strong hurricanes. Interestingly, several major hurricanes occur in the western Long Island record during the latter part of the Little Ice Age (~1550–1850 A.D.) when SSTs were generally colder than present. According to paleoclimate estimates, SSTs were likely 2°C cooler than present in the Caribbean [*Winter et al.*, 2000; *Watanabe et al.*, 2001], 1°C cooler than present in the Florida Keys during the latter part of the Little Ice Age [*Druffel*, 1982], and 1°C cooler than present during the 17th and 18th centuries at the Bermuda Rise [*Keigwin*, 1996]. The frequent occurrence of major hurricanes in the western Long Island record suggests that other climate phenomena, such as atmospheric circulation, may have been favorable for intense hurricane development despite lower SSTs.

6.4. Millennial-Scale Hurricane Activity

[55] The longest core recovered from western Long Island, core AI1, may provide initial evidence of major changes in hurricane landfalls in western Long Island over the past ~3500 years. Numerous sand layers preserved in this core are tentatively dated to 2200–900 cal yr B.P. and pre - 2800 cal yr B.P. (Figure 11). Cores from Hicks Beach, Lido Beach, and Brigantine marshes show a similar pattern with little overwash activity recorded between ~900 and 250 cal yr B.P. (Figure 14). The relatively active periods in western Long Island likely fall within the period of high hurricane frequency in the northern Gulf Coast which occurred during ~3650–930 cal yr B.P. [*Liu and Fearn*, 2000; *Liu*, 1999; *Elsner et al.*, 2000] (Figure 14). The possible synchroneity between the records from western Long Island and the northern Gulf Coast provides evidence that a millennial-scale spatial see-saw pattern of atmospherically-driven hurricane tracks, as proposed by *Liu and Fearn* [2000], may not be a major climate mechanism forcing changes in hurricane landfall. Instead, the similarity of these two distant regions may indicate that overall frequency of intense hurricanes in the western North Atlantic fluctuated on millennial timescales. In addition, a sedimentary overwash record from Vieques, Puerto Rico similarly records a period of high hurricane activity between 2500–1000 cal yr B.P. [*Donnelly and Woodruff*, 2007].

[56] If millennial-scale changes in Atlantic, Gulf of Mexico, and Caribbean hurricane frequency have indeed occurred in the past, these changes were likely climatically driven and the shoreline may have responded differently during the active periods. Additional work is necessary to determine if the millennial-scale pattern of hurricane frequency observed in western Long Island is indeed representative for the northeastern United States. The long-term fluctuations in hurricane activity observed in the Gulf Coast, Caribbean, and potentially western Long Island are not likely global in scale given that a study from the Great Barrier Reef indicates a constant 200–300 year recurrence interval throughout the past 5000 years and shows little evidence of active or inactive periods [*Nott and Hayne*, 2001]. A complete understanding of

the relationship between climate fluctuations, hurricane activity, and the coastal response will be crucial to predicting the impacts of future climate change.

7. Conclusions

[57] A record of hurricane landfall is preserved in backbarrier marshes of the New York City area. This region has been impacted by numerous strong hurricanes during the last ~3500 years even though no major hurricanes have impacted this area since 1893. Widespread storm-induced deposits preserved in backbarrier sediments indicate the likely preservation of washovers corresponding to the 1893, 1821, 1788, and 1693 hurricanes. The 1821 (possibly 1788) hurricane caused region-wide overwash from western Long Island to southern New Jersey. A localized overwash deposit is recorded at one marsh that corresponds to Hurricane Gloria which occurred in 1985 with a moderate storm surge. Coarse layers preserved likely correspond to prehistoric storms and more work is necessary to determine their spatial consistency across study sites. An apparent lull in intense hurricane landfalls prior to the historic record is evident in cores from the three study sites as well as southern New Jersey, indicating that a period of infrequent hurricane landfall may have occurred in the region between about 900 cal yr B.P. and 250 cal yr B.P. (i.e., 1693 A.D.). Despite significantly cooler than modern SSTs in the Atlantic during the latter half of the Little Ice Age, the frequency of intense hurricane landfalls increased during this time. The relatively quiescent interval spans times with relatively cool and warm Atlantic SSTs.

[58] The longest record from western Long Island reveals intervals of more frequent overwash deposition punctuating intervals of quiescent backbarrier sedimentation. Alternating periods of quiescent conditions and frequent hurricane landfall are recorded in the sedimentary record and likely indicate that climate conditions may have modulated hurricane activity on millennial timescales. Although additional records are necessary to test this hypothesis, the possible synchroneity of increased storm activity in western Long Island (2200–900 cal yr B.P. and pre 2800 cal yr B.P.) and the northern Gulf Coast (~3650–930 cal yr B.P.) suggests that landfall patterns may be caused by overall increases in storm frequency and are not simply due to changing hurricane tracks.

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